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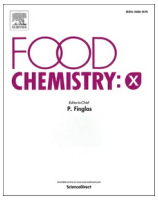

Changes provoked by altitudes and cooking methods in physicochemical properties, volatile profile, and sensory characteristics of yak meat

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ABSTRACT

The present study aimed to shed light on the effects of altitudes and three cooking methods (boiling, steaming, and roasting) on the physicochemical quality, volatile profile, and sensorial characteristics of yak meat. Composite meat samples were prepared to represent each cooking method and altitude level from the *longissimus thoracis et lumborum* (LTL) muscle of nine yaks. The techniques employed were gas chromatography-mass spectrometry (GC–MS) and electronic nose (E-nose) along with chemometrics analysis to study the changes occurring in yak volatile profile, and TBARS measurement in lipid oxidation during cooking. Among the cooking methods, boiling and steaming exhibited higher protein and fat content while lower volatile compound contents. Additionally, roasted yak meat received the highest sensory scores, along with decreased L^*-values, while elevated a^*- and b^*-values, and tenderness. A total of 138 volatile compounds were detected, and among them, 36 odorants were identified as odor-active compounds in cooked yak meat. It is evidenced that low-altitude yak presented more complex and richer flavor profiles than high-altitude ones. Moreover, yak meat from low- and high-altitude was classified into two groups by an electronic nose (E-nose) owing to distinct flavor characteristics. Overall, roasted yak meat originating from low altitudes tends to be more popular from a sensory perspective.

1. Introduction

Yaks (*Bos grunniens*), known as the "plateau ship," are an endemic species mainly inhabiting the Qinghai-Tibetan Plateau (QTP) with altitudes ranging from 2,000 to 5,000 m. With approximately 14 million yaks in China, accounting for about 90 % of the total population worldwide, yak meat is gaining popularity among consumers due to its natural pollution-free, unique flavor, and delicious and nutritious meat (Li et al., 2018).

Yak meat obtained from different altitudes exhibits variations in nutritional composition, volatile profile, and sensory attributes owing to their geographical isolation, special habits patterns, and genetic features (Han et al., 2020; Yang et al., 2020). The climatic environment exhibits variations according to the altitude of the habitat, which can potentially impact the availability of grass and forage. Additionally, the altitude of the habitat may have an effect on both the composition of milk fatty acids and the duration of the suckling period (Moreno et al., 2006). The variations in muscle composition observed among animals reared at different altitudes may be attributed to differences in feeding and suckling practices, particularly the duration of suckling prior to slaughter (Costa et al., 2011). Yang et al. (2020) conducted a comparison of protein profiles in yak meat from different altitudes and observed distinct expression patterns of various proteins in the postmortem yak muscle, specifically related to pathways involved in energy production, muscle contraction, immunity, and defense, as well as glutathione metabolism. These findings indicate a strong association between these pathways and the formation of characteristic meat signatures. Furthermore, it is widely acknowledged that the quality and availability of forage are contingent upon geographical location, thereby exerting substantial influence on milk composition. Correspondingly, these factors, in turn, could potentially contribute to disparities in the nutritional and sensory characteristics of meat. Altitude has been proven to strongly

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influence yak meat quality, with higher altitudes typically imposing a more favorable effect on the nutritional composition of yak meat than those from low altitudes (Panjono et al., 2011). Similarly, yak jerky sourced from high-altitude regions tends to be more popular compared to its low-altitude counterparts (Han et al., 2020). Nevertheless, conflicting evidence suggests that the higher the altitude, the poorer the tenderness, water-holding capacity, and color attributes of yak meat (Yang et al., 2020; Xin et al., 2022). The variances in botanical diversity and pasture availability across different altitudes may have an impact on the fermentation processes occurring in the rumen, consequently influencing the fatty acid (FA) composition of milk, including branched-chain FAs (Collomb et al., 2008), which is a key factor affecting the flavor and quality of yak meat. Concerning the flavor profile, it has been reported that higher altitude contributes to the development of the volatile compound formation of yak jerky (Han et al., 2020). However, to the best of our knowledge, the effect of altitudinal gradient on flavor development and physicochemical properties of cooked yak meat has not been systematically investigated before.

In industry, heating is the most prevailing method to attain palatable, safe, cooked meat. This process dramatically alters essential attributes of meat that are associated with consumer preferences, such as flavor and physicochemical indicators (Tornberg, 2005). Alternatively, the characterization of meat could be greatly influenced by cooking methods by reducing the nutritional value, denaturing proteins, accelerating lipid oxidation, and diminishing the moisture content (Lopes et al., 2014). Wet heating like steaming and boiling is widely employed for meat processing in China. Boiling, a mild culinary method, fits most cooked meat products. Nevertheless, more energy is transmitted to the sample by steam compared with the water which in turn, improves the heat transfer rate (Song et al., 2021). Roasting, the most widely utilized dry-air processed method for heat treatment, is commonly applied in the commercial industry owing to the generation of a volatile compound that possesses a distinctive odor during processing (Mora et al., 2011). The development of meat aroma during cooking is attributed to the interactions among non-volatile precursors such as free amino acids, peptides, reducing sugars, vitamins, nucleotides, and unsaturated fatty acids. These interactions encompass the Maillard reaction involving amino and carbonyl compounds, lipid oxidation, thermal degradation of thiamine, and the interplay among these pathways (Raza et al., 2020). Nevertheless, the flavor-binding ability can be influenced by various cooking techniques and conditions, such as heating rate, temperatures, and cooking methods. Previous studies have shown that oven-roasted beef exhibited higher levels of aldehydes and hydrocarbons, while microwave-cooked beef displayed lower levels of terpenoids (King et al., 1995). Similar results were found that roasting exhibits a greater propensity for enhancing lipid oxidation and aldehydes production in comparison to boiling or sous-vide techniques in rabbit meat (Rasinska et al., 2019). Among the volatiles observed during an aroma event, it is found that pyrazine compounds are particularly susceptible to variations in grill surface temperature (Wall et al., 2019). However, primarily due to challenges related to transportation, seasonal grazing in high-altitude areas, and the underdeveloped processing technology for yak meat, the available information on cooked yak from different altitude meat by thermal processing was limited. Besides, the specific mechanisms through which altitude affects meat quality and the subsequent cooking method requirements of yak meat are not fully understood.

Therefore, the present study aims to investigate the effects of three different cooking procedures (boiling, steaming, and roasting) on physiochemical qualities, volatile profiles, and sensory attributions of low- and high-altitude yak meat. Additionally, it could be expected to provide certain theoretical support and develop appropriate cooking methods for different altitude yak meat.

2. Material and methods

2.1. Raw materials

All procedures and protocols involving animals were approved by the Institutional Animal Care and Use Committee and Ethics Committee of Food Science and Technology, Chinese Academy of Agricultural Sciences (Beijing, China; approved ID: IFST-2019-43).

Animals were raised and managed under the same specific pathogen-free conditions. Nine male yaks of the same genetic background (average age: 3.5 years old; average live weight: 260 kg) were selected from two areas with an approximate altitude of 3,000 m (low altitude) from Xining, Qinghai, and an altitude of 4,500 m (high altitude) from Yushu, Qinghai. After the rest period and being declared healthy, they were humanely slaughtered in a local commercial abattoir.

For low-altitude yak, the *Longissimus thoracis et lumborum* (LTL) muscle was excised rapidly upon chilling at −1 °C for 48 h. After the visual fat and connective tissue were removed, each *Longissimus thoracis et lumborum* (LTL) muscle was cut into four equal 6 × 5 × 2 cm^3 steaks (length × width × height) along the direction of muscle fibers, and a total of thirty-six pieces of steaks were obtained. Subsequently, the steaks were divided into 3 groups. Each group was a batch. There were 3 independent batches cooked at different times in the present study. For each batch, twelve steaks were divided into four treatments, and each treatment had 3 steaks. The uncooked yak steaks were used as a control (the composition was presented in Table S1), and the other 3 treatments were boiling, steaming, and roasting. The high-altitude yak was processed as described above.

2.2. Preparation of yak meat with different cooking methods

A pre-experiment was conducted to identify optimal cooking times and temperatures to obtain a constant extent of doneness for different cooking treatments. Each steak was cooked independently and experiments were in duplicate to assess the consistency of the results. Prior to preparation, they were subjected to a conditioning period for half an hour at room temperature. A thermocouple was inserted into the geometric center of each sample to check the core temperature of the steaks.

2.2.1. Boiled low- and high-altitude yak meat (BLYM, BHYM)

The boiling procedure was carried out according to the method of Han et al. (2020) with minor modifications. Modifications were only done in terms of the size of the yak meat steak used. To begin, to ensure uniformity and consistency, steaks (6 × 5 × 2 cm^3) (Yin et al., 2020) were prepared and individually wrapped in food-grade polyethylene bags vacuum packing bags (PA/PE 70 μm-thick, MingKe plastic industry Co., Ltd). Samples were then immersed in 150 % (w/w) tap water (boiled in water without direct contact between meat samples and the water) in a stainless-steel pot. Boiling processing was completed after the core temperature of steaks attained 80.0 ± 0.5 °C (25–27 min).

2.2.2. Steamed low- and high-altitude yak meat (SLYM, SHYM)

Based on the method described by Song et al. (2021), steaming was conducted using a steaming casserole set (24 cm internal diameter). After the boiled tap water (98.0 ± 1.0 °C) in a 100 % steam environment was left on the bottom of the steaming casserole, steaks were placed on the interlayer steam tray of the casserole (covered with the lid) and cooked by steam generated by boiled water. The samples were removed upon the internal temperature of 80.0 ± 0.5 °C was reached (30–32 min).

2.2.3. Roasted low- and high-altitude yak meat (RLYM, RHYM)

Roasting treatment was processed in a manner similar to Domínguez et al. (2014), the steaks to be roasted were placed in a heatproof dish and roasted in a domestic oven with dry air at 200 °C for ~13–15 min until the core temperature of 80.0 ± 0.5 °C was reached.

Immediately after cooking processing, the samples were allowed to be sealed in plastic bags and cooled in running tap water. After cooling to room temperature (20.0 ± 0.5 °C), the cooking loss, Warner-Bratzler shear force (WBSF), color, and sensory evaluation were measured. The remaining samples were cut into cubes, minced with a grinder, vacuum packaged individually, and kept at −30 °C until further analysis no longer than 2 weeks.

2.3. Physicochemical examination

2.3.1. Proximate compositional analysis

The moisture and fat contents of yak meat in different treatments were assayed by the Association of Official Analytical Chemists (AOAC) procedure (AOAC, 2012). Specifically, the moisture content was assessed through the measurement of weight reduction following a 12 h drying period at a temperature of 105 °C in a DHG-9213A drying oven (Jinghong Test Equipment Co., Ltd., Shanghai, China) with a constant weight. The moisture content was determined by calculating the mass difference before and after the drying process.

Fat content was determined by the Soxhlet method. Briefly, 5 g of meat samples were weighed and subsequently transferred into a fat-free extraction thimble. After that, the thimble was plugged lightly with cotton wool. Petroleum ether was added to a clean dry flask, filling it to approximately two-thirds of its total volume. The Soxhlet apparatus was subjected to heating over a water bath in order to initiate the circulation of petroleum ether for a duration of 8–10 h for complete extraction. Following the extraction process, the solvent was eliminated through the utilization of a rotary vacuum evaporator. The flask containing the extract underwent a drying process in a preheated oven until a consistent weight (W2) was achieved. The fat content was determined using the following formula:

$$\text{Fat}\ (\%) = \frac{W2 - W1}{5} \times 100 \quad (1)$$

The Kjeldahl method was used to calculate the protein content. 20 mL of sulfuric acid was used to digest 1.0 g of each homogenized sample using a catalytic combination. Following the complete carbonization of the contents and the cessation of foam generation, the flame intensity enhanced. After the transition of the liquid to a blue-green hue, the mixture was allowed to cool to a constant volume. Then, the digested sample was distilled using a Kjeldahl apparatus (Kjeltec 2300 Analyzer Unit, Sweden). Under alkaline conditions, ammonia was distilled and collected in a boric acid solution. By titrating the borate anions created with sulfuric acid, the amount of nitrogen was calculated. Then, a conversion factor of 6.25 was employed for the calculation of the protein content.

2.3.2. Measurement of cooking loss

The cooking loss was calculated using the procedure from Rubén Domínguez et al. (2014). After cooking, the moisture on the surface of the samples was wiped gently with a paper towel. Cooking loss was measured based on the weight loss during cooking and expressed by a percentage of initial weight:

$$\text{Cooking loss}\ (\%) = \frac{m_0 - m_1}{m_0} \times 100 \quad (2)$$

Where m_0 represents the initial steak weight (g), and m_1 represents the weight of the steak after cooking, respectively.

2.3.3. Measurement of WBSF

The WBSF assay was referred to by Modzelewska-Kapituła et al. (2018). Six muscle cylinders (10 × 10 mm, about 40 mm long) were removed from cooked and chilled yak steak along the muscle fibre direction. The muscle cores were sheared with a muscle tenderness meter (C-LM4, Harbin, China), and the shear force was assayed as the average of the maximal force.

2.3.4. Color evaluation‘

The color of yak meat was determined by a Minolta CR-400 colorimeter (Minolta Model CR-400, Osaka, Japan) with a standard D65 illumination. The measurement conditions were: 10° standard observer, measurement diameter: 50 mm. The color was expressed as CIE lightness (L^*), redness (a^*), and yellowness (b^*). Before each measurement, the chroma meter was calibrated with a white tile.

2.4. Measurement of lipid oxidation

The thiobarbituric acid reactive substance (TBARS) values were determined using a spectrophotometric method to determine lipid oxidation involving measurement of absorbance of the pink-stained complex formed by thiobarbituric acid and malondialdehyde (MDA) (Brenesselová et al., 2015). Briefly, 20 g of muscle samples were minced and then mixed with 50 mL of distilled water followed by homogenization. Subsequently, 50 mL of thiobarbituric acid reagent was added into test tubes and incubated for 1 min. The slurry was filtered and the filtrates were added to the thiobarbituric acid reagent (1 mL). Following this, the test tubes for each sample were vortexed and then heated in the water bath for 45 min to develop color, followed by cooling to room temperature under tap water. The absorbance of the mixture was determined spectrophotometrically with an ultraviolet (UV) spectrophotometer (UV2550; Shimadzu, Kyoto, Japan) at 532 nm against a blank. A standard curve was constructed using known concentrations of 1,1,3,3-tetramethoxypropane to calculate TBARS concentrations. The results were expressed as milligrams of MDA equivalents/kilogram of the tissue sample.

2.5. Volatile compounds of yak meat

2.5.1. E-nose analysis

A portable electronic nose (PEN3), with an enrichment and desorption unit (EDU) from Win Muster Airsense Analytics, Inc. (Airsense, Schwerin, Germany), was carried out to discriminate the odor profile in different treatment groups. The apparatus was equipped with a sampling device, a detector unit consisting of ten metal oxide sensors (Han et al., 2020), a signal acquisition system, and data-processing software. The performance description and sensitivity of each sensor are listed in Table S2. Pre-experiments were performed to optimize the instrument parameters. Approximately 1.0 g of sample was collected and placed in a 10 mL glass vial, sealed with a polytetrafluoroethylene (PTFE) septum, and firstly allowed to equilibrate at room temperature (25 °C) for 30 min. To eliminate the humidity traces, the inside headspace was equilibrated for 1 h. The filtered and dried airflow (99 %, 300 mL/min) was employed for the E-nose, and the signals generated by the 10 sensors underwent continuous changes and were promptly recorded by the Win Muster software integrated with an electronic nose on a portable computer. The measurement commenced by introducing headspace volatiles into the sensor chamber at a flow rate of 300 mL/min. The optimal detection time was established as 60 s in order to the acquisition of a consistent signal. Simultaneously, the signals generated by the 10 sensors underwent continuous fluctuations and were promptly captured by the Win Muster software, which was connected to an electronic nose integrated into a portable computer. A cleaning phase of 110 s was set and the automatic zero phase and sample preparation phase were both set at 5 s. Simultaneously, the blank sample was detected under identical conditions to verify the convergence of response values to 1.0 for all sensors prior to each experimental test. Subsequently, the chamber was rinsed well for 180 s to allow the sensor signal to return to baseline values before the next sample injection. The response of the sensor was expressed by G/G_0, where G and G_0 represented the conductivity of the sensor when contacted by the sample's volatile gases and the conductance of the clean air, respectively.

2.5.2. Volatile compounds analysis by headspace solid-phase microextraction-gas chromatography mass spectrometry (HS-SPME-GC–MS)

The extraction of volatile compounds was adapted from that of Han et al. (2020). The minced yak meat sample (2.0 g) was placed in a 20 mL headspace vial, and 5 μL of 2-methyl-3-heptanone (0.05 μg/μL in methanol) was added as the internal standard substance. Thereafter, the vial, sealed with a polytetrafluorethylene (PTFE) septum, was equilibrated for 20 min at 55 °C. A 30/50 μm divinylbenzene/carboxen/polydimethylsiloxane (DVB/CAR/PDMS) solid-phase micro-extraction (SPME) fibre (Supelco, Inc., Bellefonte, PA, USA) was exposed above the sample to absorb odorants for 40 min at 55 °C, upon completion, then desorbed into the gas chromatography (GC) injector at 250 °C for 3 min.

Analyses of volatiles were carried out using a GC (Trace GC Ultra, Thermo Scientific) coupled to a Q-Exactive mass spectrometer (ThermoFisher Scientific, Bremen, Germany). The volatiles were separated on capillary column polar DB-WAX and non-polar DB-5 (30 m × 0.32 mm × 0.25 μm; J & W Scientific Inc., Folsom, CA, USA). Helium as a carrier gas (purity ≥ 99.999 %) flowed at a 1.0 mL/min of constant flow rate. The oven temperature was programmed as follows: the start temperature was 40 °C, held for 2 min, after this, the temperature was increased to 4 °C/min until 230 °C (DB-wax) and 250 °C (DB-5) and then kept for 5 min. The split flow rate ratio was 1:5. Then, the transfer line temperature was 250 °C and the infector mode was splitless. Mass spectra were obtained using an electron ionization source (EI, 70 eV) and the mass range acquisition was carried out with a scan range of 30–400 *m/z*. The ion source temperature was 280 °C.

2.5.3. Identification and quantification of volatile compounds

The identification of the compounds was employed on the basis of the comparison of the mass spectra with the NIST mass spectral library (version 2.0), and retention indexes (RIs) in the literature and online database (https://www.flavornet.org; https://www.odour.org.uk).

Quantitative data of the identified compounds were gained through the comparison of the peak areas of the internal standard with that of the analyzed compounds. The results were expressed as μg of volatile compounds per kg of yak meat. Calculations were performed according to the following formula:

$$C = \frac{Ax \times C0 \times V \times 1000}{A0 \times m} \quad (2)$$

Where A_x is the peak area of each identified substance, C is the contents of the measured components, C_0 is the concentration of the internal standard (μg/μL), V is the injection volume of internal standard (μL), A_0 is the peak area of the internal standard, m is the mass of the sample tested, respectively.

Odor activity values (OAVs) were obtained according to the method of Liu et al. (2018) following the formula below.

$$OAV_i = \frac{C_i}{OT_i} \quad (3)$$

Where C_i is the concentration of the compounds in yak meat and OT_i is its threshold in water. To acquire OT_i, online databases (http://www.odour.org.uk) and some published references were used. Compounds with OAV ≥ 1 were regarded as the main contributors to the yak meat flavor.

2.6. Sensory evaluation

The sensory evaluation was carried out by a trained sensory panel at the Chinese Academy of Agricultural Sciences consisting of 30 panelists (15 males and 15 females, aged 25–35 years). Panelists were trained as per the guidelines of the American Meat Science Association (AMSA, 2015) for three months. The first two independent sessions were presentations of sensory evaluation. In the following nine sessions, the scale of the evaluation and specific attributes were developed by comparing the cooked yak meat with reference samples. In the final 9 sessions, the trained panelists evaluated the cooked yak meat. To minimize the possibility of order effects and carryover effects, the presentation order of samples and tests followed a randomized balanced design (Macfie, Bratchell, Greenhoff, & Vallis, 1989). All assessors had at least one year of experience in the sensory evaluation of meat products. Yak meat was coded with three-digit numbers and offered randomly to the panelists at each booth. Before the trials, a warm-up sample was presented for panelists as panelist meat traits calibration. The color, taste, flavor, tenderness, and overall acceptability were evaluated. A 7-point hedonic scale was used for the intensity quantification of each attribute from 1 (low intensity) to 7 (high intensity) (Kong et al., 2010). Tap water was provided for the panelists to rinse their mouths between each sample.

2.7. Statistical analysis

The data were analyzed and represented as means ± standard errors (SE) using the SPSS statistics 22.0 software package (IBM, Chicago, IL, USA). The differences between means of the physicochemical characteristics, TBARS, volatile compounds profile, and sensory evaluation among different cooking methods were determined using a one-way analysis of variance (ANOVA), and the least significant difference (LSD) was used to identify significant differences at a level of $P < 0.05$. The means of low- and high-altitude samples in the evaluation of physicochemical characteristics, TBARS, volatile compounds profile, and sensory evaluation were performed with an independent *t*-test to assess the significance level of $P < 0.05$. Principal component analysis (PCA) of the E-nose data was conducted using the software XLSTAT (2016) from Addinsoft (Barcelona, Spain).

3. Results and discussion

3.1. Analysis of physicochemical characteristics of low- and high-altitude yak meat subjected to different methods of cooking

As shown in Table 1, the moisture content of yak meat was significantly ($P < 0.05$) affected by the cooking types and the order of which was as follows: steaming > boiling > roasting. Steaming, in particular, results in the formation of a coating on the surface of the steak, which likely contributes to better moisture retention during the cooking process compared to boiling. Moreover, steaming involves cooking the meat with the help of steam, which effectively transfers heat to the meat while maintaining a relatively high level of moisture due to the enclosed environment. Supporting evidence was obtained that the moisture content of the steamed cooked chicken steak reached its maximum than that of the other thermal treatments (Choi et al., 2016). Roasting, which typically involves dry heat, leads to the evaporation of moisture from the meat, resulting in a further reduction in moisture content. Similarly, wet processing methods consistently contribute to higher moisture content in contrast with dry-air processed methods (Jiao et al., 2020). Interestingly, the moisture content remained unaffected significantly ($P > 0.05$) by altitude. Similar findings have recently been reported for the moisture content in cattle-yak *longissimus thoracis* and yak *longissimus thoracis* through a comparative study (Chang et al., 2023). We speculated that the moisture content in meat is primarily determined by the inherent characteristics of the meat itself, such as the composition of muscle fibers, connective tissues, and fat content. These factors might have overshadowed the potential impact of altitude on moisture retention.

Additionally, our results revealed that roasted steaks allowed a greatly lower protein and fat content ($P < 0.05$) versus the other cooking types. Typically, protein is susceptible to denaturation when drip loss occurs, and the degree of which largely relies on cooking parameters, such as temperature and meat composition (Tornberg, 2005). Compared to boiling and steaming, protein denaturation proceeds faster during roasting owing to higher temperatures applied, which exposes hydrophobic groups and causes aggregation, thereby reducing protein

Table 1
Effects of different cooking methods on the physicochemical characteristics of low- and high-altitude yak meat.

Index	Boiling			Steaming			Roasting			Methods *P*-value	
	BLYM	BHYM	*P*-value	SLYM	SHYM	*P*-value	RLYM	RHYM	*P*-value	BLYM-SLYM-RLYM	BHYM-SHYM-RHYM
Moisture (%)	63.2 ± 0.35^{Ba}	62.4 ± 0.32^{Ba}	0.22	65.4 ± 0.61^{Aa}	64.8 ± 0.44^{Aa}	0.61	60.1 ± 0.84^{Ca}	59.4 ± 0.85^{Ca}	0.83	0.00	0.01
Protein (%)	15.9 ± 0.13^{Bb}	17.9 ± 0.15^{Aa}	0.00	16.9 ± 0.28^{Aa}	18.5 ± 0.50^{Aa}	0.07	13.8 ± 0.18^{Cb}	15.2 ± 0.20 ^{Ba}	0.00	0.00	0.01
Fat (%)	7.48 ± 0.13^{Ba}	5.90 ± 0.46 ^{Ba}	0.07	8.81 ± 0.41 ^{Aa}	7.77 ± 0.34 ^{Aa}	1.14	4.62 ± 0.36 ^{Ca}	3.61 ± 0.16^{Ca}	0.08	0.00	0.00
Cooking loss (%)	43.5 ± 0.53^{Aa}	44.1 ± 1.65 ^{Aa}	0.77	43.6 ± 0.70^{Aa}	43.6 ± 1.68^{Aa}	0.10	37.0 ± 0.68^{Ba}	37.7 ± 1.22^{Ba}	0.89	0.02	0.04
*L**-value	58.7 ± 0.50^{Aa}	53.4 ± 1.60^{Ab}	0.05	53.5 ± 0.62^{Ba}	51.5 ± 0.62^{Aa}	1.10	43.1 ± 0.80^{Ca}	38.4 ± 0.71^{Bb}	0.00	0.00	0.01
*a**-value	14.4 ± 0.60^{Ba}	12.3 ± 0.98 ^{Ca}	0.07	18.1 ± 0.90^{Aa}	14.0 ± 0.56^{Bb}	0.00	23.3 ± 0.65 ^{Aa}	20.6 ± 0.97^{Ab}	0.03	0.02	0.00
*b**-value	81.0 ± 0.88 ^{Ba}	82.9 ± 0.86^{Ba}	0.28	84.3 ± 0.57 ^{Ba}	84.6 ± 0.32^{ABa}	0.77	91.7 ± 1.58 ^{Aa}	85.3 ± 0.58^{Ab}	0.01	0.03	0.09
WBSF (N)	61.2 ± 0.40 ^{Ab}	63.0 ± 0.30^{Aa}	0.02	52.2 ± 0.60^{Bb}	55.1 ± 0.60 ^{Ba}	0.02	44.7 ± 0.9^{Ca}	49.3 ± 1.20 ^{Ca}	0.08	0.00	0.00

Note: *L**: lightness; *a**: redness; *b**: yellowness; WBSF: Warner-Bratzler shear force; BLYM: Boiled low-altitude yak meat; BHYM: Boiled high-altitude yak meat; SLYM: Steamed low-altitude yak meat; SHYM: Steamed high-altitude yak meat; RLYM: Roasted low-altitude yak meat; RHYM: Roasted high-altitude yak meat. $^{A-C}$ indicates within the same row with different letters differ significantly ($P < 0.05$) (differences among the cooking methods). $^{a-b}$ indicates within the same row with different uppercase letters differ significantly ($P < 0.05$) (differences between the low- and high-altitude yak meat).

contents (Glorieux et al., 2019). However, higher protein content was observed in roasted cooked Hengshan goat leg compared to boiling and steaming. The paradoxical phenomenon observed in this study may be attributed to the distinct attributes of each meat type, such as connective tissue content, protein solubility, and moisture retention capacity, as well as the specific cooking conditions, such as temperature, and cooking time. Analogously, we surmised that the high dry heat of the roasting causes the fat in the yak meat to melt and drip away, resulting in a reduction in fat content (Mena et al., 2020). Besides, it was observed that the protein content in high-altitude yak meat was markedly greater than in low-altitude counterparts, whereas, for the fat content, precisely the opposite was observed. These findings align with the results obtained in raw meat assays (Table S1). This finding agrees with what has been extensively reported previously (Yongjie Wang et al., 2021). In general, to adapt to a harsh environment, high-altitude yaks have perceived a more competent ability to synthesize protein, thereby, consequently resulting in an elevated protein content of yak meat (Zi et al., 2004). Moreover, it is plausible to suggest that the higher protein and lower fat contents observed in high-altitude yaks may indirectly be caused by the specific breeding conditions characterized by year-round grazing and intense muscle activity.

The extent of cooking loss depends on mass transfer during the thermal treatment process, consequently, various cooking methodologies yield different losses. In this study, the loss was substantially influenced by the type of cooking treatments ($P < 0.05$) but not altitudes ($P > 0.05$). In particular, a significantly lower cooking loss was observed for roasted steaks (37.0 % and 37.7 %) compared to the boiled (43.5 % and 44.1 %) and steamed ones (43.6 % and 43.6 %). These findings align closely with a previous study that investigate the effect of traditional cooking on cooking loss, which was 42.79 % and 42.93 % (Yang et al., 2020). Comparable findings were noted that reduced cooking loss in roasted foal steaks when compared to microwave-cooked ones (Rubén Domínguez et al., 2014). It was inferred that this phenomenon could be attributed to the development of an external hard outer crust covered on the meat samples by roasting, which slowed down the rate of sap exudation and subsequently prevented the occurrence of high cooking loss. In contrast, steaming and boiling involve moist cooking environments, which lead to higher cooking losses due to the leaching of moisture into the surrounding liquid.

We attempted to objectively study the evaluation of quality attributes of yak meat steaks rather than solely subjective assessments by panelists. Our findings indicate that boiled and steamed yak meat exhibited markedly higher *L**-value and lower *a**- and *b**-value compared to their roasted counterparts ($P < 0.05$). The observed decrease in *L**-value may be attributed to a heightened degree of moisture loss during the roasting process, facilitating the exposure of muscle fibers and consequent light dispersion (Teixeira et al., 2017). Variations in *a**- and *b**-value observed across different thermal processing methods can be attributed to the degree of myoglobin denaturation or structural modifications. This denaturation process results in the alteration of the protein's structure, thereby exposing certain amino acid residues. Consequently, the formation of novel pigments, such as hemichrome, occurs, ultimately contributing to the elevated *a**-value (Wulf & Wise, 1999). During the process of roasting, the conversion of myoglobin's iron ion from its ferrous state to the ferric state results in the formation of metmyoglobin, which manifests as a brown hue and contributes to the elevated *b**-value detected in roasted yak meat (Yu et al., 2017). These findings align with those from Hengshan goat leg meat processed by steaming, boiling, roasting, and drying (Jiao et al., 2020), and Spanish Mackerel processed through roasting, frying, boiling, and steaming (Sun et al., 2020). Besides, a study investigated the effect of cooking methods on rabbit meat and found that sous-vide cooked rabbit meat shows higher moisture content, water-holding capacity, and lower cooking losses than other samples, but the results of roasted rabbit meat samples are the opposite (Rao et al., 2022). Concerning altitude, the induction of ferrimyoglobin levels in hypoxic environments leads to browning and decreased *L**-value. This is supported by the findings that the *L**-value of yak meat for the low-altitude group (3,000 m 4,500 m) was higher throughout the postmortem process than the high-altitude ones (4,500 m) (Xin et al., 2022). However, the *a**-value results showed otherwise that high-altitude yak meat has a significantly higher *a**-value compared with low-altitude cattle (Xin et al., 2022). With rising altitude, the meat color scores of carcasses from bulls greatly increase (Panjono et al., 2009). High-altitude environments typically have lower oxygen levels. The reduced availability of oxygen can affect the development and stability of myoglobin. Thus, oxymyoglobin levels are enhanced at higher O_2 concentrations, resulting in the *a**-value increase (Murphy et al., 2015). In comparison with high-altitude yak, those from low-altitude could reduce the rate of deoxymyoglobin oxidation to metmyoglobin and promote the formation of oxymyoglobin that has a bright red color. A similar trend was observed in M. longissimus from Hanwoo steer raised at different altitudes (Panjono et al., 2011). Meat from the *longissimus thoracis* muscle of suckling beef calves from high-altitude pastures shows a tendency to be of lighter color compared to

flat areas of mountains (Gangnat et al., 2017).

WBSF is a reliable and intuitive indicator inversely reflecting meat tenderness. Unexpectedly, our data revealed that roasting cooking led to a remarkable ($P < 0.05$) lower WBSF when compared with that measured for other cooking methods. This phenomenon could be ascribed to the extended cooking time taken for wet processing techniques (boiling and steaming) rather than dry-air processed methods (roasting). They, in turn, lead to the thermal shrinkage of connective tissues and promote myofibrillar toughening or hardening (Chumngoen et al., 2016). Besides, the coagulation of proteins during roasting may be constrained by the reduced humidity levels in the surrounding environment (Głuchowski et al., 2019). In this context, other studies support these findings that cooking rabbit meat samples by boiling provoked higher shear force values than the roasting treatments (Abdel-Naeem et al., 2021). However, other studies argue for the opposite result that roasting significantly reduced the tenderness of goat meat in contrast to boiling and steaming (Jia et al., 2022). Similarly, the highest shear force was applied for the steamed salmon compared to the steaming treatment (Głuchowski et al., 2019). As the duration of microwave exposure increased, there was a statistically significant increase in the shear force of microwave-cooked yak meat (Li et al., 2019). For altitude, the WBSF of steaks from high-altitude yak was substantially higher than the low-altitude ones ($P < 0.05$). This phenomenon may be related to the physiological adaptation of yaks to harsh conditions at higher altitudes. Yaks living at high altitudes experience more challenging environmental conditions, including lower oxygen levels and colder temperatures. Notably, the finer the myofiber, the more tender the meat, and vice versa (Lee et al., 2012). These conditions result in a denser muscle structure, increased muscular fiber diameter, and higher collagen content, leading to tougher meat texture and higher WBSF values. Secondly, differences in diet and nutrition between yaks at high and low altitudes may also contribute to the observed variation in WBSF values. Yaks at high altitudes may consume more fibrous and less nutritious vegetation, resulting in meat with higher collagen content and consequently higher WBSF values (Yang et al., 2020).

3.2. Lipid oxidation of low- and high-altitude yak meat subjected to different methods of cooking

TBARS is a primary indicator of lipid oxidation extent in meat. Furthermore, volatile compounds are predominantly composed of lipid oxidation products during cooking. Appropriate levels of lipid oxidation yield desirable flavors, whereas overoxidation may generate unfavorable odors in the product and even potentially affect meat quality (Han et al., 2020). As summarized in Fig. 1, severer lipid oxidation ($P < 0.05$) was detected in roasted yak meat relative to the other cooking methods treatments. This is in agreement with the studies of Domínguez et al. (2014). The extent of lipid oxidation in cooking is influenced by various factors, such as the cooking technique employed, the temperature at which heating occurs, the duration of cooking, and the surface area exposed to water and oxygen. The application of a higher temperature during roasting produces a greater degree of oxidation compared to the changes caused by boiling and steaming. This same finding was present in previous studies that roasting increases more TBARS content in buffalo meat than boiling (Klinhom et al., 2016). The exposure to oxygen in the air during roasting further accelerates lipid oxidation. This oxidative process results in the formation of reactive oxygen species (ROS), such as free radicals, which can initiate chain reactions leading to the degradation of lipids. Instead, boiling and steaming reduce exposure to oxygen, which thus limits lipid oxidation. In specific, the presence of water acts as a barrier, preventing excessive contact between lipids and oxygen, thereby reducing the probability of lipid oxidation. Moreover, it is also suggested that cooking loss has a negative relationship with lipid oxidation (Rasinska et al., 2019), if this conclusion holds, then, our results seem to confirm this notion. Besides, our findings consistently demonstrate elevated TBARS values in low-altitude samples compared to high-altitude samples, hereby corroborating the aforementioned fat content results in this study.

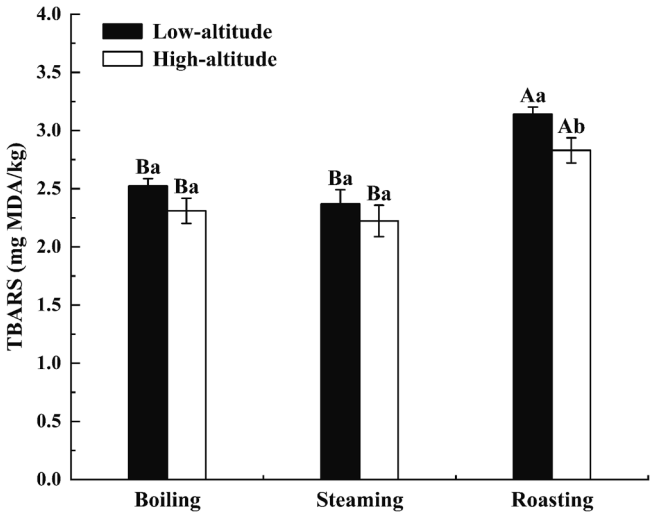

Fig. 1. Effect of cooking methods on thiobarbituric acid reactive substances (TBARS) (mg MDA/kg muscle) of low- and high-altitude yak meat. Different uppercase indicates significant differences among cooking methods at the same altitude ($P < 0.05$). Different lowercase indicates significant differences between the low- and high-altitude yak meat with the same cooking method ($P < 0.05$).

3.3. Volatile composition analysis using E-nose

3.3.1. Response signals of E-nose

E-nose is a technique consisting of a matrix of chemical sensors, allowing for a high-satisfaction sample classification owing to its sensitivity to the information about the tiny change in odor. It has been widely applied to analyze chemicals in meat and meat products (Tian et al., 2013). Furthermore, due to it being relatively unaffected by factors such as flavor enrichment mode and column polarity, among others, the E-nose is often employed in conjunction with GC–MS for flavor analysis. The radar plot enables visualization and analysis of the multidimensional data of the E-nose in a two-dimensional graph. As depicted in Fig. 2, the radar chart effectively illustrates variations in mean sensor responses across different samples. Cooked yak meat exhibits higher response values to W1W and W2W, sensitive to sulfur organic compounds, terpenes, and aromatic compounds. These findings indicate that certain sensors can be categorized into distinct groups, showing sensitivity to specific compound types. Recent studies have supported our sensor sensitivity findings. For instance, Gong et al. (2017) identified sensors R2, R6, R7, R8, and R9 as the primary sensors sensitive to aldehydes, ketones, and methyl compounds in tewed spicy beef. The E-nose results significantly identify the changes in the flavor profile of marinated roasted beef meat during frozen storage (Al-Dalali et al., 2022). In the case of low-altitude yak meat, the response values of W1W (sensitive to sulfur organic compounds and terpenes) and W2W (sensitive to aromatic compounds and sulfur organic compounds) for steamed and roasted samples were greater than boiled (Fig. 2A). A possible explanation for the higher intensity of aroma of steamed samples than was using vacuum pouches, which prevents the losses of these compounds. For high-altitude steaks, roasting was the one that showed amplified signals of W1W, W2W, W1S, and W2S (Fig. 2B), suggesting that substantially higher sulfides, terpenes, alcohols, and aromatic compounds were yielded during the roasting process. More abundant flavor profiles were identified in low-altitude yak meat represented by the raised responses of W1S, W1W, W2S, W2W, and W5S (sensitive to nitrogen oxide) (Fig. 2C-E), suggesting that N-, S-, and O-containing compounds were different among yak meat from different altitude. The

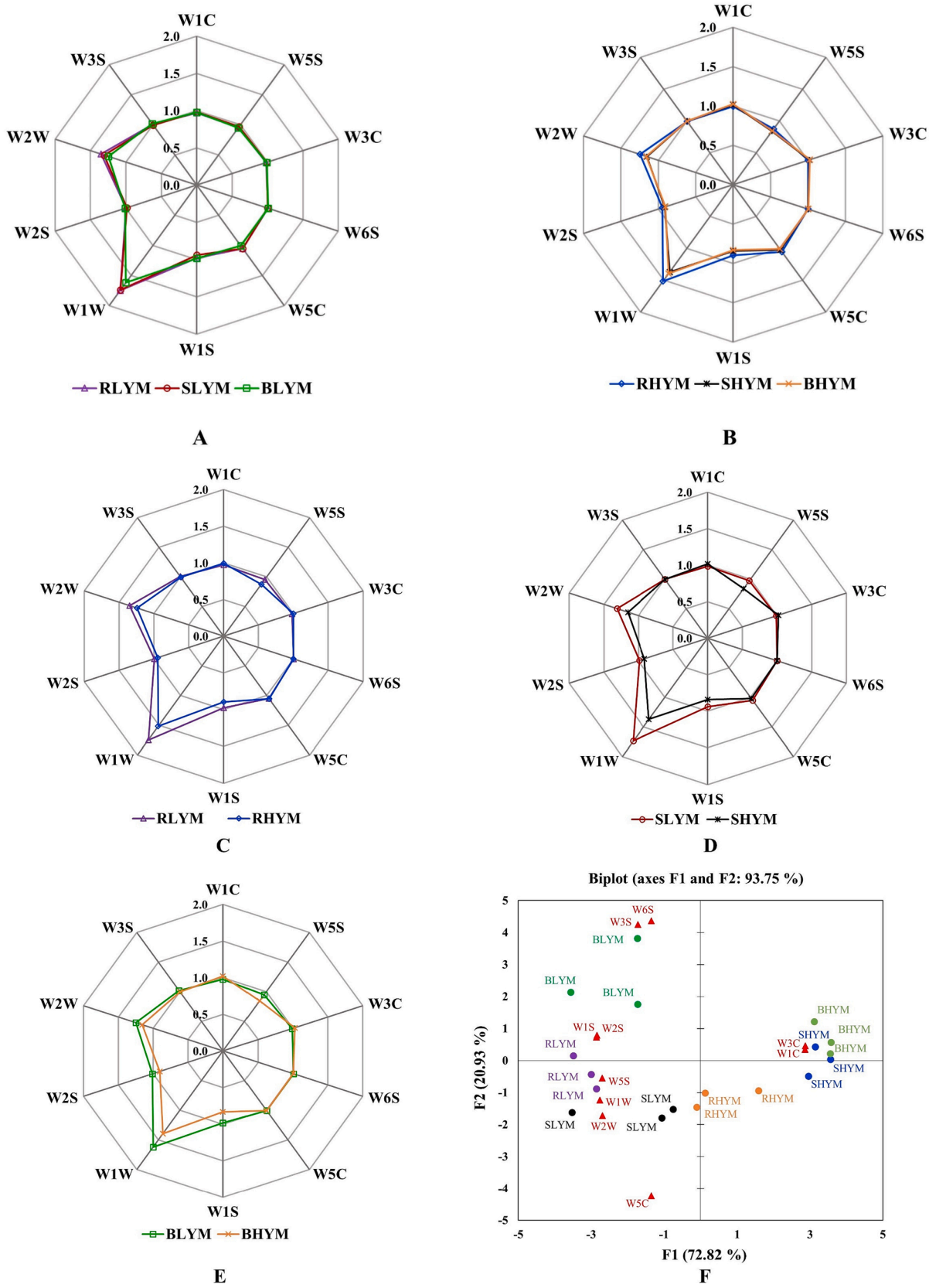

Fig. 2. Radar charts of E-nose data from RLYM, SLYM, and BLYM (A), RHYM, SHYM, and BHYM (B), RLYM and RHYM (C), SLYM and SHYM (D), BLYM and BHYM (E), PCA plot of E-nose response from low- and high-altitude yak meat subjected to different cooking methods (BLYM = Boiled low-altitude yak meat, BHYM = Boiled high-altitude yak meat, SLYM = Steamed low-altitude yak meat, SHYM = Steamed high-altitude yak meat, RLYM = Roasted low-altitude yak meat, RHYM = Roasted high-altitude yak meat) (F).

radar plot demonstrates that the aroma profiles of the cooked yak meat exhibit similarity in shape, yet display considerable variation in the intensities and ratios of the diverse volatile gases (Shen et al., 2023). This implies that altitude exerts a greater influence on the flavor of yak meat than cooking methods. In boiled pork, sensor responses of e-nose are consistent across muscle types but varied among pig breeds, suggesting breed has a more significant impact on flavor than muscle type (Han et al., 2020). Hence, the utilization of both GC–MS and E-nose, along with chemometrics, proved to be efficacious techniques for distinguishing the volatile profiles of cooked yak meat originating from diverse altitudes and cooking methods. Li et al. (2018) investigated the correlation between the responses of E-nose sensors and VOCs measured by GC–MS, and the result shows that only a portion of volatiles could be captured by the sensors. Bai et al. (2021) also studied the correlation between highly abundant volatiles and E-nose signals and revealed that W1S, W1W, W2S, W2W, and W3S sensors were positively correlated with 6 out of 36 volatiles. These findings support the efficacy of E-nose in aroma analysis. The radar chart shapes of the E-nose for volatile compounds on the ten sensors exhibit similarity, but the response number differ across various storage stages (Bu et al., 2023). Similarly, for sensory characteristics of scallop muscle cooked in different ways, the shape of the radar plot for E-nose from different is extremely similar with different number (Wang et al., 2022). This aligns with the findings of Costa et al. (2015), who found that E-nose is an effective tool to discriminate aroma attributes in braised sauce spareribs from different regions. The analysis of Peled meat samples revealed almost no significant sensor response changes in W1C, W3C, W6S, W5C, and W3S across various cooking conditions (Jin et al., 2023), while there were differences between different cooked samples for the W1S and W2S sensors. For pork from different sources, E-nose sensor responses for short-chain alkanes vary significantly among breeds, indicating breed-related flavor distinctions (Giri et al., 2010). In summary, the radar patterns of E-nose sensors are relatively similar for yak meat processed in different ways at the same altitude, suggesting a consistent volatile organic compound composition. However, altitude-dependent flavor variability is evident, with high-altitude meat exhibiting distinct sensor responses to various processing methods, while low-altitude meat shows more consistent responses across sensors.

3.3.2. PCA of E-nose data

The spatial distribution and distance of cooked yak meat aroma were analyzed by PCA (Fig. 1B). PCA is a statistical methodology commonly employed for the purpose of reducing the dimensionality of input data, primarily utilized for feature extraction. As illustrated in Fig. 2F, it can be observed that PC1 and PC2 accounted for 72.82 % and 20.93 % variations of the data, respectively. These two PCs contributed more than 90 % of the total variation, demonstrating that E-nose effectively separates the yak meat in different treatments well and reflects the majority of odor information. A clear distinguishment of flavor characteristics was, with steaks from low altitude regions (BLYM, SLYM, and RLYM) and high latitude regions (BHYM, SHYM, and RHYM) occupying opposite extremes along the PC1 axis. This finding indicated that there are substantially distinct flavors of cooked yak meat obtained from low and high altitudes. The BLYM, SLYM, and RLYM samples exhibited a certain similarity in terms of aroma attributes, while the BLYM, SLYM, and RLYM samples had similar aroma compositions. Besides, for low-altitude yak meat, the dots corresponding to the RLYM and SLYM samples exhibited identical overlaps, distinguishing them from the BLYM samples. For high-altitude samples, there was a spatial overlap observed between the distribution areas of BHYM and SHYM samples along the principal components PC1 and PC2, but deviated from the distribution of RHYM samples. Overall, it can be inferred that high-altitude yak meat exhibits distinguishable characteristics based on the dry-air and wet thermal processing methods employed. In comparison to low-altitude yak meat, boiled samples can be discerned from steamed and roasted counterparts. The combination of altitude-related factors and cooking methods likely contributes to the observed differentiation in flavor between high-altitude and low-altitude yak meat. Further studies are needed to investigate the specific chemical changes and sensory attributes that underlie these differences, providing a deeper understanding of the mechanisms responsible for the observed flavor variations. The radar map (Fig. 3B) further supported the PCA results.

3.4. Volatile profiling of cooked yak meat by HS-SPME-GC–MS

3.4.1. Volatile composition of cooked yak meat

To probe and dissect further, the volatile compounds present in cooked yak meat were analyzed by HS–SPME–GC–MS. A total of 138 volatile components were identified and grouped into 8 chemical families (Table S3; Fig. 3), including 25 aldehydes (33.63–85.76 %), 20 alcohols (5.29–9.59 %), 15 ketones (0.85–9.10 %), 22 aromatics (3.20–30.94 %), 29 hydrocarbons (0.90–11.53 %), 8 furans (0.92–2.83 %), 8 *N*-containing compounds (0.07–0.46 %), and 11 S-containing compounds (0.41–6.22 %). These classes of compounds are consistent with prior studies on the flavor profile of yak meat (Li et al., 2019). Among them, aldehydes almost had the greatest share of integral flavor, followed by aromatics.

The proportion of odorants present in yak meat was depicted in Fig. 3. When yak meat was administered in the same cooking procedure, aldehydes and furans in low-altitude yak meat accounted for a higher percentage than in the high-altitude samples. However, for ketones, aromatics, hydrocarbons, *N*-containing compounds, and S-containing compounds, the opposite is the case. We speculated that the observed discrepancy could be linked to the botanical diversity of different altitudes environments for yak, particularly in relation to the introduction of feed and forage. In terms of low-altitude yak meat, the proportions of alcohols, ketones, aromatics, *N*-containing compounds, and S-containing compounds in roasted samples were dramatically greater than in the boiled and steamed ones. For high-altitude samples, it was displayed that the concentrations of aldehydes and alcohols were found to be highest in the boiled treatment, followed by steaming, while roasting was the lowest. Contrarily, ketones, aromatics, *N*-containing compounds, and S-containing compounds accounted for the most in the roasted treatment, while they varied only slightly between steaming and boiling. Overall, the roasted treatment yielded the highest concentration of volatile flavor compounds (Table S3), possibly, at least in part, owing to the manner of thermal energy delivery. These findings are similar to the results of many researchers. Roasted foal steaks exposed to a higher temperature has the highest volatile content compared to other cooking method (grilling, microwaving, and frying) (Rubén Domínguez et al., 2014). Research on the flavor profile of Chinese Piao chicken meat also supports these findings that roasting is used to improve the flavor of meat (Y. Yu et al., 2021). Compared with boiling and steaming, roasting warmed faster and had a more drastic Maillard reaction process. Simultaneously, roasting led to lower moisture (Table 1) as a result of evaporation and transfer of free water, which in turn affects the development of volatile flavor compounds (Li et al., 2022). The specific details concerning differences in odorants will be analyzed in the following sections.

3.4.2. Odor-active compounds in cooked yak meat

It is known that the contribution of odorants to the integral flavor is determined by their concentration and odor threshold, rather than the absolute concentration levels. Therefore, it is necessary to explore the potentially crucial odorants in the comprehensive flavor of cooked yak meat. The OAVs were tested to assess the contributions of volatile flavor compounds and those with OAV $\geq$ 1 were identified as odor-active compounds. The OAVs, odor threshold, and odor descriptions of volatile compounds of yak meat were listed in Table 2. A total of 36 key volatile compounds were selected as significant contributors based on the results of OAV $\geq$ 1.

Aldehydes are a crucial component of the aroma in meat and meat

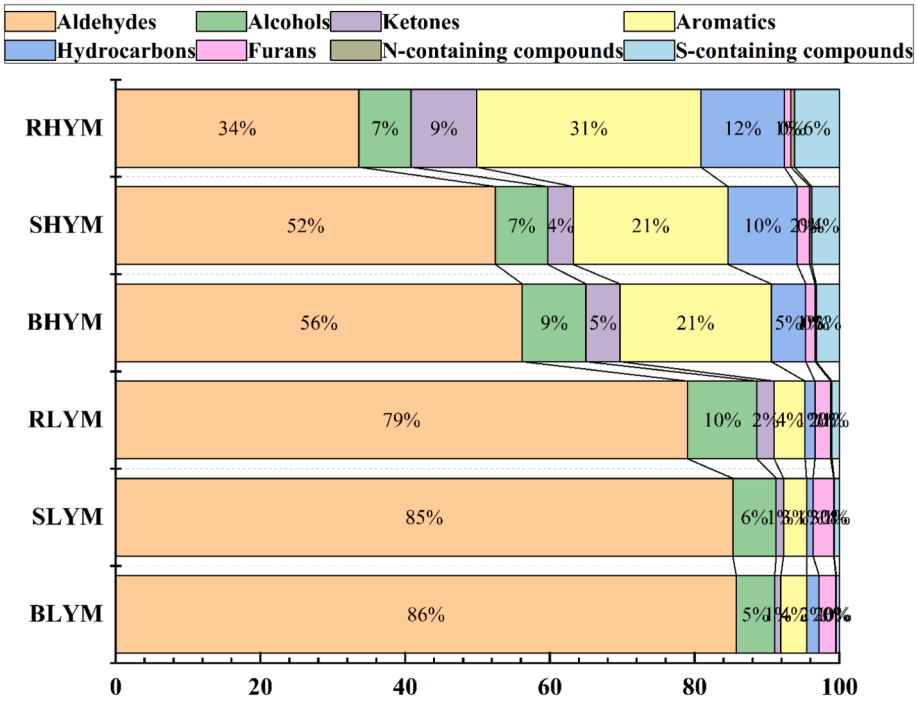

Fig. 3. Comparison of the relative percentage of volatiles (categories) from low- and high-altitude yak meat subjected to different cooking methods (BLYM = Boiled low-altitude yak meat, BHYM = Boiled high-altitude yak meat, SLYM = Steamed low-altitude yak meat, SHYM = Steamed high-altitude yak meat, RLYM = Roasted low-altitude yak meat, RHYM = Roasted high-altitude yak meat).

products, primarily generated through the lipids oxidation and degradation reactions, as well as the Strecker degradation of amino acids (Pavlidis et al., 2019). Here, among the 25 aldehydes detected, 12 of which were classified as odor-active compounds (Table 2). This result verified the previous finding that aldehydes are regarded as the most crucial substances for the overall flavor intensity of yak meat (Huang et al., 2022; Li et al., 2019). Compounds 2,3-pentanedione and 3-hydroxy-2-butanone potentially constitute significant contributors to the overall aroma of yak meat during oxidation (Huang et al., 2022). Aldehydes often exhibit significantly greater OAVs due to their elevated concentration and lower detection threshold (Table 2). This was especially the case with saturated aldehydes (nonanal, hexanal, pentanal, and heptanal), alkenals ((*E*)-2-nonenal), and alkadienals ((*E, E*)-2,4-decadienal), these aldehydes with OAVs above 100 constituted the primary aldehydes identified in this study. Additionally, the aforementioned substances were also detected in other cooked species, including lamb, and foal (Ruben Domínguez et al., 2014; Madruga et al., 2010; Rasinska et al., 2019). Nonanal accounted for around half of the total aldehydes in all treatments, potentially attributed to the multiplicity of its synthesis pathways. Additionally, nonanal is shown to give yak meat its beef fat and green grass volatile flavors (Huang et al., 2022). Heptanal is generated through the oxidation process of arachidonic acid and linoleic acid, resulting in the distinctive grassy aromatic characteristics in yak meat. Additionally, pentanal contributes to the sensory experience by providing fruity and bready flavors. In particular, the compound (*E, E*)-2,4-nonadienal was exclusively identified in low-altitude yak meat (BLYM, SLYM, RLYM), suggesting its potential utility as a distinguishing marker for differentiating yak meat from different altitudes. Besides, among the cooking methods, roasting was the one that yielded greater quantities of aldehydes compared with boiling and steaming treatments (Table S3), which coordinated the previous E-nose test results in the present study. Previous research has also reported that foal meat cooked by roasting exhibited more abundant aldehydes, whereas boiling- and steaming-cooked led to lower levels (Rubén Domínguez et al., 2014). More important, it was observed that the OAVs of pentanal, decanal, heptanal, hexanal, (*E*)-2-octenal, (*E*)-2-nonenal, (*E*)-2-decenal, and (*E, E*)-2,4-decadienal in low-altitude yak meat was significantly greater ($P < 0.05$) than those found in high-altitude samples, irrespective of the cooking techniques employed. Consequently, cooked yak meat from low altitudes was preferable in contributing a more pleasant fatty and grass flavor regardless of cooking methods.

Alcohols mainly arise through the degradation of linoleic acid and the oxidation of unsaturated lipids. As shown in Table 2, it is worth noting that major contributors among the odor-active compounds include three linear alcohols (1-hexanol, 1-pentanol, and 1-octanol) and three branched-chain alcohols (1-octen-3-ol, linalool, and methanethiol). The majority of these aromas were pleasant, including sweet, fresh, fruit, and vegetable scents, as well as floral fragrances, all of which have the potential to enhance the volatile flavor profiles of meat products. Generally, long straight-chain alcohols tend to complicate the meat flavor system by exhibiting shared characteristics of herbal and fatty odors, compared to short straight-chain alcohols owing to lower thresholds (Karabagias, 2018). Pentanol, hexanol, and 1-octen-3-ol are identified as the primary alcohols observed during the oxidation process of yak meat (Huang et al., 2022). The occurrence of 1-pentanol, 1-hexanol, and 1-octen-3-ol is also detected in ultrasonic-assisted cooked spiced beef (Zou et al., 2018). For low-altitude yak meat, the OAVs of 1-pentanol, 1-hexanol, and 1-octanol in RLYM samples were twice that of BLYM and SLYM ($P < 0.05$). The highest cooking temperature generates greater amounts of 1-hexanol and 1-octanol in beef (Kerth, 2016). However, for high-altitude ones, there was no statistically significant difference in the OAVs of linear alcohols among the cooking methods, except for 1-hexanol. The OAVs of 1-hexanol in the SHYM samples were found to be larger than the values in the BHYM and RHYM samples ($P < 0.05$). Additionally, branched-chain alcohols such as 1-octen-3-ol, known to have fruity and mushroom aroma characteristics, have a great positive impact on the formation of yak meat flavor (Huang et al., 2022). Linalool, a prominent aroma active substance in cooked meat aromas, possesses a distinct flower aroma (Ansorena et al., 2001). Viewed as a whole, the RLYM samples exhibited the highest OAVs for alcohols.

As revealed in Table 2, three ketones (namely 2-heptanone, 6-

Table 2
Odour-active compounds (OAVs ≥ 1) in low- and high-altitude yak meat subjected to different methods of cooking.

Compounds	Odor thresholds ($\mu g \cdot kg^{-1}$) [x]	Odor descriptions [y]	Boiling			Steaming		Roasting			Methods *P*-value		
			BLYM	BHYM	*P*-value	SLYM	SHYM	*P*-value	RLYM	RHYM	*P*-value	BLYM-SLYM-RLYM	BHYM-SHYM-RHYM
(*E, E*)-2,4-Nonadienal	0.19	Fatty, green	20.1 ± 0.08^{Aa}	–	0.00	19.6 ± 0.60^{Aa}	–	0.00	11.9 ± 0.27^{Ba}	–	0.00	–	–
Benzenacetaldehyde	4.00	Floral	2.77 ± 0.35^{Ca}	2.84 ± 0.30^{Ba}	0.99	4.67 ± 0.27^{Ba}	2.51 ± 0.43^{Bb}	0.00	12.4 ± 0.51^{Aa}	7.93 ± 0.30^{Ab}	0.00	0.000	0.03
onanal	1.00	Fatty, floral, wax	3042 ± 3.79^{Ba}	198 ± 3.32^{Bb}	0.00	2576 ± 3.66^{Ca}	373 ± 3.26^{Ab}	0.00	4486 ± 3.75^{Aa}	233 ± 4.30^{Bb}	0.00	0.000	0.02
(*E*)-2-Octenal	3.00	Green, nut, fat	40.6 ± 1.11^{Ab}	0.87 ± 0.01^{Aa}	0.00	46.5 ± 1.47^{Aa}	0.80 ± 0.01^{Bb}	0.00	42.5 ± 1.06^{Aa}	0.53 ± 0.0^{Cb}	0.00	0.04	0.01
Decanal	0.10	Orange, green	64.8 ± 1.28^{Ba}	7.02 ± 0.10^{Bb}	0.00	35.7 ± 1.00^{Ca}	15.5 ± 0.57^{Ab}	0.00	86.5 ± 1.07^{Aa}	5.56 ± 0.29^{Cb}	0.00	0.00	0.00
(*E*)-2-Nonenal	0.08	Fatty, tallowy	193 ± 1.92^{Ba}	15.1 ± 0.27^{Bb}	0.00	170 ± 9.52^{Ba}	16.3 ± 1.42^{ABb}	0.00	366 ± 14.4^{Aa}	18.5 ± 0.76^{Ab}	0.00	0.02	0.11
Heptanal	3.00	Fat, citrus	259 ± 1.53^{Ba}	30.2 ± 0.51^{Ab}	0.00	243 ± 0.76^{Ca}	23.3 ± 0.27^{Bb}	0.00	498 ± 1.07^{Aa}	23.0 ± 0.47^{Bb}	0.00	0.00	0.04
3-Methyl butanal	0.20	Dark chocolate	51.4 ± 1.63^{Ba}	67.1 ± 1.78^{Ab}	0.00	20.1 ± 1.91^{Cb}	36.2 ± 1.20^{Ca}	0.00	72.5 ± 2.95^{Ab}	105 ± 8.73^{Aa}	0.03	0.00	0.00
Pentanal	9.00	Fruity	194 ± 0.61^{Aa}	4.97 ± 0.28^{Cb}	0.00	207 ± 0.55^{Aa}	5.49 ± 0.22^{Bb}	0.00	160 ± 0.54^{Ba}	6.32 ± 0.31^{Ab}	0.00	0.00	0.03
(*E*)-2-Decenal	0.40	Fatty, green	25.1 ± 0.27^{Ba}	0.78 ± 0.04^{Ab}	0.00	19.1 ± 0.41^{Ca}	0.68 ± 0.04^{Bb}	0.00	52.7 ± 0.52^{Aa}	0.58 ± 0.03^{Cb}	0.00	0.00	0.02
Hexanal	10.0	Green, grass	2346 ± 0.30^{Aa}	98.3 ± 0.49^{Bb}	0.00	1994 ± 0.19^{Ba}	106 ± 0.29^{Ab}	0.00	1867 ± 0.24^{Ca}	76.7 ± 0.22^{Cb}	0.00	0.00	0.00
(*E, E*)-2,4-Decadienal	0.20	Fatty, fried	116 ± 6.35^{Aa}	1.64 ± 0.05^{Bb}	0.00	112 ± 2.59^{Aa}	1.89 ± 0.03^{Ab}	0.00	114 ± 2.31^{Aa}	1.33 ± 0.07^{Cb}	0.00	0.75	0.01
Linalool	6.00	Floral, sweet	6.56 ± 0.29^{Ca}	1.88 ± 0.15^{Bb}	0.00	8.53 ± 0.56^{Ba}	1.43 ± 0.15^{Bb}	0.00	12.6 ± 0.39^{Aa}	5.31 ± 0.40^{Ab}	0.00	0.00	0.03
1-Octanol	110	Herbal, green	1.62 ± 0.03^{Ba}	0.13 ± 0.00^{Cb}	0.00	1.43 ± 0.01^{Ca}	0.23 ± 0.01^{Ab}	0.00	3.99 ± 0.02^{Aa}	0.16 ± 0.01^{Bb}	0.00	0.00	0.02
1-Octen-3-ol	2.00	Mushroom	310 ± 1.37^{Aa}	14.4 ± 0.37^{Bb}	0.00	292 ± 1.70^{Ba}	20.0 ± 0.60^{Ab}	0.00	271 ± 2.45^{Ca}	9.25 ± 0.34^{Cb}	0.00	0.03	0.00
1-Hexanol	5.60	Mild, sweet, green fruity odor and aromatic flavour	18.8 ± 0.92^{Ba}	3.57 ± 0.05^{Bb}	0.00	10.2 ± 0.04^{Cb}	13.0 ± 0.41^{Aa}	0.02	49.9 ± 0.73^{Aa}	3.75 ± 0.12^{Bb}	0.00	0.00	0.04
1-Pentanol	360	Balsamic	1.91 ± 0.01^{Ba}	0.34 ± 0.00^{Ab}	0.00	2.31 ± 0.00^{Ba}	0.23 ± 0.01^{Bb}	0.00	4.97 ± 0.01^{Aa}	0.31 ± 0.01^{Ab}	0.00	0.02	0.02
Methanethiol	2.00	Garlic, sulfur	20.6 ± 0.58^{Ba}	2.64 ± 0.10^{Ab}	0.00	30.4 ± 1.23^{Aa}	1.54 ± 0.03^{Bb}	0.00	5.01 ± 0.04^{Ca}	1.40 ± 0.05^{Bb}	0.00	0.00	0.03
2,3-Pentanedione	29.0	Milky	1.02 ± 0.02^{Ba}	0.19 ± 0.00^{Ab}	0.00	1.21 ± 0.05^{Aa}	0.19 ± 0.00^{Ab}	0.00	0.72 ± 0.04^{Ca}	0.12 ± 0.00^{Bb}	0.00	0.00	0.03
2-Heptanone	140	Blue cheese	0.53 ± 0.01^{Ba}	0.06 ± 0.00^{Bb}	0.00	0.59 ± 0.03^{Aa}	0.07 ± 0.00^{Bb}	0.00	0.61 ± 0.19^{Aa}	0.51 ± 0.00^{Aa}	0.11	0.08	0.01
6-Methyl-5-hepten-2-one	50.0	Pepper, rubber	1.22 ± 0.11^{Ba}	0.26 ± 0.02^{Bb}	0.00	1.22 ± 0.04^{Ba}	0.29 ± 0.02^{Ab}	0.00	1.60 ± 0.08^{Aa}	0.30 ± 0.02^{Ab}	0.00	0.03	0.09
p-Xylene	140	Fatty	0.27 ± 0.00^{Ba}	0.27 ± 0.01^{Ba}	0.98	0.29 ± 0.02^{Ba}	0.22 ± 0.01^{Cb}	0.03	0.37 ± 0.02^{Ab}	0.48 ± 0.03^{Aa}	0.06	0.01	0.01

(*continued on next page*)

Table 2 (*continued*)

Compounds	Odor thresholds ($\mu g \cdot kg^{-1}$) [x]	Odor descriptions [y]	Boiling			Steaming			Roasting			Methods *P*-value		
			BLYM	BHYM	*P*-value	SLYM	SHYM	*P*-value	RLYM	RHYM	*P*-value	BLYM-SLYM-RLYM	BHYM-SHYM-RHYM	
Toluene	200	Paint	1.25 ± 0.03^{Ca}	0.52 ± 0.03^{Cb}	0.00	1.37 ± 0.03^{Ba}	0.83 ± 0.03^{Bb}	0.00	1.75 ± 0.02^{Aa}	1.37 ± 0.02^{Ab}	0.00	0.00	0.00	
Ethylbenzene	29.0	Ethereal, floral	1.12 ± 0.07^{Ba}	1.34 ± 0.07^{Ba}	1.10	1.19 ± 0.08^{Ba}	1.06 ± 0.06^{Ca}	0.37	1.70 ± 0.10^{Ab}	2.35 ± 0.15^{Aa}	0.02	0.01	0.00	
Styrene	65.0	Herbaceous, fatty	2.60 ± 0.05^{Ba}	1.98 ± 0.05^{Bb}	0.00	2.71 ± 0.06^{Ba}	1.65 ± 0.07^{Cb}	0.00	5.33 ± 0.05^{Aa}	3.84 ± 0.05^{Ab}	0.00	0.03	0.00	
D-Limonene	10.0	Citrus, mint	11.9 ± 0.34^{Ba}	3.14 ± 0.13^{Bb}	0.00	8.58 ± 0.16^{Ca}	4.71 ± 0.23^{ABb}	0.00	14.3 ± 0.56^{Aa}	5.79 ± 0.49^{Ab}	0.00	0.00	0.05	
α-Copaene	5.00	Spice	45.0 ± 1.44^{Aa}	4.36 ± 0.06^{Cb}	0.00	10.9 ± 0.17^{Cb}	35.3 ± 0.42^{Aa}	0.00	31.4 ± 0.94^{Ba}	32.8 ± 0.79^{Ba}	0.48	0.00	0.02	
β-Pinene	6.00	Pine, resin, turpentine	4.22 ± 0.13^{Aa}	1.97 ± 0.27^{Bb}	0.01	–	1.82 ± 0.17^{B}	0.00	3.97 ± 0.23^{Aa}	4.24 ± 0.39^{Aa}	0.82	0.04	0.04	
α-Pinene	3.00	Pine, turpentine	1.75 ± 0.19^{Ba}	0.74 ± 0.11^{Cb}	0.01	0.60 ± 0.10^{Cb}	1.07 ± 0.11^{Ba}	0.030	3.59 ± 0.06^{Ab}	5.51 ± 0.41^{Aa}	0.01	0.00	0.00	
2-Pentyl-furan	6.00	Fruity	128 ± 0.38^{Ba}	3.01 ± 0.26^{Bb}	0.00	130 ± 0.56^{Ba}	8.71 ± 0.32^{Ab}	0.00	1275 ± 0.60^{Aa}	1.45 ± 0.00^{Cb}	0.00	0.00	0.00	
Furfural	3.00	Almond, sweet	1.78 ± 0.02^{Ba}	1.83 ± 0.04^{Ba}	0.56	3.89 ± 0.04^{Aa}	1.10 ± 0.02^{Cb}	0.00	4.54 ± 0.23^{Aa}	3.44 ± 0.11^{Ab}	0.01	0.03	0.00	
2-*n*-Butylfuran	5.00	N.A.	5.92 ± 0.50^{Aa}	0.45 ± 0.02^{Bb}	0.00	5.39 ± 0.21^{Aa}	0.72 ± 0.01^{Ab}	0.00	4.96 ± 0.23^{Aa}	0.20 ± 0.01^{Cb}	0.00	0.21	0.00	
2,6-Diethyl-pyrazine	6.00	nutty, roasted, and grassy aroma	–	–	–	–	–	–	4.04 ± 0.09^{a}	1.06 ± 0.09^{b}	0.00	0.00	0.00	
2-Ethyl-5-methyl-pyrazine	0.04	Roasted; cocoa; nut roasted beef	–	–	–	–	–	–	18.3 ± 0.59^{b}	30.3 ± 2.22^{a}	0.01	0.00	0.00	
Carbon disulfide	95.5	Sulfury, unpleasant	1.13 ± 0.05^{Ca}	0.91 ± 0.04^{Cb}	0.02	1.82 ± 0.02^{Ba}	1.50 ± 0.06^{Bb}	0.02	3.15 ± 0.04^{Aa}	2.73 ± 0.03^{Ab}	0.00	0.00	0.00	
2-Acetylthiazoline	10.0	Popcorn	1.32 ± 0.16^{Ba}	0.31 ± 0.00^{Cb}	0.00	1.33 ± 0.11^{Ba}	0.75 ± 0.05^{Bb}	0.00	2.46 ± 0.10^{Aa}	0.99 ± 0.03^{Ab}	0.00	0.02	0.00	
Total			9813 ± 12.2^{Ba}	846 ± 10.5^{Cb}	0.00	8575 ± 16.8^{Ca}	1252 ± 25.0^{Bb}	0.00	12747 ± 10.1^{Aa}	3567 ± 22.6^{Ab}	0.00	0.00	0.00	

Note: BLYM: Boiled low-altitude yak meat; BHYM: Boiled high-altitude yak meat; SLYM: Steamed low-altitude yak meat; SHYM: Steamed high-altitude yak meat; RLYM: Roasted low-altitude yak meat; RHYM: Roasted high-altitude yak meat; N.A., not acquired. $^{A\text{-}C}$ indicates within the same row with different letters differ significantly ($P < 0.05$) (differences among the cooking methods). $^{a\text{-}b}$ indicates within the same row with different uppercase letters differ significantly ($P < 0.05$) (differences between the low- and high-altitude yak meat).

[x] Odor thresholds were mainly obtained from the literature and an online database, with water applied as the matrix: (Li et al., 2019; Pavlidis et al., 2019; Karabagias, 2018; Wall et al., 2019; Feng et al., 2017), (https://www.flavornet.org, https://www.odour.org.uk).

[y] Odor descriptions were mainly gathered from the following literature and online database: (Li et al., 2019; Pavlidis et al., 2019; Karabagias, 2018; Wall et al., 2019; Feng et al., 2017), (http://www.flavornet.org).

Methyl-5-hepten-2-one, and 2,3-pentanedione) were identified as odor-active constituents in the headspace of cooked yak meat. Ketones, which are produced through lipid oxidation, possess lower thresholds, stable properties, and long-lasting aroma perceptions. They serve as crucial intermediates in the synthesis of heterocyclic compounds, thereby enhancing the aroma profile of cooked meat. 2-heptanone promotes a sweet and fruity aroma of cooked meat, its presence enhances the overall sensory experience, adding pleasant and aromatic notes to the flavor profile. However, in the flavor profile of raw yak meat, 2-heptanone could be used as a marker of product deterioration (Huang et al., 2022). 6-Methyl-5-hepten-2-one imparts a pleasing spicy and sweet aroma, and this ketone adds complexity and depth to the flavor profile, enhancing the overall sensory perception. In microwave-cooked yak meat, 6-Methyl-5-hepten-2-one is also been detected as a significant contributor to the overall flavor (Li et al., 2019). Diketone, such as 2,3-pentanedione, often provides a typical meaty and milky aroma. Additionally, they gradually increase with the oxidation time in yak meat during oxidation (Huang et al., 2022). The aforementioned substances were also identified in microwave-cooked yak meat (Li et al., 2019).

With regard to hydrocarbons, yak meat from different cooking methods and altitudes showed significant differences (Table 2). Aliphatic hydrocarbons are derived from the process of lipid oxidation, while aromatic hydrocarbons are produced via the oxidation of branched-chain aromatic acid (Giri et al., 2010). Within aliphatic hydrocarbons, α-Copaene and D-limonene were the most abundant (Table 2). α-Copaene, as a terpenoid, endows a distinctive fruity, floral,

and sweet fragrance, whereas D-limonene possesses a naturally occurring citrus aroma and exhibits a prolonged shelf life, potentially playing a significant role in the distinctive olfactory profile of yak meat (Feng et al., 2017). They are also been identified as key aroma components of cooked beef meatballs during storage (Sun et al., 2021). These terpenoids have the potential to interact with compounds derived from other chemical reactions and constitute flavor characteristics of yak meat (Zhen et al., 2022). Furthermore, as summarized in Table 2, this study identified p-xylene, toluene, ethylbenzene, and styrene as the primary aromatic hydrocarbons detected, hypothesized to originate from the forage consumed by yaks (Muriel et al., 2004). Specifically, ethylbenzene has been characterized as possessing ethereal, floral, and concrete-like olfactory properties, which has been identified in the flesh of diverse fish species, including farmed meager (Argyrosomus regius) and gilthead sea bream (Grigorakis et al., 2003; Giri et al., 2010). Styrene has been reported to be associated with some off-flavor in cakes and chocolate (Rius et al., 2005). The presence of the above terpenes in cooked yak meat might be attributed to their occurrence in the diets of yak (Rubén Domínguez et al., 2019). More importantly, pinene and D-limonene are mainly derived from spices added, such as anise (Campo et al., 2006; Costa et al., 2015). Similarly, for dry sausages inoculated with autochthonous lactic acid bacteria, terpenes and D-limonene, γ-terpinene, styrene, α-copaene, β-caryophyllene, safrole, *cis*-anethol, and D-camphor are identified to provide pleasant fragrance and sweet odors to sausages and mainly originate from the spices used during the preparation (Montanari et al., 2016). Conversely, yaks graze on vegetation in their natural habitat, and the plants they consume may contain aromatic compounds. These compounds can be metabolized by the yak's body and transferred to its meat, contributing to their presence (Parthasarathy et al., 2018). However, it is worth noting that hydrocarbons generally possess a relatively higher threshold value, hence exerting minimal impact on the overall aroma perception of meat products.

Heterocyclic compounds, particularly those composed of furan, nitrogen-, and sulfur-containing compounds, provide a unique flavor to meat and meat products. Among the oxygen-containing heterocyclic compounds, furans are one of the richest heterocyclic compounds in cooked food and are primarily formed through Amadori rearrangement pathways or dehydrated carbohydrates (Giri et al., 2010). As presented in Table 2, a total of 3 furans, namely 2-pentyl-furan, 2-*n*-butylfuran, and furfural, were identified as odor-active compounds in the headspace of yak meat. Among these, 2-pentyl-furan and 2-*n*-butylfurans, which are formed through the oxidation of linoleic acid, are expressibly selected as the most crucial volatile flavor components facilitating the integrity of flavor profile of meat and meat products (Han et al., 2020). Similar findings for the furan have also been reported in other studies that 2-pentyl furan identified as a flavor-active volatile affected by enhancement and aging in beef muscle (Stetzer et al., 2008). In the study on the Dezhou braised chicken, 2-pentyl-furan is selected as a key flavor chemical within the chicken carcasses (Yao et al., 2022). 2-Pentyl-furan, a typical product of lipid oxidation, has also been found in other dry-cured meats (Lorenzo, 2014; Purri et al., 2010), which adds complexity and authenticity to many "heated" flavors and enhances many fruit flavors (Krishnamurthy et al., 1967). The OAVs in SHYM samples were found to be significantly higher ($P < 0.05$) compared to those in BHYM and RHYM for high-altitude yak meat while failing to attain statistical significance among low-altitude samples ($P > 0.05$). Time and/or temperature of cooking conditions could influence significantly the abundance of some furan and sulfur-containing compounds (Roldán et al., 2015). Furthermore, the compounds 2-methylfuran, 2-pentyl-furan, and carbon disulfide exhibited susceptibility to the combined influence of both parameters, resulting in elevated concentrations in lamb loin samples cooked at 80 °C for 24 h compared to the remaining three cooking conditions. The available literature data suggest that furan and its substituted derivatives can be formed from various sources. Consequently, furans have been associated with elevated temperatures during food processing. Thus, furans have been linked to high-heating processes in food (Pérez-Palacios et al., 2012), but they are also formed through oxidation of unsaturated fatty acids, namely from α-linolenic and γ-linolenic acid (Elmore et al., 1999). Furans can be generated through intricate oxidation or Maillard reactions involving diverse precursors naturally occurring in food, including ascorbic acid, carbohydrates, amino acids, fatty acids, and carotenoids (Nie et al., 2013). Therefore, it seems that the formation of furans in cooked meat at more severe cooking conditions could derive from Maillard reactions, while the furan formation from unsaturated fatty acids could occur at more moderate temperatures (Elmore & Mottram, 2006). Steaming is a gentle cooking method that helps to preserve the natural flavors of the meat (Song et al., 2021). The lower temperatures during steaming may result in less degradation or alteration of the volatile flavor compounds (Rao et al., 2022), including 2-pentyl-furan and 2-*n*-butylfurans. Consequently, these compounds are retained in higher concentrations, leading to higher OAVs in steamed samples. Secondly, the moisture-rich environment during steaming may also contribute to the higher OAVs of 2-pentyl-furan and 2-*n*-butylfurans. It is possible that the steam helps to retain and concentrate the flavor compounds, resulting in higher OAVs for 2-pentyl-furan and 2-*n*-butylfurans in steamed high-altitude yak meat.

N-containing compounds are responsible for imparting a roasted coffee, chocolate, and nut flavor to cooked beef meat. Here, only two *N*-containing compounds (2,6-diethyl-pyrazine and 2-ethyl-5-methyl-pyrazine) were identified as odor-active compounds in cooked yak meat (Table 2). These compounds are produced through Strecker degradation reactions involving amino acids and reductones (Wall et al., 2019). It is noteworthy to draw that they were exclusively detectable in the RLYM and RHYM samples. With the higher the heating temperature, the formation of pyrazines becomes more stable owing to the relative stability. All three of these compounds exhibited a positive response to variations in cooking temperature, which is a characteristic feature of Maillard products (Kerth, 2016). Cooked beef brisket using oven roasting method releases a more intense aroma than in boiled samples, in particular, pyrazines (2-methyl and 2,5-dimethylpyrazine) were found to be more abundant in the former (Utama et al., 2018). 2,3,5-trimethyl pyrazine, as a key aroma compound, is found to contribute to "roasted flavor" profiles in beef extract through addition experiments (Takakura et al., 2014). There were 11 pyrazines found in roasted tilapia, of which 10 pyrazines can't be identified in microwave-heated tilapia, boiled tilapia, and steamed tilapia (Zhang et al., 2022). Consequently, both of these compounds have the ability to generate a distinctive roasted yak meat flavor and act as a sign to discriminate yak meat from various thermal processing types.

Sulfur-containing compounds, characterized by their low threshold values and intense flavor intensity, are categorically known to be derived from sulfur amino acids, thiamine, or glutathione (Alim et al., 2019). In this study, two S-containing compounds (carbon disulfide and 2-acetylthiazoline) were characterized as odor-active compounds (Table 2). Carbon disulfide, documented to impart a cabbage flavor, significantly contributes to the flavor profile of cooked beef. Additionally, 2-acetylthiazoline (meaty aroma) has been specifically regarded as the characteristic flavor of roasted meat (Raza et al., 2020). 2-Acetylthiazole has also been identified in the roasted meat of domestic duck, roasted beef (Rochat et al., 2007), cooked beef (Machiels et al., 2004), and thermally processed giant African snail meats (Lasekan et al., 2018). The OAVs of these compounds in the roasted yak meat were substantially higher compared to boiled and steamed samples ($P < 0.05$). This echoes the aforementioned findings of E-nose that roasting cooking modified the volatile profile of yak meat, especially enhanced S-containing compounds. S-containing amino acids, such as cysteine and methionine, could be particularly reactive in the Maillard reaction. During roasting, these amino acids undergo reactions that generate S-containing compounds, including thiols, disulfides, and sulfides. These compounds often have strong and distinct odors, contributing to the rich aromatic profile of roasted yak meat. Secondly, the higher temperatures

during roasting may promote the release of volatile sulfur compounds from the meat matrix. Heat can disrupt the chemical bonds that trap or bind sulfur compounds, allowing them to be released into the surrounding environment as volatile compounds. These sulfur compounds have low thresholds, meaning that even small amounts can have a significant impact on the perceived aroma of the yak meat. From an altitude point of view, the observed OAVs from low-altitude samples were much greater than the high-altitude ones ($P < 0.05$). Firstly, it is possible that the differences in the availability and metabolism of S-containing amino acids, such as cysteine and methionine in low-altitude and high-altitude environments contribute to the variation in sulfur compound levels. Secondly, environmental factors, such as soil composition and vegetation, may influence the sulfur content in the forage consumed by yaks. It is known that sulfur is an essential nutrient for plants, and the sulfur content in the forage can vary depending on the geographical location and altitude. Therefore, differences in the sulfur content of the forage consumed by low-altitude and high-altitude yaks may contribute to the disparity in sulfur compound levels in their meat. In summary, S-containing compounds might play a pivotal role in the characteristic flavor of low-altitude yak meat.

Taken together, the following constituents were presumed as characteristic odor-active compounds to contribute strongly to the integral flavor of cooked yak meat: nonanal, decanal, heptanal, pentanal, hexanal, (*E*)-2-octenal, (*E*)-2-nonenal, 3-methyl butanal, 1-octen-3-ol, (*E*, *E*)-2,4-decadienal, 2-heptanone, styrene, α-copaene, and 2-pentylfuran. In the case of altitude, the OAVs of odor-active compounds increased in the low-altitude yak meat compared with high-altitude samples. Notably, the presence of (*E*, *E*)-2,4-nonadienal was exclusively observed in low-altitude yak meat. Concerning thermal techniques, the OAVs of odor-active compounds followed the order of roasting > steaming > boiling, suggesting that roasted yak meat displayed a more comprehensive flavor profile. Moreover, it is noteworthy that 2,6-diethyl-pyrazine and 2-ethyl-5-methyl-pyrazine, which exhibit nutty, roasted, and grassy characteristics, exclusively exhibited significant influence on the flavor profile in roasted samples. Consequently, these compounds could potentially serve as distinctive indicators of roasted yak meat. Furthermore, it is noteworthy that 2,6-diethyl-pyrazine and 2-ethyl-5-methyl-pyrazine (nutty, roasted, and grassy), only exhibited significant influence on the flavor profile in roasted samples. Consequently, these compounds could potentially serve as distinctive indicators of roasted yak meat.

3.5. Sensory attributes of low- and high-altitude yak meat subjected to different methods of cooking

Sensory evaluation remains the key criterion for evaluating food quality in traditional methods of meat quality evaluation, as it takes into account the assessment of physicochemical indexes which may not fully represent the output of the human sensory system. The sensory attributes of beef samples significantly influence consumers' overall preference (Jiang et al., 2023). As summarized in Table 3, the tenderness attribute scores were highest in roasted yak meat, second on steamed, while the lowest scores were detected in boiled samples ($P < 0.05$). When cooked using methods that preserve moisture and break down connective tissues, these naturally tender fibers contribute to the overall tenderness perception. On the other hand, Boiling, with its extended cooking time, might not allow for optimal collagen breakdown, leading to less tender meat. Moreover, roasted samples received significantly higher scores in color, taste, and flavor scores when compared with the boiling- and steaming-cooked samples ($P < 0.05$). Thus, yak meat cooked by roasting was more favorable and thus achieved remarkably the highest overall acceptability scores, which were well above the scores for boiled and steamed samples. Generally, when yak meat is subjected to dry heat at high temperatures, the Maillard reaction between amino acids and reducing sugars leads to the formation of brown pigments. These pigments contribute to the appealing brown color of the roasted meat. Additionally, the Maillard reaction generates various flavor compounds, such as pyrazines and diacetyl, which contribute to the characteristic taste and flavor profiles associated with roasted meat. In contrast, boiling and steaming involve moist heat, which can extract and dilute some flavor compounds, resulting in milder taste and flavor profiles. Furthermore, the texture and mouthfeel of the roasted meat can positively influence taste and flavor perception. Roasting can result in the formation of a desirable crispy and browned exterior while maintaining a juicy and tender interior. These textural contrasts, along with the visually appealing color, can enhance the overall sensory experience and lead to higher scores in taste and flavor evaluations. Similarly, greater color, flavor, taste, and overall acceptability scores were observed for oven-cooked beef meat, as compared to the sous-vide-cooked counterparts (Gök et al., 2019). Concerning altitude, when subjected to identical cooking processing, low-altitude yak meat tended to have higher overall acceptability scores ($P < 0.05$) due to its more pronounced aromatic profiles and tenderness qualities. The variances in elevation can potentially impact the constitution and accessibility of volatile compounds within the plant species consumed by yaks. In particular, yaks residing at lower altitudes may enjoy a more abundant and varied assortment of food resources, consequently exerting an influence on the aromatic profile of their meat (Huamán-Castilla et al., 2020). Flora thriving at lower elevations might exhibit increased variety and greater quantities of aromatic compounds, including terpenoids, phenols, and aldehydes (Chrysargyris et al., 2021; Kumar et al., 2022). For instance, a study on the volatile constituents of Thymus *serpyllum L.*

Table 3
Effects of different methods of cooking on the sensory attributes of low- and high-altitude yak meat.

Index	Boiling			Steaming			Roasting			Methods *P*-value	
	BLYM	BHYM	*P*-value	SLYM	SHYM	*P*-value	RLYM	RHYM	*P*-value	BLYM-SLYM-RLYM	BHYM-SHYM-RHYM
Tenderness	5.18 ± 0.17^{Ca}	4.32 ± 0.11^{Cb}	0.00	5.70 ± 0.12^{Ba}	4.81 ± 0.06^{Bb}	0.00	6.18 ± 0.13^{Aa}	5.54 ± 0.13^{Ab}	0.01	0.00	0.00
Color	5.36 ± 0.13^{Ba}	5.73 ± 0.12^{Ba}	0.06	5.19 ± 0.15^{Ba}	5.62 ± 0.16^{Ba}	0.04	6.06 ± 0.15^{Ab}	6.47 ± 0.10^{Aa}	0.01	0.03	0.04
Taste	5.13 ± 0.16^{Ba}	5.30 ± 0.14^{Ba}	0.33	5.07 ± 0.12^{Ba}	5.34 ± 0.14^{Ba}	0.08	6.30 ± 0.11^{Aa}	6.24 ± 0.08^{Aa}	0.67	0.04	0.04
Flavor	4.80 ± 0.07^{Ba}	4.47 ± 0.11^{Bb}	0.04	4.90 ± 0.11^{Ba}	4.58 ± 0.12^{Ba}	0.07	5.91 ± 0.23^{Aa}	5.31 ± 0.07^{Ab}	0.01	0.03	0.04
Overall acceptability	5.58 ± 0.06^{Ba}	5.05 ± 0.11 ^{Bb}	0.01	5.07 ± 0.08 ^{Ca}	4.85 ± 0.07 ^{Ba}	0.13	6.50 ± 0.10 ^{Aa}	5.99 ± 0.10 ^{Ab}	0.01	0.01	0.04

Note: BLYM: Boiled low-altitude yak meat; BHYM: Boiled high-altitude yak meat; SLYM: Steamed low-altitude yak meat; SHYM: Steamed high-altitude yak meat; RLYM: Roasted low-altitude yak meat; RHYM: Roasted high-altitude yak meat. $^{A-C}$ indicates within the same row with different letters differ significantly ($P < 0.05$) (differences among the cooking methods). $^{a-b}$ indicates within the same row with different uppercase letters differ significantly ($P < 0.05$) (differences between the low- and high-altitude yak meat).

grown at different altitudes in the Western Himalayas found that the concentration of certain compounds, such as thymol and carvacrol, increased with decreasing altitude (Kumar et al., 2022). These aromatic compounds could be absorbed by yaks during grazing and subsequently contribute to the flavor and aroma of meat. Secondly, it has been observed that yaks living at higher altitudes generally have more robust musculature. This can be attributed to the adaptation of yaks to harsh environmental conditions, including lower oxygen levels at high altitudes. The enhanced muscle development leads to alterations in muscle fiber composition and arrangement, which could potentially impact the tenderness attributes of the meat (Shah et al., 2023). Low-altitude yak meat may display enhanced tenderness due to a different composition of muscle fibers and collagen content. In summary, the RLYM sample was preferred among the panel. Recently, a quantitative proteomic analysis in cattle-yak and yak *longissimus thoracis* also revealed that highland yak muscle has worse tenderness as a result of the differences in abundance of the collagens and the connective tissue composition, and their assembly structures (Chang et al., 2023). However, for traditional Tibetan yak jerky, high altitude accelerates lipid oxidation, contributing to the development of the flavor profile, thus, high-altitude yak jerky with a natural drying time of 75 d tends to be more popular (Han et al., 2020). The meat of *M. longissimus* from Hanwoo (Korean cattle) steer from high raising altitude exhibits reduced saturated fatty acids and increased unsaturated fatty acids concentrations in comparison to that from lower altitudes (Panjono et al., 2011), while for sensory properties, there is no significant difference between these samples with different raising altitudes (Panjono et al., 2011). For Tibet pigs, the high-altitude breed sample exhibits lower L^* and higher a^* values than high-altitude ones, which is likely contrary to our current observation. These differences may be due to species differences, yaks belong to the ruminant species, which have unique physiological and biochemical characteristics in their digestive systems that enable efficient utilization of food resources in high-altitude environments, resulting in distinct a* value patterns (Gan et al., 2019). Another study compared three different pig breeds at different altitudes and found that the high-altitude breeds (Tibetan and Liang-Shan pigs) had better meat quality attributes than the flatland breed (Duroc×(Landrace × Yorkshire) cross). The high-altitude breeds had a slower rate of glycolysis metabolism, which may have contributed to their better meat quality (Shen et al., 2014). However, the findings were the opposite in yak meat from different altitudes that the glycolysis metabolism of high-altitude postmortem yak muscle is higher (Yang et al., 2020). Thus, there is no clear consensus on the specific mechanisms that affect yak meat quality in animals living at high altitudes and more research is needed to fully understand the relationship between altitude and meat quality in different animal species.

4. Conclusion

In summary, a total of 138 volatile compounds were identified, of which 36 compounds were chosen as odor-active compounds in cooked yak meat. Roasting emerges as the most highly recommended cooking method for yak meat since it induces great consumer acceptability. Moreover, roasting cooking endowed yak meat with richer heterocyclic compounds and ketones, thereby contributing the typical aroma of yak meat and greatly enriching the flavor profile. The application of the roasting technique yielded reduced cooking loss and fat content, whereas induced lipid oxidation more compared with boiling and steaming. Steaming, in contrast, revealed superior nutritional health indicators compared with boiling and roasting but unfortunately, most consumers did not accept its plain sensorial attributes. The types and contents of volatile compounds in low-altitude yak meat (BLYM, SLYM, and RLYM) were greater than those of low-altitude ones (BHYM, SHYM, and RHYM), especially aldehydes. The compound (*E*, *E*)-2,4-nonadienal was identified as a potential valuable flavor maker for differentiating cooked yak meat from different altitudes. Based on PCA analyses of E-nose, yak meat could be separately distributed into two groups, including low-altitude (BLYM, SLYM, and RLYM) and high-altitude yak meat (BHYM, SHYM, and RHYM) samples. This finding suggests that the volatile composition of yak meat varies significantly depending on the altitude at which it is sourced. It may be concluded that the odor-active compounds generated and sensory properties of low-altitude yak meat were improved compared to high-altitude samples. Particularly noteworthy is RLYM, which is prominent in the formation of odor compounds. The present study may provide valuable information for the possible thermal processing technology applicable to yak meat sourced from varying altitudes.

CRediT authorship contribution statement

Xijin Zhu: Investigation, Writing – original draft, Formal analysis. **Chao Yang:** Software, Formal analysis, Writing – review & editing. **Yu Song:** Writing – review & editing. **Yu Qiang:** Investigation, Visualization. **Dong Han:** Methodology, Conceptualization. **Chunhui Zhang:** Project administration, Funding acquisition.

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

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