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Research Article

Difference in Quality and Volatile Flavor Compounds of *Zingiber officinale* Roscoe with Different Drying Methods

Jiani Chen, Jinhua Wang, Yonghui Ge, Hongrui Ping, and Wenxuan Liu

School of Food Science and Engineering, Guiyang University, Guiyang 550000, China

Correspondence should be addressed to Jinhua Wang; wangjh963@126.com and Yonghui Ge; skyge@163.com

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In order to study the effect of different drying methods on the quality of ginger (*Zingiber officinale* Roscoe) in Guizhou Province, the study comparatively analyzed the edible quality, functional components, and volatile flavor compounds of dried ginger. The results revealed that vacuum freeze-drying (VFD) was superior to vacuum microwave drying (WAD), hot air drying (HAD), and natural drying (ND) in terms of retaining ginger color change, rehydration rate, flavonoids, and ginger spicy element. The polyphenol retention in VFD ginger was second only to that in WAD ginger. A total of 86 volatile flavor compounds were detected in fresh ginger and all four drying samples. Ester and aldehyde compounds were identified as the main flavor components in dried ginger, with variations observed among the different drying methods. Principal component analysis (PCA) and the nearest neighbor algorithm successfully distinguished the ginger samples treated with different drying methods. The aroma activity value (OAV) was calculated based on the threshold, and 12 volatile flavor compounds with OAV ≥1 were identified as the key aroma components of ginger. The aroma profiles of ginger were generally similar across the four different drying methods, among which WAD ginger exhibited distinct flavor characteristics associated with drying. This study employed physicochemical properties, active components, and GC-IMS to evaluate the effect of different drying methods on ginger, providing valuable insights for the processing and flavor quality control of drying ginger.

1. Introduction

Ginger (*Zingiber officinale* Roscoe), belonging to the genus *Zingiber*, is commonly known as spicy cloud or indixin. It is a valuable plant with both medicinal and edible uses. The dried ginger, ginger slices, and ginger leaves are commonly used in traditional medicines [1, 2]. Ginger is a rich source of essential nutrients such as vitamins, proteins, and minerals [3]. Moreover, it contains various bioactive compounds including curcumin, polysaccharides, gingerols, flavonoids, and ginger essential oil, which contribute to its diverse pharmacological effects such as antibacterial, anti-inflammatory, and lipid-lowering properties [4–6]. China is the second-largest producer of ginger globally, accounting for approximately 28% of the total ginger cultivation. Ginger varieties in China are mainly classified into two categories: big seed ginger and small seed ginger. Small seed ginger, also known as Xiao Huang ginger, is highly regarded for its small tubers, vibrant color, and strong aroma [7]. Among them, Guizhou small yellow ginger stands out as a prominent variety in the market.

Fresh ginger has a high moisture content, making it susceptible to spoilage during storage [8]. Therefore, drying technology for ginger has become a common prestorage treatment method and a focal point of research. Muthukumar et al.'s [9] research showed that drying temperature has an impact on drying characteristics and quality aspects of black ginger dried in an electric dryer, and the increase of drying temperature could improve the product quality of black ginger. Nazmi and Ahmet [10] investigated the effects of convection and microwave drying methods from the perspectives of drying characteristics, color, rehydration, and microstructural properties of ginger, whose result showed that the rehydration rate of ginger was highest and the quality was optimal at 60°C. Gingerol in ginger spicy element, a nonvolatile pungent compound, is the most abundant bioactive substance in ginger, possessing significant nutritional and medicinal value [11, 12].

Several studies have shown that gingerol has the ability to inhibit lipid oxidation [13], exhibit neuroprotective effects [14], and promote blood circulation [15]. Jung et al. [16] studied the heat-induced conversion of gingerols to shogaols, which were found to be affected by the heating type and sample type, and moist heat treatment at a higher temperature for the preset time is advantageous to obtain the ginger products with high quantity of bioactive components of shogaols.

The evaluation of the edibility and functional quality of ginger also considers the presence of volatile components, which are commonly analyzed using gas chromatography-mass spectrometry (GC-MS) [17–19]. However, gas chromatography-ion mobility spectrometry (GC-IMS) has emerged as a promising technology for food analysis and quality testing. GC-IMS utilizes gas phase separation for analysis and offers advantages such as lower detection limits (the detection limit can be as low as ppbv level), higher speed, greater sensitivity, and easier operation compared to other detection methods [20]. In a study by Yu et al. [20], the consequence of drying methods on the volatile differences of dried citrus peel as it is affected by cultivars was analyzed on GC-MS and GC-IMS. The results showed that there were significant differences in the volatile components of different samples, suggesting that sun-drying was the best drying method of preserving total volatiles in dried citrus peel. Bai et al. [21] used GC-IMS to detect the difference of volatile compounds in ginger before and after drying during hot air drying, and the results showed that the alterations of ginger volatile compounds were intimately related to moisture diffusion during drying.

In summary, existing literature predominantly focuses on the effects of drying methods on ginger and drying quality, with limited reports on the impact of drying methods on the volatile flavor substances of Guizhou ginger. Therefore, this experiment aims to evaluate the effects of four different drying methods (vacuum freezing, vacuum microwave, hot air, and natural drying) on the quality and volatile flavor substances of Guizhou ginger, as well as to promote the healthy growth of the ginger industry in Guizhou.

2. Materials and Methods

2.1. Materials and Reagents. The samples of ginger (*Zingiber officinale* Roscoe) used in the experiment were collected in Zhenning County (longitude E 26.08, latitude N 105.74), Anshun City, Guizhou Province, China, in May 2022, and were identified as Xiao Huang ginger by Deng Chaoyi, a senior researcher of Guizhou Qianxinan Prefecture Agricultural and Forestry Research Institute.

2.2. Drying Methods. Fresh ginger, free from decay, disease loss, and sprouting, was carefully selected and prepared by washing, peeling, and cutting into slices of 3-4 mm thickness. The ginger slices, weighing 500 g, were subjected to four different drying methods: vacuum freeze-drying (VFD), vacuum microwave drying (WAD), hot air drying (HAD), and natural drying (ND). The drying parameters were determined based on pre-experiments, following the method outlined by Lv et al. [22] with slight modifications, to achieve a moisture content of less than 8% in the dried product, indicating the completion of the drying process. Each drying method was performed in triplicate.

For the VFD method, the fresh ginger slices were prefrozen in a tray and evenly placed in a refrigerator set at −80°C for 24 hours. Subsequently, the prefrozen ginger slices were transferred to a LC-12N-50A vacuum freeze dryer (Shanghai Lichen Bonsey Instrument Technology Co., Ltd.) with the cold hydrazine temperature lowered to −50°C. The cold trap temperature was maintained at −60°C throughout the drying process, with a vacuum level of 2.0 Pa. The total drying time for VFD was 48 hours.

In terms of the WAD method, the fresh ginger slices were evenly spread on a material tray inside a WBZ-16 microwave drying vacuum (Guiyang Xinqi Microwave Industry Co., Ltd.). The microwave power was set at 500 w, with a drying interval of 2 minutes every 5 minutes. The vacuum level was maintained at 0.06 MPa, and the drying temperature ranged between 40 and 45°C. The total drying time for WAD was 2.5 hours.

For the HAD method, the fresh ginger slices were evenly placed in a tray inside a 101-2 electric blast dryer (Tianjin Teste Instruments Co., Ltd.). The electric blast dryer was set at a constant temperature of 50°C, and the drying process lasted for 36 hours.

As for the ND method, the fresh ginger slices were laid flatly on a material tray and naturally dried at room temperature in a sunny indoors window. The total drying time for ND was 168 hours.

2.3. Quality Changes of Ginger

2.3.1. Browning Degree of Ginger. According to reference [23] and modification, ginger powder was homogenized with distilled water at 0~4°C at a material-liquid ratio of 1 : 4 for 2 min, centrifuged at 4000 r/min for 5 min, and the absorbance value of the supernatant was measured at 410 nm using an enzyme-labeled instrument (Multiskan Sky Full wavelength microplate reader, Thermo, USA)

2.3.2. Color Variation of Ginger. The colorimeter (CR-10 colorimeter, Konica Minolta Ltd., China) was used to assess the color variation between freeze-dried ginger and fresh ginger. $\triangle E$ indicates the color difference value. The measured parameters include brightness, represented by value L; red-green hue, represented by degree a; and yellow-blue hue, represented by degree b. The subscript 0 (L_0, a_0 and b_0) denote the measurements for fresh ginger, while the superscript asterisk (L^*, a^*, and b^*) indicates the measurements for freeze-dried ginger.

$$\Delta E = \sqrt{\left(L^* - L0\right)^2 + \left(a^* - a0\right)^2 + \left(b^* - b0\right)^2}. \tag{1}$$

2.3.3. Determination of Rehydration Rate of Different Dried Ginger. According to the industry standard SN/T 0230.2016, in each group, about 5 g of dried ginger slices were prepared (sample mass m_1 before rehydration), placed in 250 mL, 95°C constant temperature water, soaked for 10 min, and then pulled out. Filter paper was used to absorb the surface water of ginger slices and then mass was weighed (sample mass m_2 after rehydration). The rehydration ratio is calculated as

$$R = \frac{m2}{m1}. \tag{2}$$

2.3.4. Determination of the Main Active Ingredients of Ginger. According to previous studies, polyphenol content determination was performed. Folin–Ciocalteu colorimetric method [24, 25] was used as reference, and the standard curve was drawn with gallic acid as the standard. The linear equation $Y = 0.0506X + 0.1028$, $R2 = 0.9948$ was obtained, and the total phenolic content was expressed as gallic acid equivalent (mg/g).

According to a previous study, in terms of determination of flavonoid content, the sodium nitrite and aluminum nitrate color development method [26] was used to draw the standard curve with rutin as the standard. The linear equation $Y = 4.5308X - 0.0144$, $R2 = 0.9998$ was obtained, and the total flavonoid content was expressed as rutin equivalent (mg/g).

According to a previous study, in terms of determination of ginger spicy element content, the vanillin method [27] was used to draw the standard curve with vanillin as the standard. The linear equation $Y = 0.0726X - 0.1933$, $R2 = 0.998$ was obtained, and the ginger spicy element content was expressed as vanillin equivalent (mg/g) × 2.003 (the conversion factor between vanillin and ginger spicy element).

2.3.5. Hardness Determination of Ginger Treated with Different Drying Methods. The method described in reference [28] was modified to determine the hardness of the samples on a texture analyzer (TA.XTplus Texture Analyser, Stable Micro Systems, GBR). The adapted probe P/2 was selected to pierce the ginger slices, and the speed was set to 3 mm/s firstly, 1 mm/s during, and 3 mm/s after the test with a compression distance of 1 mm. 10 measurements were performed on the samples obtained with different drying methods, and the average value was recorded.

2.3.6. Microstructure Determination. The samples were plated with gold spray and fixed on a short column of a scanning electron microscope at an accelerating voltage of 15 kv, and the microstructure was observed and photographed on a scanning electron microscope.

2.4. GC-IMS Analysis Conditions. The sample was smashed, 0.1 g of dried sample was taken, and 1 g of fresh ginger was sampled and placed in a 20 mL headspace vial with 50 μl of internal standard 100 ppm 2-octanol, and the incubation temperature was 60°C. The incubation time had been 20 min. The incubation speed was 500 rpm. Headspace injection (FlavourSpec® GC-IMS flavor analyzer, G.A.S., Germany) conditions were as follows. The headspace injection needle temperature was 85°C. The injection volume was 500 μl. Column type was polyethylene glycol (30 m × 0.53 mm, 1 μm, RESTEK, USA). The column temperature was 60°C. The analysis time had been 50 min. Carrier gas/drift gas was high-purity nitrogen (purity ≥99.999%). The drift gas flow rate was always maintained at 150 mL/min. The initial carrier gas flow rate was 2.0 mL/min. The initial carrier gas flow rate of 2.0 mL/min had been maintained for 2 min, and the carrier gas flow rate increased to 10 mL/min from 2 to 10 min, reaching 100 mL/min from 10 to 50 min. The IMS detector temperature was 45°C.

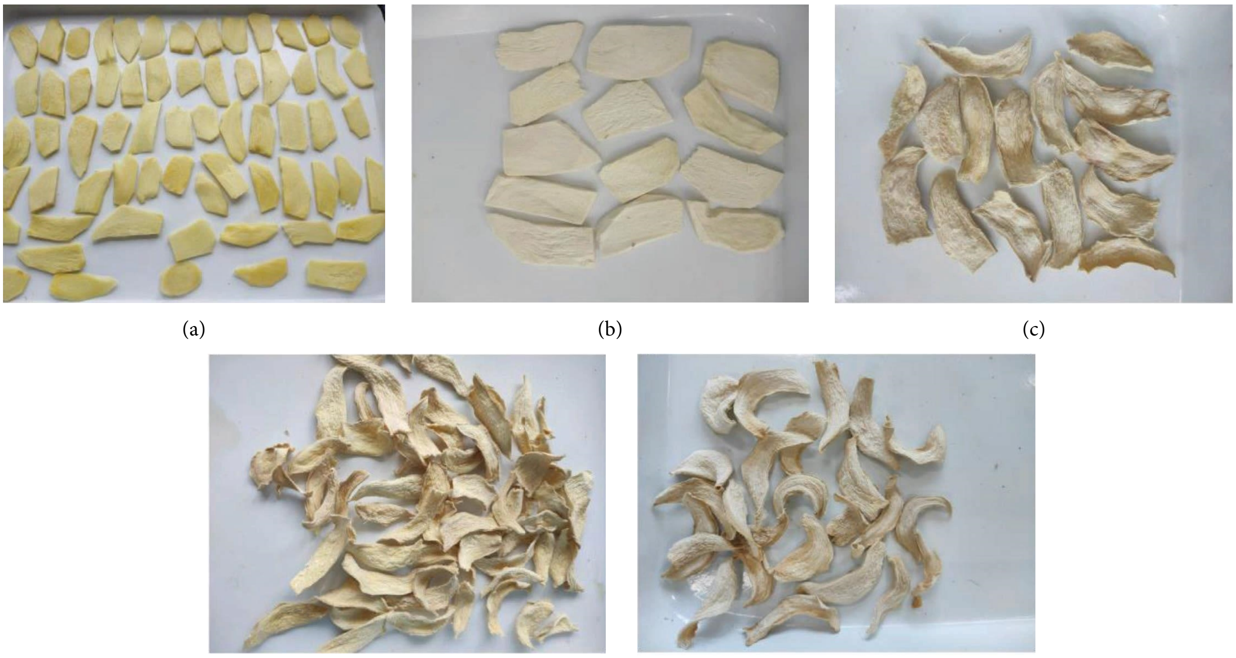
2.5. Evaluation of Odor Activity Value. The flavor contribution of each volatile flavor substance was evaluated by using odor activity value (OAV) [29] (C is the concentration of the volatile flavor substance to be measured (μg/g); T is the threshold value of the substance in air [30] (μg/g)). The following formula is used:

$$OAV = \frac{C}{T}. \tag{3}$$

2.6. Data Processing. Volatile flavor substances were analyzed and plotted on the analysis software configured for the GC-IMS instrument, VOCal was used for qualitative and quantitative analysis of spectra and data, and the application software's built-in NIST database and IMS database allow qualitative analysis of volatiles, and Reporter and Gallery Plot plug-ins were used to construct fingerprint and difference spectra of sample volatiles. Dynamic PCA plug-in and GraphPad (version 9.0) were mainly used for dynamic principal component analysis. Significance and correlation analysis was performed on SPSS (version 26.0). OriginPro 2021 was used for graphing and analysis of experimental data.

3. Results and Discussion

3.1. Effect of Different Drying Methods on Physicochemical Properties and Active Ingredients of Ginger. The results of quality analysis of ginger treated with different drying methods are presented in Figure 1 and Table 1. From the graphs, it was evident that the appearance of ginger treated with four different drying methods differed significantly from that of fresh ginger (Figure 1(a)), which had a white appearance. HAD ginger (Figure 1(d)) and ND ginger (Figure 1(e)) exhibited severe browning, noticeable wrinkling, and a hard texture, with the lowest retention of ginger polyphenols and ginger spicy element. However, ND ginger had a higher flavonoid content, possibly due to the disruption of enzyme and substrate distribution during drying with the other three methods. This disruption leads to the oxidation or polymerization of some flavonoids, resulting in higher flavonoid loss [31]. WAD ginger (Figure 1(c)) appeared lightly crumpled with a crunchy texture and retained the highest flavonoid content, as well as a higher retention of polyphenols and ginger spicy element. VFD ginger (Figure 1(b)) had a porous sponge-like structure,



(a) (b) (c)

(d) (e)

Figure 1: Changes of appearance of *Zingiber officinale* Roscoe treated with different drying methods.

Table 1: Drying results of *Zingiber officinale* Roscoe treated with different drying methods.

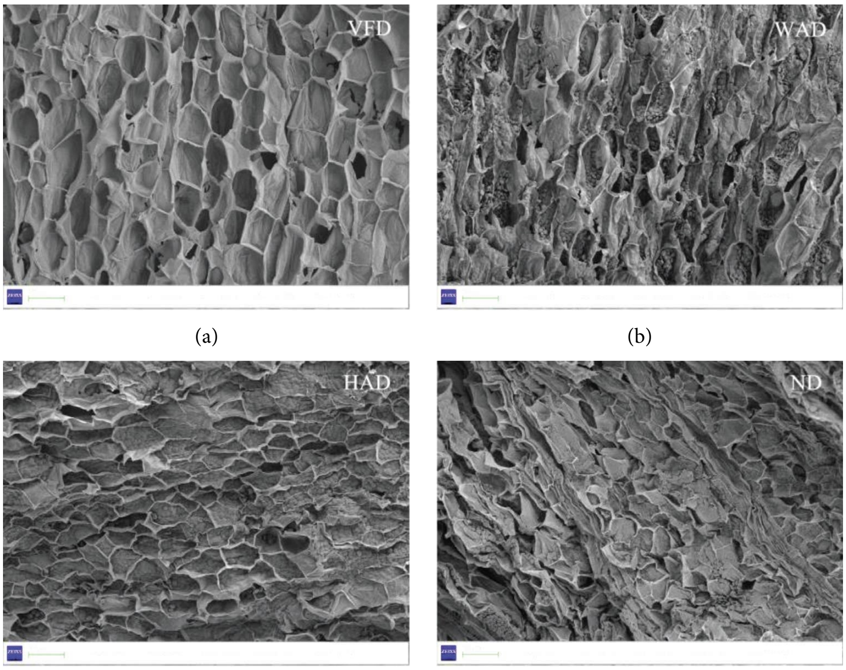
Group	Fresh ginger	VFD	WAD	HAD	ND
Browning degree	0.19 ± 0.01d	0.83 ± 0.04c	1.04 ± 0.07b	1.42 ± 0.06a	1.44 ± 0.06a
Color deviation $\triangle E$	—	9.26 ± 0.85d	15.04 ± 1.18c	16.03 ± 1.12b	21.22 ± 1.04a
Rehydration rate (%)	—	573.63 ± 2.57a	365.12 ± 1.13b	364.03 ± 2.24b	339.12 ± 0.61c
Polyphenol (mg/g)	10.63 ± 0.48a	9.61 ± 0.44c	10.25 ± 0.19b	8.93 ± 0.13d	9.21 ± 0.14d
Flavonoid (mg/g)	29.90 ± 1.07a	25.39 ± 1.55b	21.23 ± 0.55d	20.95 ± 0.61d	24.50 ± 0.68c
Ginger spicy element (mg/g)	11.68 ± 0.06a	10.98 ± 0.16b	9.61 ± 0.07c	9.43 ± 0.11d	9.20 ± 0.02e
Hardness (g)	—	791.38 ± 42.00d	1283.88 ± 248.61b	1494.66 ± 319.71b	1759.01 ± 303.06a

The above active ingredient contents were calculated based on the water content of ginger in different drying methods converted to dry matter; different letters indicate significant differences ($P < 0.05$).

which allows for quicker restoration of its original properties upon rehydration, with a significantly higher rehydration rate compared to other drying methods.

3.2. Comparison of Microstructure of Ginger Treated with Different Drying Methods. SEM images of ginger treated with different drying methods are shown in Figure 2. Combined with the hardness evaluation in Table 1, it can be observed that the internal pore size of VFD ginger (Figure 2(a)) is mostly round or oval, with uniform and fluffy pores. The porous and full structure, along with the low relative density, results in a low hardness of ginger (791.38 g). The microstructures of WAD ginger (Figure 2(b)) and HAD ginger (Figure 2(c)) both exhibit varying degrees of collapse, with significantly contracted internal pore sizes compared to VFD ginger. The pores in WAD and HAD ginger are numerous and disorganized. Presumably water leaves the product quickly at high temperatures leading to a more compact structure and higher hardness values of 1283.88 g and 1494.66 g, respectively. ND ginger has the highest hardness value of 1759.01 g, and its microstructure (Figures 2(d)) shows severe collapse, with visibly atrophied and varied cell pore sizes and numerous dense pores.

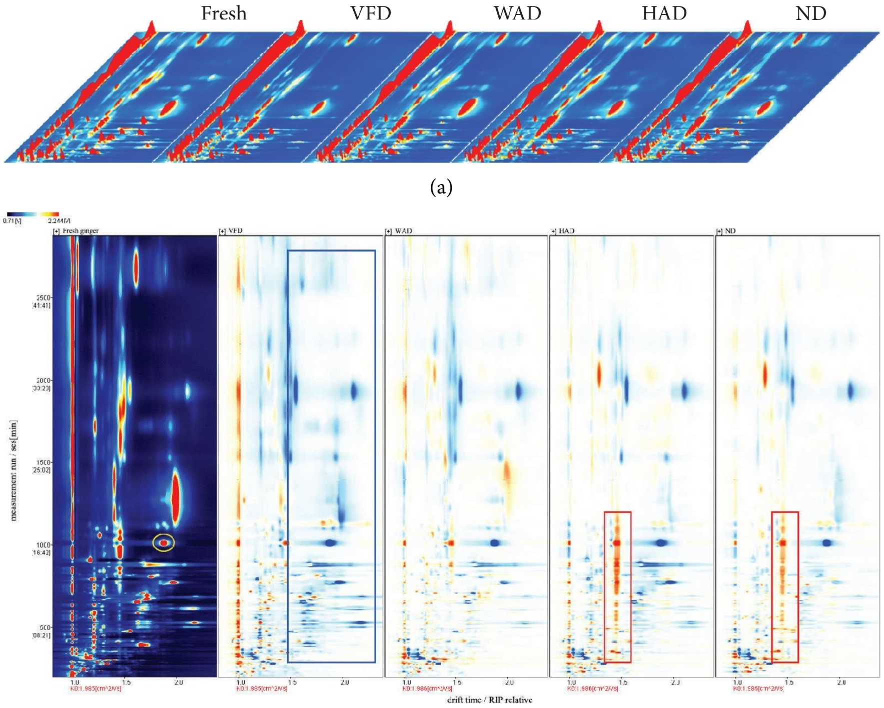
3.3. Qualitative and Quantitative Analysis of Volatile Components of Ginger by Different Drying Methods. The Reporter plug-in program on the LAV analysis software, coupled with the GC-IMS instrument, was used to analyze the volatile flavor substances in ginger treated with five different methods. The spectra of fresh ginger samples were selected as a reference in Figure 3, and the spectra of other drying treatments were subtracted from the signal peaks in the fresh ginger spectra to obtain the GC-IMS difference spectra of ginger treated with different drying methods. The figure shows that there is not much difference in the composition of volatile substances among ginger samples with different treatments. The migration time mostly falls within the range of 1.0–2.0 ms, while the retention time ranges from 250 to



(a) (b)

(c) (d)

Figure 2: Scanning electron microscopic results of *Zingiber officinale* Roscoe treated with different drying methods.



(a)

(b)

Figure 3: Three-dimensional spectrogram of GC-IMS and difference plot of volatile compounds of *Zingiber officinale* Roscoe treated with different drying methods.

1500 s. In the difference spectrum, white indicates that the substance has the same concentration as in fresh ginger, the blue area indicates a lower concentration in the sample compared to fresh ginger, and the red area indicates a higher concentration. The darker the color, the greater the variation in substance content. For instance, the volatile substance

2-nonanone, located in the yellow round box area, exhibits considerable variation in content, with the highest concentration in fresh ginger and relatively low concentrations in WAD and ND ginger.

Based on the retention and migration times of volatile flavor substances in ginger treated with different methods, qualitative analysis of these substances was performed using two databases, NIST and IMS, in the application software. As shown in Figure 4 and Table 2, the same types of volatile substances were detected in all five ginger samples, with a total of 98 volatile substances identified. Among them, 85 were detected qualitatively, including 24 terpenes, 21 aldehydes, 13 ketones, 11 alcohols, 11 esters, 2 ethers, 2 pyrazines, and 1 aromatic hydrocarbon substance. The presence of multiple signal peaks for some compounds may be attributed to different product ions produced by volatile substances depending on their concentration during analysis [32], resulting in the simultaneous detection of monomers, dimers, and trimers of the same compound. 2-Octanol was used as an internal standard to calculate the differences in the content and proportion of volatile flavor substances in ginger treated with different methods. Table 2 and Figure 5 reveal that the main volatile flavor substances in ginger with different treatments are esters, terpenes, aldehydes, ketones, and alcohols. The content of esters and aldehydes significantly increases after drying fresh ginger, with ester content increasing due to esterification reactions between alcohols and carboxylic acids during drying [33]. The increase in aldehydes can be attributed to the decomposition or oxidation of other compounds at high temperatures [34, 35]. The content of alcohols, terpenes, and ketones decreases in fresh ginger after drying. The decrease in alcohols may be due to the low boiling point of some small molecular alcohols, resulting in less volatility at higher drying temperatures. Terpenes and ketones have active chemical properties. Among them, terpenes are hydrocarbons with relatively strong atmospheric reactivity, which are prone to form particulate aerosols during the drying process, resulting in reduced contents.

3.4. Fingerprint Analysis of Ginger Treated with Different Drying Methods by GC-IMS. The GC-IMS fingerprint profiles of ginger with different treatments were constructed using the Gallery Plot plug-in in LAV software. This analysis provided a deeper understanding of the changes in volatile components of ginger treated with different drying methods. The results are presented in Table 2 and Figure 6. Each treatment of ginger had three parallel samples, with each row representing the signal peaks selected from one sample, and each column representing the signal peaks of the same VOC in different samples. This information provided a comprehensive view of the volatiles present in different treatments of ginger, as well as the differences between the dried ginger samples.

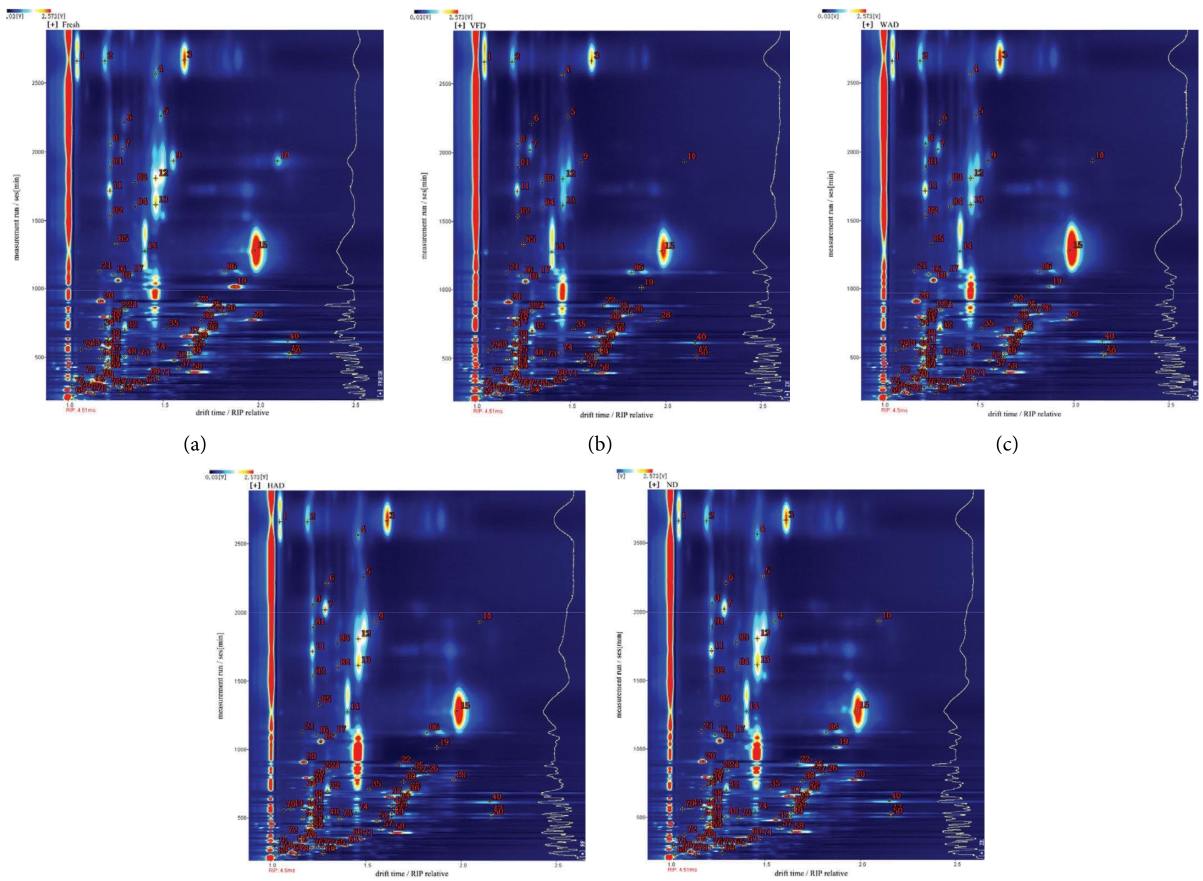
Table 2 and Figure 6 demonstrated significant differences in the composition of volatile substances in ginger with different treatments. The concentration of volatile substances in region A was highest in fresh ginger and decreased after drying. Some of the volatile substances in this region included 2-decenal, (E)-2-octenal, (E)-2-heptenal, (E)-2-hexenal, acrolein, 2-methylpropanal, 2-undecanone, 2-nonanone, 6-methyl-5-hepten-2-one, 2-heptanone, 2-but anone, trimethylpyrazine, 4-methyl-1-pentanol, 1-butanol, ethanol, terpinolene, beta-ocimene, beta-pinene, (−)-beta-pinene, camphene, 3-carene, alpha-pinene, pentyl butanoate, ethyl acetate, 2,3-pentanedione, and more.

The concentration of volatile substances in region B was higher than that in vacuum freeze-dried (VFD) ginger. It included substances like 2-octanone, (E)-beta-ocimene, 1,8-cineole, 1,4-cineole, and diethyl acetal. Under vacuum conditions, water evaporated directly into the gaseous state during ginger drying, which might have led to the release of these volatile substances due to cell rupture.

The concentration of volatile substances in region D was higher in vacuum microwave drying (WAD) ginger. It included substances like myrcene, alpha-thujene, alpha-terpineol, terpinen-4-ol, tetrahydro-linalool, and others. The increase in myrcene could be due to the thermal decomposition of beta-pinene during the drying process. The volatile substances in region were the characteristic flavor substances of high-temperature air drying (HAD) ginger. They included 2-methyl-1-propanol, linalool, propyl acetate, pentanal, acetone, and others. The increase in the content of propyl acetate and linalool was particularly significant. The rise in propyl acetate might be attributed to the oxidation or cleavage of unsaturated fatty acids in ginger under high temperature and aerobic conditions [36]. The increase in linalool might be a result of the longer drying time of HAD compared to WAD, leading to further reactions of myrcene to produce linalool.

Region G represented the unique volatile components in natural drying (ND) ginger, with higher content compared to other drying methods. It included substances like diethyl succinate, (E, E)-alpha-farnesene, beta-elemene, junipene, hexanal, (E)-2-pentenal, methacrolein, butanal, propanal, acetaldehyde, 1-penten-3-one, 4-methyl-3-penten-2-one, 3-octanone, p-xylene, 3-sec-butyl-2-methoxypyrazine, and more. Beta-elemene, in particular, belonged to pungent substances with antitumor and anti-inflammatory effects [37]. Butanal, propanal, and acetaldehyde had strong odors at high concentrations. Because the natural drying (ND) ginger temperature is lower, beta-elemene in ginger can be preserved better. (E,E)-alpha-farnesene and diethyl succinate in ginger were due to lower drying temperatures but longer drying times, resulting in the generation of substances with strong odors such as butanal, propanal, and acetaldehyde.

Region C showed relatively stable changes in the content of volatile substances during ginger drying. Several substances, including citral, phenylethyl 2-methylpropanoate, alpha-terpinene and alpha-phellandrene were detected in all five samples. This indicates that drying had less effect on the main flavor substances of ginger. The concentration of volatiles in region E, including ethyl butanoate and citronellyl formate, was higher than that in fresh ginger. This could be attributed to the increase in temperature during drying, which favors the formation of esters.



(a) (b) (c) (d) (e)

FIGURE 4: Location points of characteristic peaks of volatile substances in *Zingiber officinale* Roscoe treated with different drying methods.

3.5. Cluster Analysis of Ginger Treated with Different Drying Methods. The principal component analysis (PCA) results are presented in Figure 7. The 1st principal component (PC1) contributed 43%, the 2nd principal component (PC2) contributed 23%, and the cumulative contribution of the first 2 principal components was 66%. The ginger samples treated with different drying methods were clearly separated in the figure, with fresh ginger samples grouped on the left and ginger samples with different drying methods on the right. Fresh ginger and VFD ginger showed the greatest difference and were furthest apart, with fresh ginger being closer to WAD ginger, HAD ginger, and ND ginger, which means they had similar flavors. The differences between the different treatments of ginger mainly stem from the contribution of different volatile flavor substances, with fresh ginger having a richer flavor component compared to dried ginger.

By calculating the Euclidean distance between each pair of samples, we obtained the nearest neighbor-Euclidean distance plots for ginger samples treated with different drying methods. The results, shown in Figure 8, indicated that the five different treatments of ginger could be clearly distinguished. Notably, ND ginger and HAD ginger had the closest distance and highest similarity, which could be attributed to the similar principles underlying these two drying methods. The flavor of ginger became more similar after drying, likely due to the increase in hexanal, p-xylene and diethyl succinate resulting from these two drying methods. This demonstrated that the nearest neighbor-Euclidean distance plot aligned with the results of PCA analysis.

3.6. Analysis of Characteristic Aroma Substances in Ginger Treated with Different Drying Methods. OAV is often used to evaluate the contribution of volatile compounds [38]. To determine the contribution of each volatile flavor substance to the overall flavor characteristics of ginger, we calculated the odor activity value (OAV). By referring to Table 2, we identified volatile substances with OAV >1. Twelve volatile substances with significant aroma characteristics in ginger were retained for aroma characterization. As depicted in Figure 8 and Table 2, there were noticeable differences in the aroma profiles of ginger treated with different treatments, in which there were five main aroma components, namely, grassy aroma contributed by 2-decenal and (E, Z)-2,6-nonadienal, nutty aroma contributed by 2-methylpropanal and 3-methylbutanal, fruity aroma contributed by 2-undecanone, 2-nonanone, citral, and rthyl butanoate, pungent aroma contributed by 2-heptanone and cineole, and creamy aroma contributed by diacetyl.

Table 2: Qualitative and quantitative analysis of characteristic flavor substance of *Zingiber officinale* Roscoe treated with different drying methods.

Count	Compound	CAS#	Formula	MW	RI	Rt (sec)	Dt (RIPrel)	Aroma description	Odor thresholds (μg/g)	Content (μg/g)					OAV				
										Fresh ginger	VFD	WAD	HAD	ND	Fresh ginger	VFD	WAD	HAD	ND
Terpenes																			
4	(E,E)-alpha-farnesene	C502614	$C_{15}H_{24}$	204.4	1823.5	2564.692	1.46182	Fruit aroma	—	17.22 ± 4.10a	3.79 ± 0.59c	11.61 ± 0.36b	13.45 ± 0.04ab	14.60 ± 1.12ab	—	—	—	—	—
12	Junipene	C475207	$C_{15}H_{24}$	204.4	1661.9	1806.031	1.46174	Timber aroma	—	33.13 ± 8.27a	10.62 ± 0.39b	26.60 ± 1.74a	26.09 ± 0.19a	27.76 ± 1.03a	—	—	—	—	—
13	Beta-elemene	C515139	$C_{15}H_{24}$	204.4	1609.9	1613.493	1.46174	Fennel aroma (pungent aroma)	—	58.42 ± 16.64a	16.14 ± 0.15c	40.21 ± 2.40b	48.96 ± 0.37ab	52.50 ± 2.14ab	—	—	—	—	—
24	Terpinolene (M)	C586629	$C_{10}H_{16}$	136.2	1311.9	845	1.30409	Timber aroma	200	2.69 ± 0.41a	1.33 ± 0.10b	3.00 ± 0.04a	1.38 ± 0.01b	1.42 ± 0.16b	0.03	0.01	0.03	0.01	0.01
25	Terpinolene (D)	C586629	$C_{10}H_{16}$	136.2	1311.9	845	1.74194			3.54 ± 0.49a	0.86 ± 0.21c	2.77 ± 0.20b	1.29 ± 0.02c	1.45 ± 0.18c					
29	(E)-beta-ocimene	C3779611	$C_{10}H_{16}$	136.2	1279.6	788.988	1.22079	Grassy aroma, timber aroma, fruit aroma	18.7	3.89 ± 0.63b	2.37 ± 0.06c	5.40 ± 0.04a	2.84 ± 0.004c	2.71 ± 0.10c	0.21	0.13	0.29	0.15	0.14
30	Gamma-terpinene	C99854	$C_{10}H_{16}$	136.2	1264	764	1.21694	Fruit aroma	1400	3.33 ± 0.55b	1.83 ± 0.24c	4.63 ± 0.25a	1.87 ± 0.01c	1.94 ± 0.09c	<0.01	<0.01	<0.01	<0.01	<0.01
31	Beta-ocimene	C13877913	$C_{10}H_{16}$	136.2	1248	739.013	1.21694	Grassy aroma, flower aroma	—	2.18 ± 0.34a	0.94 ± 0.11c	2.50 ± 0.09a	1.31 ± 0.03bc	1.45 ± 0.21b	—	—	—	—	—
38	Alpha-terpinene	C99865	$C_{10}H_{16}$	136.2	1184	640.915	1.21501	Fruit aroma	2350	4.56 ± 0.84b	2.26 ± 0.05d	5.78 ± 0.18a	3.31 ± 0.02c	3.32 ± 0.38c	<0.01	<0.01	<0.01	<0.01	<0.01
39	Alpha-phellandrene (M)	C99832	$C_{10}H_{16}$	136.2	1172.5	616.854	1.66997	Pepper aroma (pungent aroma)	2900	16.03 ± 3.40ab	7.92 ± 0.18c	18.08 ± 0.18a	14.57 ± 0.07ab	12.76 ± 0.29b	0.01	<0.01	0.01	0.01	0.01
40	Alpha-phellandrene (D)	C99832	$C_{10}H_{16}$	136.2	1172.5	616.854	2.15578			15.25 ± 3.39ab	6.20 ± 0.37c	17.51 ± 0.51a	11.99 ± 0.08b	11.85 ± 0.92b					
41	Myrcene (M)	C123353	$C_{10}H_{16}$	136.2	1160	591.867	1.21886	Fat aroma	130	13.25 ± 2.58a	6.20 ± 0.16c	15.26 ± 0.22a	9.59 ± 0.08b	9.79 ± 0.93b	0.15	0.06	0.18	0.10	0.10
42	Myrcene (D)	C123353	$C_{10}H_{16}$	136.2	1159.5	590.941	1.6372			6.03 ± 1.18a	1.55 ± 0.04c	7.77 ± 1.17a	3.34 ± 0.04bc	3.57 ± 0.85b					
45	Beta-pinene (M)	C127913	$C_{10}H_{16}$	136.2	1127.2	530.824	1.21516	Fat aroma	180	10.66 ± 2.08ab	6.83 ± 0.21c	12.47 ± 0.08a	9.02 ± 0.06b	8.67 ± 0.11bc	0.22	0.07	0.22	0.15	0.14
46	Beta-pinene (D)	C127913	$C_{10}H_{16}$	136.2	1126.9	530.215	1.63683			13.63 ± 2.96ab	5.19 ± 0.80d	16.03 ± 0.31a	11.17 ± 0.09bc	10.32 ± 0.66c					
47	Beta-pinene (T)	C127913	$C_{10}H_{16}$	136.2	1127.2	530.824	2.16111			15.06 ± 3.31a	1.38 ± 0.52d	10.87 ± 0.28b	7.33 ± 0.03c	6.31 ± 1.07c					
48	(−)-Beta-pinene (M)	C18172673	$C_{10}H_{16}$	136.2	1111.6	504.029	1.29912	Fat aroma	2000	3.67 ± 0.78ab	2.17 ± 0.09d	4.36 ± 0.03a	3.12 ± 0.02bc	2.60 ± 0.14cd	0.01	<0.01	0.01	0.01	0.01
49	(−)-Beta-pinene (D)	C18172673	$C_{10}H_{16}$	136.2	1112.3	505.247	1.63683			9.31 ± 1.98ab	4.52 ± 0.25c	10.83 ± 0.24a	8.01 ± 0.30b	7.80 ± 0.34b					
50	(−)-Beta-pinene (T)	C18172673	$C_{10}H_{16}$	136.2	1112.7	505.856	2.16298			9.53 ± 2.10a	1.76 ± 0.46c	8.72 ± 0.38a	5.07 ± 0.06b	5.71 ± 1.04b					
53	Camphene	C79925	$C_{10}H_{16}$	136.2	1091.9	472.972	1.2133	Camphor aroma (pungent aroma)	180	4.61 ± 0.93a	1.31 ± 0.22c	4.82 ± 0.11a	2.62 ± 0.03b	2.90 ± 0.39b	0.03	0.01	0.03	0.01	0.02
55	3-Carene	C13466789	$C_{10}H_{16}$	136.2	1144.4	561.882	1.65922	Fat aroma	9300	1.30 ± 0.25a	0.24 ± 0.03c	1.06 ± 0.06a	0.62 ± 0.02b	0.69 ± 0.10b	<0.01	<0.01	<0.01	<0.01	<0.01
58	Alpha-pinene	C80568	$C_{10}H_{16}$	136.2	1031.7	395.632	1.64242	Grassy aroma, timber aroma	100	27.43 ± 6.01a	10.59 ± 0.71c	28.51 ± 0.50a	20.99 ± 1.01b	20.41 ± 1.36b	0.27	0.11	0.29	0.21	0.20
59	Alpha-thujene	C2867052	$C_{10}H_{16}$	136.2	1041.4	407.202	1.2133	Pungent aroma	—	2.42 ± 0.53b	1.59 ± 0.09c	3.07 ± 0.02a	2.41 ± 0.20b	2.19 ± 0.01b	—	—	—	—	—
36	1,4-Cineole	C470677	$C_{10}H_{18}O$	154.3	1206.3	677.934	1.72009			9.39 ± 2.06ab	6.17 ± 0.50c	10.84 ± 0.10a	8.24 ± 0.07bc	8.12 ± 0.02bc					
Ethers																			
32	1,8-Cineole (M)	C470826	$C_{10}H_{18}O$	154.3	1218.7	695.517	1.30176	Camphor aroma (pungent aroma)	2.67	7.02 ± 1.40b	4.98 ± 0.40c	11.20 ± 0.22a	6.68 ± 0.05b	5.67 ± 0.35bc	9.24	6.20	12.37	7.88	7.56
33	1,8-Cineole (D)	C470826	$C_{10}H_{18}O$	154.3	1218.7	695.517	1.72395			8.26 ± 1.86b	5.39 ± 0.35c	11.00 ± 0.42a	6.11 ± 0.03c	6.40 ± 0.68bc					
Aldehydes																			
1	Citral (M)	C5392405	$C_{10}H_{16}O$	152.2	1839.9	2657.736	1.04996	Lemon fragrant (fruit aroma)	60	64.46 ± 14.25b	41.44 ± 2.68c	80.66 ± 4.52a	58.23 ± 1.68b	54.18 ± 0.42bc	3.33	1.72	4.25	3.01	2.67
2	Citral (D)	C5392405	$C_{10}H_{16}O$	152.2	1839.9	2657.736	1.19565			40.93 ± 8.97b	20.73 ± 1.29c	52.08 ± 0.92a	36.94 ± 0.15b	32.68 ± 0.65b					
3	Citral (T)	C5392405	$C_{10}H_{16}O$	152.2	1841	2663.938	1.61311			94.28 ± 20.85b	40.94 ± 2.81c	121.98 ± 5.32a	84.47 ± 0.55b	73.39 ± 2.78b					
5	2-Decenal	C3913711	$C_{10}H_{18}O$	154.3	1764.7	2257.647	1.48983	Fruit aroma	1	18.74 ± 4.52a	2.19 ± 0.18c	9.79 ± 0.14b	9.57 ± 0.02b	7.49 ± 0.27b	18.74	2.19	9.79	9.57	7.49
17	(E)-2-octenal	C2548870	$C_8H_{14}O$	126.2	1435.2	1104.402	1.33225	Fruit aroma	2.7	2.50 ± 0.40a	0.88 ± 0.05d	2.09 ± 0.05b	1.14 ± 0.01c	1.02 ± 0.005cd	0.93	0.33	0.78	0.52	0.38
23	(E)-2-heptenal	C18829555	$C_7H_{12}O$	112.2	1312.5	846.216	1.26848	Fat aroma, fruit aroma	2800	2.00 ± 0.28a	0.82 ± 0.09b	1.94 ± 0.03a	0.93 ± 0.004b	1.05 ± 0.15b	<0.01	<0.01	<0.01	<0.01	<0.01
26	Octanal	C124130	$C_8H_{16}O$	128.2	1297.8	819.527	1.81841	Fruit aroma	5	2.68 ± 0.44b	0.93 ± 0.01d	3.91 ± 0.35a	1.79 ± 0.01c	1.08 ± 0.41d	0.54	0.19	0.78	0.36	0.22
34	(E)-2-hexenal (M)	C6728263	$C_6H_{10}O$	98.1	1229.5	711.25	1.18031	Grassy aroma	3.1	0.71 ± 0.14a	0.35 ± 0.10bc	0.23 ± 0.02c	0.31 ± 0.004c	0.51 ± 0.06b	0.39	0.14	0.10	0.14	0.23
35	(E)-2-hexenal (D)	C6728263	$C_6H_{10}O$	98.1	1228.9	710.324	1.5196			0.48 ± 0.11a	0.10 ± 0.07b	0.09 ± 0.01b	0.11 ± 0.01b	0.21 ± 0.03b					
43	(E)-2-pentenal	C1576870	C_5H_8O	84.1	1147	566.879	1.10898	Grassy aroma	2700	0.65 ± 0.08d	0.44 ± 0.03e	0.79 ± 0.05c	0.90 ± 0.01b	1.01 ± 0.02a	<0.01	<0.01	<0.01	<0.01	<0.01
52	Hexanal	C66251	$C_6H_{12}O$	100.2	1097.1	480.279	1.56033	Grassy aroma	160	6.20 ± 1.24b	3.54 ± 0.12c	8.60 ± 0.24a	6.68 ± 0.06b	7.31 ± 0.90ab	0.04	0.02	0.05	0.04	0.05
60	Pentanal	C110623	$C_5H_{10}O$	86.1	998.4	358.484	1.4204	Nutty aroma	3090	1.39 ± 0.28b	1.75 ± 0.07b	2.81 ± 0.03a	3.51 ± 0.02a	3.20 ± 0.76a	<0.01	<0.01	<0.01	<0.01	<0.01
63	3-Methylbutanal	C590863	$C_5H_{10}O$	86.1	923.8	302.458	1.39801	Nutty aroma	2	8.62 ± 1.91b	5.31 ± 0.28c	12.24 ± 0.60a	7.72 ± 0.09b	7.14 ± 0.48bc	4.31	2.66	6.12	3.86	3.57
66	Acrolein	C107028	C_3H_4O	56.1	858.4	261.048	1.05657	Pungent aroma	8.3	0.74 ± 0.15a	0.25 ± 0.06b	0.31 ± 0.04b	0.37 ± 0.01b	0.35 ± 0.08b	0.09	0.03	0.04	0.04	0.04

Table 2: Continued.

Count	Compound	CAS#	Formula	MW	RI	Rt (sec)	Dt (RIPrel)	Aroma description	Odor thresholds (μg/g)	Content (μg/g)					OAV				
										Fresh ginger	VFD	WAD	HAD	ND	Fresh ginger	VFD	WAD	HAD	ND
68	2-Methylpropanal	C78842	C_4H_8O	72.1	820	239.412	1.27754	Fruit aroma	1	1.05 ± 0.23a	0.42 ± 0.03b	1.11 ± 0.23a	0.40 ± 0.03b	0.36 ± 0.02b	1.05	0.42	1.11	0.40	0.36
69	Acetaldehyde	C75070	C_2H_4O	44.1	787.8	222.668	1.0296	Pungent aroma	10000	2.43 ± 0.53a	1.09 ± 0.08c	2.22 ± 0.08ab	1.76 ± 0.003b	2.12 ± 0.04ab	<0.01	<0.01	<0.01	<0.01	<0.01
75	Diethyl acetal	C105577	$C_6H_{14}O_2$	118.2	901.7	287.785	1.02446	Grassy aroma, sweet aroma	—	1.37 ± 0.34c	2.03 ± 0.14b	2.72 ± 0.12a	1.82 ± 0.02b	1.63 ± 0.05bc	—	—	—	—	—
76	Methacrolein	C78853	C_4H_6O	70.1	888.6	279.413	1.21587	Stink smell	25	0.30 ± 0.08d	0.63 ± 0.11c	2.55 ± 0.02a	1.24 ± 0.01b	2.35 ± 0.22a	0.01	0.03	0.10	0.05	0.09
77	Butanal	C123728	C_4H_8O	72.1	887.9	278.948	1.27625	Fruit aroma	180	1.37 ± 0.29c	1.12 ± 0.07c	2.87 ± 0.03a	1.83 ± 0.01b	1.93 ± 0.13b	0.01	0.01	0.02	0.01	0.01
78	Propanal	C123386	C_3H_6O	58.1	813	235.691	1.14008	Pungent smell	36	1.08 ± 0.17b	1.92 ± 0.17b	4.29 ± 0.26a	4.45 ± 0.03a	5.09 ± 0.96a	0.03	0.05	0.12	0.12	0.14
84	(E,Z)-2,6-nonadienal	C557482	$C_9H_{14}O$	138.2	1605.4	1597.68	1.35655	Grassy aroma	3.9	2.31 ± 0.39c	2.15 ± 0.19c	5.24 ± 0.52a	3.03 ± 0.03b	3.01 ± 0.09b	0.59	0.55	1.34	0.78	0.77
Ketones																			
9	2-Undecanone (M)	C112129	$C_{11}H_{22}O$	170.3	1693	1932.178	1.55555	Citrus aroma (fruit aroma)	30	30.47 ± 6.03a	2.71 ± 0.59c	11.58 ± 0.71b	6.83 ± 0.07bc	10.19 ± 1.78b	1.65	0.11	0.43	0.26	0.40
10	2-Undecanone (D)	C112129	$C_{11}H_{22}O$	170.3	1693	1932.178	2.10113			18.98 ± 3.07a	0.45 ± 0.13b	1.43 ± 0.36b	0.86 ± 0.13b	1.70 ± 0.44b					
19	2-Nonanone	C821556	$C_9H_{18}O$	142.2	1395.5	1013.142	1.87569	Fruit aroma	31	37.49 ± 5.96a	1.17 ± 0.85c	10.83 ± 1.45b	1.01 ± 0.05c	6.37 ± 3.28bc	1.21	0.04	0.35	0.03	0.21
20	6-Methyl-5-hepten-2-one	C110930	$C_8H_{14}O$	126.2	1344.9	907.842	1.17698	Fruit aroma	1800	28.76 ± 4.94b	14.31 ± 0.74d	35.88 ± 0.54a	20.48 ± 0.20c	22.58 ± 0.21c	0.02	0.01	0.02	0.01	0.01
27	2-Octanone	C111137	$C_8H_{16}O$	128.2	1292.4	810.273	1.75672	Flower aroma, grassy aroma	60	8.56 ± 1.44a	6.75 ± 0.27b	8..41 ± 0.23a	7.59 ± 0.05ab	7.07 ± 0.16ab	0.14	0.11	0.14	0.13	0.12
37	2-Heptanone	C110430	$C_7H_{14}O$	114.2	1190.9	655.723	1.62756	Pungent aroma	3.5	25.70 ± 5.63a	8.06 ± 1.33d	21.73 ± 1.43ab	13.30 ± 0.11cd	16.90 ± 2.35bc	7.34	2.30	6.21	3.80	4.83
54	2,3-Pentanedione	C600146	$C_5H_8O_2$	100.1	1070.9	444.35	1.2133	Nutty aroma	63	17.30 ± 3.78ab	6.62 ± 0.54c	18.48 ± 0.38a	13.19 ± 0.14b	13.68 ± 1.08b	0.27	0.11	0.29	0.21	0.22
61	Diacetyl	C431038	$C_4H_6O_2$	86.1	962.3	329.862	1.18531	Creamy aroma	3	6.61 ± 1.51b	3.00 ± 0.34c	9.02 ± 0.54a	5.97 ± 0.01b	5.85 ± 0.84b	2.20	1.00	3.01	1.99	1.95
64	2-Butanone	C78933	C_4H_8O	72.1	911.1	293.933	1.24315	Pungent aroma	—	5.64 ± 1.02a	1.36 ± 0.05d	3.07 ± 0.10c	4.48 ± 0.05b	4.85 ± 0.05ab	—	—	—	—	—
67	Acetone	C67641	C_3H_6O	58.1	831.7	245.824	1.11068	Pungent aroma	20000	18.93 ± 4.13b	10.92 ± 0.45c	24.61 ± 0.48a	21.16 ± 0.26ab	20.31 ± 0.95ab	<0.01	<0.01	<0.01	<0.01	<0.01
72	1-Penten-3-one	C1629589	C_5H_8O	84.1	1010.5	371.507	1.08098	Pungent aroma	1	0.25 ± 0.04b	0.16 ± 0.01c	0.36 ± 0.01a	0.26 ± 0.001b	0.29 ± 0.01b	0.25	0.16	0.36	0.26	0.29
74	4-Methyl-3-penten-2-one	C141797	$C_6H_{10}O$	98.1	1133.6	542.207	1.45097	Sweet aroma	200	0.60 ± 0.31b	0.42 ± 0.06b	0.48 ± 0.02b	1.18 ± 0.01a	1.30 ± 0.04a	<0.01	<0.01	<0.01	0.01	0.01
80	3-Octanone	C106683	$C_8H_{16}O$	128.2	1263.2	762.749	1.6993	Fruit aroma	1.3	0.14 ± 0.02b	0.09 ± 0.01b	0.19 ± 0.003b	0.14 ± 0.01b	0.68 ± 0.10a	0.11	0.07	0.15	0.11	0.52
Alcohols																			
8	Alpha-terpineol	C98555	$C_{10}H_{18}O$	154.3	1722.1	2058.324	1.22475	Camphor aroma (pungent aroma)	100000	10.87 ± 2.91b	3.95 ± 0.20c	15.78 ± 0.34a	10.62 ± 0.59b	9.49 ± 1.09b	<0.01	<0.01	<0.01	<0.01	<0.01
11	Terpinen-4-ol	C562743	$C_{10}H_{18}O$	154.3	1638.1	1715.295	1.22228	Pepper aroma (pungent aroma)	11700	28.30 ± 5.46b	12.89 ± 0.09d	38.39 ± 0.54a	22.81 ± 0.15bc	20.34 ± 2.82c	<0.01	<0.01	<0.01	<0.01	<0.01
16	(Z)-3-Hexenol	C928961	$C_6H_{12}O$	100.2	1433.9	1101.161	1.24216	Grassy aroma	—	2.45 ± 0.40b	1.34 ± 0.11d	3.53 ± 0.10a	1.73 ± 0.10cd	2.29 ± 0.38bc	—	—	—	—	—
18	Tetrahydro-linalool	C78693	$C_{10}H_{22}O$	158.3	1415.5	1058.07	1.26571	Flower aroma	—	12.68 ± 1.72b	8.49 ± 0.66c	22.13 ± 2.37a	12.85 ± 0.13b	13.45 ± 2.80b	—	—	—	—	—
22	4-Methyl-1-pentanol	C626891	$C_6H_{14}O$	102.2	1333.6	885.694	1.67519	Alcohol aroma	820	38.49 ± 6.90a	11.47 ± 1.57c	26.61 ± 2.75b	12.72 ± 0.65c	24.54 ± 8.42b	0.05	0.01	0.03	0.02	0.03
44	1-Butanol	C71363	$C_4H_{10}O$	74.1	1145.1	563.178	1.17838	Alcohol aroma	480	3.34 ± 0.68a	0.95 ± 0.09c	3.88 ± 0.08a	2.19 ± 0.02b	1.68 ± 0.23b	0.01	<0.01	0.01	<0.01	<0.01
51	2-Methyl-1-propanol (M)	C78831	$C_4H_{10}O$	74.1	1105.4	493.677	1.17411	Alcohol aroma	700	0.60 ± 0.12c	0.77 ± 0.05bc	0.31 ± 0.01d	1.15 ± 0.01a	0.88 ± 0.17b	<0.01	<0.01	<0.01	<0.01	<0.01
73	2-Methyl-1-propanol (D)	C78831	$C_4H_{10}O$	74.1	1105.5	493.834	1.36747			0.17 ± 0.03c	0.35 ± 0.04b	0.08 ± 0.01c	1.17 ± 0.01a	1.09 ± 0.08a					
62	Ethanol	C64175	C_2H_6O	46.1	938.7	312.811	1.1312	Alcohol aroma	620	21.60 ± 4.77a	6.79 ± 1.08b	6.65 ± 0.48b	9.28 ± 0.08b	8.13 ± 2.12b	0.03	0.01	0.01	0.01	0.01
81	Borneol	C507700	$C_{10}H_{18}O$	154.3	1683.4	1892.509	1.2256	Camphor aroma (pungent aroma)	52	10.81 ± 3.17b	4.25 ± 0.39c	16.80 ± 0.99a	11.93 ± 0.13b	9.13 ± 1.10b	0.21	0.08	0.32	0.23	0.18
82	Linalool	C78706	$C_{10}H_{18}O$	154.3	1586.3	1532.907	1.2256	Flower aroma, timber aroma	110	8.82 ± 2.02a	1.15 ± 0.12d	6.32 ± 1.14b	9.89 ± 0.30a	3.87 ± 0.56c	0.08	0.01	0.06	0.09	0.04
Esters																			
6	Diethyl succinate (M)	C123251	$C_8H_{14}O_4$	174.2	1755.1	2211.125	1.29931	Grape aroma (fruit aroma)	790	6.29 ± 1.44a	0.46 ± 0.08c	1.96 ± 0.15bc	2.16 ± 0.09b	1.65 ± 0.06bc	0.02	0.01	0.03	0.03	0.03
7	Diethyl succinate (D)	C123251	$C_8H_{14}O_4$	174.2	1712.9	2017.393	1.28948			6.96 ± 1.16b	6.05 ± 0.68b	17.95 ± 4.25a	21.39 ± 0.05a	20.26 ± 2.63a					
14	Phenylethyl 2-methylpropanoate (M)	C103480	$C_{12}H_{16}O_2$	192.3	1501.9	1276.199	1.40492	Rose aroma (grassy aroma)	—	81.92 ± 17.96ab	52.21 ± 2.39c	96.77 ± 3.22a	75.58 ± 7.02b	69.07 ± 0.46bc	—	—	—	—	—
15	Phenylethyl 2-methylpropanoate (D)	C103480	$C_{12}H_{16}O_2$	192.3	1503.4	1280.551	1.98237			257.42 ± 54.98b	96.33 ± 13.64d	370.27 ± 3.79a	220.23 ± 1.19bc	197.08 ± 8.18c					
28	Pentyl butanoate	C540181	$C_9H_{18}O_2$	158.2	1271	775.106	1.963	Fruit aroma	6500	17.89 ± 2.75a	1.59 ± 0.75c	11.00 ± 0.42b	1.80 ± 0.03c	8.55 ± 3.87b	<0.01	<0.01	<0.01	<0.01	<0.01
56	Ethyl butanoate (M)	C105544	$C_6H_{12}O_2$	116.2	1051.3	419.382	1.21143	Fruit aroma	4	4.03 ± 0.81b	3.53 ± 0.18b	6.02 ± 0.39a	4.46 ± 0.01b	4.29 ± 0.03b	1.34	1.20	2.08	1.58	1.51
57	Ethyl butanoate (D)	C105544	$C_6H_{12}O_2$	116.2	1050.9	418.773	1.58085			1.32 ± 0.27c	1.26 ± 0.06c	2.30 ± 0.14a	1.85 ± 0.03b	1.74 ± 0.12b					
65	Ethyl acetate	C141786	$C_4H_8O_2$	88.1	892.3	281.753	1.33084	Fruit aroma	4700	13.90 ± 3.03a	2.19 ± 0.31b	2.76 ± 0.08b	2.93 ± 0.50b	1.80 ± 0.04b	0.003	0.001	0.001	0.001	0.001

Table 2: Continued.

Count	Compound	CAS#	Formula	MW	RI	Rt (sec)	Dt (RIPrel)	Aroma description	Odor thresholds (μg/g)	Content (μg/g)					OAV				
										Fresh ginger	VFD	WAD	HAD	ND	Fresh ginger	VFD	WAD	HAD	ND
70	Propyl acetate (M)	C109604	$C_5H_{10}O_2$	102.1	988.1	349.646	1.16577	Fruit aroma	600	0.45 ± 0.09d	1.09 ± 0.01b	1.71 ± 0.05a	1.73 ± 0.01a	0.60 ± 0.05c	<0.01	<0.01	<0.01	0.01	<0.01
71	Propyl acetate (D)	C109604	$C_5H_{10}O_2$	102.1	988.1	349.646	1.47795			0.30 ± 0.16c	1.16 ± 0.09b	1.05 ± 0.24b	4.83 ± 0.04a	0.41 ± 0.06c					
83	Citronellyl formate	C105851	$C_{11}H_{20}O_2$	184.3	1653.7	1774.13	1.35357	Sweet aroma, grassy aroma	—	2.21 ± 0.33d	2.33 ± 0.12cd	5.42 ± 0.62a	2.98 ± 0.06bc	3.44 ± 0.16b	—	—	—	—	—
Pyrazines																			
21	Trimethylpyrazine	C14667551	$C_7H_{10}N_2$	122.2	1443.9	1125.333	1.16815	Nutty aroma	50	0.72 ± 0.13a	0.24 ± 0.01b	0.68 ± 0.04a	0.33 ± 0.001b	0.37 ± 0.03b	0.01	<0.01	0.01	0.01	0.01
85	3-Sec-butyl-2-methoxypyrazine	C24168705	$C_9H_{14}N_2O$	166.2	1520	1327.421	1.25536	Grassy aroma	—	0.51 ± 0.13b	0.32 ± 0.08b	0.44 ± 0.09b	0.34 ± 0.05b	1.98 ± 0.14a	—	—	—	—	—
Aromatic hydrocarbon substance																			
79	p-Xylene	C106423	C_8H_{10}	106.2	1142.5	558.348	1.07188	Nutty aroma	2200	0.23 ± 0.04c	0.14 ± 0.01c	0.30 ± 0.002b	0.48 ± 0.01a	0.47 ± 0.06a	<0.01	<0.01	<0.01	<0.01	<0.01
Reference sample																			
99	2-Octanol	C123966	$C_8H_{18}O$	130.2	1442.3	1121.542	1.82334	—	—	—	—	—	—	—					

M indicates volatile substance monomer, D indicates volatile substance dimer, T indicates volatile substance trimer; "—" indicates threshold values that cannot be queried and OAV values that cannot be calculated; count 86–98 are unknown compounds; 1,8-cineole and 1,4-cineole are the same as cineole, the threshold values are the same, and OAVs are combined. The same letter indicates that the difference is not significant and different letters indicate significant differences ($P < 0.05$).

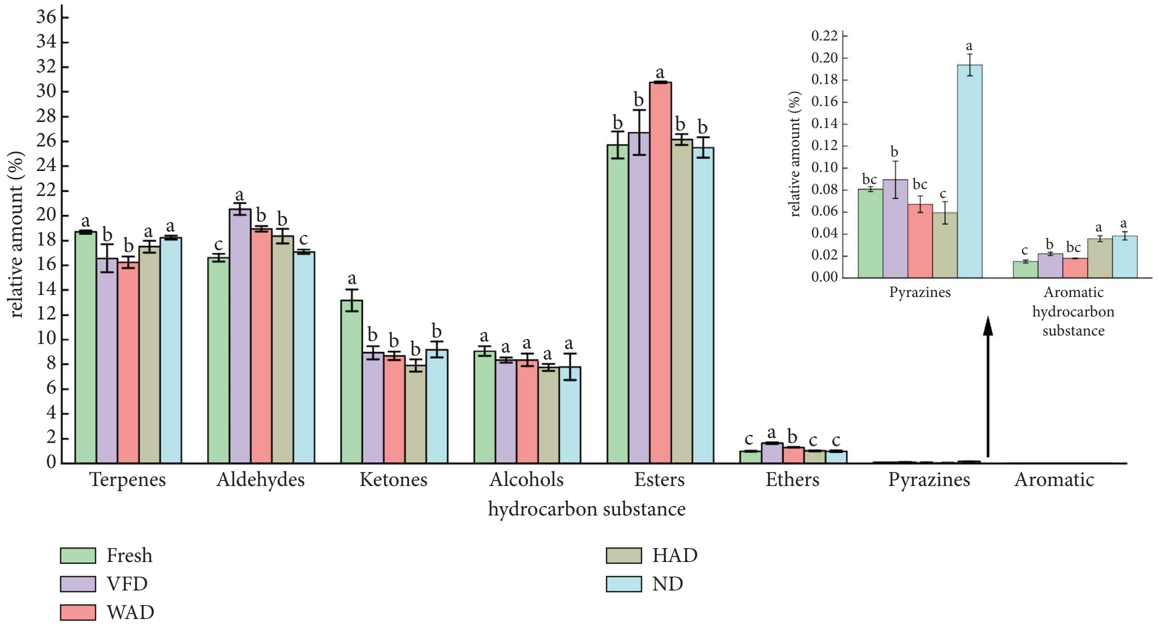


FIGURE 5: Relative content of compounds of *Zingiber officinale* Roscoe treated with different drying methods.

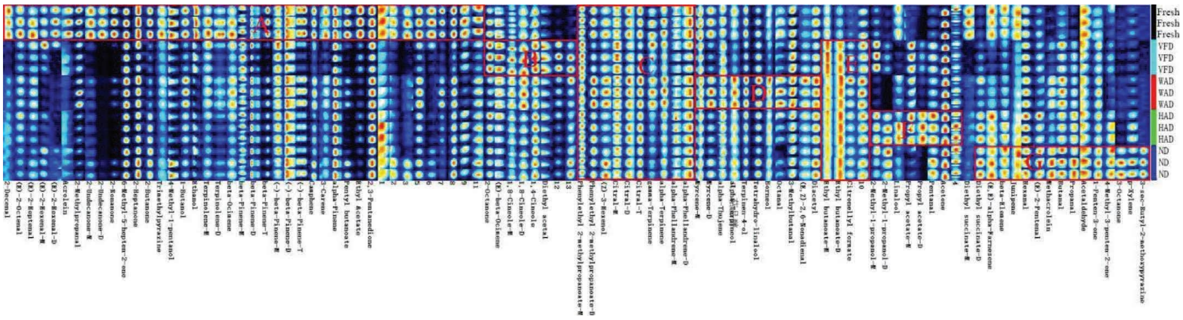


FIGURE 6: Fingerprint of volatile compounds of *Zingiber officinale* Roscoe treated with different drying methods by GC-IMS.

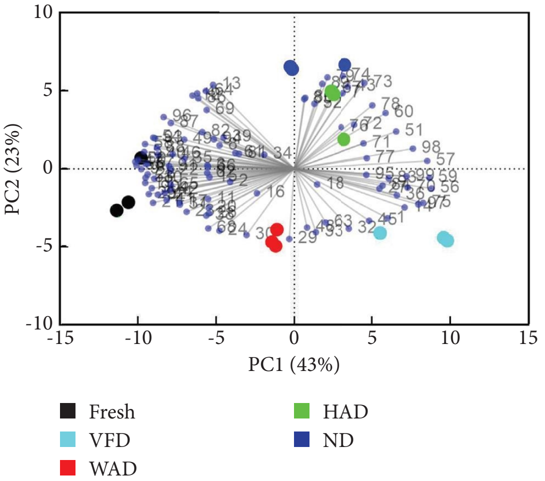


FIGURE 7: Principal component analysis (PCA) and loading diagram of volatile matter in *Zingiber officinale* Roscoe treated with different drying methods.

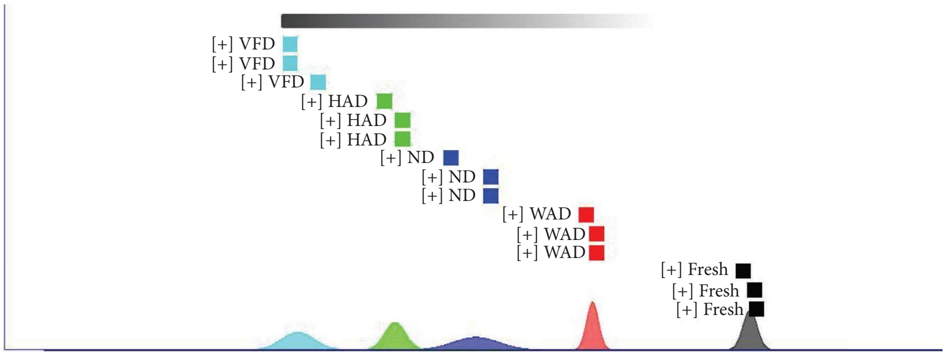


Figure 8: Similarity analysis of fingerprint of *Zingiber officinale* Roscoe treated with different drying methods.

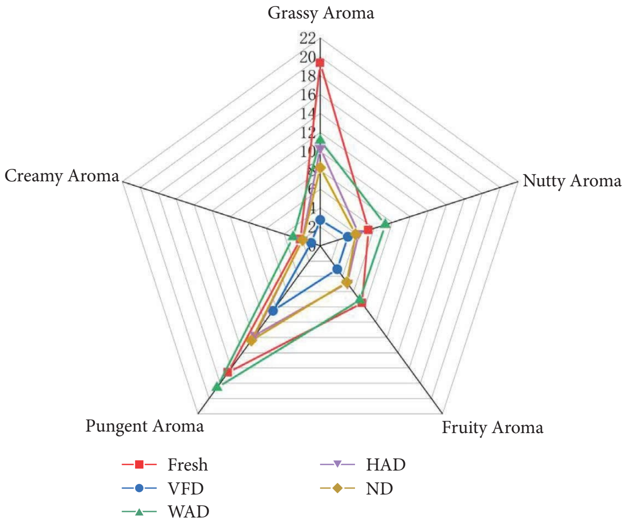


Figure 9: Radar chart of odor of *Zingiber officinale* Roscoe treated with different drying methods.

As observed in Figure 9, the aroma profiles of ginger were generally similar across the five different treatments. Fresh ginger exhibited more prominent grassy, fruity, and pungent aromas. However, the different drying methods leaded to a reduction in 2-decenal content in ginger, resulted in a significant reduction of grassy aroma of gingers. This reduction had the greatest impact on the volatile components. The aroma of VFD, HAD, and ND ginger also diminished due to water evaporation during processing. Among these, the aroma characteristics of HAD ginger and ND ginger were more similar, with grassy and pungent scented being the main characteristic. On the other hand, VFD ginger experienced the most aroma loss, possibly due to the vacuum environment during drying, which leaded to strong water transpiration. Although some volatile flavor substances were carried away with the water vapor [39], the lower drying temperature limited their transformation and results in weaker aromatic odor. WAD ginger, on the other hand, exhibits the highest levels of nutty and creamy aromas. This drying method imparts distinct flavor characteristics to the dried ginger, retaining pungent and fruity aromas to some extent.

4. Conclusions

In this study, the quality of processed ginger was analyzed using different drying methods, revealing significant effects on the physicochemical properties and active ingredients of ginger. Among the methods, VFD demonstrated the best quality, closely resembling the appearance of fresh ginger and retaining high levels of flavonoids, polyphenols, and ginger spicy element. VFD ginger also exhibited the highest rehydration rate, with a porous and full internal structure and minimal shrinkage.

The volatile flavor substances of fresh ginger and ginger treated with the four drying methods were analyzed using GC-IMS. A total of 86 volatile substances were identified in the five samples, including terpenes, aldehydes, ketones, alcohols, esters, ethers, pyrazines, and aromatic hydrocarbon substances. Many of these substances existed as monomers, dimers, and trimers. By constructing GC-IMS fingerprint profiles, the characteristic flavor substances of ginger treated with different drying methods could be determined. The results indicated that the content of terpenes, ketones, and alcohols relatively decreased during the drying process, while ethers remained more stable. Esters and aldehydes increased to varying degrees in all four dried samples.

The volatile flavor substances of ginger treated with different drying methods also exhibited noticeable differences. VFD treatment resulted in a significant loss of ginger's volatile components, while the differences between HAD and ND treatments were less pronounced. Principal component analysis and nearest neighbor algorithm were employed to analyze the samples, effectively differentiating ginger samples treated with different drying methods. The variations in the content of volatile flavor substances contributed to differences in aroma composition among the five samples. Fresh ginger exhibited a distinct grassy, fruity, and pungent aroma. WAD ginger retained the fruity and pungent aroma characteristics of fresh ginger, while also displaying a more prominent nutty and creamy aroma in terms of flavor.

The application of GC-IMS in dried ginger provides a novel reference method for studying the effect of different drying methods on the volatile flavor substances of ginger. This approach also offers a theoretical basis for quality control of ginger under various drying conditions.

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Jiani Chen contributed to the conceptualization, methodology, investigation, data curation, and writing of the original draft and editing. Jinhua Wang contributed to the supervision, review and editing of the manuscript, and project administration. Yonghui Ge helped to discuss the results and perfected the language and manuscript revision. Hongrui Ping and Wenxuan Liu performed the investigation and data curation.

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