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Research Article

Tracking changes in flavor characteristics of dried pork slice during air fryer processing based on E-nose, gas chromatography-ion mobility spectrometry, and lipidomics techniques

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Abstract: In this study, the changes in flavor characteristics of dried pork slice at various stages of air fryer processing were systematically traced and analyzed using E-nose, gas chromatography-ion mobility spectrometry (GC-IMS) and lipidomics. The results showed that the volatile organic compounds (VOCs) and lipid composition of dried pork slice changed significantly at different processing stages. The analysis showed that the E-nose was able to differentiate between the odor profiles of different processing stages of dried pork slice, with significant differences between the samples. The GC-IMS detected 74 VOCs during the processing of dried pork slice, of which 61 were characterized and 19 differential signature VOCs were screened based on the partial least squares discriminant analysis (PLS-DA) model. Aldehydes and pyrazines increased significantly as the processing stage progressed, especially in the finished product stage. A total of 780 lipids were detected by lipidomics, among which triglycerides and phosphatidylcholine accounted for 50.26% and 35.00%, respectively, as well as degraded significantly during processing, and 38 differential lipid compounds were screened by using the PLS-DA model. Correlation analysis revealed that ethyl 2-hydroxypropanoate-D, ethyl 2-hydroxypropanoate-M, and 1-butanol,3-methyl-,acetate-D showed negative correlation with 38 differential lipids, while positive and negative correlations were found between the remaining 16 major VOCs and the differential lipids, indicating that lipid degradation was closely related to the generation of flavor compounds. This study revealed the key data of lipid degradation and flavor generation, which provided a scientific basis for optimizing the air fryer processing and enhancing the flavor quality of dried pork slice.

Keywords: air fryer; dried pork slice; volatileorganic compounds; lipidomics

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1 Introduction

The dried pork slice is a traditional meat product in China, which is popular among consumers by virtue of its high protein content, low fat content, delicious taste, and portability[1]. The traditional process of deep-frying or baking dried pork slice involves complex steps of heat treatment, curing and dehydration, which work together through processes such as the Maillard reaction and lipid oxidation to form the unique flavor of dried pork slice[2]. The flavor of dried pork slice depends not only on the quality and composition of the raw materials used, but was also significantly affected by the processing conditions. In recent years, the air fryer, as an innovative cooking technology, generated hot air by heating the heat pipe inside the machine at a high temperature, and then used the fan to blow the high temperature air into the pot to heat the food, so that the hot air circulated in the closed space, and the use of the food's own grease to fry the food. Thus, the food was dehydrated and the surface becomes golden and crispy to achieve the effect of frying[3]. Compared with traditional heating methods, air fryer was special in their ability to mimic the taste and appearance of fried food, while reducing the use of oil and grease. It also cooked faster and distributed heat more evenly, which not only improved cooking efficiency, but also helped to maintain the nutrition and flavor of the food[4]. It has been shown that air fryer can significantly affect the texture and flavor composition of meat products. Wang et al.[5] explored the effect of air fryer on volatile organic compounds (VOCs) in chicken and showed that air fryer processing can significantly change the composition of VOCs components, especially the generation of specific flavor compounds under high-temperature short-time treatment. Cao et al.[6] compared the effects of air fryer with traditional deep-frying methods in the processing of chicken nuggets, and air fryer were a healthy alternative cooking method that can reduce the oxidative degradation of lipids in chicken nuggets and generate more heterocyclic compounds and fewer aldehydes when compared to the conventional frying method in chicken nuggets processing.

However, there is still limited research on the effect of air fryer on the flavor, texture and nutritional value of traditional meat products such as dried pork slice. Therefore, the present study aimed to fill this research gap by investigating the dynamic changes in the flavor components of air fryer-processed dried pork slice.

The flavor profile of dried pork slice is a complex system. To gain a deeper understanding of the flavor composition of dried pork slice and its formation mechanism, the application of modern analytical techniques can provide new opportunities for flavor research. The combination of E-nose and gas chromatography-ion mobility spectrometry (GC-IMS) is commonly used in food flavor analysis, quality discrimination, and variety identification. Sun et al.[7] used GC-IMS in combination with E-nose to analyze and compare the aroma characteristics of four famous Chinese roasted chickens, effectively differentiating them. In addition, as an important component of meat, lipids participate in a variety of complex biochemical reactions during the heating process of meat. Lipid metabolism, particularly the oxidative breakdown of lipids, occurs mainly through mechanisms such as autoxidation, enzyme-catalysed oxidation and photo-oxidation. During autoxidation, unsaturated fatty acids react with oxygen molecules to produce peroxides. These peroxides are odorless, unstable and readily decompose into volatile compounds such as aldehydes, ketones and alcohols[8]. Lipidomics, as an emerging branch of metabolomics, can explore the important role of lipids in the formation of food flavor, and to analyze the effects of different processing steps on lipid composition and its impact on the final flavor[9]. Gao et al.[10] used lipidomics to reveal a positive correlation between the relative content of specific lipid molecules and key flavor compounds, such as ethyl isovalerate and ethyl caproate, suggesting that *Lactobacillus lactis* IMAUJBH1 promoted the formation of unique flavors in fermented Inner Mongolian lamb sausages by regulating lipid metabolism.

At present, the research on dried pork slice mainly focuses on the processing techniques of dried pork slice to improve the taste and tenderness of dried pork slice, and some of the existing studies have only analysed the differences in flavor substances at different processing stages. Some existing studies did not identify the pattern of flavor formation in dried pork slice, particularly the characteristic compounds decisive for the final flavor. The aim of this study was to systematically investigate the lipid degradation and VOCs formation pattern during the processing of dried pork slice by air fryer processing method, combining E-nose, GC-IMS and lipidomics methods. Through sensory perception, chemical composition analysis and lipid composition analysis, the differences in the composition of flavor components of dried pork slice at different processing stages were explored, in order to obtain the fingerprints of the signature characteristics of dried pork slice at different processing stages, and to reveal the relationship between the aroma characteristics and the lipid composition and flavor. This study will reveal the complex relationship between lipids and VOCs under air fryer processing conditions, and provide a scientific basis for optimising the processing technology of dried pork slice and improving product quality.

2 Materials and methods

2.1 Samples

Freshly slaughtered three-way crossbred pig hindquarters were purchased at Wal-Mart supermarket and stored in a thermostat at 4 °C and promptly shipped to the laboratory. Sugar, fish sauce, Baijiu, pepper, and five-spice powder were purchased from the supermarket. All food materials were food grade and comply with Chinese government food hygiene standards. Methyl tert-butyl ether (MTBE), methanol (MeOH), dichloromethane (DCM), acetonitrile, ammonium formate, and isopropanol were of high-performance liquid chromatography (HPLC) grade and purchased from Thermal Fisher Scientific (Shanghai, China).

2.2 Sample preprocessing

According to the conventional processing method of dried pork slice, the processing stages of meat products can be divided into raw meat (R), marinated meat (M), semi-finished meat (S) and finished meat (F). The specific steps of sample preparation for each stage were shown below. The raw meat: excess fat, tendons, and other undesirable parts were removed from the pork, which was then washed, cut into small pieces, and ground using a meat grinder. The marinated meat: nitrite (0.07%, *m*/*m*), sugar (13%, *m*/*m*), fish sauce (7%, *m*/*m*), five-spice powder (0.15%, *m*/*m*), and Baijiu (2%, *m*/*m*) were added to the raw meat and mixed well. The marinating time was 1 h. The marinating temperature was room temperature (approximately 23 °C). The semi-finished products: the marinated meat was pressed into slices of 3 mm thickness, 20 cm width, and 30 cm length, and the dried slices were laid flat on a baking sheet and dried in an oven (BHX-I, Expro, China) at a drying temperature of 80 °C and a drying time of 40 min. The finished meat: the dried meat was cut into length of 7 cm and width of 5 cm, then fried in an air fryer (MF-KZE5004, Midea, China) at a temperature of 180 °C for 2 min. Then allowed to cool to room temperature.

Each processing stage (raw material, marinating, roasting and finished product) was sampled as a separate experimental group, with a sample size of three individual samples per group. The samples were collected immediately after the completion of each processing stage. The samples were rapidly frozen after collection and stored at −80 °C to maintain the volatile components and lipids in the samples without degradation or change. The raw meat should be purchased fresh on the test date.

2.3 E-nose analysis

The samples were weighed to 10 g, placed in a 50 mL centrifuge tube, and tested after 30 min of enrichment. The sample preparation time was 5 s, the sampling time was 1 s/group, and the injection flow rate was 400 mL/min. The analytical sampling time and the sensor self-cleaning time were both 100 s. The data were collected from 68 to 70 s for summarizing and analyzing the results. The E-nose had ten different sensors and the types of compounds to which each sensor was sensitive, as shown in Table 1.

Table 1 E-nose sensors.

Sensors number	Sensor	Performance description
1	W1C	Aromatic organic compounds
2	W5S	Nitrogen oxides
3	W3C	Ammonia and aromatic compounds
4	W6S	Hydrides
5	W5C	Alkenes, aromatics, polar molecules
6	W1S	Alkanes
7	W1W	Sulfides
8	W2S	Alcohols, some aromatic compounds
9	W2W	Aromatic ingredients and organic sulfides
10	W3S	Alkanes and aliphatics

2.4 GC-IMS analysis

VOCs from dried pork slice at different processing stages were analyzed by a GC-IMS instrument (Flavor Spec®-G.A.S. Dortmund, Germany) with a slight modification of the method[11]. The device consists mainly of a gas chromatograph (Agilent, USA), an autosampler (Agilent, USA) and a headspace sampling device (Agilent, USA), which includes a GC with an MXT 5 column (15 m × 0.53 mm). The 2 g of sample was accurately weighed and placed in a 20 mL headspace vial and incubated at 60 ℃ for 15 min (incubation speed 500 r/min). The sample was autosampled at 85 ℃ for 500 μL. The gas chromatographic separation was carried out on a DB-WAX capillary column (15 m × 0.53 mm, 1.0 μm) with helium (purity ≥ 99.999%) as the carrier gas at a temperature of 60 ℃ for 30 min. The starting gas flow rate was 2.0 mL/min for 2 min, which was maintained for 2 min, linearly scaled up to 10.0 mL/min within 8 min, and linearly increased to 100.00 mL/min within 10 min, which was maintained for 10 min. The ionisation source for the IMS detector was a tritium source (^{3}H), high purity nitrogen (purity ≥ 99.999%) at a flow rate of 150 mL/min and a temperature of 45 ℃.

2.5 Lipid extraction procedure

The method of lipid extraction was referred to and slightly modified from Wang et al.[12]. The 25 mg of sample was weighed into a 2 mL centrifuge tube, and 200 μL of water and 480 μL of extraction solution (MTBE:MeOH = 5:1, *V*/*V*) were added. Then the steel beads were added and processed by grinding at 35 Hz for 4 min, sonicated in an ice-water bath for 5 min, repeated the grinding and sonication for three times, and left at –40 ℃ for 1 h. The mixture was centrifuged for 15 min (900 × *g*, 4 ℃), and 300 μL of supernatant was taken into a centrifuge tube and dried under vacuum. A 200 μL of the solution (DCM:MeOH = 1:1, *V*/*V*) was added for reconstitution, vortexed for 30 s, sonicated for 10 min in an ice-water bath, centrifuged for 15 min (16 200 × *g*, 4 ℃), and 100 μL of the supernatant was taken in the injection vial and used for the ultra-high performance liquid chromatography-tandem mass spectrometry (UHPLC-MS/MS) analysis.

2.6 UHPLC-MS/MS analysis

The UHPLC-MS/MS analysis was performed using a UHPLC system (Vanquish, Thermo Fisher Scientific, MA, USA) equipped with a Kinetex C_{18} column (2.1 mm × 100 mm, 1.7 μm, Phenomen). Mobile phase A was H_2O-acetonitrile (2:3, *V*/*V*) containing 10 mmol/L ammonium formate; mobile phase B was acetonitrile-isopropanol (1:9, *V*/*V*), and 50 mL of a 10 mmol/L aqueous ammonium formate solution was added per 1 000 mL. The gradient elution procedure was performed as follows: 0.0–1.0 min, 40% B; 1.0–12.0 min, 40%–100% B; 12.0–13.5 min, 100% B; 13.5–13.7 min, 100%–40% B; 13.7–18.0 min, 40% B. The mobile phase flow rate was 0.3 mL/min, the column temperature was 55 ℃, and the injection volume was 2 μL. After separation, MS1 and MS2 data acquisition was performed on a Thermo Q Exactive Orbitrap mass spectrometer (Thermo Fisher Scientific, MA, USA) under the control of control software (Xcalibur, version: 4.0.27, Thermo, USA). Detailed parameters were as follows: sheath gas flow rate was 10 L/min, aux gas flow rate was 3.33 L/min, capillary temperature was 320 (positive), 300 ℃ (negative), respectively, full MS resolution was 70 000, MS/MS resolution was 17 500, collision energy was 15/30/45 eV in normalized collisional energy (NCE) mode, spray voltage was 5 (positive) or –4.5 kV (negative), respectively.

2.7 Data analysis

All test samples were measured at least three times in parallel. All results were shown as the average ± standard deviation (SD). One-way analysis of variance (ANOVA) was performed using SPSS 19.0 software and differences were considered significant at $P < 0.05$. VOCal software and its Reporter and Gallery Plot plug-ins were used for the qualitative and quantitative analysis of volatiles in the samples and the comparison of difference spectra. The relative content and variability of each group of samples were analyzed by normalisation based on the compound peak volume data of the samples. SIMCA 14.1 software and Origin 2022 software were used for dimensionality reduction and cluster analysis of the E-nose and GC-IMS data. The variable importance for the projection (VIP) of the analytical model was calculated by partial least squares discriminant analysis (PLS-DA) separately. The screening could distinguish the differentially affected VOCs (VIP > 1) in the dried pork slice at different processing stages. Lipidomics analyses were performed using MetaboAnalyst 5.0 (https://www.metaboanalyst.ca/) for multivariate statistical analyses of log-transformed data. To characterise the variability of lipids in dried pork slice at different processing stages, principal component analysis (PCA), PLS-DA and differential lipid analysis were performed. Lipids at VIP > 1.5 and $P < 0.05$ were considered as significant differential lipids.

3 Results and discussion

3.1 Results of different processing stages of dried pork slice by E-nose

3.1.1 E-nose results in dried pork slice processing

The E-nose technology could monitor and analyse volatile odors during the processing of dried pork slice. As can be seen in Figure 1A, the response value of group R to all the sensors was low, which was due to the fact that raw pork has a light odor, usually only salty, metallic and bloody[13]. The response values of the W5S sensor in the other three groups were significantly higher than those of the other sensors. W5S was sensitive to nitrogen oxides, indicating that nitrogen oxides were the main aroma components in the processing of dried pork slice, with group S showed the highest response, followed by groups M, F, and R. Sulfur-containing compounds were the key substances in producing the basic meat aroma. The W1W sensor was sensitive to sulfur compounds, the higher response values in groups M and S indicate that these compounds were more abundant at these stages, leading to a more intense meat aroma. Zhu et al.[14] explored the flavor of yak meat and found that roasting amplified the signals of W1W, W2W, W1S, and W2S, which was consistent with the present study. The highest response values of W1S, W1W, and W2S were found for group S. Roasting increases the sensitivity of meat products to alkanes, sulfur compounds, alcohols, and some aromatic compounds, suggesting that olefins, as well as aliphatic compounds, were less prevalent during the processing stage. Therefore, nitrogen oxides, alkanes, sulfides, alcohols, and some aromatic compounds were the main flavor substances in the dried pork slice products. Based on the radar plot of the response signals from the E-nose, it could be seen that the ingredients added in

group M during the processing of dried pork slice played a major role in influencing the overall flavor of the dried pork slice, attributed to the penetration of salt and flavorings during the curing process, which induced the initial onset of lipid oxidation and the generation of more flavor compounds[15].

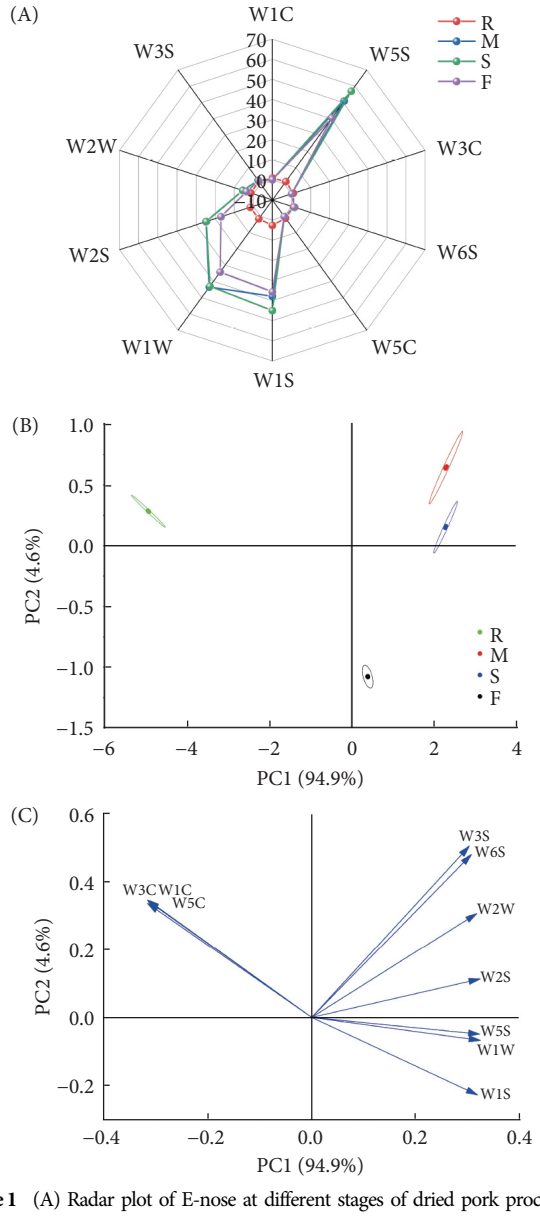

Figure 1 (A) Radar plot of E-nose at different stages of dried pork processing; (B) PCA plot of E-nose at different stages of dried pork processing; (C) loading analysis of E-nose at different stages of dried pork processing.

3.1.2 *Statistical analysis of E-nose results*

The PCA was performed on the data of the E-nose response values of the four processing stages of dried pork slice (Figure 1B). According to the PCA results, PC1 accounted for 94.9% and PC2 for 4.6% of the total variance, together explaining 99.5% of the variance. This indicates that the data after principal component dimensionality reduction could reflect the overall information of the original data. The four samples were clearly distinguishable, indicating that the E-nose was able to discriminate the odor characteristics at different processing stages, with significant variability observed among the samples. Group R was located on the left side of the *X*-axis, while groups M, S, and F were located on the right side of the *X*-axis. The results showed that the aroma characteristics of group R were differed from those of groups M, S, and F. Groups M and S were relatively close to each other, indicating similar volatile components.

Loading analysis is related to PCA and is based on the same algorithm, but the difference is that the loading algorithm focuses on the sensors. Loading analysis determines the magnitude of the contribution of different sensors to the odor differentiation of the sample. As shown in Figure 1C, the main response sensors of the sample on PC1 were W2S, W1W, W5S, and W1S. The main response sensors on PC2 were W3S and W6S. The major components of the odor during the processing of dried pork slice were alcohols, and some aromatic compounds, followed by sulfur compounds. This was determined based on the magnitude of sensor contribution and the type of odor sensitivity of the sensors. Overall, the E-nose analysis suggests that there were sensory differences between the samples at the four stages of dried pork slice processing. However, these differences need to be further confirmed by GC-IMS.

3.2 Volatile flavor substances in dried pork slice processing stage

3.2.1 *GC-IMS topographic plots of dried pork slice processing stages*

The GC-IMS technique was used to analyze the differences of VOCs during the processing of dried pork slice. The GC-IMS spectra provided detailed information on all the compounds, with the three-dimensional spectra displayed in Figure 2A. The signal intensities of the ion peaks of the four processing stages of dried pork slice varied, indicating the differences in the contents of VOCs. To visually distinguish the differences of VOCs during the processing of dried pork slice, dimensionality reduction was performed. The GC-IMS spectra were then analyzed in detail using the two-dimensional top view (Figure 2B) and the difference spectra (Figure 2C). As shown in Figure 2B, the horizontal coordinate represents the ion migration time (drift time), and the vertical coordinate represents the retention time. Each signal point in the spectrum represents a volatile component. A volatile compound may produce one or more bright spots; a stronger signal response indicates a higher concentration of VOCs. The retention times of most of the compounds during the processing stages of dried pork slice ranged from 200 to 1 400 s, while the drift times ranged from 8 to 14 ms. The VOCs of dried pork slice samples from different processing stages were well separated from each other. Group R served as the control. Samples from each group were compared to the control; they appeared white if their VOCs content was similar, and red or blue if their VOCs content was higher or lower than that of the control. As shown in Figure 2C, the VOCs composition varied significantly among the sample groups, with an increasing area of red indicating higher VOCs content in groups M, S, and F. This indicates that VOCs content increased with each processing stage, and some VOCs were present from the raw material stage through to the finished product. The peaks in the chromatograms of groups M, S, and F became increasingly dense, indicating that the number of flavor ions increased with processing depth. The red coloration in the spectra increased starting from the late processing stages, indicating a higher response intensity of the flavor substances. This increase may be due to the heat treatment during the processing of dried pork slice, which causes fat decomposition and protein denaturation. The addition of flavors

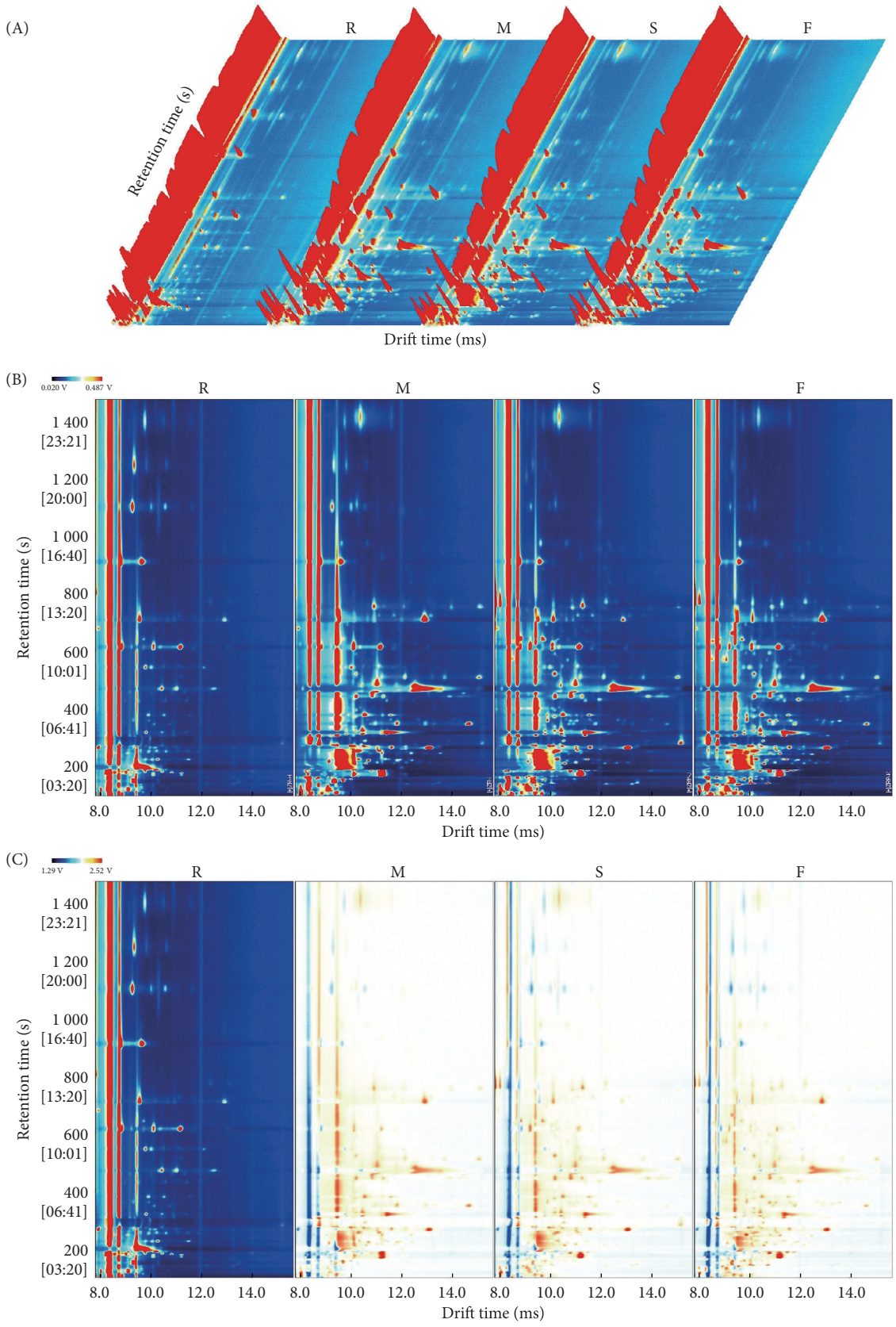

Figure 2 (A) Three-dimensional spectra of volatile components; (B) GC-IMS two-dimensional spectra of volatile components; (C) GC-IMS differential spectrum of volatile components; (D) fingerprint of volatile components during different stages of dried pork slice; (E) cluster analysis of VOCs content in different processing stages of dried pork slice.

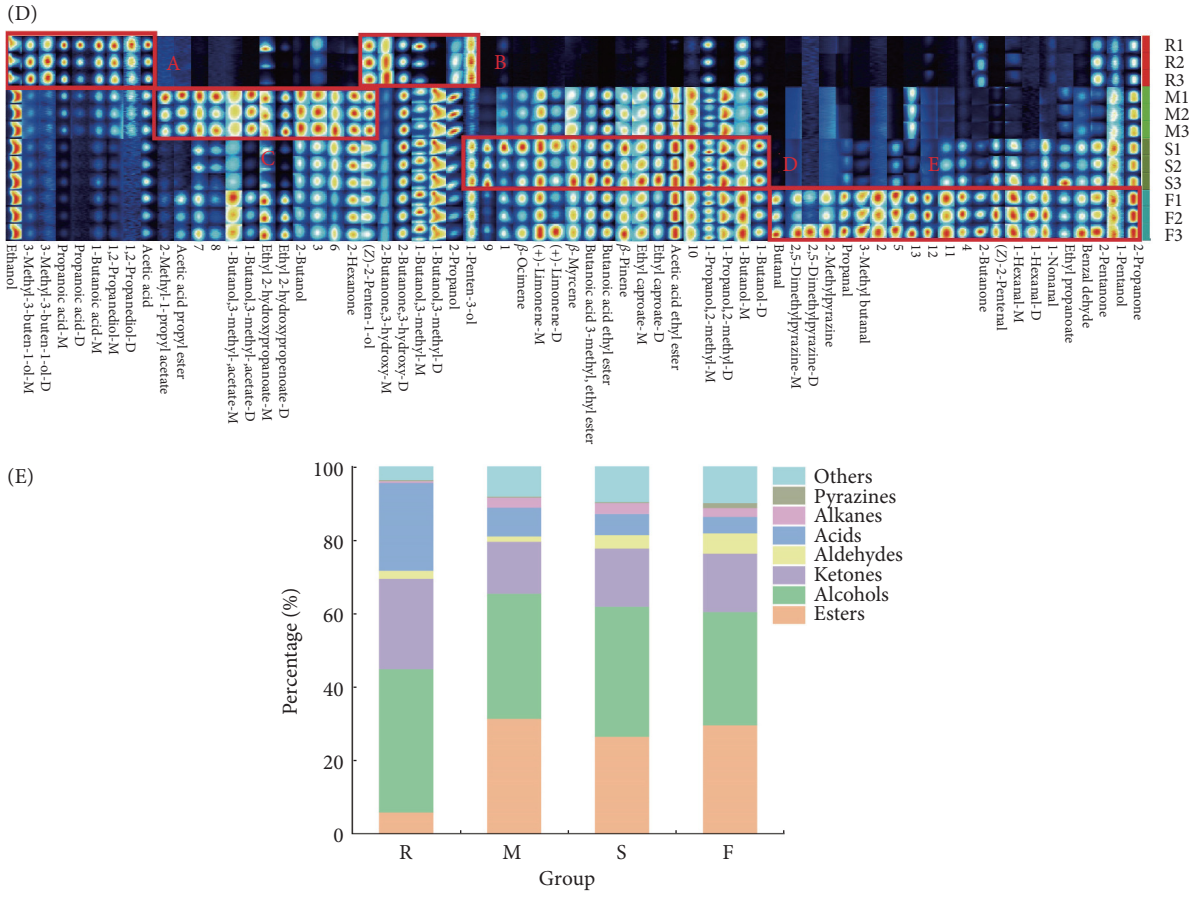

Figure 2 *(Continued)*

likely enhances the production of flavor precursor substances through osmosis and preliminary chemical reactions[16].

3.2.2 Characterization and relative content analysis of VOCs in dried pork slice processing

The Gallery plot (Figure 2D) combined with the different sample groups presents the complete VOCs information for each sample and the differences in VOCs between the samples. The entire fingerprint plot in each row indicates all VOCs detected in the samples (one dot for one compound). Each column indicates the same VOCs between different samples. The concentration of the substance correlating with the color of the signal peaks; the darker the color, the higher the VOCs concentration. The numbers indicate volatile compounds that were not clearly identified, and the brighter the color, the higher the content. As shown in Figure 2D, significant differences were observed in the concentrations of VOCs in dried pork slice across the four different processing stages. A total of 74 volatile compounds were detected in the processing of dried pork slice using GC-IMS, and 13 substances were not characterized due to the limitation of the GC-IMS spectral library.

To further explore the types of VOCs in the processing of dried pork slice, retention time and ion mobility time were used for qualitatively analysis, while peak volume was used to quantitatively analysis. The results were shown in Table S1 and Figure 2E. The 74 peaks detected were identified by the NIST 2014 and IMS databases built into the GC-IMS system. A total 61 VOCs were detected, including 9 ketones, 16 alcohols, 12 esters, 11 aldehydes, 5 acids, 5 hydrocarbons, and 3 pyrazines. Among these, alcohols were the most diverse category.

The changes in VOCs during the processing of dried pork slice were analyzed from Figures 2D and E, can be roughly divided into five different regions (A, B, C, D, and E). Regions A and B represent the VOCs of raw meat, characterized by fewer flavor substances and a lighter flavor profile of raw meat[17]. The main flavor compounds in these regions include 1-penten-3-ol, 2-butanone, 3-hydroxy-M, 1,2-propanediol-M, 1,2-propanediol-D, 3-methyl-3-buten-1-ol-M, 3-methyl-3-buten-1-ol-D, (*Z*)-2-penten-1-ol. Notably, 1-penten-3-ol, an unsaturated alcohol with a grassy and slightly fruity aroma, was commonly found in fresh raw meat[11]. The combination of Figure 2E also showed that raw meat was mainly dominated by alcohols, acids and ketones. In raw meat, alcohols were derived from the maturation and storage process, and lipids in pork produce alcohols through microbial fermentation and animal metabolism[18].

The fingerprints of group M showed significant enhancement of compound signals contributed to the characteristic flavor of dried pork slice. The flavor substances in the region C were primarily 2-methyl-1-propyl acetate, acetic acid propyl ester, 1-butanol, 3-methyl-,acetate-M, 1-butanol,3-methyl-,acetate-D, ethyl 2-hydroxypropanoate-M, ethyl 2-hydroxypropanoate-D, 2-butanol, (*Z*)-2-penten-1-ol, 2-hexanone, which were mainly esters and alcohols. In group M, a decrease in the content of 1-penten-3-ol was seen, probably due to the fact that its production was related to the enzymatic oxidation of lipids, and the addition of salt during the curing process inhibited the enzyme activity, which in turn reduced the amount of 1-penten-3-ol produced[19]. Notably, the content of ester volatiles in group M increased significantly, while the content of acids was decreasing. Ester compounds usually impart fruity and

sweet flavors to food products, suggesting that the increase in esters contribute significantly to the flavor of the finished dried pork slice[20]. The addition of ingredients such as salt to group M might lead to a decrease in the pH of the meat, contributing to the degradation or conversion of some acids and resulting in a decrease in the acid content. In contrast, the increase in the overall flavor substance content in group M was associated with the addition of ingredient such as curing salt, fish sauce, and spices, which could generate richer flavor by altering the chemical environment of the meat product and enhancing the conversion of proteins and sugars[21].

After roasting the dried pork slice meat to obtain group S, the fingerprints showed more volatile compounds, especially in the alkyl ketones, aldehydes, and esters. The main flavor substances that could be seen in the region D were ethyl caproate-M, ethyl caproate-D, butanoic acid 3-methyl, ethyl ester, butanoic acid ethyl ester, 1-butanol-M, 1-butanol-D, 1-propanol,2-methyl-M, 1-propanol,2-methyl-D, acetic acid ethyl ester, (+)-limonene-M, (+)-limonene-D, β-myrcene, and β-pinene. After roasting at high temperatures, the terpenes from the spices create more complex layers of flavor by evaporating and diffusing the characteristic aromas of fruity, woody and fresh grassy notes that blend with the meat itself[22]. After dried pork slice was baked, the amino acids and added sugars in the meat underwent a Maillard reaction after heating, producing a variety of volatile compounds, such as aldehydes and ketones[23]. Additionally, the fat, protein and sugar in the meat undergo thermal degradation, producing more volatile flavor substances that impact the characteristic charred and baked flavor to the dried meat[24].

Dried pork slice was processed in an air fryer to form the finished product. Region E in the Figure 2D shows the main flavor substance of the finished product, comprising (*Z*)-2-pentenal, 1-hexanal-M, 1-hexanal-D, butanal, propanal, 3-methyl butanal, 1-nonanal, 2,5-dimethylpyrazine-M, 2,5-dimethylpyrazine-D, 2-methylpyrazine, 1-pentanol, 2-butanone, 2-pentanone, and 2-propanone. The finished product had a rich variety of volatile flavor substances, mainly containing aldehydes, pyrazines, alcohols, esters, and ketones. 3-Methylbutyraldehyde was the more volatile and may originate from metabolic degradation of fats and carbohydrates, as well as from proteolytic production in meat[25]. Nonanal had a sweet and fruity flavor[26]. The aldehyde content in the finished product reached the highest compared to the other three groups, with typical fruity aroma, which was the key compound in dried pork slice. The 2-butanone, 2-pentanone and 2-propanone in the region E belong to 2-ketone compounds, which had the aroma of meat and cream and could enhance the aroma of dried pork slice[27]. Among them, pyrazines were important volatile components of meat products (especially fried and grilled meat). Due to the fact that pyrazines were mainly formed on the surface of meat and were associated with the aroma of roasted meat[28]. In this study, the use of an air fryer to simulate the effect of deep-frying while reducing the use of fats and oils greatly promoted the Millard reaction and lipid oxidation, reduced water activity and specific heat capacity, and significantly contributed to the formation of VOCs, resulting in the unique flavor profile of dried pork slice. Liu et al.[29] investigated the effect of frying temperature in an air fryer on the quality attributes of sturgeon fillets and found that more flavor compounds (e.g., aldehydes, alcohols, and esters) were produced in air fryer-treated fillets. The types and concentrations of VOCs were maximized at the finished product stage, which was consistent with observations of the flavor-enhancing effects of traditional baking and processing methods in previous studies[24].

3.2.3 Multivariate statistical analysis of VOCs in dried pork slice processing

PCA was used to investigate the variation in VOCs during the processing of dried pork slice. As shown in Figure 3A, the results indicated that the two principal components, PC1 (56.5%) and PC2 (23.6%), explained 80.1% of the total variance, suggesting that these components effectively captured the information in the original data. The samples were dispersed in different areas, allowing for better distinction of VOCs during the processing of dried pork slice. Group R was farther away from the other three samples, indicating that there were significant differences in the composition of VOCs, and the two samples, groups S and F, were more similar, in which group F was more concentrated in distribution, indicating that the VOCs of the finished product had reached a more stable state after the processing. This might be attribute to the final baking process allowed the volatile flavor substances to reach the highest level and stabilize within a specific range[30].

PLS-DA is a supervised analysis method that facilitates the statistical analysis and visualization of complex data, enabling the construction of predictive models[31]. It can be used to model the correlation between the intensity of VOCs measured by GC-IMS and the sample category, allowing for the identification of key variables influencing the grouping. PLS-DA was used to analyze the VOCs in the processing stages of dried pork slice, with results shown in Figure 3B. These results were consistent with those from PCA, clearly distinguished samples from different processing stages. The models were R^2_X (independent variable fit index) = 0.956, R^2_Y (dependent variable fit index) = 0.990 and Q^2 (model prediction index) = 0.98, when R^2 and Q^2 were greater than 0.5, this indicated that the model possesses strong explanatory and predictive capabilities, effectively differentiating VOCs across different processing stages and highlighting their differences. Figure 3C shows the validation of the model made by PLS-DA after a permutation test. R^2 intersected the vertical axis at (0, 0.18), and Q^2 intersected at (0, −0.451), with both regression lines having steep slopes, indicating strong predictive ability and no overfitting. The validation confirmed that this model was suitable for classifying and distinguishing VOCs in samples from different processing stages of dried pork slice. The VIP value was a quantitative index of the influence of each VOCs on the flavor of the samples during the processing. A higher VIP value indicated a more significant difference, allowing for the identification of potential markers. After screening, a total of 19 volatile compounds with VIP > 1 were identified, as shown in Figure 3D.

The 19 key characteristic VOCs identified by VIP were clustered and analyzed. As shown in Figure 3E, the key characteristic VOCs in the samples from the four groups showed a better clustering. The red color expressing the high content of volatile components and the blue color indicating the reduced content. The group R samples contained high levels of ethanol, 2-propanone, propanoic acid-M, 1,2-propanediol-M, acetic acid, 2-butanone, 3-hydroxy-D, and 1-butanolic acid-M. The VOCs in the samples were primarily associated with those found in fresh meat. These compounds were mainly associated with the natural metabolism of fresh meat and usually predominate in raw, untreated meat[32]. The VOCs of ethyl 2-hydroxypropanoate-D, ethyl 2-hydroxypropanoate-M, 1-butanol, 3-methyl-, acetate-D in group M had a significant effect on cured meat. The production of esters increased dramatically during the curing and fermentation of meat products, and the esterification reaction became more active, particularly after adding specific flavorings[33]. It was showed that the use of salts and seasonings can

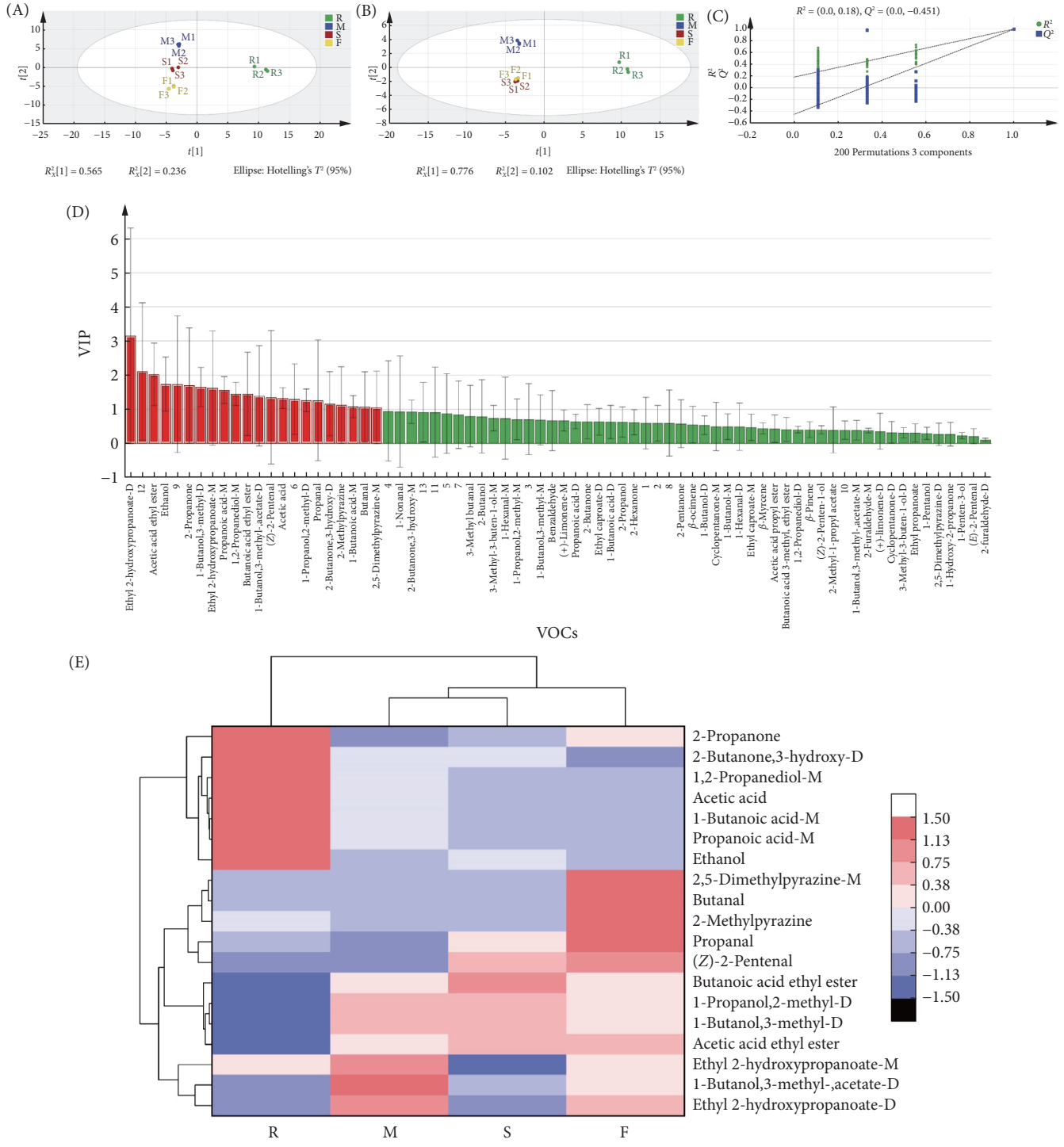

Figure 3 (A) PCA; (B) PLS-DA; (C) model cross-validation diagram; (D) VIP value of the PLS-DA model; (E) cluster analysis of key compounds of volatile flavor compounds during different stages of in dried pork slice.

significantly modulate the production of ester compounds[34], which was consistent with the significant elevation of ester compounds that we observed in the present study. Butanoic acid ethyl ester was the most significant volatile component in group S. The group S used roasting to treat dried pork slice, where the concentrations of butyric acid and ethanol in the meat were relatively high and the activity of enzymatic and chemical reactions was enhanced by initial heat treatment or fermentation, thus promoting the production of esters. Other studies had also found that ethyl butyrate plays a significant role in some fermented and dried meat products. In a study of fermented sausages, Yoo et al.[35] found that the concentration of ethyl butyrate gradually increased during drying and fermentation and that its production was closely related to the activities of fermenting microorganisms. The results of the present study were consistent with this finding, and the process conditions at the semi-finished product stage were critical for the production of ethyl butyrate. There were more substances in group F that had a significant effect on the odor of dried pork slice, such as (*Z*)-2-pentenal, propanal, 2-methylpyrazine, butanal, and 2,5-dimethylpyrazine-M. The high-temperature treatment in the air

fryer accelerated the degradation of fatty acids, resulting in significant amounts of (*Z*)-2-pentenal and propanal. Pyrazine compounds such as 2-methylpyrazine and 2,5-dimethylpyrazine-M were significantly increased at the finished product stage, mainly attributed to the enhancement of the Maillard reaction. These compounds have nutty, roasted and caramelized aromas and play an important role in the flavor enhancement of the finished product. The production of pyrazines played an important role in the Maillard reaction, especially at high-temperatures when sugars react with amino acids to produce large amounts of pyrazines[36]. During thermal processing of meat products, the generation of pyrazines had a decisive influence on the aroma and flavor of the final product. The GC-IMS technique revealed significant changes in a variety of volatile flavor compounds at the finished product stage, especially (*Z*)-2-pentenal, propionaldehyde, 2-methylpyrazine, butyraldehyde, and 2,5-dimethylpyrazine-M. These compounds increased significantly during high-temperature roasting and drying profoundly affecting the aroma of the final product. Comparison with other studies further demonstrated that the generation of these volatile compounds was the key to enhance the flavor of dried pork slice. The results were consistent with the GC-IMS fingerprinting results.

3.3 Lipidomics results during the processing of dried pork slice

3.3.1 *Lipid composition of dried pork slice during processing*

A total of 780 lipid compounds were identified from dried pork slice samples at the processing stage using UHPLC-MS in both positive and negative ion modes. These metabolites were categorized using Lipidmaps, and five major groups were obtained, as shown in Figure 4A, including sphingolipids (SP) (8.85%), fatty acyls (FA) (5.51%), glycerophospholipids (GP) (35.00%), glycerol

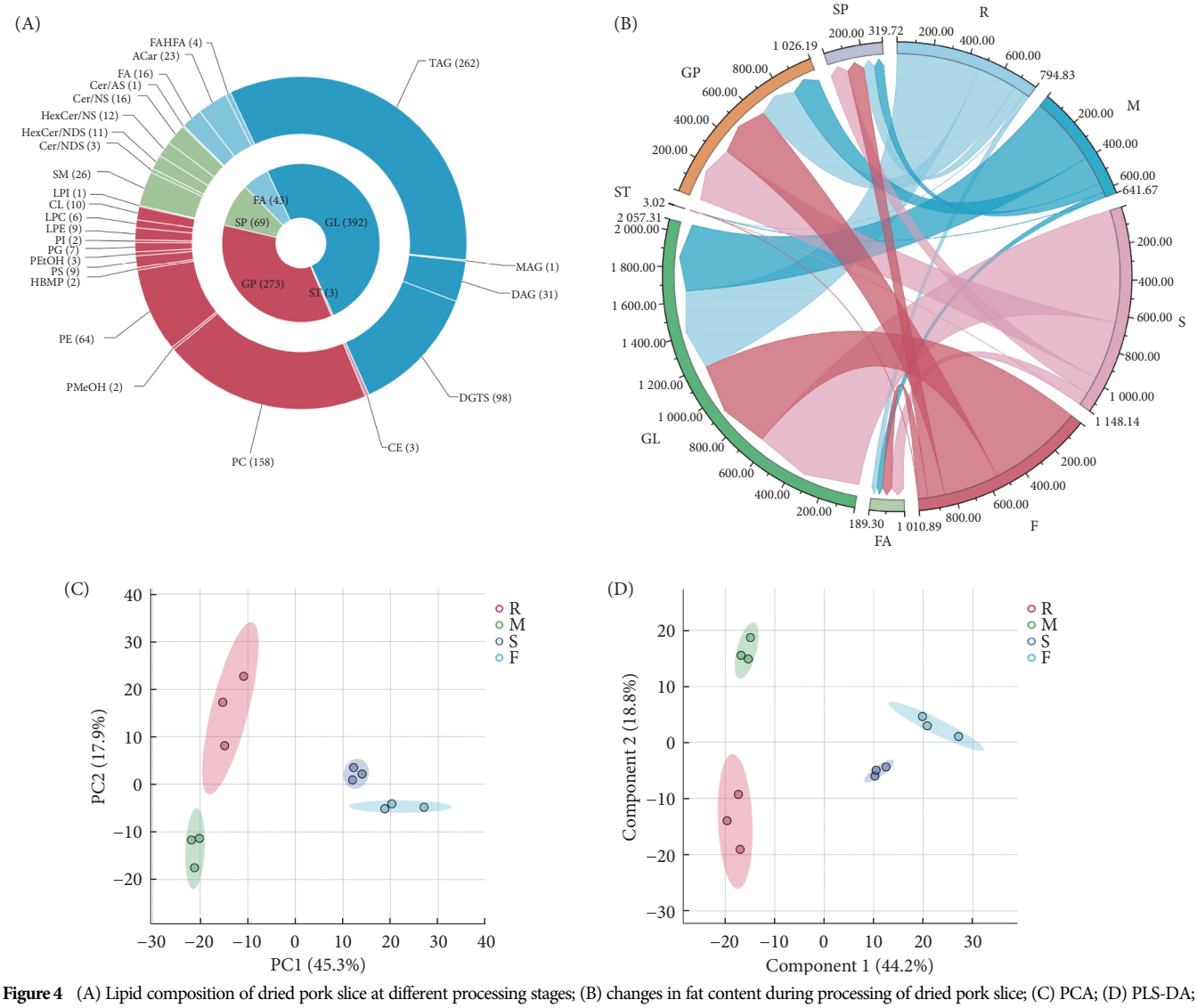

Figure 4 (A) Lipid composition of dried pork slice at different processing stages; (B) changes in fat content during processing of dried pork slice; (C) PCA; (D) PLS-DA; (E) VIP scoring plot of PLS-DA; (F) clustered heatmap of differential lipids of dried pork, screened under the conditions of VIP > 1.5 and $P < 0.05$. MAG, monoacylglycerol; CE, cholesterol esters; PMeOH, phosphatidylmethanol; HBMP, hemibismonoacylglycerophosphate; PS, glycerophosphoserines; PEtOH, phosphatidylethanol; PG, glycerophosphoglycerols; PI, glycerophosphoinositols; LPE, lysophosphatidylethanolamine; LPC, lysophophatidylcholine; CL, cardiolipins; LPI, lysophosphatidylinositol; SM, sphingomyelins; Cer/NDS, ceramide non-hydroxyfatty acid-dihydrosphingosine; HexCer/NDS, hexosylceramide non-hydroxyfatty acid-dihydrosphingosine; HexCer/NS, hexosylceramide non-hydroxyfatty acid-sphingosine; Cer/NS, ceramide non-hydroxyfatty acid-sphingosine; Cer/AS, ceramide alpha-hydroxy fatty acid-sphingosine; ACar, acylcarnitine; FAHFA, fatty acid ester of hydroxyl fatty acid.

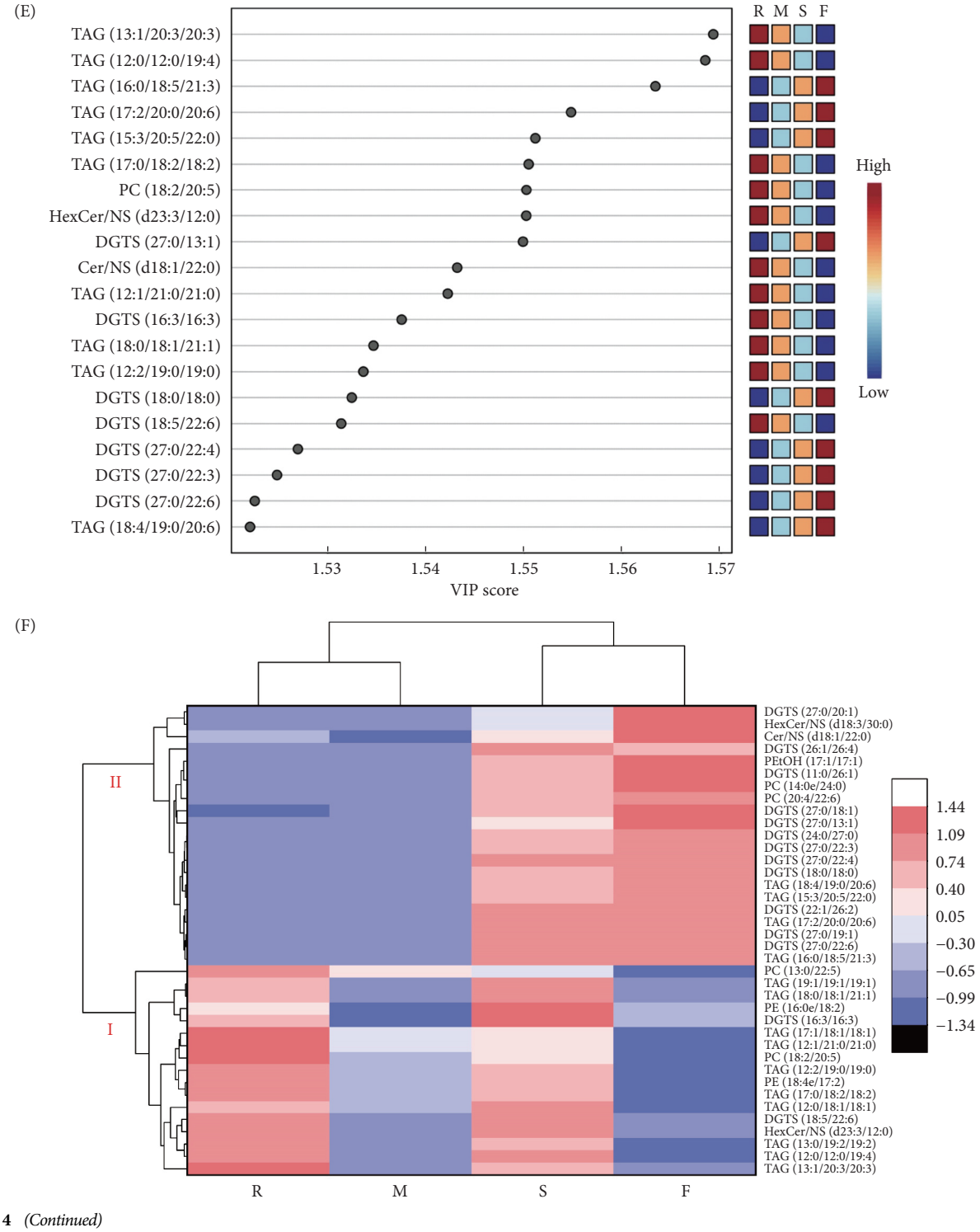

Figure 4 *(Continued)*

esters (GL) (50.26%), and sterol lipids (ST) (0.38%). In order to better understand the changes in lipid molecules during the processing of dried pork slice, these five lipids were further categorized to obtain 26 subclasses, of which the most abundant subclass of lipids was triglycerides (TAG), with a total of 262 species. TAG was the predominant form of stored fat in pork, and its decomposition to form free fatty acids was the key to flavor formation. The findings of Xia et al.[37] in their study of roasted meat flavor were consistent with the present study, in which they pointed out that the decomposition of TAG during high-temperature roasting was the key to flavor enhancement of meat products. Subsidiarily, the lipids contained in dried pork were 158 phosphatidylcholine (PC), 98 diacylglycerol (DGTS), 64 phosphatidylethanolamine (PE), 31 diglycerols (DAG) and other lipids. During the processing of dried pork slice, lipids primarily exist in the form of TAG and PC. The fatty acids produced by TAG decomposition were easily oxidized at high-temperature to produce a series of complex volatile compounds, such as (*Z*)-2-pentenal and propionaldehyde, which impart a distinctive aroma to dried pork slice. This process explained the importance of TAG in the

processing of dried pork slice and could be used as a precursor substance for (*Z*)-2-pentenal measured by GC-IMS. The flavor of meat and its products was related to the composition of phospholipids, and PC and PE were important components of phospholipids. Wang et al.[38] studied free fatty acids and phospholipids in duck meat for identification and quantitative analysis. It was found that the molecular species of phospholipids changed considerably during the processing of duck meat, which was one of the main factors in the formation of the flavor of duck meat products. The presence and transformation of lipids was an important basis for the formation of the final flavor and texture of dried pork slice.

3.3.2 *Lipid dynamics during the processing of dried pork slice*

As shown by the dynamics of lipid content (Figure 4B), all lipid classes showed significant changes ($P < 0.05$) during the processing stages. This indicated the prevalence of metabolic changes during the processing of dried pork slice, as observed through overall lipidomics. GL and GP played a crucial role throughout the processing. At the raw material stage, the contents of GL and GP were high. As processing progressed, especially in group M, the breakdown of GL and degradation of GP increased significantly, likely due to lipid catabolism and transformation processes. In a study of traditionally fermented sausages, salt penetration and curing conditions promoted fat hydrolysis and oxidation, leading to a reduction in total lipids[39]. This also provided precursors for the production of subsequent flavor substances, which was consistent with the reduction in lipid content observed in this study. Salt might cause the dissolution of myofibrillar proteins, leading to muscle swelling and increasing its water absorption capacity, possibly affecting lipid content and stability. The lipid content was significantly higher ($P < 0.05$) in all samples in group S. The main reason for this was that the water in the meat was evaporated, resulting in the drying of the meat, which led to an increase in the relative concentration of fat. In addition, fat in pork melts and was released when heated, which not only increases the surface lipid layer, but might also lead to redistribution of fat, resulting in an increase in overall lipid content in the samples. The changes in muscle tissue structure during the roasting process, such as denaturation and aggregation of proteins, especially myofibrillar proteins and collagen, led to the tightening of the structure of the dried meat, which led to the release of lipids from the muscle fibers, and further affected the distribution and content of lipids. The air fryer treatment yielded a dried pork product with a significant reduction in lipid content. The main reason for this comes from the fact that the hot air circulation technology of the air fryer effectively separates the water and fat in the meat, while TAG and phospholipids were more prone to thermal decomposition and oxidation, generating volatile fatty acids, aldehydes, and ketones. Air fryer could significantly accelerate the decomposition and volatilisation of fat due to its high temperature and hot air circulation function, thus significantly reducing the fat content in the finished product[3]. Ferreira et al.[40] investigated air fryer processing of sardines and found that air fryer processed meat products had faster lipid degradation and more volatiles production, resulting in lower lipid content. This was consistent with the results of the present study, suggesting that the efficient heating and lipid oxidizing effects of the air fryer were the main reasons for the reduction in lipids. This cooking method not only changed the chemical and physical properties of lipids and reduced the fat content, but also enhanced the overall acceptability of the food by improving its texture and appearance.

3.3.3 *Multivariate statistical analysis of the lipid content of dried pork slice at the processing*

The PCA score plot (Figure 4C) shows that the variance explained by the first two principal components (PC1 and PC2) was 45.3% and 17.9%, respectively. The plot showed that the distributions of PCs did not overlap, indicating that the lipids of the samples at the four processing stages of dried pork slice were different from each other, where the distributions of groups S and F were closer to each other, suggesting that the lipids of the two groups had similarities, and that the trend of the lipids tended to be stabilized at the subsequent processing stages. The total variance of the PLS-DA scatter plot was 63.0% (Figure 4D), with 44.2% for component 1, 18.8% for component 2, $R^2 = 0.907$, and $Q^2 = 0.749$. The relatively high values of the Q^2 and R^2 confirmed the strong discriminatory and predictive power of the constructed PLS-DA model for the test samples in this study. The clear separation between the samples observed in the PCA and PLS-DA models for the four stages of dried pork slice processing suggests that the lipid profile of dried pork slice changed during the different processing stages and was strongly influenced by heat treatment.

3.3.4 *Analysis of differential fats in the processing stages of dried pork slice*

The VIP score plot was obtained by PLS-DA, as shown in Figure 4E. The top 20 different lipids were shown in the graph, and the highest scores were mainly for TAG and PC, which significantly influenced the final quality of dried pork slice by the variation of these lipids at different processing stages. TAG (13:1/20:3/20:3) and TAG (12:0/12:0/19:4) were the two lipids with the highest VIP scores, contributing more to groups R and M, might be potential markers for distinguishing raw meat from meat that has been heat-treated. In general, the higher the VIP score, the greater the contribution of lipids to classification. Therefore, in this study, VIP > 1.5 and $P < 0.05$ were used as the criteria to identify differential lipids, resulting in the identification of 38 differential lipids, mainly including GL and GP. To visually compare the relative content of differential lipids in each sample, peak area was used as a measure, followed by systematic cluster analysis. The results were shown in Figure 4F, and most of the 38 identified lipids were clustered into 2 classes. The contents of most of the differential lipids in the first class showed a decreasing trend in the processing stage of dried pork slice at the marinated meat stage, which could be seen in PC (13:0/22:5), TAG (19:1/19:1/19:1), TAG (18:0/18:1/21:1), DGTS (16:3/16:3), TAG (17:1/18:1/18:1), TAG (12:1/21:0/21:0), PC (18:2/20:5), TAG (12:2/19:0/19:0), PE (18:4e/17:2), TAG (17:0/18:2/18:2), TAG (12:0/18:1/18:1), DGTS (18:5/22:6), HexCer/NS (d23:3/12:0), TAG (13:0/19:2/19:2), TAG (12:0/12:0/19:4), and TAG (3:1/20:3/20:3) were the characteristic lipid substances of the raw meat, which was in agreement with the results of VIP scoring plot. The lipid changes in group M were not significant, indicating that the processing treatment at this stage had less effect on the lipids. However, with further heating and drying treatments, significant changes in lipid composition occurred in group S. In particular, the contents of some key lipids such as TAG and PC increased significantly, and the changes in these lipids may be closely related to the generation of flavor. The changes in the lipid profile of group F were more significant, with the highest levels of class II lipids, DGTS (27:0/20:1), HexCer/NS (d18:3/30:0), Cer/NS (d18:1/22:0), DGTS (26:1/26:4), PEtOH (17:1/17:1), DGTS (11:0/ 26:1), PC (14:0e/24:0), PC (20:4/22:6), DGTS (27:0/18:1), DGTS (27:0/13:1), DGTS (24:0/27:0), DGTS (27:0/22:3), DGTS (27:0/22:4), DGTS (18:0/18:0) TAG (18:4/19:0/20:6), TAG

(15:3/20:5/22:0), DGTS (22:1/26:2), TAG (17:2/20:0/20:6), DGTS (27:0/19:1), DGTS (27:0/22:6), and TAG (16:0/18:5/21:3) were all higher than the other three groups, while the other lipids were significantly reduced, probably due to lipid degradation or transformation caused by heat treatment and oxidation. At the finished product stage, TAG levels increased significantly during the processing of dried pork slice, likely due to the concentration of lipids as a resulting from moisture loss during drying. In this study, the results were consistent with the study of Yang et al.[41] on ham processing, where the TAG increased with processing time during the late processing period. The results of the present study were consistent with those found by Cao et al.[42] in their study of lipid degradation during the processing of air-dried camel jerky, which revealed that the degradation of both TAG and PG significantly affected the production of flavor compounds, thereby enhancing the sensory properties of the product. Similarly, it was shown that dried pork slice underwent a complex lipid metabolism during processing, and the changes in lipids not only affected the lipid composition of the final product, but also had a significant impact on its flavor and texture.

3.4 Correlation analysis of VOCs and differential lipids in pork preserved meat

In this study, correlation analyses revealed the relationships between 19 major volatile flavor compounds and 38 differential lipids screened by lipidomics during the processing of dried pork slice. The results showed significant positive and negative correlations between different lipids and specific volatile compounds (Figure 5). Ethyl 2-hydroxypropanoate-D, ethyl 2-hydroxypropanoate-M and 1-butanol, 3-methyl-, acetate-D were negatively correlated with 38 lipids. 1-Butanoic acid-M, 2-butanone, 3-hydroxy-D, acetic acid, 1,2-propanediol-M, propanoic acid-M, 2-propanone and ethanol a total of 7 VOCs were positively correlated with most of the TAG, PE classes and with the most DGTS, PC classes were negatively correlated. Interestingly, 2,5-dimethylpyrazine-M, butanal, 2-methylpyrazine, propanal, 1-propanol, 2-methyl-D, (*Z*)-2-pentenal, butanoic acid ethyl ester, 1-butanol, 3-methyl-D, acetic acid ethyl ester, a total of 9 VOCs were negatively correlated with most of the TAG and PE classes and positively correlated with most of the DGTS and PC classes. During processing, TAG may generate short-chain fatty acids and compounds such as ketones and aldehydes through oxidation or esterification reactions, resulting in the characteristic flavor of dried pork slice. This was similar to the findings of Guo et al.[43] in the processing of air-dried lamb shanks from Xinjiang, where triglyceride degradation during lipid oxidation was an important pathway for the generation of key volatile flavor substances (e.g., aldehydes, ketones, and short-chain fatty acids), and these compounds made a significant contribution to the flavor profiles of the products. Furthermore, correlation analysis between different lipids and odor of sturgeon surimi by Xu et al.[44] also showed that glycerophospholipid oxidation contributes to flavor formation. Therefore, different lipids might play a dominant role in the formation of key volatile compounds during the processing of dried pork slice. Ethyl 2-hydroxypropanoate-D, ethyl 2-hydroxypropanoate-M, and 1-butanol,3-methyl-,acetate-D

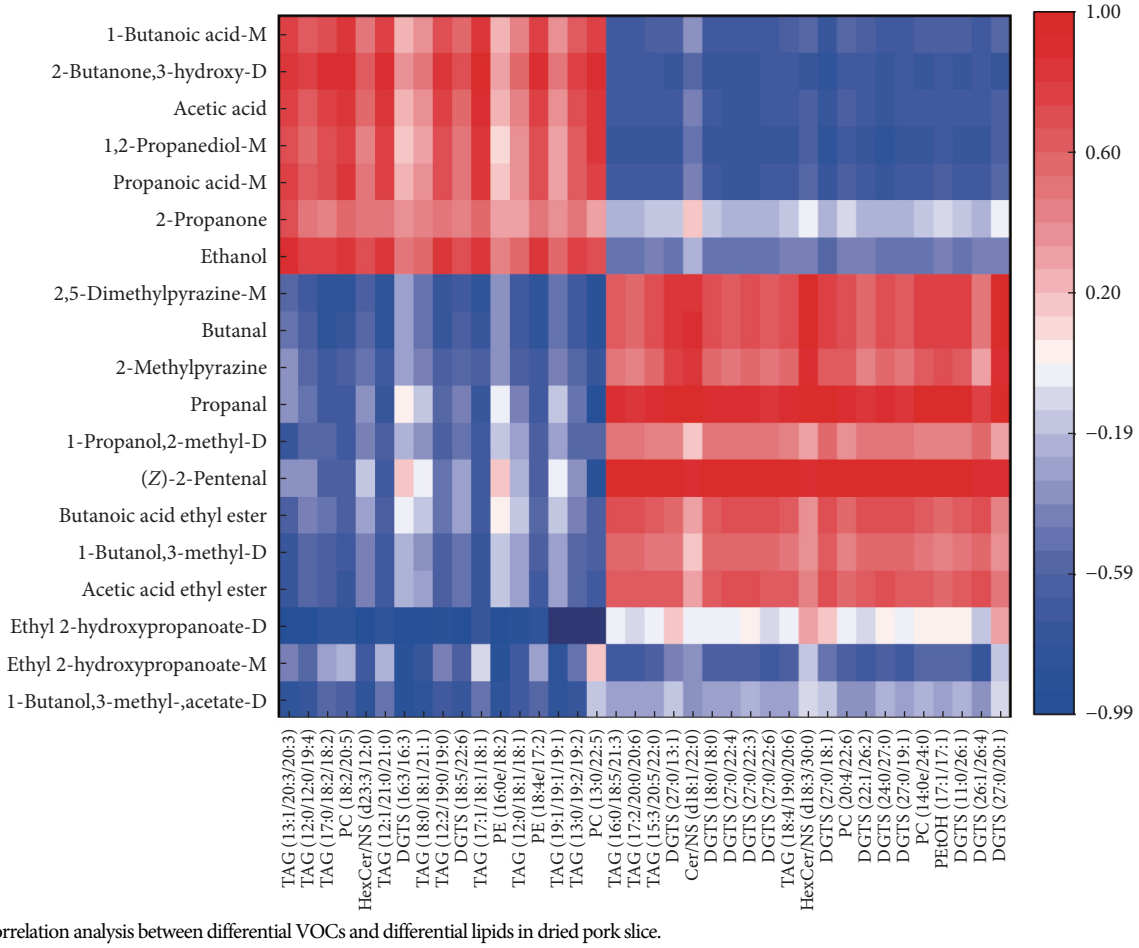

Figure 5 Correlation analysis between differential VOCs and differential lipids in dried pork slice.

showed negative correlation with 38 differential lipids. It indicated that as the lipid content decreased, the content of these volatile compounds increased. It was possible that the processing conditions (e.g., temperature, processing method) of the lipids had an effect on the degradation rate of the lipids and the generation of volatile compounds, and that the lipids were more easily degraded into small molecule compounds. This was similar to the findings of Cheng et al.[45] where lipids were involved in Strecker degradation in the Maillard reaction during heating of roasted lamb, thus showing a negative correlation. Therefore, it was possible to control these conditions thereby optimizing flavor generation.

4 Conclusion

In this study, the VOCs and lipid composition of dried pork processed in an air fryer were determined based on E-nose, GC-IMS, and lipidomics analyses. E-nose analysis showed that the main components of the odor during the processing of dried pork were alcohols, some aromatic compounds and sulphur compounds. GC-IMS detected 61 VOCs, which could be classified into 8 groups, with the highest content of alcohols and esters. 19 VOCs with VIP > 1 were screened according to the PLS-DA model. Lipidomics analysis identified 26 subclasses and 780 lipids, and the lipids with the highest number of species were GL and GP. The 38 key lipids, mainly TAG, PC, and DGTS, were screened with VIP > 1.5, $P < 0.05$ as the screening condition. Correlation analysis showed that ethyl 2-hydroxypropionate-D, ethyl 2-hydroxypropionate-M, and 1-butanol,3-methyl-,acetate-D were negatively correlated with the 38 differential lipids, and the remaining 16 VOCs were positively and negatively correlated with the 38 differential lipids. The air fryer treatment accelerated lipid degradation and accumulation of flavor compounds at the finished product stage, which significantly enhanced the flavor quality of dried pork slice. This study revealed the evolution of flavor during air fryer processing, which provides a reference for further optimizing the processing technology to enhance the flavor and quality of dried pork slice.

Conflict of interest

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

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Authors contribution

Shuangmin Liang: Investigation, data curation, visualization, writing-original draft. **Huaying Chen**: Resources, formal analysis, writing-original draft. **Xuehai Ge:** Data curation, validation. **Zhiping Xiao**: Data curation. **Jiangping Fan**: Formal analysis. **Zhiqiang Xu**: Methodology. **Chunlian Song**: Supervision. **Changrong Ge**: Project administration, writing-review & editing. **Zhichao Xiao**: Conceptualization, writing-review & editing, funding acquisition, supervision.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.26599/FSAP.2025.9240104.

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