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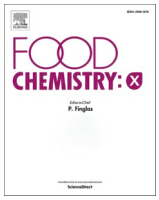

Characterization of flavor profile of beef jerky from different regions of China using gas chromatography–mass spectrometry, electronic tongue, and electronic nose

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ABSTRACT

This research utilized gas chromatography–mass spectrometry (GC–MS), electronic tongue (*E*-tongue), electronic nose (E-nose), and sensory analysis to investigate the flavor profiles of beef jerky from four specific regions of China: Xinjiang, Tibet, Sichuan, and Inner Mongolia. Physical analysis revealed that beef jerky from Inner Mongolia had lower moisture content and water activity, while Tibet and Inner Mongolia samples exhibited lower pH values. Seventy-two volatile compounds were identified and quantified among all samples, indicating significant regional variations in aldehydes, alcohols, and esters. Heatmap cluster analysis clearly explained the unique regional flavor profiles. Furthermore, partial least squares regression analysis using *E*-nose and E-tongue showed significant correlations with the volatile compounds and sensory attributes. These findings indicate the efficacy of a multi-faceted analytical approach for flavor differentiation and emphasize the need for further research to understand the mechanisms behind developing characteristic flavors in beef jerky.

1. Introduction

Beef jerky is a traditional dried meat product that is favored by the Chinese consumers due to its rich nutritional benefits, extended shelf-life, and distinctive flavor (Wen et al., 2021). They are typically prepared by cutting raw beef into strips, seasoning with spices, curing, air-drying, and roasting (Karami et al., 2024). Xinjiang, Tibet, Sichuan, and Inner Mongolia are China's primary processing regions for beef jerky (Han et al., 2020). Additionally, local cattle breeds, environmental conditions, traditional processing techniques, and regional variations could influence beef jerky's sensory characteristic (Wang et al., 2024). The final beef jerky products reach a water activity (aw) of 0.6–0.9 at ambient temperature, successfully suppressing microbial proliferation through a low aw system (Lim et al., 2012). The sensory characteristics of beef jerky are primarily determined by its flavor, which has a substantial impact on consumer preferences and purchasing decisions, frequently determining the success of a product in the market (Khan et al., 2015). Beef jerky produced in different regions exhibits distinct flavor profiles, enhancing its regional identity. However, the distinct flavor profiles of beef jerky processed in various regions still need to be defined.

Headspace solid phase micro-extraction gas chromatography–mass spectrometry (HS-SPME-GC–MS) is one of the most commonly employed techniques for analyzing volatile compounds (Acquaticci

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Fig. 1. Geographical distribution of beef jerky from different regions of China.

et al., 2024). SPME can extract analytes from complex food matrices, including meat, offering simplicity, speed, and solvent-free operation advantages. GC–MS is the most used technique for quantitative and qualitatively assessing foods' volatile compounds (Fang et al., 2017). Furthermore, electronic nose (*E*-nose) and electronic tongue (E-tongue) techniques, utilizing a collection of electrochemical sensors, have been extensively utilized in flavor analysis to mitigate the influence of subjective biases in sensory assessment (Mahanti et al., 2024; Martínez et al., 2025). Recently, GC–MS, *E*-nose, and E-tongue were used together to analyze the aroma and taste profiles of various food matrices, such as fish, coffee, meat, and tea (Fu et al., 2024). However, limited research has assessed the differences in flavor profiles of beef jerky, especially in the different regions, utilizing a combination of *E*-tongue, E-nose, and GC–MS techniques.

This study aimed to visually analyze beef jerky's flavor profiles from four regions of China utilizing GC–MS, E-tongue, and E-nose techniques. The physical properties of beef jerky, including pH, moisture content, aw, and color, were analyzed. The flavor profiles of beef jerky from four regions in China were determined. The correlation among the volatile compounds, E-tongue, E-nose, and sensory attributes in beef jerky was also elucidated. The findings from this study can contribute to a clear understanding of beef jerky's flavor profile and offer valuable insights for improving its quality.

2. Materials and methods

2.1. Sample collection

Samples of beef jerky were obtained from four distinct regions in China: Xinjiang (Yili), Tibet (Naqu), Sichuan (Ganzi), and Inner Mongolia (Baotou). Samples from each region were collected from a local industrial company, with three separate batches of 2.0 kg each collected. The time intervals between the three batches of different region's samples ranged from 7 to 14 days. The relative positions of these sampling locations are depicted in Fig. 1. The beef jerky samples in different regions were processed using traditional methods. In Xinjiang (Yili), the Halal-certified beef from Xinjiang brown cattle was marinated with vegetable oil, salt, white sugar, sesame, chili powder, Sichuan peppercorns, monosodium glutamate (MSG), mixed spice, soy sauce, and baijiu for 12 h. The marinated beef was roasted at 80 °C for 8 h and then naturally air-dried for 72 h. In Tibet (Naqu), the yak meat was marinated with salt, chicken essence, Sichuan peppercorns, white pepper, and chili powder for 12 h. The marinated yak meat was air-dried at 5 to 15 °C for 120 h. In Sichuan (Ganzi), the yak meat was cut into strips and then marinated with salt, white sugar, green Sichuan peppercorns, mixed spice, baijiu, chicken essence, MSG, ethyl maltol, and sodium nitrite for 12 h. The marinated yak meat was then naturally air-dried for 24 h. In Inner Mongolia (Baotou), the beef from grass-fed cattle was marinated for 2 h with salt, soy sauce, ginger, onion, MSG, and spices. The marinated beef was air-dried for 48 h and finally roasted by charcoal to achieve 80 % to 100 % dryness. After collection, the samples were transported to the laboratory in a sterilized ice box. The samples were stored at −80 °C for further analysis.

2.2. Physiochemical properties

The moisture content of beef jerky was determined by dehydrating it at 105 °C until the weight remained consistent. The aw of beef jerky was calculated with an AquaLab 4TE DUO water activity meter (Decagon Devices, Pullman, WA, USA). The pH value was measured according to the method outlined by Lim et al. (2014). For this purpose, a homogenate prepared using an aliquot of 10.0 g beef jerky with a 10-fold dilution. The pH was recorded at 25 °C using a Mettler Toledo pH meter (Shanghai, China). For the purpose of calibrating the pH meter, buffer solutions with pH values of 4.00, 6.86, and 9.18 were employed at ambient temperature. Color assessment of beef jerky was conducted using a ZE-6000 colorimeter (Juki Corp., Tokyo, Japan), with a D65 light source and a 10° observer with 8 mm diameter measuring area and 50 mm diameter illumination area. A white reference plate ($L^* = 95.26$, $a^* = -0.89$, $b^* = 1.18$) served as the standard background, with a total of 30 measurements recorded at 10 s intervals.

2.3. GC–MS analysis

Volatile compounds were analyzed following the method described by Wu et al. (2024), with minor modifications. For this purpose, a Shimadzu TQ8050NX GC–MS system equipped with a DB-WAX UI column was utilized for analysis. Briefly, a 15 mL screw-neck sample vial was filled with a 3.00 g portion of the sample. An internal standard of 10 μL of o-dichlorobenzene (200 mg/L) was added. The mixture underwent thorough vertexing and incubated in a water bath (50 °C) for 25 min. A SPME fiber was then inserted into the vial for 45 min for volatile compounds' extraction. Following extraction, the SPME fiber underwent desorption in the GC injection port (230 °C) for 3 min. The GC–MS parameters were set as follows: injection port temperature at 230 °C, ion source temperature at 230 °C, and interface temperature at 250 °C. The oven temperature program began at 40 °C and was held for 3 min, then increased to 200 °C at a rate of 5 °C per min, followed by a rise to 230 °C at a rate of 10 °C per min, concluding with a final hold of 2 min. The identification of volatile compounds was conducted by comparing their mass spectra with the NIST20 library or by calculating their linear retention index (LRI) in relation to standard alkanes (C7-C40). Quantification of volatile compounds was achieved by dividing the peak areas of the analytes by the peak area of the IS and multiplying this ratio based on the initial concentration of the IS, expressed in μg/kg.

2.4. E-nose analysis

Following the method outlined by Yao et al. (2024), the olfactory profiles of beef jerky samples were assessed using a commercial PEN3.5 E-nose, Win Muster Airsense Analytics Inc. (Schwerin, Germany). Three grams of samples were placed in an airtight vial (20-mL) and incubated at 50 °C for 45 min. A hollow needle attached to tubing was employed to puncture the vial seal and extract volatile gases from the headspace at a consistent flow rate. Analysis parameters were defined as follows: sample injection had a detection time of 120 s, with internal flow rates set at 300 mL·min^{-1}, and data collection occurred at intervals of 100 and 105 s. Table S1 presents the system which comprises the 10 metal oxide gas sensors and their specific sensitivity characteristics.

2.5. E-tongue analysis

The taste characteristics of beef jerky samples were analyzed with a S-5000Z taste sensor, *E*-tongue instrument (Insent Inc., Atsugi-shi, Japan) that is equipped with five chemical sensors for bitterness and aftertaste bitterness (aftertaste-B) (C00), astringency and aftertaste astringency (aftertaste-A) (AE1), umami and richness (AAE), saltiness (CT0), and sourness (CA0), as well as two reference electrodes. Precisely, about 30.0 g minced beef sample was blended with distilled water (150 mL) for extracting flavor constituents. After centrifuged at 2265 $\times g$ for 10 min at 4 °C, the water phase obtained was used for E-tongue measurements to evaluate the taste attributes of the beef jerky sample (Zhu et al., 2022).

2.6. Sensory analysis

Following the method outlined by Yao et al. (2024), the sensory evaluation of beef jerky samples was undertaken in accordance with humanistic ethics in China, following the acquisition of informed consent from all participants. The sensory analysis was conducted by an experienced sensory panel of 15 members (eight males and seven females). Panelists underwent a comprehensive training program designed to enhance their familiarity with the sensory attributes of the beef jerky samples. Training sessions were conducted four times per week over two weeks, with each session lasting 2 h. During these sessions, the panelists were introduced to the specific sensory characteristics of the samples and were trained to use the sensory scale effectively. Their expertise was validated through repeatability and discrimination tests to confirm consistency and reliability in their evaluations. The sensory evaluation involved three separate sessions, with each panelist assessing samples from all beef jerky. To minimize bias, the same panelists participated across all sessions, and samples were randomly assigned a three-digit code and presented on white plates. Each panelist assessed each sample once per session, and the evaluations were distributed evenly across the three sessions. Between samples, the panelists were instructed to use purified water to neutralize their palates. Panelists were instructed to assess sensory indicators using a scale ranging from 0 to 9, where 0 indicated minimal sensory intensity and 9 indicated maximal sensory intensity.

2.7. Statistical analysis

Three independent batches of beef jerky were collected, with each batch undergoing triplicate measurements. Data from all measurements were analyzed using the General Linear Models procedure in Statistics 9.0 (Analytical Software, USA). The results were presented as mean values ± standard error. The significance of the sample effects was evaluated through an analysis of variance (ANOVA) technique. Tukey's multiple comparison tests was employed to compare the means indicated significant differences ($P < 0.05$). The differences between groups (Xinjiang, Tibet, Sichuan, and Inner Mongolia beef jerky) were analyzed with mixed models with each batch (market) as a random effect and group as a fixed effect. Additionally, the sensory evaluation data were examined by setting different treatments as fixed factors and the session numbers as a random factor. Data plotting was performed using Origin 2018 (Origin Lab Corporation, Northampton, MA, USA). To visualize the data, a heatmap was generated using Chi Plot's heatmap tool (https://www.chiplot.online/). The partial least squares regression (PLSR) model was developed using Unscrambler software (version 10.4), elucidating the interrelationships among *E*-tongue, E-nose, sensory assessment, and volatile compounds.

Table 1
Physicochemical properties of beef jerky from different regions of China.

	Xinjiang	Tibet	Sichuan	Inner Mongolia
Water activity	0.63 ± 0.01^{a}	0.63 ± 0.01^{a}	0.62 ± 0.01^{a}	0.59 ± 0.00^{b}
Moisture content (%)	14.78 ± 0. 25^{b}	14.32 ± 0.56^{b}	16.99 ± 0.37^{a}	12.18 ± 0.11^{c}
pH	5.91 ± 0.02^{b}	5.81 ± 0.01^{d}	6.10 ± 0.01^{a}	5.86 ± 0.01^{c}
L^*-value	24.69 ± 2.10^{a}	24.82 ± 1.67^{a}	24.78 ± 2.61^{a}	20.59 ± 2.07^{b}
a^*-value	6.58 ± 1.98^{ab}	8.17 ± 1.99^{a}	4.56 ± 0.54^{b}	6.07 ± 0.72^{ab}
b^*-value	9.56 ± 3.51^{a}	11.84 ± 1.91^{a}	4.82 ± 0.48^{b}	9.95 ± 1.86^{a}

All data are expressed as the means ± standard error of triple measurements. Different lowercase letters (a-d) in the same row indicate significant differences ($P < 0.05$).

3. Results and discussion

3.1. Physiochemical property analysis

Table 1 presents the physiochemical parameter differences among beef jerky samples from Xinjiang, Tibet, Sichuan, and Inner Mongolia regions. The moisture contents and water activity of beef jerky in Inner Mongolia were significantly lower than those in Xinjiang, Tibet, and Sichuan ($P < 0.05$). These differences could be due to the variation in local climate and production processes (Shi et al., 2020). Dehydration of beef jerky aims to decrease moisture content, thereby suppressing microbial and biochemical activities, ultimately prolonging shelf-life and enhancing meat quality (Šuput et al., 2019). The pH level of beef jerky is a crucial factor influencing its flavor, texture, and general safety (Aung & Nam, 2024). The pH values of the beef jerky samples ranged from 5.81 to 6.10 across all samples analyzed. Significant differences in pH values were observed, with samples from Tibet and Inner Mongolia exhibiting markedly lower pH levels compared to those from Xinjiang and Sichuan ($P < 0.05$). These lower pH values may be attributed to the fermentation process, during which organic acids, particularly acetic and lactic acids, accumulate (Shi et al., 2020). Table 1 illustrated that the beef jerky samples from Inner Mongolia displayed significantly lower L^*-values than those from other regions ($P < 0.05$). The lower L^*-values in Inner Mongolia were related to its moisture contents. Significant differences were found in the a^*-values of beef jerky between Tibet and Sichuan, with values in Tibet being significantly higher ($P < 0.05$). On the other hand, no significant differences were found between Tibetan samples and those from Xinjiang and Inner Mongolia ($P > 0.05$). This observed difference may be attributed to the lower pH of the beef jerky in Tibet, which may facilitate the production of nitrosomyoglobin (Hu et al., 2022). The b^*-value indicates the presence of yellow pigments resulting from the interaction of lipid oxidation products with amines in the head groups of phospholipids or proteins (Xu et al., 2019). The beef jerky in Xinjiang, Tibet, and Inner Mongolia had higher b^*-values than in Sichuan ($P < 0.05$).

3.2. Volatile compound analysis

3.2.1. Contents of volatile compounds

Table 2 shows that 72 volatile compounds were found in the beef jerky. These included 12 aldehydes, 8 acids, 10 esters, 18 alcohols, 5 ketones, and 19 other compounds. The origin of these compounds is generally attributed to lipid oxidation, carbohydrate and amino acid metabolisms, bacterial esterification, and the presence of spices (Adeyemi et al., 2025). The flavor of meat products is considerably enhanced by aldehydes, which are primarily produced through the oxidation and breakdown of lipids. This is due to the exceptionally low

Table 2
Contents of volatile compounds (ng/g) in beef jerky from different regions of China.

Volatile compound	Retention time (min)	LRI	Xinjiang	Tibet	Sichuan	Inner Mongolia
Aldehyde (12)						
2-Methyl-butanal	3.29	864	8.79 ± 0.13^{a}	0.21 ± 0.01^{d}	1.26 ± 0.05^{b}	0.75 ± 0.02^{c}
Heptanal	9.55	1632	160.12 ± 5.76^{a}	17.94 ± 0.65^{b}	28.35 ± 1.08^{b}	17.00 ± 0.39^{b}
Octanal	12.58	1939	64.68 ± 2.32^{a}	5.05 ± 0.07^{d}	28.67 ± 1.09^{b}	16.64 ± 0.48^{c}
Hexadecanal	33.09	3478	1.18 ± 0.03^{d}	4.60 ± 0.06^{a}	2.25 ± 0.09^{c}	4.10 ± 0.12^{b}
Benzaldehyde	19.01	2736	56.98 ± 2.05^{a}	27.85 ± 0.32^{c}	19.38 ± 0.60^{d}	35.04 ± 0.86^{b}
Hexanal	6.67	1315	56.50 ± 2.03^{a}	4.36 ± 0.30^{c}	46.09 ± 1.76^{b}	3.68 ± 0.16^{c}
Nonanal	15.61	2297	190.17 ± 8.41^{a}	8.13 ± 0.29^{c}	167.28 ± 7.70^{a}	54.00 ± 1.57^{b}
2-Nonenal	19.42	2783	32.69 ± 1.18^{a}	4.98 ± 0.26^{bc}	7.76 ± 0.28^{b}	4.45 ± 0.14^{c}
2-Heptenal	13.56	2071	11.21 ± 0.40^{a}	1.94 ± 0.03^{c}	3.01 ± 0.14^{b}	3.26 ± 0.13^{b}
2-Octenal	16.56	2438	15.12 ± 0.54^{a}	6.40 ± 0.09^{b}	3.24 ± 0.12^{c}	3.65 ± 0.18^{c}
2-Undecenal	24.80	3146	1.78 ± 0.06^{a}	0.53 ± 0.01^{d}	1.00 ± 0.04^{c}	1.27 ± 0.04^{b}
2,4-Decadienal	26.15	3209	2.20 ± 0.08^{a}	0.72 ± 0.01^{c}	1.18 ± 0.04^{b}	0.82 ± 0.04^{c}
Total			601.43 ± 22.92^{a}	82.72 ± 2.02^{d}	309.46 ± 12.94^{b}	144.65 ± 4.11^{c}
Ketone (5)						
2-Hexanone	2.25	714	4.09 ± 0.14^{a}	0.95 ± 0.03^{c}	1.11 ± 0.09^{bc}	1.39 ± 0.07^{b}
Acetophenone	22.30	3009	3.89 ± 0.06^{a}	1.06 ± 0.07^{c}	1.25 ± 0.05^{c}	3.09 ± 0.10^{b}
Fenchone	15.60	2318	46.07 ± 1.52^{a}	19.76 ± 0.71^{b}	11.21 ± 0.43^{c}	15.18 ± 0.44^{c}
6-Methyl-5-hepten-2-one	14.02	2125	5.91 ± 0.22^{b}	4.96 ± 0.19^{b}	14.95 ± 0.57^{a}	2.04 ± 0.05^{c}
Piperone	24.23	3119	0.97 ± 0.03^{c}	5.94 ± 0.21^{a}	2.71 ± 0.10^{b}	1.08 ± 0.04^{c}
Total			60.94 ± 1.90^{a}	32.67 ± 1.22^{b}	31.22 ± 1.23^{b}	22.77 ± 0.70^{c}
Alcohol (18)						
1-Nonanol	17.47	2560	0.19 ± 0.01^{c}	3.56 ± 0.05^{a}	0.27 ± 0.01^{c}	1.90 ± 0.08^{b}
1-Octanol	20.15	2847	21.42 ± 0.77^{a}	3.71 ± 0.09^{c}	0.53 ± 0.02^{d}	9.17 ± 0.37^{b}
1-Pentanol	11.63	1856	17.16 ± 0.62^{a}	2.11 ± 0.06^{b}	1.89 ± 0.07^{b}	1.02 ± 0.03^{b}
1-Hexanol	14.61	2196	17.82 ± 0.64^{a}	1.19 ± 0.02^{b}	0.26 ± 0.01^{b}	1.08 ± 0.03^{b}
1-Heptanol	17.46	2558	11.48 ± 0.41^{a}	1.03 ± 0.01^{b}	0.88 ± 0.04^{b}	1.20 ± 0.06^{b}
2,3-Butanediol	20.63	2891	6.80 ± 0.24^{b}	3.08 ± 0.10^{d}	4.22 ± 0.16^{c}	11.42 ± 0.33^{a}
Benzyl alcohol	27.70	3269	7.77 ± 0.28^{a}	0.04 ± 0.01^{d}	0.90 ± 0.03^{c}	1.89 ± 0.06^{b}
Phenylethyl alcohol	28.46	3298	2.93 ± 0.10^{a}	0.58 ± 0.02^{bc}	0.38 ± 0.02^{c}	0.82 ± 0.02^{b}
2-Propyl-1-heptanol	12.95	2002	14.11 ± 0.51^{b}	42.74 ± 0.61^{a}	4.59 ± 0.21^{c}	4.24 ± 0.15^{c}
1-Octen-3-ol	17.31	2531	47.72 ± 1.71^{a}	25.83 ± 0.37^{b}	15.02 ± 0.57^{c}	12.72 ± 0.37^{c}
Linalool	19.85	2820	62.43 ± 2.95^{a}	14.86 ± 0.30^{c}	3.89 ± 0.17^{d}	23.24 ± 0.80^{b}
Geraniol	27.10	3245	1.11 ± 0.04^{b}	0.27 ± 0.01^{c}	7.90 ± 0.30^{a}	1.21 ± 0.04^{b}
Eucalyptol	10.20	1672	67.58 ± 2.43^{b}	74.55 ± 2.22^{b}	646.68 ± 24.64^{a}	70.23 ± 1.85^{b}
Terpinen-4-ol	21.27	2932	14.13 ± 0.53^{b}	22.15 ± 0.32^{b}	193.71 ± 9.52^{a}	10.18 ± 0.33^{b}
α-Terpineol	23.85	3084	13.58 ± 0.45^{b}	24.65 ± 0.35^{a}	11.05 ± 0.42^{c}	8.30 ± 0.24^{d}
α-Cadinol	35.07	3555	0.82 ± 0.03^{c}	1.59 ± 0.02^{a}	1.58 ± 0.06^{a}	1.39 ± 0.04^{b}
2-Octen-1-ol	21.61	2962	7.81 ± 0.47^{a}	2.38 ± 0.09^{c}	5.06 ± 0.19^{b}	2.11 ± 0.06^{c}
2-Furanmethanol	22.67	3031	6.56 ± 0.33^{c}	7.16 ± 0.17^{c}	13.23 ± 0.50^{b}	23.30 ± 0.68^{a}
Total			321.39 ± 12.46^{b}	231.51 ± 4.76^{c}	912.04 ± 36.90^{a}	185.43 ± 5.50^{c}
Acid (8)						
Acetic acid	17.18	2520	22.48 ± 1.02^{b}	11.50 ± 1.08^{c}	15.35 ± 0.69^{bc}	105.78 ± 3.08^{a}
Butanoic acid	21.81	2975	5.37 ± 0.08^{b}	5.29 ± 0.19^{b}	4.07 ± 0.27^{b}	8.69 ± 0.83^{a}
Formic acid	3.67	914	1047.98 ± 55.22^{a}	452.97 ± 16.28^{b}	202.16 ± 13.29^{c}	216.45 ± 6.30^{c}
Decanoic acid	38.84	3700	6.17 ± 0.41^{bc}	4.44 ± 0.16^{c}	11.58 ± 0.44^{a}	6.88 ± 0.66^{b}
Hexanoic acid	26.98	3129	30.05 ± 0.43^{a}	14.00 ± 0.92^{b}	3.42 ± 0.13^{c}	12.02 ± 1.15^{b}
Octanoic acid	31.59	3419	10.83 ± 0.22^{a}	4.66 ± 0.44^{c}	7.42 ± 0.28^{b}	6.32 ± 0.38^{b}
Propanoic acid	19.52	2794	3.29 ± 0.09^{b}	2.20 ± 0.08^{b}	2.11 ± 0.10^{b}	6.83 ± 0.66^{a}
Heptanoic acid	29.34	3241	3.70 ± 0.37^{c}	5.29 ± 0.19^{ab}	4.18 ± 0.40^{bc}	6.57 ± 0.39^{a}
Total			1129.90 ± 57.74^{a}	500.34 ± 19.30^{b}	250.29 ± 15.51^{c}	369.53 ± 13.08^{bc}
Ester (10)						
Ethyl hexanoate	11.09	1739	54.85 ± 1.52^{b}	110.45 ± 13.39^{a}	22.74 ± 0.87^{b}	96.48 ± 9.22^{a}
Ethyl octoate	16.83	2475	71.60 ± 3.24^{a}	36.51 ± 1.72^{b}	7.21 ± 0.68^{c}	12.93 ± 1.24^{c}
Ethyl decanoate	22.13	2994	26.40 ± 1.24^{b}	21.94 ± 1.44^{bc}	60.82 ± 2.72^{a}	16.36 ± 0.97^{c}
Ethyl butyrate	5.62	1185	7.48 ± 0.56^{b}	51.29 ± 3.37^{a}	10.90 ± 0.49^{b}	8.79 ± 0.26^{b}
Ethyl valerate	8.19	1492	0.39 ± 0.01^{c}	21.69 ± 0.78^{a}	1.03 ± 0.05^{c}	3.08 ± 0.29^{b}
Ethyl nonanoate	19.65	2783	1.06 ± 0.02^{b}	4.87 ± 0.18^{a}	4.82 ± 0.18^{a}	1.59 ± 0.09^{b}
Ethyl heptanoate	13.97	2095	2.52 ± 0.04^{c}	9.89 ± 0.36^{a}	3.87 ± 0.15^{b}	3.21 ± 0.19^{bc}
Ethyl palmitate	35.42	1632	3.76 ± 0.26^{a}	1.16 ± 0.04^{b}	4.43 ± 0.17^{a}	1.19 ± 0.03^{b}
Linalyl acetate	20.03	2839	70.20 ± 5.25^{a}	12.45 ± 0.45^{b}	1.24 ± 0.12^{b}	4.08 ± 0.24^{b}
Terpinyl acetate	23.51	3081	1.52 ± 0.04^{b}	2.38 ± 0.16^{b}	39.55 ± 1.51^{a}	2.22 ± 0.06^{b}
Total			239.78 ± 11.85^{a}	272.62 ± 21.70^{a}	156.60 ± 6.85^{b}	149.85 ± 12.28^{b}
Other (19)						
β-Ocimene	5.07	1119	10.79 ± 0.49^{b}	2.36 ± 0.09^{c}	8.61 ± 0.81^{b}	18.87 ± 0.76^{a}
$_{D}$-Limonene	9.86	1668	41.15 ± 0.59^{a}	15.88 ± 1.04^{b}	5.75 ± 0.42^{c}	3.97 ± 0.12^{c}
Caryophyllene	20.99	2918	46.15 ± 2.09^{a}	24.88 ± 1.28^{b}	6.90 ± 0.26^{c}	2.26 ± 0.06^{c}
Estragole	22.82	3040	50.72 ± 1.72^{a}	8.28 ± 0.86^{b}	9.05 ± 0.34^{b}	3.46 ± 0.10^{c}
trans-Isoeugenol	36.92	3627	8.85 ± 0.13^{a}	3.64 ± 0.13^{b}	2.07 ± 0.08^{c}	4.27 ± 0.25^{b}
Methyl eugenol	30.60	3382	6.46 ± 0.09^{a}	1.70 ± 0.11^{c}	3.28 ± 0.12^{b}	1.25 ± 0.07^{c}
Anethole	26.51	3221	175.97 ± 18.50^{a}	4.07 ± 0.15^{b}	14.58 ± 0.96^{b}	3.53 ± 0.31^{b}
β-Sesquiphellandrene	25.16	3166	6.67 ± 0.30^{b}	2.11 ± 0.14^{b}	42.30 ± 3.08^{a}	6.82 ± 0.65^{b}
α-Curcumene	25.31	3170	21.04 ± 0.70^{b}	7.16 ± 0.26^{bc}	66.54 ± 6.25^{a}	4.33 ± 0.13^{c}
α-Pinene	5.13	1128	36.86 ± 1.67^{a}	4.58 ± 0.16^{c}	12.48 ± 0.47^{b}	14.15 ± 1.19^{b}

(*continued on next page*)

Table 2 (*continued*)

Volatile compound	Retention time (min)	LRI	Xinjiang	Tibet	Sichuan	Inner Mongolia
β-Bisabolene	24.23	3119	12.82 ± 0.30^{a}	4.13 ± 0.15^{b}	3.20 ± 0.15^{c}	0.92 ± 0.03^{d}
α-Farnesene	24.73	3139	1.47 ± 0.02^{b}	0.92 ± 0.03^{b}	1.00 ± 0.04^{b}	15.22 ± 0.44^{a}
Anethole	26.51	3221	0.83 ± 0.01^{c}	29.12 ± 1.20^{a}	20.34 ± 0.88^{b}	2.32 ± 0.07^{c}
3-Carene	8.43	1516	4.99 ± 0.12^{b}	3.55 ± 0.23^{b}	15.06 ± 0.57^{a}	4.75 ± 0.22^{b}
Terpinolene	9.33	1612	5.01 ± 0.15^{b}	6.23 ± 0.22^{b}	38.22 ± 1.46^{a}	3.68 ± 0.14^{b}
γ-Terpinene	11.27	1817	5.34 ± 0.08^{c}	22.45 ± 0.81^{bc}	130.73 ± 8.59^{a}	39.95 ± 1.30^{b}
α-Cubebene	17.40	2551	3.51 ± 0.11^{b}	1.49 ± 0.05^{c}	13.55 ± 0.43^{a}	3.66 ± 0.11^{b}
Safrole	27.61	3265	3.94 ± 0.06^{b}	2.08 ± 0.10^{b}	85.34 ± 3.25^{a}	7.85 ± 0.47^{b}
Eugenol	33.73	3503	3.27 ± 0.05^{b}	4.71 ± 0.17^{b}	53.19 ± 3.50^{a}	7.50 ± 0.37^{b}
Total			445.85 ± 26.49^{a}	149.36 ± 7.13^{b}	523.19 ± 31.02^{a}	148.79 ± 6.61^{b}

All data are expressed as the means ± standard error of triple measurements. Different lowercase letters (a-d) in the same row indicate significant differences ($P < 0.05$). LRI: linear retention index.

odor thresholds of aldehydes (Flores et al., 2015). Results revealed that Nonanal showed a lower content in Tibet and Inner Mongolia beef jerky than in the other samples ($P < 0.05$). Heptanal presented a higher content in Xinjiang beef jerky than in the other samples ($P < 0.05$). Hexanal and heptanal are oxidative derivatives produced from linoleic acid and arachidonic acid, characterized by sebaceous, fresh, fatty, and green odors (Tanimoto et al., 2015). The content of octanal in Xinjiang beef jerky is much higher than in the other samples ($P < 0.05$). The contents of nonanal in Xinjiang and Sichuan beef jerkies were much higher than those in the other samples ($P < 0.05$). The oxidation of oleic acid produces octanal and nonanal, which may impart a roasted aroma to beef jerky (Shahidi et al., 2014; Xie et al., 2008).

Alcohols exert a less substantial effect on meat flavor than aldehydes, but they are crucial in defining the overall flavor profile of beef jerky. Saturated alcohols, which predominantly arise from lipid oxidation and the Strecker degradation pathway, have higher odor thresholds and thus play a diminished role in the flavor profile. On the other hand, unsaturated alcohols possess lower odor thresholds and contribute more prominently to the flavor. The levels of eucalyptol and terpinen-4-ol were significantly higher in Sichuan beef jerky compared to the other samples ($P < 0.05$). Moreover, lipid oxidation leads to the formation of 1-octen-3-ol, which has a distinct mushroom-like odor (Pham et al., 2008), and its concentration was significantly elevated in Xinjiang beef jerky relative to the other samples ($P < 0.05$). The levels of 1-hexanol and 1-pentanol were significantly higher in Xinjiang beef jerky compared to the other samples ($P < 0.05$). Moreover, 1-hexanol and 1-pentanol are primary lipid oxidation products, providing musty, sweet, woody flavors and balsamic odors with the samples (Wang, Chen, et al., 2022).

Regarding the acids (e.g., hexanoic acid, octanoic acid, propanoic, and decanoic acid), their higher threshold values may have minimal impact on flavor development (Wang, Li, et al., 2022). The total acid content in Xinjiang beef jerky was significantly higher than in the other beef jerky samples ($P < 0.05$). Esters, formed through the esterification of carboxylic acids and alcohols, contribute to the characteristic fruity, floral, and pleasant odors found in meat products (Domínguez et al., 2014; Marco et al., 2006). The ester levels in beef jerky from Xinjiang and Tibet were significantly higher compared to the other samples ($P < 0.05$). Notably, the concentrations of ethyl octoate and linalyl acetate isovalerate in Xinjiang beef jerky were significantly higher than in the other samples ($P < 0.05$). Additionally, the levels of ethyl butyrate, ethyl heptanoate, ethyl valerate, and acetate isovalerate were significantly higher in Tibet beef jerky than in the other samples ($P < 0.05$). Esters are volatile, highly aromatic compounds that mainly impart fruity notes to fermented meat products (Sidira et al., 2015). Ester levels generally indicate the availability of suitable substrates and the enzymatic activity of esterases produced by microorganisms (Corral et al., 2013). The production of esters via the esterification of acetyl-CoA or acyl-CoA with alcohols plays a vital role in imparting fruity, sweet, and floral aromas to meat products (Dzialo et al., 2017).

3.2.2. Heatmap cluster analysis of volatile compounds

The creation of a heatmap enabled the visualization of variations and distribution patterns of volatile compounds among the four beef jerky samples from different regions. Heatmap cluster analysis indicated a significant correlation between beef jerky samples and volatile compounds (Fig. 2). Specifically, the Tibet and Inner Mongolia beef jerky exhibited comparable effects on the content and type of volatile compounds, clustering into a single branch, while the Xinjiang and Sichuan beef jerky samples were far from them. This indicated significant differences in volatile compounds between beef jerky from different regions. Positive correlations were observed between Tibet and Inner Mongolia beef jerky and key volatile compounds such as heptanoic acid, ethyl hexanoate, hexadecanal, 1-nonaol, 2,3-butanediol, propanoic acid, butanoic acid, and acetic acid. However, the Xinjiang and Sichuan beef jerky showed negative or no significant correlations with these compounds. Thus, the flavor characteristics of Tibet and Inner Mongolia beef jerky are similar in flavor profiles, as indicated by the heatmap analysis.

3.3. Electronic nose analysis

Representing the human sense of smell, the electronic nose (*E*-nose) is capable of detecting various molecules with precision. Usually fitted with between 5 and 100 sensitive sensors, it can identify subtle differences in volatile compounds (Ghasemi-Varnamkhasti et al., 2018). The W5S sensor showed the most pronounced response to beef jerky among all sensors (Fig. 3A), suggesting that beef jerky samples may contain higher concentrations of volatile compounds with a nitrogen oxide group (Wen et al., 2022). The sensors W1W, W2W, W1S, W2S, and W5S of the Xinjiang and Sichuan beef jerky samples had higher response values than those of the other samples, which indicated that Xinjiang beef jerky was found to be rich in volatile compounds, including alcohols, aldehydes, ketones, and methyl compounds, contributing collectively to its distinctive meaty flavor. Principal component analysis (PCA) is a comprehensive and intuitive representation of the data, making it a standard tool for analyzing differences in volatile compound profiles or flavor characteristics among samples (Wen et al., 2022). As shown in Fig. 3B, PCA was employed to investigate further the difference in beef jerky flavor characteristics based on *E*-nose data. PC1 and PC2 accounted for 81.6 % and 12.6 % of the total variance, respectively, suggesting that these principal components effectively capture the diverse flavor profiles of beef jerky across different regions. The beef jerky of Xinjiang and Sichuan were clustered in the positive axis of PC1, and this may be due to the types and contents in several volatile compounds of these two beef jerky samples, which is consistent with the results obtained via the above heatmap analysis. The beef jerky from Inner Mongolia and Tibet was grouped along the negative axis of PC1, indicating that the flavors of beef jerky from these regions are similar. The results indicated that the *E*-nose response sensors successfully differentiated the beef jerky flavor from various regions.

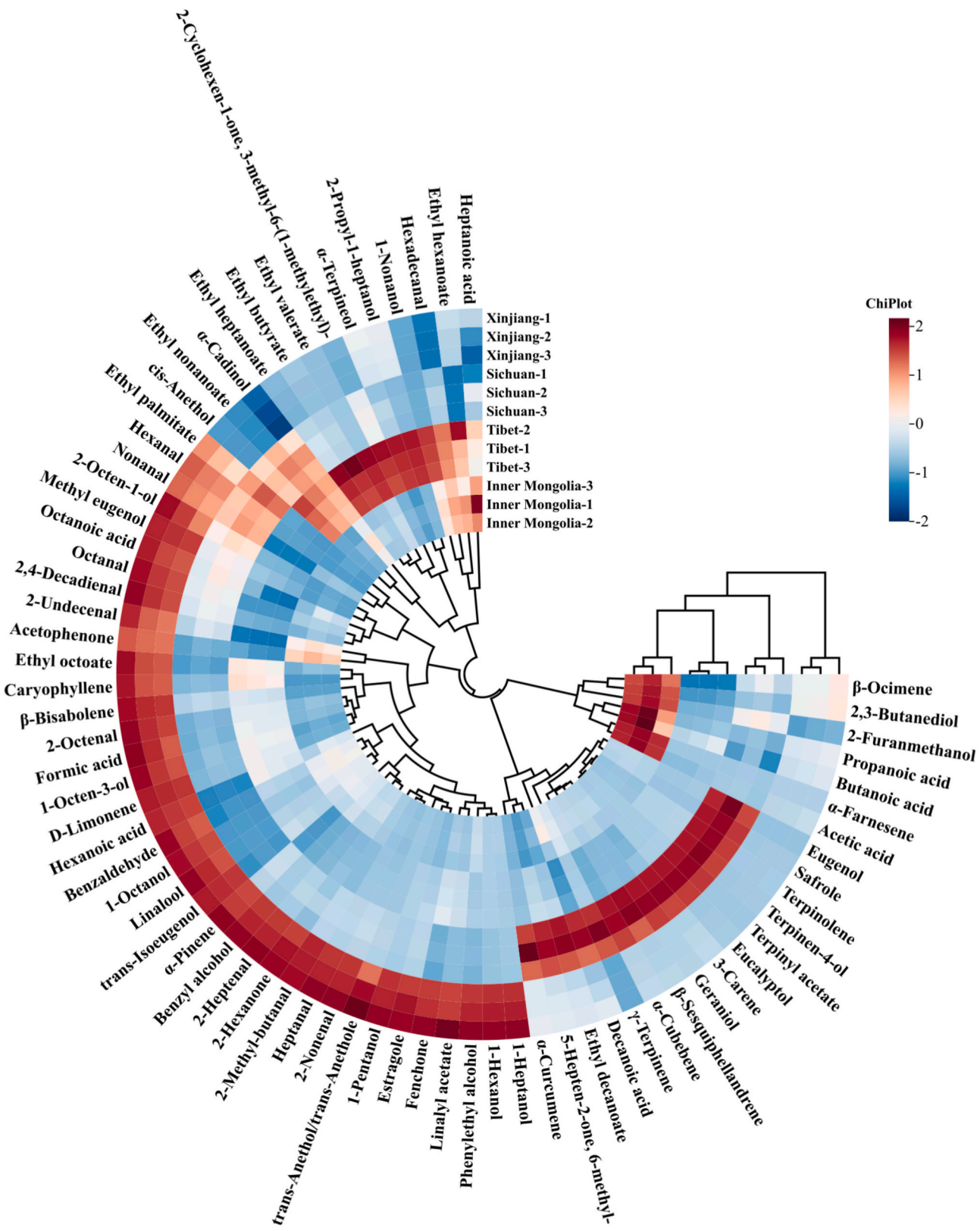

Fig. 2. Heatmap cluster analysis of the volatile compounds of beef jerky from different regions of China. The vertical axis represented the sample number, and the horizontal axis represented the detected volatile compounds.

3.4. Electronic tongue analysis

E-tongue is a widely adopted, objective, and efficient instrument for assessing the taste characteristics of food (He et al., 2024; Zhang et al., 2024). As shown in Fig. 4A, the beef jerky is notably rich in umami, saltiness, and richness intensity. Sichuan beef jerky showed the highest richness, followed by Xinjiang, Inner Mongolia, and Tibet beef jerky. However, when it comes to umami and saltiness, there were no

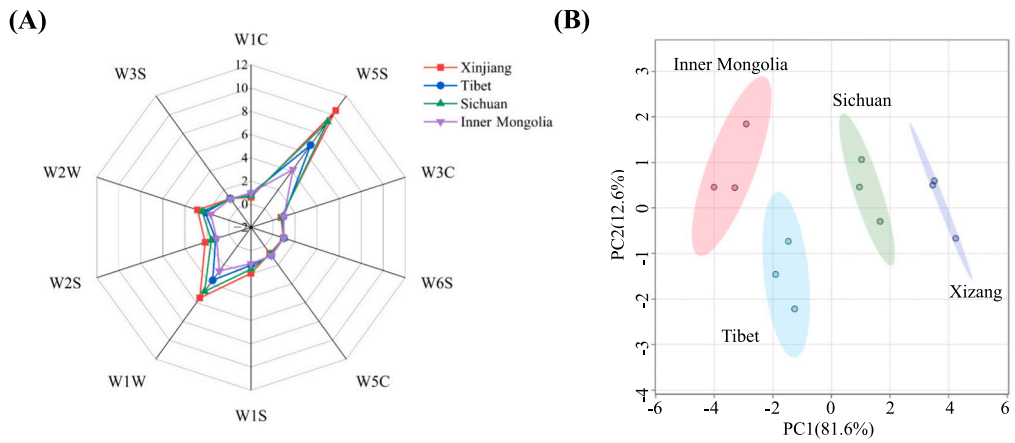

Fig. 3. Radar fingerprint (A) and principal components analysis (PCA) (B) of electronic nose (*E*-nose) data for beef jerky from different regions of China.

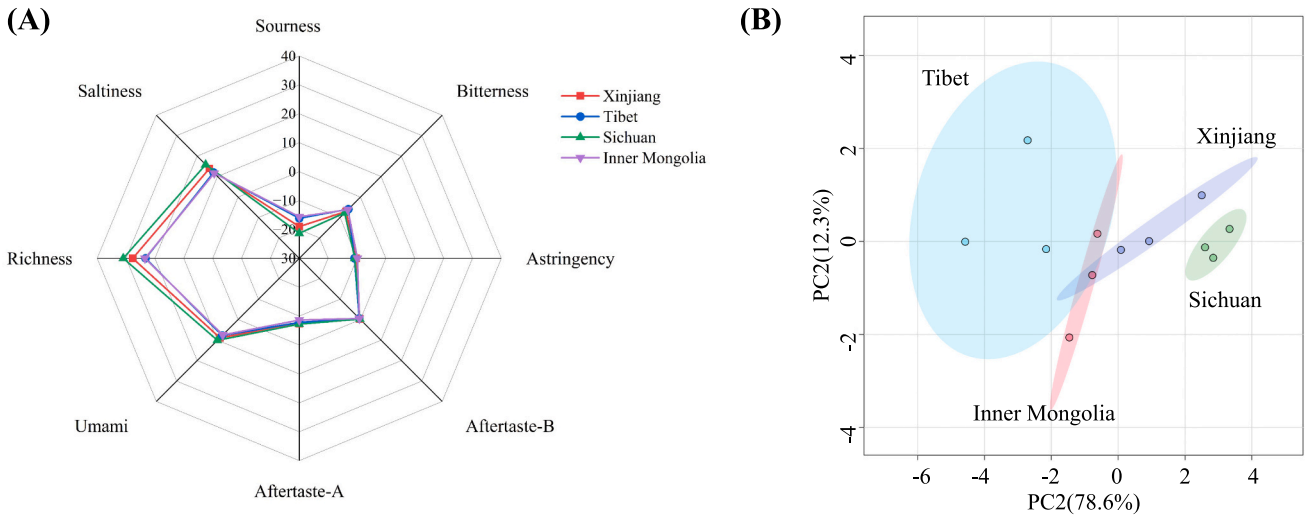

Fig. 4. Radar fingerprint (A) and PCA (B) of the electronic tongue (E-tongue) data for beef jerky from different regions of China.

Table 3
Sensory evaluation of beef jerky from different regions of China.

	Xinjiang	Tibet	Sichuan	Inner Mongolia
Color	8.09 ± 0.28^{ab}	7.78 ± 0.37^{ab}	7.64 ± 0.20^{b}	8.21 ± 0.63^{a}
Taste	6.08 ± 0.23^{b}	7.53 ± 0.44^{a}	6.31 ± 0.31^{b}	7.86 ± 0.75^{a}
Odor	7.86 ± 0.32^{a}	6.34 ± 0.16^{b}	7.52 ± 0.78^{a}	6.04 ± 0.82^{b}
Hardness	7.14 ± 0.72^{b}	7.10 ± 0.13^{b}	6.48 ± 0.59^{b}	8.02 ± 0.60^{a}

All data are expressed as the means ± standard error of triple measurements. Different lowercase letters (a-b) in the same row indicate significant differences ($P < 0.05$).

discernible variations among the beef jerky with different regions, and their response intensity values were quite similar. In order to better visualize the *E*-tongue detection results of beef jerky in different regions, PCA was performed, and the results are shown in Fig. 4B. The PCA map additionally exhibited the differences among beef jerky according to the *E*-tongue response sensors. The PC1 and the PC2 explained that the main variance covered the more minor part of the variance. PC1 represented about 78.6 % of the total information, and PC2 displayed 12.3 % of the information. The beef jerky from Xinjiang and Sichuan was clustered in the positive axis of PC1, which was consistent with the above E-nose results. The beef jerky of Inner Mongolia and Tibet were clustered in the negative axis of PC1, which may be due to their relatively high sourness, astringency, bitterness, aftertaste-A, and aftertaste-B. It is noted that the sourness of Inner Mongolia and Tibet beef jerky detected by *E*-tongue is consistent with their pH results. These results indicated that the *E*-tongue response sensors could help us rapidly identify beef jerky in different regions based on taste characteristics.

3.5. Sensory analysis

Table 3 indicates the results of sensory attributes (color, odor, taste, and hardness) of beef jerky in different regions. Tibet and Inner Mongolia samples showed significantly higher taste intensities than the other beef jerky samples ($P < 0.05$), aligning with the E-tongue results. This suggested that the sensory attributes of the beef jerky from different regions may be related to the local ingredients and processing techniques aligning with the results of Park et al. (2007). Xinjiang and Sichuan samples showed significantly higher odor intensities than the other samples ($P < 0.05$), aligning with the E-nose results. Meanwhile, the Xinjiang and Sichuan samples showed higher most volatile compound contents than others, resulting in higher odor scores. The color intensity of beef jerky in Sichuan beef jerky was the lowest among all samples ($P < 0.05$). Inner Mongolia's higher hardness score suggests a firmer texture ($P < 0.05$), consistent with its relatively low moisture content. These findings emphasize the importance of tailoring processing techniques to enhance the sensory attributes of beef jerky based on

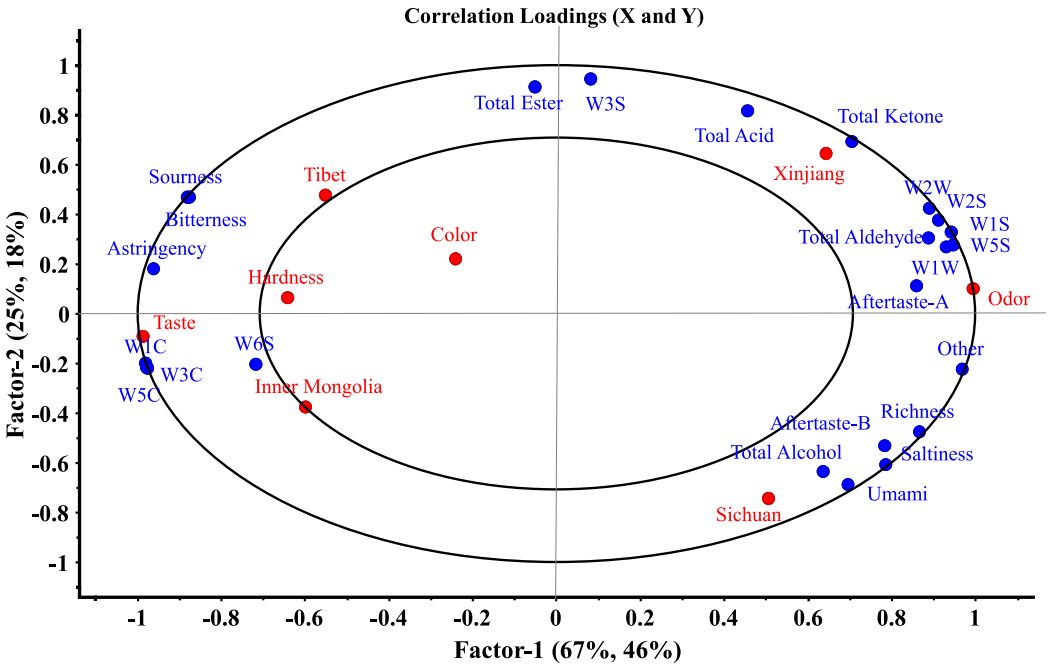

Fig. 5. An overview of the variation found in the mean data from the partial least squares regression correlation loading plot for beef jerky models. The *X*-matrix designated the volatile compounds, E-nose, and E-tongue, and the *Y*-matrix represented the sensory attributes and beef jerky samples in the correlation loading plot.

regional preferences and consumer expectations.

3.6. PLSR analysis

PLSR analysis revealed the relationships between the electronic tongue (*E*-tongue), electronic nose (E-nose), volatile compounds, and sensory characteristics in beef jerky samples. The *X*-matrix comprised the volatile compounds, *E*-tongue, and E-nose measurements. At the same time, the *Y*-matrix represented the sensory attributes and individual beef jerky samples in the correlation loading plot (Fig. 5). The first two factors differentiated the beef jerky samples, contributing 92 % of the *X*-matrix variation and 64 % of the *Y*-matrix variation. Most variables were situated between the inner and outer ellipses, $r^2 = 0.5$ and 1.0, demonstrating the appropriateness of the PLSR model in explaining these variables. As indicated in Fig. 5, the beef jerky in different regions was well distinguished. It was observed that beef jerky from Xinjiang and Sichuan was located on the right quadrant. It correlated well with W1S, W2S, W5S, W3S, W1W, W2W, aftertaste-A, richness, aftertaste-B, saltiness, and umami. In addition, those flavor characteristics are closely related to some volatile compounds, such as acid, aldehyde, ketone, alcohol, and others. Furthermore, integrating GC–MS and *E*-nose provided macroscopic data from E-nose analysis and microscopic insights into volatile components via GC–MS.

It was observed that beef jerky from Tibet and Inner Mongolia was located in the left quadrant. It correlated well with astringency, bitterness, sourness, W1C, W3C, W6S, and W5C. The W1C, W3C, W5C, and W6S sensors positively correlate with esters (ethyl butyrate, ethyl hexanoate, and ethyl valerate). These compounds were detected at elevated concentrations in the Tibet and Inner Mongolia beef jerky. Furthermore, these taste properties (astringency, bitterness, and sourness) detected by E-tongue are closely related to sensory taste, which indicates that electronic sensory analysis can reliably reflect human taste perceptions (Yin et al., 2024). In addition, those odor properties (W1C, W3C, W5C, and W6S) are closely related to ester compounds. Therefore, the integrated analysis of E-nose, E-tongue, volatile compounds, and sensory attributes provides comprehensive insights into the regional-induced flavor variation of beef jerky.

4. Conclusions

In conclusion, there are notable variations in the physicochemical properties of beef jerky from different regions. Furthermore, seventy-two volatile compounds were identified, revealing significant differences in aldehydes, alcohols, and esters among the regions. Heatmap cluster analysis highlights the distinct flavor profiles associated with beef jerky from four specific areas. Additionally, E-tongue and E-nose analyses demonstrated strong correlations between the volatile compounds and sensory attributes, as indicated by PLSR analysis. Thus, the integration of GC–MS, E-nose, E-tongue, and sensory analysis proved to be an effective method for evaluating the flavors of beef jerky across different regions. Further comprehensive studies are recommended to understand the mechanisms underlying the development of these distinctive flavors.

CRediT authorship contribution statement

Bayierta Bayinbate: Writing – original draft, Software, Methodology, Investigation, Data curation. **Linwei Yang:** Methodology, Formal analysis. **Iftikhar Hussain Badar:** Formal analysis, Data curation. **Yue Liu:** Software, Methodology. **Lang Zhang:** Formal analysis, Data curation. **Yingying Hu:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Baocai Xu:** Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2025.102245.

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