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Identification of Characteristic Flavor Compounds in Tibetan Sheep, Goat and Local Sheep Meat Using GC-IMS Combined with HS-SPME-GC-MS and Chemometrics

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ABSTRACT

This study focuses on Tibetan lamb meat from the Qinghai Tibet Plateau, local sheep meat from Shandong, and goat meat. Using a combination of headspace solid-phase microextraction gas chromatography-mass spectrometry (HS-SPME-GC-MS) and headspace gas chromatography-ion mobility spectrometry (HS-GC-IMS), the differences in volatile flavor compound composition and overall flavor profile of the three types of lamb meat were systematically analyzed and compared. Qualitative analysis of flavor compounds was conducted using GC-MS and principal component analysis (PCA) was used to identify the dominant factors affecting flavor differences in different types of lamb meat; Using GC-IMS to obtain fingerprint and two-dimensional differential spectra of volatile substances, achieving intuitive and sensitive differentiation of three types of lamb flavor characteristics. The results showed that GC-MS identified a total of 19 volatile substances, including 8 aldehydes, 5 alcohols, 4 esters, and 2 other compounds. Among them, 16 were detected in Tibetan sheep, 11 in local sheep and 15 in goats. The content of aldehydes such as hexanal and heptanal in Tibetan sheep was significantly higher than that in the other two types of lamb meat; GC-IMS detected a total of 26 volatile compounds, including 8 esters, 6 aldehydes, 9 alcohols and 2 others. Butyl formate and n-hexanol are characteristic flavor compounds of Tibetan sheep, while 2-furanyl methanol acetate is a unique substance of goats. Principal component analysis shows that aldehydes are the core contributing category to the flavor differences among the three types of lamb meat; The HS-GC-IMS fingerprint spectrum intuitively presents the differences in the content and types of three volatile substances in lamb meat.trans-2-Decenal, 1-octen-3-ol, hexanal, 2-heptenal, and nonanal were identified as key volatile compounds through the combination of variable importance in projection (VIP) from PLS-DA and ROAV. The aroma profile radar chart shows that Tibetan sheep exhibit a prominent fatty aroma, goat displays a distinct mushroom-like aroma, while sheep overall present a mild odor. Two analytical techniques collaborated to verify significant differences in volatile flavor compounds among Tibetan sheep, local sheep and goats, providing theoretical basis and data support for lamb breed identification, quality evaluation and development of specialty meat products.

KEYWORDS

Mutton; Volatile flavor compounds; Gas chromatography-mass spectrometry; s Gas chromatography ion mobility spectrometry combined

1. INTRODUCTION

1.1. Research Background and Significance

China is a major country in mutton production and consumption [1]. Mutton products are rich in resources with increasing output, occupying an important position in the meat industry. Mutton is favored by consumers due to its nutritional advantages of high protein, low fat, rich unsaturated fatty acids and various minerals [2]. Different breeds of mutton show significant differences in flavor quality due to differences in growth environment, breed characteristics and feeding methods. Among them, Tibetan sheep mainly live in the harsh natural environment of high altitude, cold and hypoxia on the Qinghai-Tibet Plateau, with the characteristics of cold resistance and rough feeding tolerance [3], and their meat has the nutritional characteristics of high protein and low fat. Shandong local sheep is a representative breed in the Central Plains agricultural region with strong adaptability and mild meat quality. Goat meat is delicious and rich in nutrients, but its flavor characteristics are significantly different from those of sheep and Tibetan sheep [4]. Volatile flavor compounds are the key substances constituting mutton flavor, affecting food attractiveness by stimulating the olfactory system of consumers [5]. These compounds cover aldehydes, alcohols, esters, ketones and other categories, and their types, contents and interactions form the unique flavor profile of different breeds of mutton. In recent years, there have been many studies on the quality of single-breed mutton, but there is still a lack of systematic flavor comparison studies on three different ecological breeds of mutton (Tibetan sheep, local sheep and goats) using the combined technology of GC-MS and GC-IMS. Clarifying the flavor differences and characteristic volatile substances of Tibetan sheep, local sheep and goats can not only provide a scientific basis for consumers to choose, but also lay a theoretical foundation for meat product processing enterprises to develop characteristic products and achieve precise flavor control, which is of great practical significance for promoting the differentiated and high-quality development of China's mutton industry.

1.2. Research Status and Analytical Techniques

Gas chromatography-mass spectrometry (GC-MS) is a classic method in the field of flavor research, with the advantages of high separation efficiency and accurate qualitative analysis. It can comprehensively detect small molecular volatile compounds in meat and is widely used in the identification of volatile components in meat, effectively helping to explore key compounds related to mutton flavor [6]. Gas chromatography-ion mobility spectrometry (GC-IMS) is a new rapid detection technology, combining the high-efficiency separation ability of gas chromatography with the high sensitivity of ion mobility spectrometry [8]. It has excellent detection effect on trace volatile substances, outstanding performance in isomer separation, and the advantages of simple operation, fast detection speed and no need for complex pretreatment, especially suitable for constructing flavor fingerprints to realize rapid differentiation of different samples [7]. At present, the combined technology of GC-MS and GC-IMS has been applied in meat product flavor analysis, variety identification and quality monitoring [9], proving its synergistic advantage in clarifying complex flavor differences [10]. However, the application of this combined technology in the systematic flavor comparison of three kinds of mutton (Tibetan sheep, local sheep and goats) has not yet formed a perfect analysis system, and relevant studies are still in the exploratory stage.

1.3. Research Contents and Objectives

Existing studies mostly use a single analytical technique for the comparison of mutton flavor of different breeds, which is difficult to comprehensively and accurately capture the flavor difference characteristics [11]. Based on this, this study adopts the combined technology of HS-SPME-GC-MS and HS-GC-IMS to systematically analyze the volatile flavor substances of three kinds of mutton (Tibetan sheep, local sheep and goats), aiming to achieve the following objectives: 1.

Comprehensively capture and identify volatile flavor substances in the three kinds of mutton using two analytical techniques, and clarify the differences in their types and contents; 2. Analyze the key compound categories dominating the flavor differences of the three kinds of mutton through principal component analysis (PCA); 3. Construct volatile flavor fingerprints of the three kinds of mutton to realize intuitive and visual differentiation of flavor differences; 4. Clarify the synergistic effect of the two analytical techniques in mutton flavor research, and provide more comprehensive technical support for the evaluation of mutton flavor quality.

2. MATERIALS AND METHODS

2.1. Materials and Equipment

2.1.1. Raw Material Preparation

The raw materials selected for this experiment were Tibetan sheep meat from Haibei Tibetan Autonomous Prefecture, Qinghai Province, and local sheep meat and goat meat purchased from Haiyue Longgong Market in Zibo City, Shandong Province. The three mutton samples were removed of fascia, washed, cut into uniform small pieces, and then ground into homogeneous samples by a meat grinder. Each sample was divided into 50 g portions, vacuum-sealed and stored in a -20 ℃ low-temperature refrigerator for later use.

2.1.2. Laboratory Instrument

Table 1. Main Instruments and Equipment

instrument	Model	Manufacturer
Gas Chromatography-Mass Spectrometry Analyzer	7890A	Agilent Technologies, Inc.
Metal Bath with Solid Phase Microextraction Probe Stand	Kl01	Beijing Kanglin Technology Co., Ltd.
Gas Chromatography-Ion Mobility Spectrometer	FlavourSpec®	G.A.S., Germany
Meat Slicer	MLMQYJR09BLWSD	Hunan Yangzi Intelligent Technology Co., Ltd.
ElectronicAnalyticalBalance	AL104	Mettler-Toledo Instruments Co., Ltd.
Low Temperature Freezer	BCD-290W	Qingdao Haier Co., Ltd.
SolidPhase Microextraction Holder	SPME-GC-PT	Beijing Kanglin Technology Co., Ltd.

2.2. Experimental Methods

2.2.1. Sample Processing

Accurately weigh 2 g of mutton homogeneous sample into a 20 mL headspace bottle and quickly seal it. Place the headspace bottle on a metal bath, heat and equilibrate at 60 ℃ for 30 min, then insert the extraction needle using a solid-phase microextraction handle for headspace extraction, ready for subsequent GC-MS analysis; for GC-IMS analysis, weigh 2 g of mutton homogeneous sample into a 20 mL headspace bottle and seal it for later use [12].

2.2.2. HS-SPME-GC-MSAnalysis

Chromatographic conditions were slightly modified with reference to the experimental conditions of Yang Shengnan et al. [11]. HP-5MS chromatographic column was used, high-purity helium was used as carrier gas, inlet temperature was 250 ℃, carrier gas flow rate was 1 mL/min, and split ratio was 4:1. Temperature programming: initial temperature 40 ℃, hold for 1 min, rise to 250 ℃ at 5 ℃/min, hold for 5 min. Mass spectrometry conditions were electron impact (EI) ion source, energy 70 eV, ion source temperature 230 ℃, transmission line temperature 250 ℃, scanning range 35~500 m/z.

2.2.3. HS-GC-IMSAnalysis

GC-IMS analysis was slightly adjusted with reference to relevant literature methods. Headspace conditions: incubation at 50 ℃ for 20 min, injection needle temperature 80 ℃, incubation speed 500 r/min. FlavourSpec® instrument conditions: chromatographic column type MXT-5 (15 m×0.53 mm ID×1 μm), analysis time 20 min, carrier/drift gas was high-purity nitrogen.

2.2.4. Determination of Key Flavor Compounds

Relative odor activity value (ROAV) is often used to represent the contribution of each aroma component to the overall odor of the sample, calculated by formula [14]

$$ROAV = \frac{C_i}{C_{max}} \times \frac{T_{max}}{T_i} \times 100 \quad (1)$$

2.3. Qualitative Analysis of Volatile Components

HS-GC-MS qualitative analysis: Search and match with NIST standard library through mass spectrogram, combined with manual proofreading, select components with forward and reverse matching degree greater than 700 as qualitative results, and analyze and verify the spectrogram combined with relevant literature to ensure qualitative accuracy.

HS-GC-IMS qualitative analysis: Use the built-in LAV (Laboratory Analytical Viewer) analysis software of the instrument, combined with the built-in NIST2014 database and IMS database, match according to the gas chromatography retention time and ion migration time of volatile substances to complete the qualitative analysis of characteristic flavor substances [13].

2.4. Data Processing

GC-MS data were analyzed by principal component analysis using the PCA plug-in of Origin2024 software, and principal component analysis plots were drawn; GC-IMS data were used to construct two-dimensional difference spectra of volatile organic compounds using Reporter and Gallery plug-ins in LAV, and fingerprint spectra of characteristic volatile aroma components of mutton of different breeds were constructed for visual difference analysis. All experiments were set with 3 groups of parallel repetitions, and the data were expressed as mean values.

3. RESULTS AND DISCUSSION

3.1. Qualitative Analysis Results of Volatile Flavor Substances by HS-GC-MS

A total of 19 volatile components were detected in the three kinds of mutton, including 8 aldehydes, 5 alcohols, 4 esters and 2 other compounds. Among them, 16 volatile compounds were detected in Tibetan sheep, 11 in local sheep and 15 in local goats, and 8 volatile components were common to the three kinds of mutton. Overall, there were significant differences in the types of volatile components among the three kinds of mutton, which were closely related to the growth characteristics, fat composition and metabolic modes of different breeds of mutton [14].

Aldehydes are the main products of lipid oxidation with generally low thresholds, and make a decisive contribution to the overall flavor intensity and characteristic flavor of mutton [15]. As shown in Appendix 1, the content of aldehydes in Tibetan sheep was significantly higher than that in goats and local sheep, among which the relative contents of hexanal (14.403%), heptanal (15.351%), 2-heptenal (10.946%) and nonanal (20.897%) were particularly prominent. Hexanal has a fresh fruity and green aroma, 2-heptenal brings fruity and fatty aroma, and nonanal has a strong fatty taste. These high-content aldehyde compounds together constitute the rich characteristic flavor profile of Tibetan sheep meat [16]. This result may be related to the fact that Tibetan sheep grow in a high-altitude environment with large amount of exercise, resulting in unique fat composition and different oxidation characteristics from plain breeds [18]. The hexanal content of local sheep was close to that of Tibetan sheep, but the contents of other aldehydes such as 2-heptenal and nonanal were significantly lower than those of Tibetan sheep; all aldehyde contents of goats were the lowest among the three, such as hexanal only 3.356%, which was also an important reason for the significant flavor difference between goats and Tibetan sheep and sheep.

Alcohols are mainly produced by the degradation of fatty acids during lipid oxidation, with relatively high odor thresholds. Although their contribution to flavor is not as great as that of aldehydes, they can superimpose with aldehydes to further enrich the flavor layers of mutton [17]. As shown in Table 2, the alcohol content of goats was significantly higher than that of Tibetan sheep and local sheep, among which the contents of 1-pentanol (8.421%), 1-octen-3-ol (8.628%) and 2-octen-1-ol (4.746%) were the highest among the three. 1-octen-3-ol is a natural equivalent spice, which can endow mutton with mushroom-like and fruit and vegetable flavors [19]. However, high concentration of alcohols will bring vanilla, woody and even slight irritation to meat products [20], which may be an important reason for the unique irritation of goat flavor. The overall alcohol content of Tibetan sheep was extremely low, such as 1-octanol only 0.27%, and the alcohol content of local sheep was also generally low. Due to the moderate alcohol content of the two, combined with the soft aroma of esters, the overall flavor was more warm and coordinated.

Esters are usually produced by the esterification reaction of alcohols and fatty acids, mostly presenting soft flavors such as fruity aroma [20], which are important substances constituting the flavor layer of mutton and can neutralize the greasy feeling caused by some fatty acids. As shown in Table 2, the ester content of goats was the highest, and vinyl hexanoate (17.312%), ethyl n-hexanoate (19.475%), ethyl octanoate (15.543%) etc. were unique or high-content esters of goats. These esters endowed goats with rich fruity aroma and alleviated the irritation caused by high-content alcohols to a certain extent [21]; the content of each ester component of local sheep, such as ethyl nonanoate (0.631%), was slightly higher than that of Tibetan sheep; the ester content of Tibetan sheep was the lowest, only ethyl octanoate (0.193%) and ethyl nonanoate (1.152%) were detected, which was consistent with the low intramuscular fat content of Tibetan sheep.

In order to clarify the common and unique components of volatile flavor substances (VOCs) in the three types of mutton (TS, GT, SH), Venn diagram analysis was carried out (Figure 1), and the discussion was carried out combined with the specific substance composition. As can be seen from Figure 1, a total of 19 VOCs were detected in the three types of mutton, among which 8 core components were common to the three, which were the material basis for forming the basic flavor of mutton; TS and SH shared 3 kinds, TS and GT shared 4 kinds, while SH and GT had no shared substances, indicating significant differences in flavor substance composition among different breeds. From the perspective of unique components, TS had 1 unique VOC (o-isopropyl toluene), providing unique material support for its flavor characteristics; SH had no unique VOC, and the least types of esters were detected (only 2 kinds: ethyl octanoate and ethyl nonanoate), which was consistent with its low intramuscular fat content; GT had 3 unique VOCs, enriching its flavor diversity. Further analysis of substance composition showed that the 8 common components of the three types of mutton were mainly aldehydes and alcohols (such as hexanal, 2-heptenal, 1-pentanol, 1-octen-3-ol, etc.), which were the key to forming the basic flavors such as fatty aroma and mushroom aroma of mutton; the 3 common components of TS and SH (octanal, nonanal, decanal) and 4 common components of TS and GT (1-octanol, ethyl octanoate, ethyl nonanoate, 5-(2-furylmethyl)-) further shaped the flavor differences of different breeds of mutton. In summary, the volatile flavor substances of the three types of mutton have both a common core skeleton and their own unique component differences, which are an important material basis for the formation of flavor characteristics of different breeds of mutton.

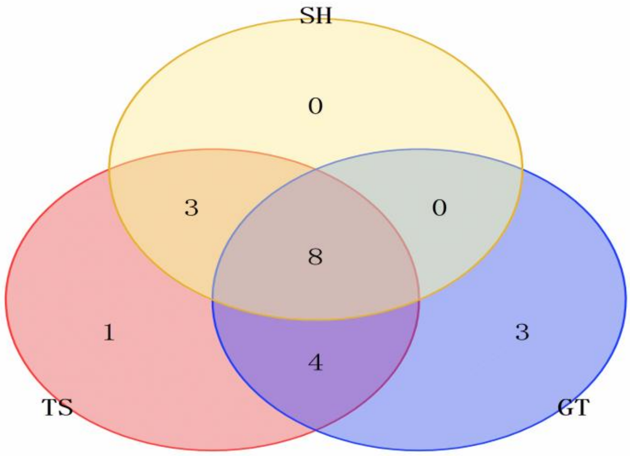


Figure 1. Venn diagram of three types of mutton VOCs

3.2. Analysis Results of Volatile Flavor Substances by HS-GC-IMS

3.2.1. HS-GC-IMS Fingerprint and Two-Dimensional Spectrum Analysis

HS-GC-IMS was used to analyze the differences of volatile components in three mutton samples. Fingerprints can intuitively reflect the overall differences of volatile organic compounds in different samples. Comparing the fingerprint spectra of the three types of mutton, it can be seen that the total content of characteristic flavor substances in Tibetan sheep is significantly higher than that in the other two types of mutton; the peak intensity of local sheep samples is medium with fewer peaks; the peak intensity of goat samples is between Tibetan sheep and local sheep, but the peak distribution has obvious specificity.

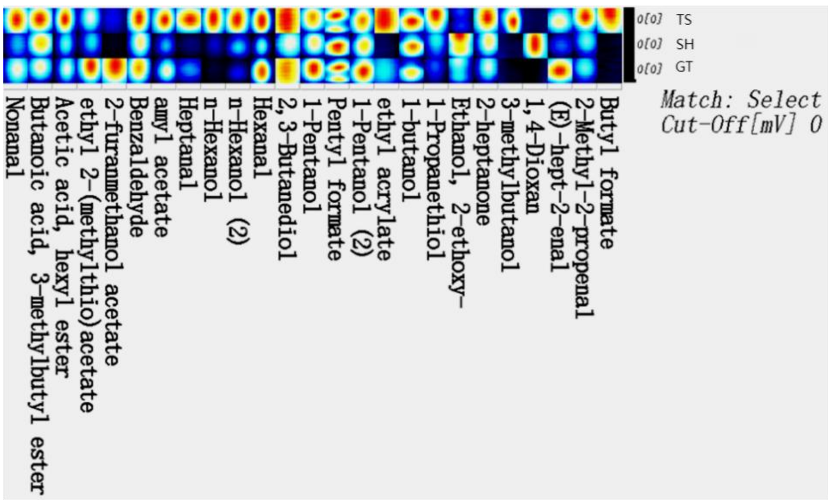


Figure 2. Characteristic flavor fingerprint profiles of mutton samples from different breeds (In the figure: TS stands for Tibetan sheep; SH stands for sheep; GT stands for goat)

In order to compare the flavor substance differences among three types of lamb meat, the odor spectrum of Tibetan lamb was selected as the reference. After subtracting the reference from other sample spectra, two-dimensional differential spectra were obtained (Figure 3). The vertical axis of the two-dimensional spectrum represents retention time, while the horizontal axis represents migration time. The red vertical lines indicate reaction ion peaks. The brightness of different colors in the spectrum represents substance concentration: red indicates higher concentration than the reference (Tibetan lamb), blue indicates lower concentration than the referenceandn white indicates identical concentration.

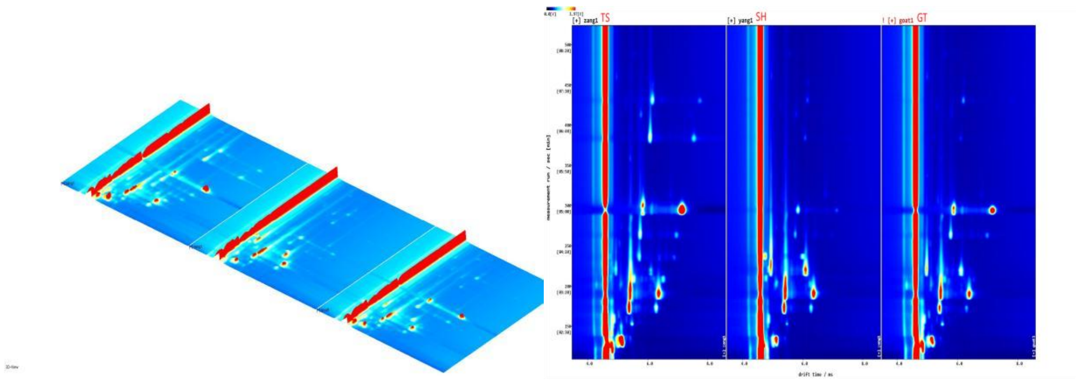


Figure 3. 3D spectra (a) and 2D spectra (b) of VOCs in three kinds of mutton

To visually compare the flavor differences among three types of lamb meat, the odor profile of Tibetan lamb was selected as the reference. Subtracting the reference profile from the other samples' profiles yielded two-dimensional differential spectra (Figure 3). In these spectra, the vertical axis represents retention time, while the horizontal axis shows migration time. The red vertical lines denote reaction ion peaks, and the intensity of different colors corresponds to substance concentration: red indicates higher concentration than the reference (Tibetan lamb), blue signifies lower concentration, and white represents equal concentration [22].

3.2.2. HS-GC-IMS Qualitative Analysis

According to the gas chromatography retention time and ion migration time of volatile substances, combined with GC-IMS library matching for qualitative analysis, the results showed that a total of 26 volatile substance monomers and some dimers of substances were detected in the three mutton samples, mainly including esters, aldehydes, alcohols, pyrazines, aromatics and ethers. These aroma components together constitute the characteristic flavor of the three types of mutton.

Esters account for a high proportion in mutton, mainly presenting fruity and sweet aroma, which are the main contributors to fruity flavor in samples. Aldehydes bring rose and bitter almond aromas, which can enrich the aroma components of mutton. Alcohols provide slight fatty aroma. Ketones and thioethers can bring creamy and fruity aromas, which can bring unique flavor to mutton.

3.3. Comprehensive Analysis of GC-IMS and HS-SPME-GC-MS

The VOCs detected by GC-IMS and HS-SPME-GC-MS were drawn into a Venn diagram. Studies have shown that 5 flavor substances were detected together, namely hexanal, nonanal, 2-heptenal, heptanal and 1-pentanol.

The combined analysis of GC-IMS and HS-SPME-GC-MS significantly improved the analysis range of VOCs in complex systems through technical complementarity. This combined determination technology has both the high-throughput and rapid screening ability of GC-IMS and the high-resolution and accurate qualitative advantages of HS-SPME-GC-MS, which can systematically analyze the volatile components of samples.

The detection results of GC-IMS and HS-SPME-GC-MS are mainly aldehydes, alcohols and ester flavor substances. Low threshold contributes more to mutton flavor, and vice versa. Aldehydes contribute greatly to mutton flavor, mostly showing fatty, fresh and fruity flavors. Alcohols have high thresholds, mostly showing mushroom and wine aromas. Esters have fruity and burnt aromas, which can enhance the fresh and sweet taste of mutton. The synergistic effect of these components together constitutes the flavor profile of mutton.

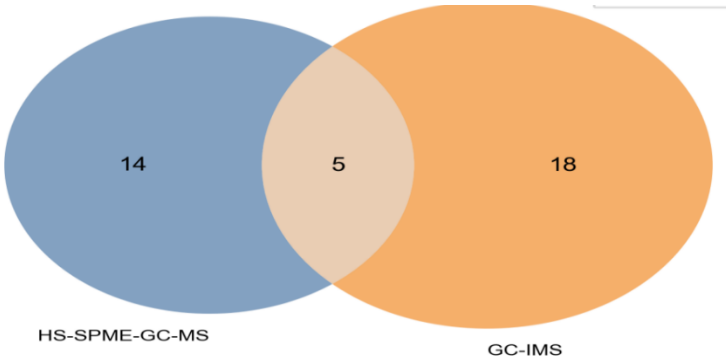


Figure 4. Venn diagram of VOCs for two analytical techniques

3.4. Screening of Differential Volatile Compounds

In order to reveal the differences of volatile compounds in different mutton, the data of volatile aroma components detected by GC-IMS and HS-SPME-GC-MS were processed respectively. The contribution rates of the first and second principal components in HS-SPME-GC-MS and GC-IMS were high enough to fully characterize the overall characteristics of volatile flavor components in the three types of mutton.In the PCA plots constructed based on GC-IMS and HS-SPME-GC-MS technologies, the three samples were separated in space, indicating that there were certain differences in the composition and content of their volatile components. This result confirms that the PCA model can effectively distinguish the flavor attributes of different mutton. The discrimination trends revealed by the two analytical techniques are consistent, providing a reliable statistical basis for the evaluation of mutton flavor quality.

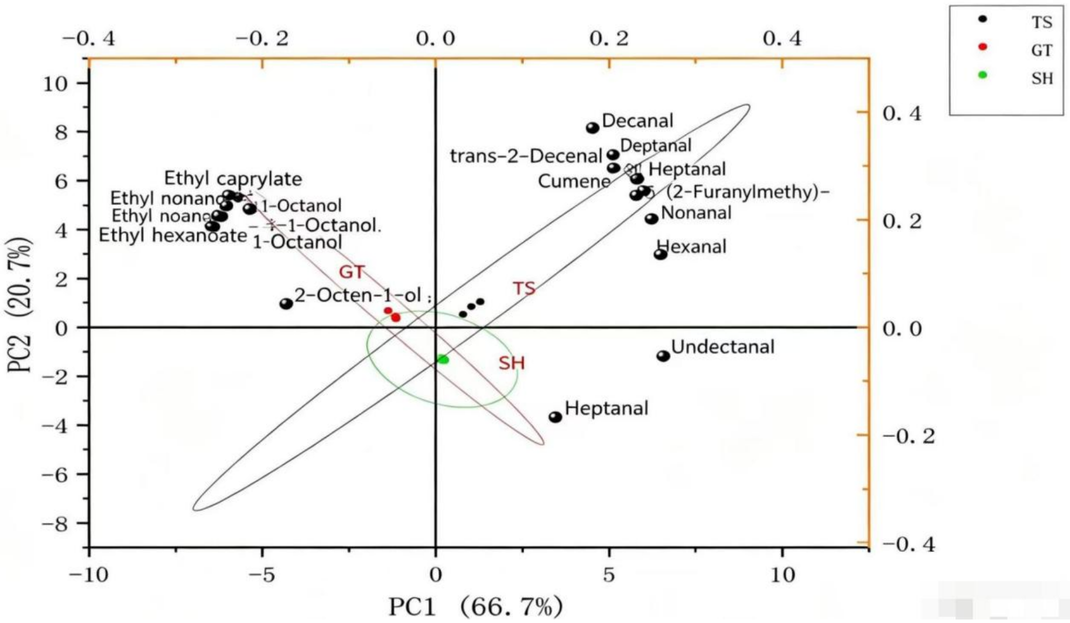


Figure 5. PCA score plot of VOCs in three types of mutton by HS-SPME-GC-MS

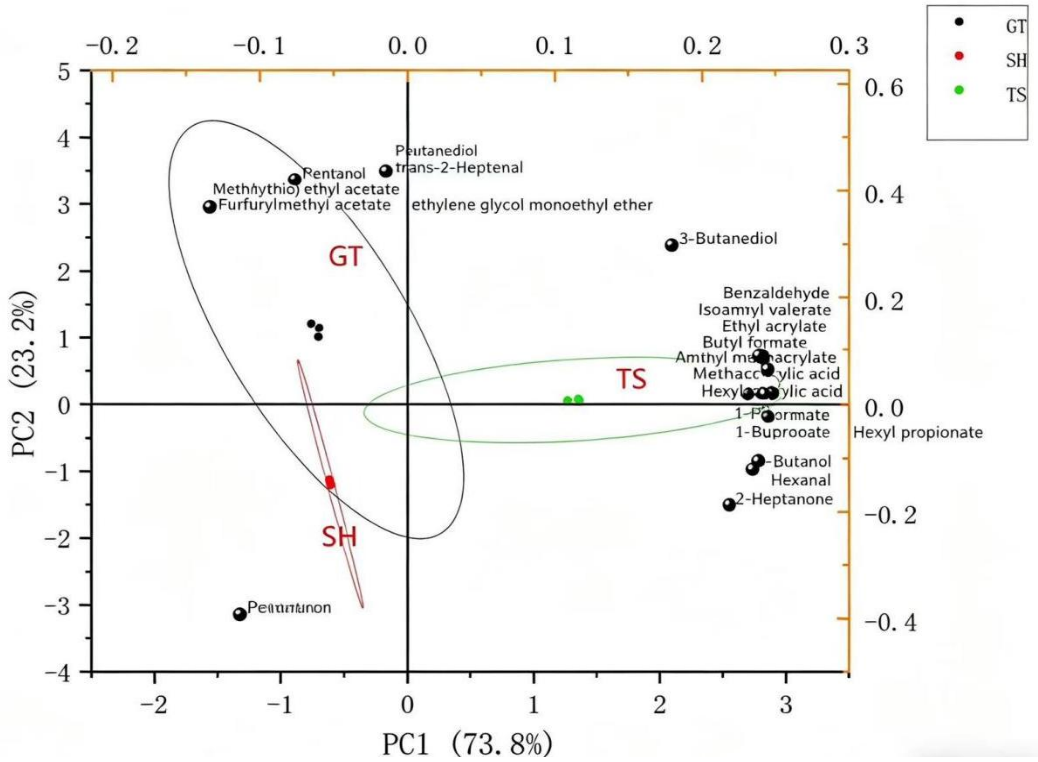


Figure 6. PCA score plot of VOCs in three types of mutton byGC-IMS

PLS-DA can maximize the differences between groups and obtain better separation effect than PCA. The three types of mutton show obvious grouping characteristics in the figure, indicating that the PLS-DA model successfully amplifies the differences between groups and can effectively realize the discrimination of mutton of different breeds.

Permutation test is used to verify the robustness of the PLS-DA model and prevent overfitting of the model. All verification parameter intercepts are close to 0 and the Q^2 intercept is negative, confirming that the model is stable and reliable without overfitting. This model can effectively distinguish the flavor characteristics of different mutton.

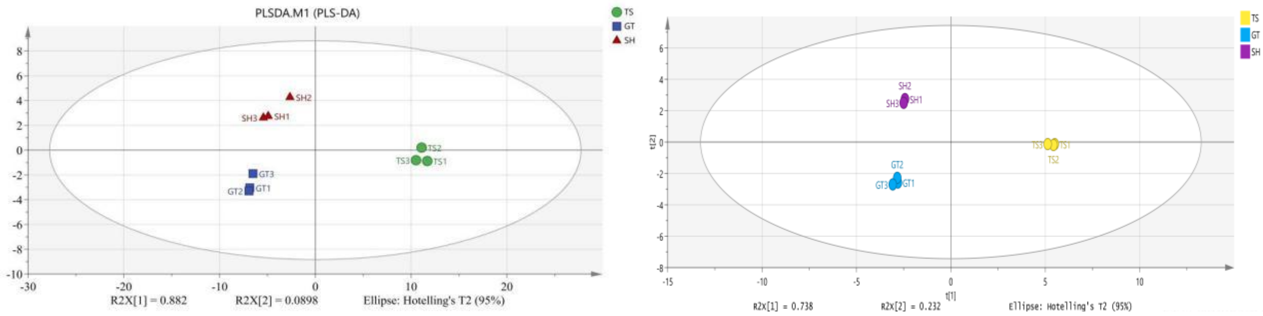
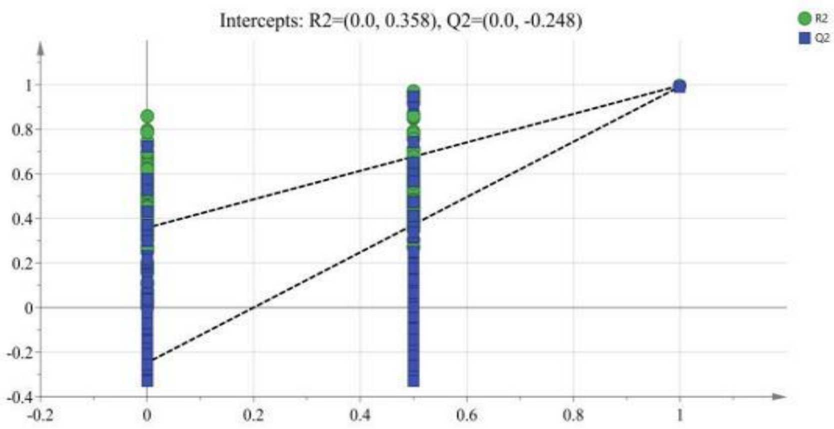
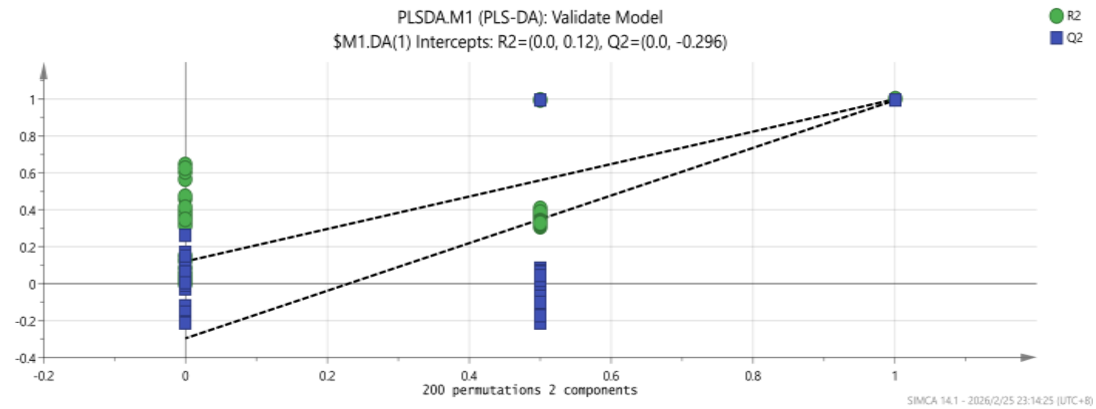


Figure 7. 3 types of mutton VOCs PLS-DA analysis (in the figure: TS represents Tibetan sheep, SH represents sheep, ZT represents goat)



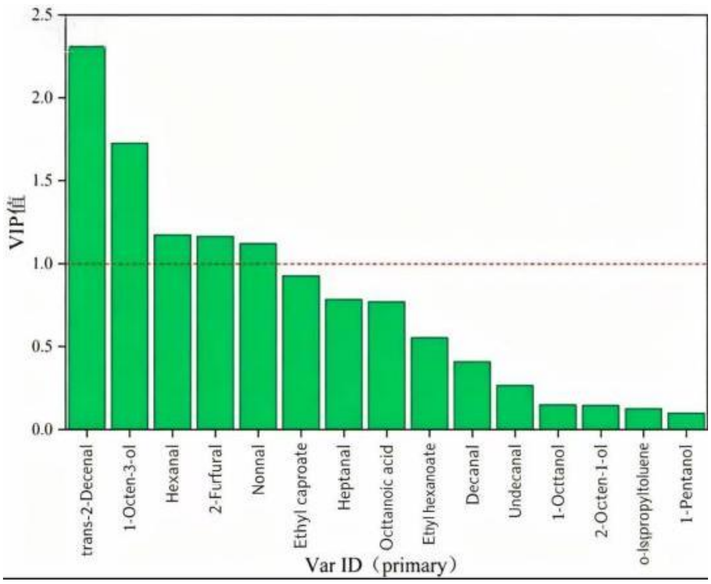
(a) HS-SPME-GC-MS



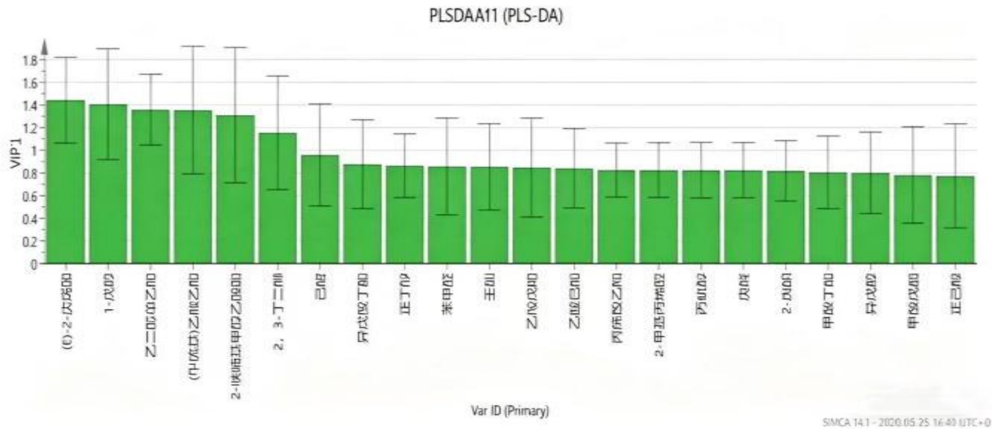
(b) GC-IMS

Figure 8. 3 types of mutton VOCs permutation test

In order to deeply analyze the characteristic variables with the greatest contribution of various volatile compounds in mutton, this study calculated the VIP of various volatile components based on the PLS-DA model, usually taking VIP>1 as the threshold for screening important variables. In HS-SPME-GC-MS analysis, a total of 5 significantly different compounds with VIP>1 were identified. In GC-IMS analysis, a total of 6 significantly different compounds with VIP>1 were identified.



(a) HS-SPME-GC-MS



(b) GC-IMS

Figure 9. 3 types of mutton VOCs VIP plot

3.5. Identification of Key Flavor Substances

The key flavor contributors of Tibetan sheep are concentrated in aldehydes, with trans-2-decenal as the absolute dominant; nonanal, heptanal, hexanal, 2-methylacrolein and propanethiol all have ROAV ≥ 1, which together strengthen the fatty and grassy base of Tibetan sheep.

Goats have more diverse flavor contributors, with significant differences from the other two types of mutton: 1-octen-3-ol is the core source of grassy and mushroom aromas of goats and a key substance distinguishing them from Tibetan sheep and sheep; hexanal, heptanal, vinyl hexanoate, ethyl n-hexanoate, butyl isovalerate and amyl formate have ROAV between 1-10, among which esters add slight fruity aroma to goats and improve flavor softness.

Sheep flavor is between Tibetan sheep and goats, with significant sample specificity: hexanal and 2-heptenal are unique sources of nutty and fatty aromas of Tibetan sheep, significantly different from goats. In addition, similar to goats, sheep lack octanal, decanal and ester compounds, and the flavor is mainly aldehyde fatty aroma with simpler layers than Tibetan sheep.

Overall, the flavor differences of the three types of mutton are significant: Tibetan sheep are dominated by trans-2-decenal + high ROAV aldehydes, with rich and unified flavor; goats are characterized by 1-octen-3-ol + esters, with fresh flavor; sheep are based on hexanal + 2-heptenal, with both richness and uniqueness in flavor.

In terms of intra-group stability, Tibetan sheep have the smallest ROAV fluctuation and the most stable flavor; sheep have the largest fluctuation and weak flavor consistency; goats are in the middle. From the perspective of characteristic markers, trans-2-decenal can be used as a sheep identification index, 1-octen-3-ol can be used as a goat identification index, and 2-heptenal can be used as a Tibetan sheep identification index [24].

In international meat research, mutton flavor is usually summarized as fatty, fruity, grassy, roasted, floral and sweet. Through the cumulative contribution of ROAV values of key aroma compounds, aroma characteristic radar charts of different mutton were obtained. The results showed that the dimension of fatty aroma was significantly higher than the other five aroma dimensions, and the intensity was in the order of Tibetan sheep > sheep > goats. Tibetan sheep have prominent fatty aroma and obvious grassy aroma, with rich and recognizable flavor. Goats have slightly stronger fruity and grassy aromas, with mild and balanced flavor. Sheep have prominent fruity aroma.

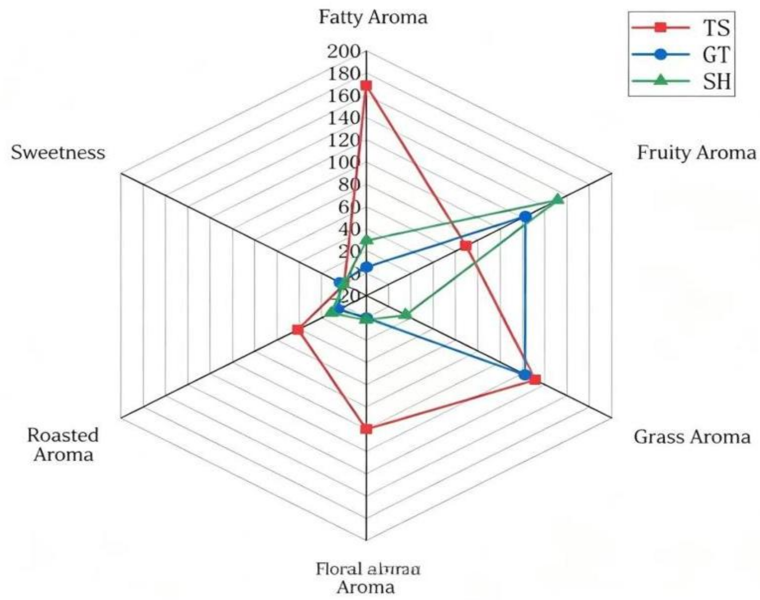


Figure 10. Three types of mutton aroma characteristic radar chart

4. CONCLUSION

This study adopts the combined technology of HS-SPME-GC-MS and HS-GC-IMS, combined with principal component analysis and fingerprint visual analysis, to systematically explore the volatile flavor differences of Tibetan sheep, Shandong local sheep and goats, providing theoretical and technical support for mutton variety identification, quality evaluation and characteristic meat product development.The two analytical techniques are complementary and synergistic, confirming that there are significant species differences in volatile flavor compounds among the three types of mutton. GC-MS identified a total of 19 volatile components; HS-GC-IMS detected 25 compounds, capturing more trace substances, among which 2-furylmethyl acetate was unique to goats.The three types of mutton have their own unique flavor profiles, and the core differences originate from the composition and content of aldehydes, alcohols and esters. Tibetan sheep are dominated by high-content aldehydes, forming a rich and unique flavor, related to high-altitude growth characteristics; goats show the characteristics of "high alcohol and high ester" with unique substances; local sheep have balanced and mild flavor with moderate content of various substances.Five key volatile compounds, namely trans-2-decenal, 1-octen-3-ol, hexanal, 2-heptenal and nonanal, were screened out by VIP in PLS-DA and ROAV, which are the core substances of volatile flavor differences among Tibetan sheep,

sheep and goats.The aroma characteristic radar chart shows that Tibetan sheep present significant fatty aroma, goats present obvious mushroom aroma, and sheep have a mild overall odor.In summary, the flavor differences of the three types of mutton are jointly determined by species characteristics and growth environment. The combined technology can effectively analyze these differences, providing a guarantee for the differentiated development of the mutton industry.

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