

Effects of different natural exogenous additives on the physicochemical and flavor properties of crispy fried spareribs

Fanyi Gong¹, Qingyang Meng², Bowen Liao¹, Buzhou Xu¹, Yong Tang^{1,3,4}, Chang Su^{1,3,4}, Dong Zhang^{1,3,4} ✉

¹School of Food and Bioengineering, Xihua University, Chengdu 610039, China

²Sichuan Dekon Food and Agriculture Group, Chengdu 610225, China

³Chongqing Key Laboratory of Speciality Food Co-built by Sichuan and Chongqing, Chengdu 610039, China

⁴Food Industry Collaborative Innovation Center, Xihua University, Chengdu 610039, China

✉ Address correspondence to Dong Zhang, dongzhang@mail.xhu.edu.cn

Received: September 15, 2024; Revised: September 29, 2024; Accepted: October 22, 2024

Abstract: This study aimed to investigate the effects of different exogenous additives on the physicochemical properties and volatile flavor substances of crispy fried spareribs. Results showed that the addition of rattan pepper, *Houttuynia cordata*, *Litsea*, and plum had no significant effect ($P > 0.05$) on the texture properties of crispy fried spareribs. These ingredients had a certain effect on the thiobarbituric acid reactive substances value of crispy fried spareribs, but the difference was not significant ($P > 0.05$). Moreover, they could improve the sensory scores of crispy fried spareribs to a certain extent. A total of 91 volatile flavor substances were identified from 5 groups of crispy fried spareribs. Adding exogenous additives increased the types and contents of volatile flavor substances in crispy fried spareribs and increased the contents of key volatile flavor substances such as 1-octen-3-ol, linalool, 1-hexanol, and 1-dodecen-3-ol. Combined with sensory scores and physicochemical indexes, these findings showed that adding rattan pepper, *H. cordata*, *Litsea*, and plum could improve the taste and quality of crispy fried spareribs, thus having good application prospects.

Keywords: crispy fried spareribs; exogenous additives; physicochemical properties; volatile flavor substances; sensory scores

Citation: F. Y. Gong, Q. Y. Meng, B. W. Liao, et al., Effects of different natural exogenous additives on the physicochemical and flavor properties of crispy fried spareribs, Food Sci. Anim. Prod. 2 (2024) 9240093. <https://doi.org/10.26599/FSAP.2024.9240093>.

1 Introduction

Fried food is loved by consumers all over the world because of its attractive color and good flavor^[1-2]. Crispy fried spareribs, as a type of fried food, have crispy skin, a tender and juicy taste, and an enticing color. However, the crispy fried spareribs that are currently sold in the market are mainly available in their original flavor only, thus being unable to meet the increasingly diverse needs of consumers. Adding appropriate exogenous additives is a feasible strategy to improve the quality and taste of meat products^[3]. Dua et al.^[4] found that the addition of olive leaf extract not only enhanced the antioxidant capacity of fried mutton ribs but also reduced the total bacterial count, psychrophilic bacteria count, and mold count of fried mutton ribs. Fried mutton ribs with added olive leaf extract had higher sensory scores. Gao et al.^[5] found that the addition of papaya anthocyanins could inhibit the formation of heterocyclic amines in fried meat products and improved their antioxidant capacity. Deng et al.^[6] found that the addition of alkaline amino acids could inhibit the formation of total heterocyclic amines in fried meat products, reduced the oxidation of fried meat products to a certain extent, and significantly improved water-holding capacity. Although researchers have explored the effects of some exogenous additives on the safety, oxidation characteristics, and sensory quality of fried meat products, systematic research is lacking on the impact of different natural exogenous additives on the quality characteristics, especially flavor characteristics, of crispy pork ribs. Rattan pepper, *Houttuynia*

cordata, *Litsea*, and plum are plant foods that are often eaten in Sichuan and Chongqing areas of China. They are also used as seasonings for food processing in Southwest China. Few studies have been conducted on the effects of adding rattan pepper^[7], *H. cordata*^[8], *Litsea*^[9], and plum on the quality characteristics of crispy fried spareribs, and systematic research is lacking as to which flavor substances these exogenous additives will give crispy fried spareribs.

In this study, appropriate amounts of rattan pepper, *H. cordata*, *Litsea*, and plum were added to spareribs during the salting stage and then the spareribs were fried with hanging paste. The sensory scores, thiobarbituric acid reactive substances (TBARS) value, and texture properties of different crispy fried spareribs were analyzed. The effects of different exogenous additives on the volatile flavor components of crispy fried spareribs were studied by using comprehensive two-dimensional gas chromatography time-of-flight mass spectrometry (GC × GC-TOF-MS), and the mechanism of aroma production in different crispy fried spareribs were analyzed. This research is expected to produce crispy fried sparerib products that meet the needs and improve the satisfaction of consumers, and increase the economic benefits of related industries.

2 Materials and methods

2.1 Materials

The same batch of 10 kg fresh pork spareribs from 5-month old female fragrant pigs were purchased from Century Parkson

Shopping Supermarket in Pidu District, Chengdu City, Sichuan Province, and transported to the laboratory before being cut into similar-sized blocks. The pH of lean meat on spareribs was 6.02. Other food materials were purchased from Century Oarkson Shopping Supermarket. Rattan pepper and *Litsea* (Zuichuanwei, Chengdu, China), *H. cordata* (ChuanweiHuiguan, Chengdu, China), and plum (Gan Mei, Moccas, Huzhou, China) were purchased from Taobao.

2.2 Basic formula of crispy fried spareribs

The basic formula for crispy fried spareribs was as follows: 10% egg, 1.2% salt, 1% sugar, 0.1% five-spice powder, 0.2% pepper powder, 0.2% Sichuan pepper powder, 1% cumin powder, and 4% cooking wine (each addition was measured as a percentage of the mass of spareribs).

2.3 Preparation of crispy fried spareribs

The production of crispy fried spareribs in this work followed the method used by Wang et al.^[10] with some modifications. Fresh pork spareribs were cut into similarly sized chunks, washed with water to remove blood, and then marinated. The spareribs marinated with the basic formula were denoted as control (Con) group, while the spareribs marinated with 5% fresh rattan pepper, 5% fresh *H. cordata*, 5% fresh *Litsea*, and 5% plum were denoted as experimental groups, namely Rat, Hou, Lit, and Plu, respectively. Before marinating, the exogenous additives were crushed into a certain particle size with a crusher (SMF2002, Supor, Hangzhou, China), and then 5% of the exogenous additives were added to each group (each addition was measured as a percentage of the mass of spareribs). Then, the spareribs were marinated at 4 °C for 30 min. Afterward, the marinated spareribs were fully mixed with batter, pre-fried at 180 °C for 3 min at a fryer (L-101C, Guangdong Demas Intelligent Kitchen Equipment Co., Ltd., Foshan, China) until the surface was slightly yellow, and then removed from the oil. The pre-fried spareribs were then deep-fried at 180 °C for 3 min until

their surface became golden and crisp, and were finally removed. These crispy fried spareribs were used to determine various indexes.

2.4 Sensory evaluation of crispy fried spareribs

In reference to the method of Cheng et al.^[11] with slight modifications, 8 food professionals, including 4 males and 4 females, were selected. Before conducting the evaluation, the professionals rinsed their mouths with warm water and then rated the sample according to the scoring rules shown in Table 1. The evaluation was performed under normal light and room temperature in the sensory laboratory. The experimental plan was approved by the School of Food and Biotechnology of Xihua University. The rights and privacy of all participants are protected, and all the participants agreed to the collection and use of their personal information and related experimental data.

2.5 Determination of texture properties of crispy fried spareribs

In reference to the method adopted by Liu et al.^[12] with slight modifications, the crispy fried spareribs were boneless, and meat was taken from each sparerib. A P/36R texture analyzer (TA. XT Plus, Stable Micro Systems, London, UK) was used to measure the parameters, namely, pre-test, test, and post-test speeds were all 1 mm/s, compression interval of 5 s, compression degree of 50%, and tested at room temperature. Each group was repeated 6 times, and the test result was the average of the 6 repeated measurements. Hardness, springiness, cohesiveness, and chewiness were selected as evaluation indicators.

2.6 Determination of TBARS value of crispy fried spareribs

The absorbance of the supernatant of the sample at 532 nm was measured, and the TBARS value was calculated according to the method of Chen et al.^[13].

Table 1 Sensory evaluation criteria of crispy fried spareribs.

Sensory property	Scoring rule	Level	Score
Color	The color is attractive and bright	Excellent	21–25
	The color is relatively good	Good	16–20
	The color is average	General	11–15
	The color is dull and lackluster	Bad	0–10
Aroma	Pure and rich aroma	Excellent	21–25
	The aroma is relatively pure	Good	16–20
	The aroma is average	General	11–15
	The aroma is light and impure	Bad	0–10
Taste	Pure taste, no greasy feeling	Excellent	21–25
	The taste is relatively pure, with a slight greasy sensation	Good	16–20
	The taste is average, with a greasy sensation	General	11–15
	Poor taste, obvious greasy feeling	Bad	0–10
Texture	Crispy on the outside and tender on the inside, with a great taste	Excellent	21–25
	Crispy on the outside and tender on the inside, with a good taste	Good	16–20
	The sample is relatively hard and has a poor taste	General	11–15
	The sample is hard and has a poor taste	Bad	0–10
Overall acceptability	Highly recommended	Excellent	21–25
	Recommended	Good	16–20
	Acceptable	General	11–15
	Not recommended	Bad	0–10

2.7 Determination of volatile flavor substances of crispy fried spareribs

2.7.1 Static headspace solid-phase microextraction

Following the method described by Li et al.^[14] with slight modifications. A total of 2 g (accurate to 0.001 g) of the sample was placed in a 15 mL extraction bottle, equilibrated in a water bath at 60 °C for 20 min, extracted in a water bath at 60 °C for 30 min, and analyzed at the GC injection port for 5 min.

2.7.2 GC × GC-TOF-MS conditions

The determination of volatile flavor compounds referred to the method used by Ruan et al.^[15], combined with compound retention index and mass matching of over 80% of compounds to identify volatile compounds.

2.7.3 Confirmation of key flavor compounds

The evaluation of key flavor compounds referred to the method of Zhong et al.^[16]. With the use of relative odor activity value (ROAV), ROAV_{stan} with the largest contribution of volatile flavor components was set as 100. Other volatile flavor components were calculated according to the following formula:

$$\text{ROAV}_A \approx 100 \times \frac{C_A}{C_{\text{stan}}} \times \frac{T_{\text{stan}}}{T_A}$$

Where C_A and T_A were the relative content (%) and threshold (μg/kg) of the volatile flavor substance, respectively. C_{stan} and T_{stan} were the relative content (%) and threshold (μg/kg) of volatile flavor substances that contributed the most to the overall flavor, respectively.

2.8 Statistical analysis

IBM SPSS 27.0 software was used to analyze the data, and one-way analysis of variance and Duncan multiple-range test were performed to determine the significance of the differences. The significance level was set at 0.05. Origin 2022 software was used to plot the resulting data. Three batches of crispy fried spareribs (replicates) were prepared on different days. For each crisp fried spareribs batch, related indexes were measured in triplicate.

3 Results and discussion

3.1 Effects of exogenous additives on the sensory scores of crispy fried spareribs

Adding different exogenous additives can lead to differences in the flavor of the product^[17]. As shown in Figure 1, the influence of different exogenous additives on sensory scores of crispy fried spareribs was compared by analyzing the color, taste, aroma, texture, and overall acceptability. Using different exogenous additives can significantly improve the sensory quality of crispy fried spareribs. No significant difference ($P > 0.05$) was found in the color score of crispy fried spareribs with different exogenous additives compared with the control group. This condition may be due to the fact that during the high temperature frying process, crispy fried spareribs mainly undergo caramelization and Maillard reactions^[18], which have a greater impact on color than exogenous additives do. The taste and aroma scores of crispy fried spareribs in different groups had considerable differences, which were attributed to the inconsistent composition of different exogenous additives. During the high temperature frying process, substances related to taste and aroma in the exogenous additives evaporate and diffuse,

thereby enhancing the aroma and taste scores of crispy fried spareribs. The use of exogenous additives can also mask some unpleasant flavors to a certain extent, thereby improving aroma and taste scores. No significant difference ($P > 0.05$) in texture scores was found between the crispy fried spareribs with different exogenous additives and the control group. This result may be due to the high temperature during the frying process, which affects the texture properties of crispy fried spareribs more than exogenous additives do. In terms of overall acceptability, crispy fried spareribs with exogenous additives scored higher, especially the ones with rattan pepper, *Litsea*, and plum. This result indicated that the use of exogenous additives had a good improvement effect on the sensory quality of crispy fried spareribs.

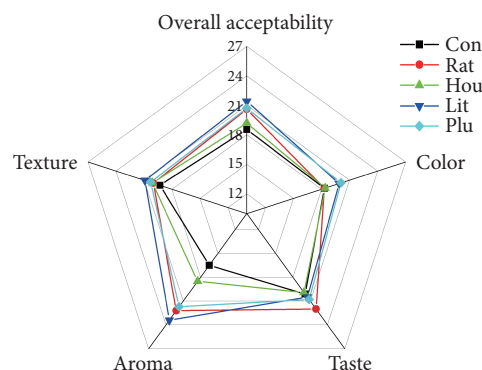
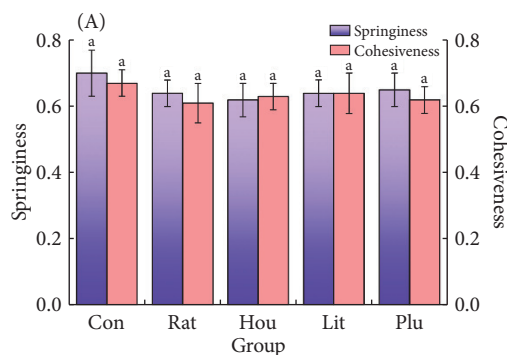


Figure 1 Sensory scores of crispy fried spareribs. Con: control group; Rat: rattan pepper group; Hou: *H. cordata* group; Lit: *Litsea* group; Plu: plum group.

3.2 Effects of exogenous additives on the texture properties of crispy fried spareribs

As shown in Figure 2, Some differences in hardness, springiness, and cohesiveness were found among different groups, but they were not significant ($P > 0.05$). This result may be due to the fact that during frying process, high temperature promotes the rapid evaporation of water on the surface of pork spareribs, denaturation and contraction of muscle protein^[19], resulting in a smaller muscle fiber gap and the formation of a hard shell on the surface of pork spareribs. High temperature can promote serious tissue and structure denaturing of meat^[20], and has a far greater effect than that of exogenous additives. In terms of chewiness, the use of exogenous additives could reduce the chewiness of crispy fried spareribs to some extent, which may be due to certain components in exogenous additives that can improve the chewiness and softness of the meat to a certain extent. The results of texture properties are consistent with the sensory scores. In short, the effect of different exogenous additives on the texture properties of crispy fried spareribs is relatively small.



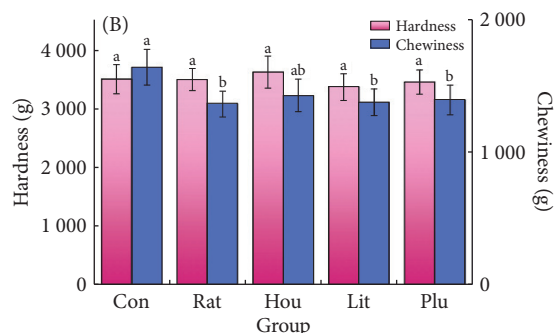


Figure 2 Effects of different exogenous additives on the texture properties of crispy fried spareribs. (A) Springiness and cohesiveness; (B) Hardness and chewiness. Con: control group; Rat: rattan pepper group; Hou: *H. cordata* group; Lit: *Litsea* group; Plu: plum group. Different lowercase letters in the same index indicate significant differences ($P < 0.05$).

3.3 Effects of exogenous additives on the TBARS value of crispy fried spareribs

The TBARS value reflects the content of malondialdehyde, which is the degradation product of lipid peroxidation^[21]. As shown in Figure 3, the use of different exogenous additives could lead to some differences in the TBARS value of crispy fried spareribs. In general, using different exogenous additives can reduce the TBARS value of crispy fried spareribs to a certain extent ($P > 0.05$). This may be related to the antioxidant active ingredients contained in the exogenous additive. Dhimi et al.^[22] pointed out that rattan pepper contained limonene, linalool, 1,8-cineole, and other bioactive ingredients with antioxidant effects. Song et al.^[23] found that *H. cordata* had excellent antioxidant effects. According to Liu et al.^[24], *Litsea* had a high antioxidant component, thus having great application potential in the food industry. Plum is rich in VC, organic acids, and other antioxidants, thus also having certain antioxidant effect.

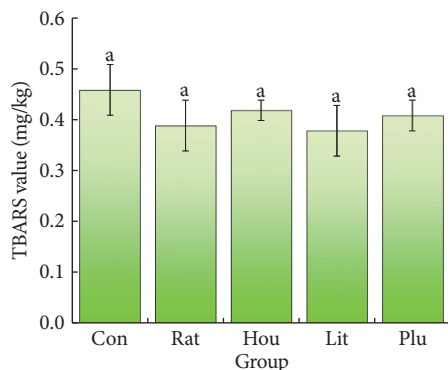


Figure 3 Effects of different exogenous additives on TBARS value of crispy fried spareribs. Con: control group; Rat: rattan pepper group; Hou: *H. cordata* group; Lit: *Litsea* group; Plu: plum group. Different lowercase letters indicate significant differences ($P < 0.05$).

3.4 Effects of exogenous additives on the volatile flavor compounds of crispy fried spareribs

3.4.1 Volatile flavor compound composition

Principal component analysis (PCA) and partial least squares-discriminant analysis (PLS-DA) were conducted on the detected data to investigate the effects of different exogenous additives on volatile flavor compounds in crispy fried spareribs. As shown in Figure 4A, the PCA results showed that the cumulative contribution rate of PC1 and PC2 were 78.2%, indicating that these

two principal components could represent most of the information about the overall characteristics of the samples. No overlap was observed between the 5 groups of samples, demonstrating differences in volatile flavor substances among different treatment groups. Figure 4B shows the PLS-DA score plot of volatile flavor compounds, with PC1 and PC2 from GC × GC-TOF-MS explaining 70.8% of the total variance. In the score plot, the points representing the 5 groups of samples are dispersed and do not overlap, which further supports the PCA results^[25].

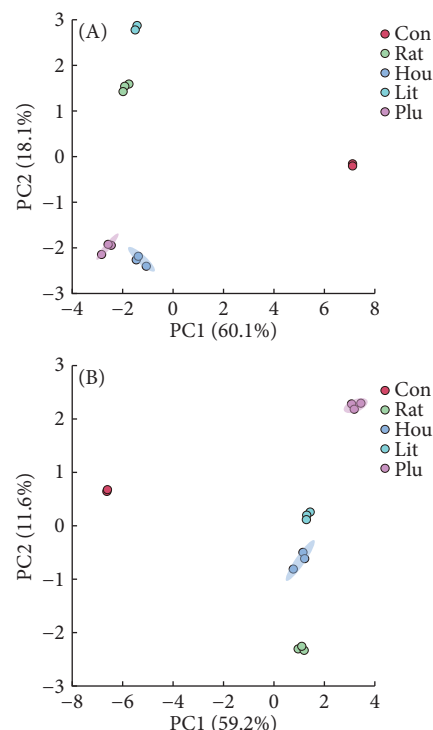


Figure 4 (A) PCA and (B) PLS-DA score plots of volatile flavor compounds of different crispy fried spareribs. Con: control group; Rat: rattan pepper group; Hou: *H. cordata* group; Lit: *Litsea* group; Plu: plum group.

According to Figure 5, a total of 91 volatile flavor compounds were analyzed and detected in the 5 groups of crispy fried sparerib samples with different exogenous additives. According to Figure 6 and Table 2, the samples contain 23 alcohols, 13 aldehydes, 13 ketones, 2 acids, 7 esters, 1 ether, 28 hydrocarbons, and 4 other substances. The highest relative content was hydrocarbons, accounting for 30.77% of the total, followed by alcohols. The quantity and relative content of volatile flavor substances were significantly increased in the 4 experimental groups with different exogenous additives than that in the control group. Compared with control group, there were 19, 28, 29 and 31 more volatile flavor compounds in groups Rat, Hou, Lit and Plu, respectively. And the degree of change in the total volatile flavor compounds in each group of samples varied. New volatile flavor compounds were detected from the samples with different exogenous additives, including (–)-*trans*-isopiperitenol, terpinen-4-ol, neral, β -ocimene, and other compounds. The highest relative content of alcohol compounds in crispy fried spareribs was found in the control group, reaching 24.18%, while the other 4 experimental groups had relative contents of 14.39%, 20.90%, 18.54%, and 15.63%, respectively. The relative content of hydrocarbons in the control group of crispy fried spareribs was 23.54%, while the relative contents of hydrocarbons to total volatile flavor compounds was relatively high in the other 4 experimental groups, reaching 61.86%, 42.28%, 52.97%, and 54.20%, respectively.

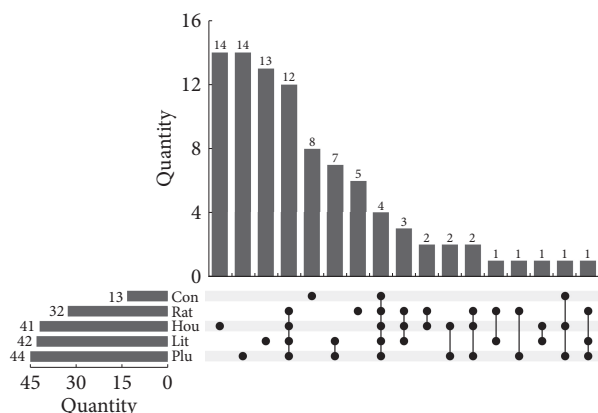


Figure 5 Upset diagram of volatile flavor substances of different crispy fried spareribs. Con: control group; Rat: rattan pepper group; Hou: *H. cordata* group; Lit: *Litsea* group; Plu: plum group. Points and lines represent the intersection between different groups; the left bar graph shows the amount of volatile compounds in each group; the upper bar graph corresponds to the number of volatile compounds in the intersection below.

Eight volatile flavor compounds had a relative content greater than 5% in the control group of crispy fried spareribs, including 2,6-octadiene-4,5-diol (8.85%), *trans*-2-methyl-cyclopentanol (8.89%), 4-(1-methylethyl)-benzaldehyde (10.74%), hexanal (11.00%), 2-methyl-3-heptanone (13.13%), hexanoic acid (7.92%), geranyl propionate (9.46%), and *D*-limonene (14.30%). Eight volatile flavor compounds had a relative content greater than 5% in the crispy fried spareribs with rattan pepper, including linalool (11.85%), 2-methyl-3-heptanone (5.32%), *o*-cymene (8.18%), (1*S*,5*S*)-6,6-dimethyl-2-methylenebicyclo[3.1.1]heptane (9.45%), *D*-limonene (11.36%), β -myrcene (6.31%), γ -terpinene (5.98%), and *p*-cymene (8.78%). Six volatile flavor compounds had a relative content greater than 5% in the crispy fried spareribs with *H. cordata*, namely linalool (9.96%), 4-(1-methylethyl)-benzaldehyde (6.17%), *D*-limonene (8.44%), β -myrcene (6.03%), 4-methylene-1-(1-methylethyl)-bicyclo[3.1.0]hexane (6.10%), and 1-methyl-3-(1-methylethyl)-benzene (6.79%). Four volatile flavor compounds had a relative content greater than 5% in the crispy fried spareribs with *Litsea*, namely linalool (7.70%), (*E*)-3,7-

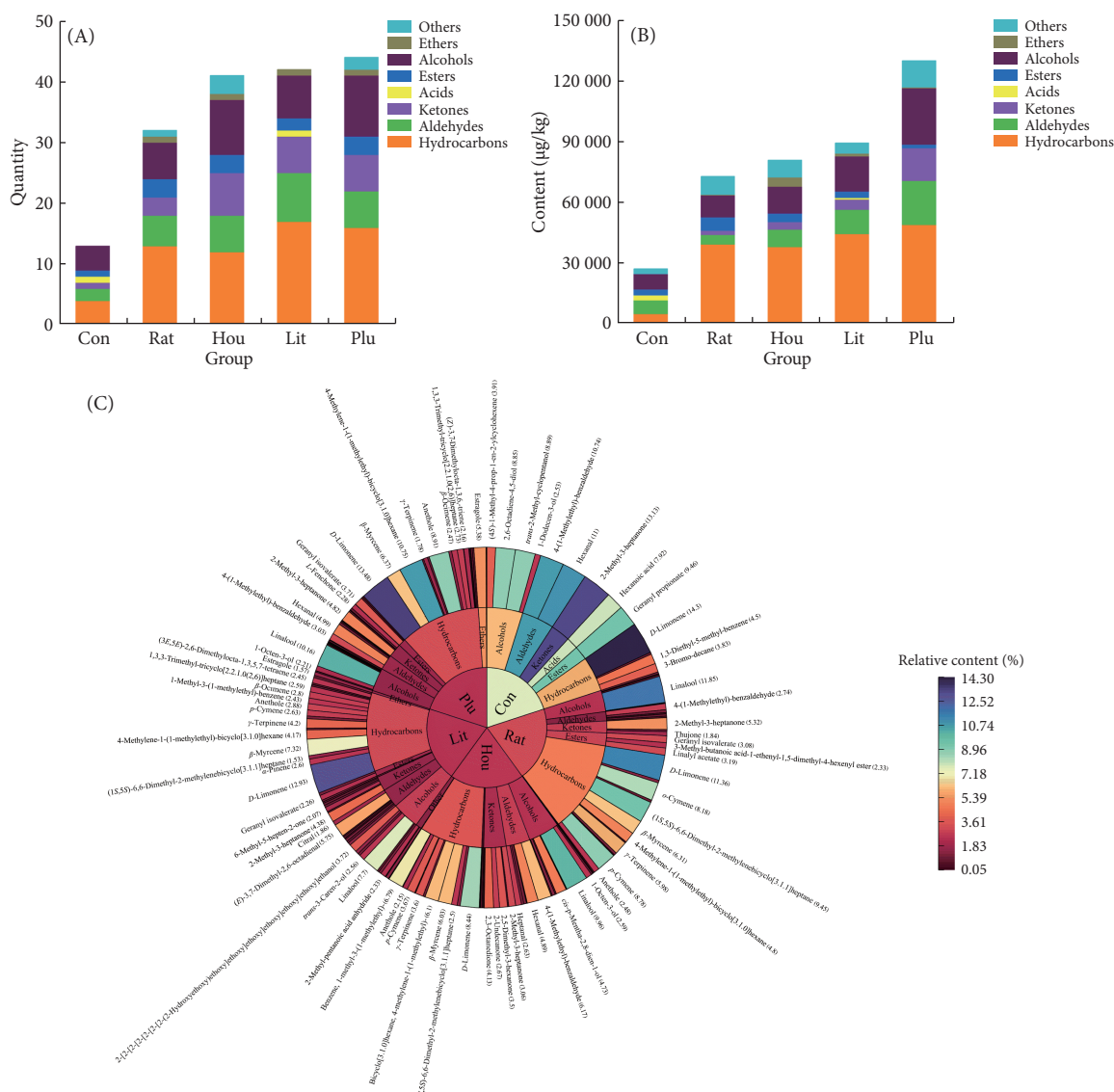


Figure 6 (A) Quantity, (B) content and (C) relative content sunburst diagram of volatile flavor substances in different crispy fried spareribs. Con: control group; Rat: rattan pepper group; Hou: *H. cordata* group; Lit: *Litsea* group; Plu: plum group.

Table 2 Types and relative contents of volatile flavor compounds in different crispy fried spareribs.

Volatile flavor compound	CAS	Relative content (%)				
		Con	Rat	Hou	Lit	Plu
2-Caren-10-al	6909-19-9		0.87 ± 0.13 ^a			
<i>cis</i> -5-Ethenyltetrahydro- $\alpha,\alpha,5$ -trimethyl-2-furanmethanol	5989-33-3		0.38 ± 0.06 ^c	0.78 ± 0.13 ^b	1.15 ± 0.11 ^a	0.60 ± 0.16 ^b
1-Octen-3-ol	3391-86-4		0.78 ± 0.10 ^c	2.59 ± 0.31 ^a	0.85 ± 0.05 ^c	2.21 ± 0.09 ^b
Linalool	78-70-6		11.85 ± 0.37 ^a	9.96 ± 0.63 ^b	7.70 ± 0.26 ^c	10.16 ± 0.31 ^b
α -Terpineol	98-55-5		0.21 ± 0.03 ^b	0.08 ± 0.01 ^c		0.52 ± 0.03 ^a
1-Hexanol	111-27-3					0.31 ± 0.03 ^a
<i>cis</i> -1-Methyl-4-(1-methylethenyl)-cyclohexanol	7299-41-4	3.91 ± 0.20 ^a		0.31 ± 0.02 ^b		0.37 ± 0.03 ^b
2,7-Dimethyl-2,6-octadien-1-ol	22410-74-8					0.37 ± 0.02 ^a
2,6,6-Trimethyl-bicyclo[3.1.1]heptan-2-ol	473-54-1					0.18 ± 0.05 ^a
<i>L</i> - α -Terpineol	10482-56-1					0.65 ± 0.03 ^a
6,6-Dimethyl-bicyclo[3.1.1]hept-2-ene-2-methanol	515-00-4					0.26 ± 0.01 ^a
Alcohols						
<i>trans</i> -3-Caren-2-ol	93905-79-4				2.56 ± 0.06 ^a	
(-)- <i>trans</i> -Isopiperitenol	74410-00-7				1.07 ± 0.07 ^a	
Geraniol	106-24-1				1.49 ± 0.12 ^a	
2-[2-[2-[2-[2-[2-(2-Hydroxyethoxy)ethoxy]ethoxy]ethoxy]ethoxy]ethoxy]ethanol	5117-19-1				3.72 ± 0.12 ^a	
<i>cis</i> - <i>p</i> -Mentha-2,8-dien-1-ol	3886-78-0			4.73 ± 0.37 ^a		
Terpinen-4-ol	562-74-3			0.62 ± 0.07 ^a		
Dimethyl-silanediol	1066-42-8			1.33 ± 0.09 ^a		
(<i>E</i>)-2-Octen-1-ol	18409-17-1			0.50 ± 0.05 ^a		
2,6-Octadiene-4,5-diol	4486-59-3	8.85 ± 0.13 ^a				
<i>trans</i> -2-Methyl-cyclopentanol	25144-04-1	8.89 ± 0.14 ^a				
1-Dodecen-3-ol	4048-42-4	2.53 ± 0.02 ^c				
(<i>R</i>)- $\alpha,\alpha,4$ -Trimethylcyclohex-3-ene-1-methanol	7785-53-7		0.30 ± 0.09 ^a			
4-Isopropylcyclohexa-1,3-dienecarbaldehyde	1197-15-5		0.62 ± 0.16 ^a	0.35 ± 0.02 ^b		
Nonanal	124-19-6		1.00 ± 0.10 ^b	1.21 ± 0.10 ^a	1.10 ± 0.11 ^{ab}	1.03 ± 0.07 ^b
Benzaldehyde	100-52-7		0.65 ± 0.22 ^a			
4-(1-Methylethyl)-benzaldehyde	122-03-2	10.74 ± 0.64 ^a	2.74 ± 0.13 ^c	6.17 ± 0.47 ^b	1.28 ± 0.04 ^d	3.03 ± 0.32 ^c
Hexanal	66-25-1	11.00 ± 0.10 ^a	1.21 ± 0.13 ^c	4.89 ± 0.37 ^b	0.92 ± 0.16 ^c	4.99 ± 0.82 ^b
Octanal	124-13-0			1.04 ± 0.11 ^a		0.64 ± 0.05 ^b
Aldehydes						
Neral	106-26-3				0.57 ± 0.06 ^a	0.32 ± 0.01 ^b
3-Caren-10-al	5114-01-2					0.21 ± 0.01 ^a
3,7-Dimethyl-6-octenal	22457-25-6				0.77 ± 0.13 ^a	
7-Methyl-3-methylene-6-octenal	55050-40-3				0.59 ± 0.05 ^a	
(<i>E</i>)-3,7-Dimethyl-2,6-octadienal	141-27-5				5.75 ± 0.10 ^a	
Citral	5392-40-5				1.86 ± 0.04 ^a	
Heptanal	111-71-7			2.63 ± 0.08 ^a		
2-Methyl-3-heptanone	13019-20-0	13.13 ± 0.10 ^a	5.32 ± 0.08 ^b	3.06 ± 0.26 ^c	4.38 ± 0.05 ^d	4.82 ± 0.06 ^c
[1 <i>S</i> -(1 α ,4 β ,5 α)]-4-Methyl-1-(1-methylethyl)-bicyclo[3.1.0]hexan-3-one	471-15-8		0.90 ± 0.04 ^a			
Thujone	546-80-5		1.84 ± 0.31 ^a	0.60 ± 0.05 ^b	0.66 ± 0.08 ^b	0.68 ± 0.16 ^b
6-Methyl-5-hepten-2-one	110-93-0				2.07 ± 0.14 ^a	0.31 ± 0.09 ^b
Fenchone	1195-79-5				0.98 ± 0.04 ^a	1.01 ± 0.18 ^a
<i>L</i> -Fenchone	7787-20-4				1.02 ± 0.10 ^b	2.28 ± 0.13 ^a
Ketones						
(-)-Carvone	6485-40-1					0.10 ± 0.02 ^a
2-(2-Butynyl)-cyclohexanone	54166-48-2				0.68 ± 0.08 ^a	
2,5-Dimethyl-3-hexanone	1888-57-9			3.50 ± 0.38 ^a		
2-Undecanone	112-12-9			2.67 ± 0.08 ^a		
2,3-Octanedione	585-25-1			4.13 ± 5.21 ^a		
(<i>Z</i>)-Tetrahydro-6-(2-pentenyl)-2 <i>H</i> -pyran-2-one	25524-95-2			0.49 ± 0.09 ^a		
4-Methyl-1-(1-methylethyl)-bicyclo[3.1.0]hexan-3-one	1125-12-8			0.48 ± 0.10 ^a		

Table 2 (Continued)

	Volatile flavor compound	CAS	Relative content (%)				
			Con	Rat	Hou	Lit	Plu
Acids	<i>cis</i> -Isocitral	72203-97-5				0.87 ± 0.02 ^a	
	Hexanoic acid	142-62-1	7.92 ± 0.38 ^a				
	Geranyl isovalerate	109-20-6		3.08 ± 0.60 ^b		2.26 ± 0.04 ^c	3.71 ± 0.18 ^a
	3-Methyl-butanoic acid-1-ethenyl-1,5-dimethyl-4-hexenyl ester	1118-27-0		2.33 ± 0.05 ^a			
Esters	Linalyl acetate	115-95-7		3.19 ± 0.32 ^a	0.73 ± 0.10 ^c	1.16 ± 0.17 ^b	0.67 ± 0.11 ^c
	Hexanoic acid, 2-methylphenyl ester	15806-41-4					0.64 ± 0.15 ^a
	(1 <i>S</i> -Endo)-1,7,7-trimethyl-bicyclo[2.2.1]heptan-2-ol acetate	5655-61-8			0.23 ± 0.02 ^a		
	Geranyl acetate	105-87-3			0.31 ± 0.04 ^a		
Ether	Geranyl propionate	105-90-8	9.46 ± 0.41 ^a				
	Estragole	140-67-0		0.49 ± 0.07 ^c	0.29 ± 0.01 ^c	1.57 ± 0.28 ^b	5.38 ± 0.06 ^a
	α -Pinene	80-56-8		1.27 ± 0.14 ^b		2.60 ± 0.17 ^a	
	<i>o</i> -Cymene	527-84-4		8.18 ± 0.23 ^a	1.39 ± 0.09 ^b		
Hydrocarbons	5-Isopropyl-2-methylbicyclo[3.1.0]hexan-2-ol	117305-49-4		1.03 ± 0.19 ^b	0.28 ± 0.03 ^c		1.36 ± 0.29 ^a
	(1 <i>S</i> ,5 <i>S</i>)-6,6-Dimethyl-2-methylenebicyclo[3.1.1]heptane	18172-67-3		9.45 ± 0.34 ^a	2.50 ± 0.15 ^b	1.53 ± 0.04 ^c	
	<i>D</i> -Limonene	5989-27-5	14.30 ± 0.15 ^a	11.36 ± 0.40 ^b	8.44 ± 0.15 ^c	12.93 ± 0.67 ^{ab}	13.48 ± 2.80 ^{ab}
	β -Myrcene	123-35-3		6.31 ± 0.19 ^b	6.03 ± 0.3 ^b	7.32 ± 0.20 ^a	6.37 ± 0.45 ^b
	4-Methylene-1-(1-methylethyl)-bicyclo[3.1.0]hexane	3387-41-5		4.80 ± 0.08 ^c	6.10 ± 0.48 ^b	4.17 ± 0.62 ^c	10.75 ± 0.10 ^a
	Caryophyllene	87-44-5		0.62 ± 0.13 ^b	0.99 ± 0.04 ^a	0.75 ± 0.02 ^b	0.76 ± 0.13 ^b
	γ -Terpinene	99-85-4		5.98 ± 0.06 ^a	3.60 ± 0.39 ^c	4.20 ± 0.37 ^b	1.78 ± 0.29 ^d
	4-Methyl-1-(1-methylethyl)-bicyclo[3.1.0]hex-2-ene	28634-89-1		1.16 ± 0.23 ^a			0.88 ± 0.07 ^b
	3-Carene	13466-78-9		0.44 ± 0.02 ^b	0.34 ± 0.04 ^b	1.21 ± 0.15 ^a	
	β -Ocimene	13877-91-3				2.80 ± 0.14 ^a	2.47 ± 0.36 ^b
	(<i>Z</i>)-3,7-Dimethylocta-1,3,6,-triene	3338-55-4					2.16 ± 0.20 ^a
	1-Methyl-4-(1-methylethylidene)-cyclohexene	586-62-9					0.45 ± 0.07 ^a
	(4 <i>E</i> ,6 <i>Z</i>)-2,6-dimethylocta-2,4,6-triene	7216-56-0					0.42 ± 0.02 ^a
	(2 <i>R</i> ,5 <i>R</i>)-2-Methyl-5-propan-2-ylbicyclo[3.1.0]hexan-2-ol	17699-16-0					0.72 ± 0.12 ^a
	1,3,3-Trimethyl-tricyclo[2.2.1.0(2,6)]heptane	488-97-1				2.59 ± 0.07 ^b	2.73 ± 0.05 ^a
	2,6-Dimethyl-2,4,6-octatriene	3016-19-1				0.77 ± 0.02 ^a	0.23 ± 0.04 ^b
	1-Methyl-3-(1-methylethyl)-benzene	535-77-3			6.79 ± 0.76 ^a	2.43 ± 0.16 ^b	
	Camphene	79-92-5				0.70 ± 0.03 ^a	
	(3 <i>E</i> ,5 <i>E</i>)-2,6-Dimethylocta-1,3,5,7-tetraene	460-01-5				2.45 ± 0.04 ^a	
	(+)-3-Carene	20296-50-8				1.01 ± 0.14 ^a	
Others	(4 <i>S</i>)-1-Methyl-4-prop-1-en-2-ylcyclohexene	5989-54-8	0.91 ± 0.02 ^a				
	<i>p</i> -Cymene	99-87-6		8.78 ± 0.22 ^a	3.67 ± 0.22 ^b	2.63 ± 0.10 ^c	
	Anethole	50770-19-9		2.48 ± 0.15 ^c	2.15 ± 0.04 ^d	2.88 ± 0.05 ^b	8.91 ± 0.18 ^a
	1-Bromo-pentane	110-53-2					0.73 ± 0.29 ^a
	1,3-Diethyl-5-methyl-benzene	2050-24-0	4.50 ± 0.31 ^a				
	3-Bromo-decane	30571-71-2	3.83 ± 0.23 ^a				
	(<i>Z</i>)-1-Methoxy-4-(prop-1-en-1-yl)benzene	25679-28-1		0.41 ± 0.04 ^c	1.4 ± 0.06 ^d		0.13 ± 0.04 ^a
	2,3-Dimethyl-pyrazine	5910-89-4					0.25 ± 0.02 ^a
	Hexanoic acid anhydride	2051-49-2			0.31 ± 0.03 ^a		
	2-Methyl-pentanoic acid anhydride	63169-61-9			2.33 ± 0.15 ^a		

Notes: Values are expressed as mean ± standard deviation. Con: control group; Rat: rattan pepper group; Hou: *H. cordata* group; Lit: *Litsea* group; Plu: plum group. Different superscript lowercase letters in the same row show significant difference ($P < 0.05$).

dimethyl-2,6-octadienal (5.75%), *D*-limonene (12.93%), and β -myrcene (7.32%). Six volatile flavor compounds had a relative content greater than 5% in the crispy fried spareribs with plum, namely linalool (10.16%), estragole (5.38%), *D*-limonene (13.48%),

β -myrcene (6.37%), 4-methylene-1-(1-methylethyl)-Bicyclo[3.1.0]hexane (10.75%), and anethole (8.91%). Most of these volatile flavor substances can satisfy people and have a unique aroma, thus offering a good sensory experience.

Alcohols are the main flavor compounds of crispy fried spareribs. The relative content of alcohol substances in the control group was 24.18%, and the relative content of alcohol substances in each experimental group (14.39%, 20.90%, 18.54%, 15.63%) was lower than in the control group. Alcohol substances mainly come from the oxidative degradation of unsaturated fatty acids or the Strecker degradation of amino acids. The relative content of alcohol substances in the experimental group of crispy fried spareribs is relatively low possibly because of the presence of antioxidant components in natural exogenous additives, which can inhibit the degradation of unsaturated fatty acids and amino acids to a certain extent during heat processing. Linalool and 1-octen-3-ol were detected in all 4 experimental groups, with linalool providing a floral flavor at low concentrations and a spicy flavor at high concentrations^[26]. 1-Octen-3-ol has a mushroom-like aroma and is a typical meat-flavored active compound^[27]. Its formation and content can be controlled and optimized by adjusting the processing to improve the sensory quality of meat products.

Aldehydes in meat products mainly come from the oxidative degradation of lipids and the Strecker degradation of amino acids. Its threshold is generally low and makes an important contribution to the overall odor characteristics of meat products^[28]. Group Rat crispy fried spareribs contained specific aldehyde substances such as benzaldehyde with an almond taste, which mainly came from the amino acid Strecker degradation^[29]. Group Lit crispy fried spareribs contained specific aldehyde substances such as (*E*)-3,7-dimethyl-2,6-octadienal, a key aroma component in the seed of *Litsea*, which has a strong lemon flavor, can remove the smell and enhance the flavor^[30].

The thresholds of ketone substances are generally higher, thus having little influence on the overall flavor of crispy fried spareribs, but they have a unique floral and fruity fragrance^[31]. Group Hou crispy fried spareribs contained a specific ketone substance, 2-undecanone, with aroma of citrus oil and *Ruta graveolens*. It naturally exists in *H. cordata* and is an important compound with various biological activities^[6]. In addition, studies have shown that 2-undecanone can induce cell mitosis by inhibiting protein kinase B-mammalian target of rapamycin (Akt-mTOR) signaling, thus playing a protective role in kidney inflammation^[32].

Hydrocarbons have a high sensory threshold and have little impact on the overall flavor of crispy fried spareribs. However, under certain conditions, alkenes can form aldehydes and ketones, which can help improve the overall flavor quality of crispy fried spareribs. β -Myrcene, which has a sweet orange flavor and a fragrant, woody aroma, was detected in all 4 experimental groups^[33]. As one of the main components of many plants, β -myrcene also has antioxidant, anti-inflammatory, and analgesic effects, and its potential health benefits have been demonstrated in many animal experiments^[34].

A small amount of other substances were detected in the experimental group. These substances have a roasted meat flavor

and a nutty, meaty aroma, contributing to the overall flavor of crispy fried spareribs. Specific pyrazine compounds, 2,3-dimethylpyrazine, was detected in group Plu crispy fried spareribs. It is a volatile compound with odor activity that produces high olfactory effects at very low concentrations, giving the crispy fried spareribs a caramelized and meaty flavor. Generally speaking, the Maillard reaction can promote the formation of 2,3-dimethylpyrazine^[35].

In short, the use of natural exogenous additives can increase the types and content of volatile flavor substances, especially hydrocarbon, alcohol, and aldehyde substances, in crispy fried spareribs. The use of different natural exogenous additives endows different groups of crispy fried spareribs with unique volatile flavor substances, thus leading to different flavors of crispy fried spareribs.

3.4.2 Identification of key flavor compounds

Table 3 shows the quantities and criteria for determining key flavor compounds in each group. This study analyzed the ROAV of each group of volatile flavor compounds by using odor thresholds^[36], as shown in Table 4. Hexanal was the key volatile flavor compound with the highest contribution in control group Con, i.e., ROAV = 100.00. *o*-Cymene was the key volatile flavor compound with the highest contribution in group Rat. 1-Octen-3-ol was the key volatile flavor compound with the highest contribution in groups Hou and Plu, while linalool was the key volatile flavor compound with the highest contribution in group Lit. A high ROAV corresponds to a great contribution of the volatile flavor compound to the overall volatile flavor components of crispy fried spareribs.

Table 4 shows a total of 35 volatile flavor compounds with sensory thresholds. Crispy fried spareribs had 17 key flavor compounds ($1 \leq \text{ROAV} \leq 100$), namely 1-octen-3-ol, linalool, 1-hexanol, 1-dodecen-3-ol, (*R*)- $\alpha,\alpha,4$ -trimethyl-3-cyclohexene-1-methanol, nonanal, hexanal, octanal, heptanal, linalyl acetate, geranyl propionate, α -pinene, *o*-cymene, (1*S*,5*S*)-6,6-dimethyl-2-methylenecyclo[3.1.1]heptane, β -myrcene, *p*-cymene, and anethole. These volatile flavor compounds give crispy fried spareribs a unique flavor. Eleven compounds ($0.1 \leq \text{ROAV} < 1$) had an important modification effect on the overall flavor of crispy fried spareribs, namely benzaldehyde, neral, *L*-fenchone, hexanoic acid, *D*-limonene, 4-methylene-1-(1-methylethyl)-bicyclo[3.1.0]hexane, caryophyllene, γ -terpinene, 3-carene, 1-methyl-4-(1-methylethylidene)-cyclohexene, and 1-methyl-3-(1-methylethyl)-benzene. These key flavor compounds and modified flavor compounds constitute the characteristic flavor of each group of crispy fried spareribs. The ROAVs of 1-octen-3-ol, linalool, (*R*)- $\alpha,\alpha,4$ -trimethyl-3-cyclohexene-1-methanol, nonanal, linalyl acetate, α -pinene, *o*-cymene, (1*S*,5*S*)-6,6-dimethyl-2-methylenecyclo[3.1.1]heptane, and β -myrcene in the crispy fried spareribs with rattan pepper were higher than those in the control group. Among them, 1-octen-3-ol, linalool, nonanal, *o*-cymene, and β -myrcene contributed more to the formation of flavor compounds in the crispy fried spareribs, indicating that the

Table 3 Number of key flavor compounds and the judgment criteria in different crispy fried spareribs.

Judgment criteria	Type	Number				
		Con	Rat	Hou	Lit	Plu
$1 \leq \text{ROAV} \leq 100$	Key flavor compounds	3	12	10	9	8
$0.1 \leq \text{ROAV} < 1$	Flavor compounds with modifying effects	2	5	7	9	7
$0 < \text{ROAV} < 0.1$	Potential flavor compounds	0	2	4	2	5

Notes: Rat: rattan pepper group; Hou: *H. cordata* group; Lit: *Litsea* group; Plu: plum group.

Table 4 ROAVs of volatile flavor components in different crispy fried spareribs.

Flavor compound	Flavor description	Threshold value (µg/kg)	ROAV (%)				
			Con	Rat	Hou	Lit	Plu
<i>cis</i> -5-Ethenyltetrahydro- $\alpha,\alpha,5$ -trimethyl-2-furanmethanol	Earthy smell, floral fragrance, woody aroma	6 000		< 0.01	0.01	0.01	< 0.01
1-Octen-3-ol	Mushroom flavor, delicate fragrance, fat aroma	1		38.14	100.00	66.23	100.00
Linalool	Woody aroma, floral fragrance, sweetness, camphoraceous aroma	6		96.58	64.09	100.00	76.62
α -Terpineol	Pine resin fragrance, terpene aroma, woody aroma, floral fragrance	330		0.03	0.01		0.07
1-Hexanol	Alcoholic taste, sweetness	6					2.34
<i>L</i> - α -Terpineol	Pine resin fragrance, terpene aroma, woody aroma, floral fragrance	330					0.09
1-Dodecen-3-ol	Terpene odors	100	1.04				
(<i>R</i>)- $\alpha,\alpha,4$ -Trimethylcyclohex-3-ene-1-methanol	Lilac fragrance	6		2.44			
Nonanal	Rose fragrance, citrus fragrance	1		48.90	46.72	85.71	46.61
Benzaldehyde	Bitter almond aroma	85		0.37			
Hexanal	Fatty aroma, grassy scent, and apple fragrance	4.5	100.00	13.15	41.96	15.93	50.18
Octanal	Citrus fragrance	1			40.15		28.96
Neral	Lemon fragrance	100				0.44	0.14
Heptanal	Fruity aroma	1.8			56.41		
<i>L</i> -Fenchone	Fruity aroma, fresh aroma, woody aroma	110				0.72	0.94
2-Undecanone	Citrus fragrance, aroma of rue plants	3 400			0.03		
Hexanoic acid	Dry cheese flavor	3 000	0.11				
Linalyl acetate	Floral fragrance, fruity aroma	40		3.90	0.70	2.26	0.76
Geranyl propionate	Sweet grape fragrance, rose fragrance	10	38.70				
Estragole	Licorice flavor, fennel aroma	6 300		< 0.01	< 0.01	0.02	0.04
α -Pinene	Pine resin scent	14		4.44		14.47	
<i>o</i> -Cymene	Woody aroma	4		100.00	13.42		
(1 <i>S</i> ,5 <i>S</i>)-6,6-Dimethyl-2-methylenebicyclo[3.1.1]heptane	Pine resin aroma, resin aroma	140		3.30	0.69	0.85	
<i>D</i> -Limonene	Sweet orange flavor, citrus flavors	1 800	0.33	0.31	0.18	0.56	0.34
β -Myrcene	Sweet orange flavor, balsamic aroma, woody aroma	13		23.74	17.91	43.88	22.17
4-Methylene-1-(1-methylethyl)-bicyclo[3.1.0]hexane	Woody aroma, sweetness	980		0.24	0.24	0.33	0.50
Caryophyllene	Woody aroma, clove aroma	64		0.47	0.60	0.91	0.54
γ -Terpinene	Gasoline smell, turpentine smell	1 000		0.29	0.14	0.33	0.08
3-Carene	Lemon flavor, pine resin aroma	770		0.03	0.02	0.12	
1-Methyl-4-(1-methylethylidene)-cyclohexene	Citrus flavor	200					0.10
1-Methyl-3-(1-methylethyl)-benzene	Fruity aroma	800			0.33	0.24	
Camphene	Camphoraceous aroma	26 000				< 0.01	
<i>p</i> -Cymene	Aromatic fragrance	5		85.87	28.34	40.99	
Anethole	Sweet and fragrant flavor	15		8.08	5.53	14.96	26.88
2,3-Dimethyl-pyrazine	Nutty aroma	123					0.09

Notes: Con: control group; Rat: rattan pepper group; Hou: *H. cordata* group; Lit: *Litsea* group; Plu: plum group.

addition of rattan pepper can endow more volatile flavor compounds to the crispy fried spareribs and enhance the sensory experience that they provide. The addition of *H. cordata* resulted in higher ROAVs for octanal and heptanal in crispy fried spareribs than that adding rattan pepper. These two flavor compounds give crispy fried spareribs a unique fruity aroma. In each experimental group, the addition of *Litsea* resulted in higher ROAVs for linalool and nonanal in crispy fried spareribs, while the addition of plum resulted in higher ROAVs for 1-octen-3-ol and anethole in crispy

fried spareribs. The types of key volatile flavor compounds in crispy fried spareribs from different experimental groups varied, which was the one of the main reasons for the differences in their sensory scores.

4 Conclusion

In this study, the effects of different exogenous additives on the physicochemical properties and volatile flavor substances of crispy

fried spareribs were investigated. The addition of rattan pepper, *H. cordata*, *Litsea*, and plum had no obvious effect on the texture characteristics and TBARS value of crispy fried spareribs. However, they had a particular effect on the sensory score of crispy fried spareribs. A total of 91 volatile flavor substances were identified from 5 groups of crispy fried spareribs by using the GC×GC-TOF-MS technique, including 23 alcohols, 13 aldehydes, 13 ketones, 2 acids, 7 esters, 1 ether, 28 hydrocarbons, and 4 other substances. The composition and content of volatile flavor compounds in 5 groups of crispy fried spareribs exhibited considerable differences. 1-Octen-3-ol, linalool, 1-hexanol, 1-dodecen-3-ol, (*R*)- α ,4-trimethyl-3-cyclohexene-1-methanol, nonanal, hexanal, octanal, heptanal, linalyl acetate, geranyl propionate, and several hydrocarbons were identified as the main volatile flavor compounds in crispy fried spareribs. The addition of rattan pepper, *H. cordata*, *Litsea*, and plum can provide crispy fried spareribs with improved flavor substances, thus enhancing their sensory quality. This study did not systematically explore the molecular mechanism of different natural exogenous additives regulating the quality characteristics of crispy fried spareribs, which needs to be explored in the future research.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

This research was funded by the Natural Science Foundation of Sichuan Province-Science and Technology Education Joint Fund Project of Sichuan Province (2024NSFSC2081), the Science and Technology Department of Sichuan Province (2023YFN0015), and Chongqing Municipal Technology Innovation and Application Development Special Key Project (CSTB2023TIAD-KPX0029).

References

- [1] J. Shen, M. Zhang, L. L. Zhao, et al., Schemes for enhanced antioxidant stability in frying meat: a review of frying process using single oil and blended oils, *Crit. Rev. Food Sci. Nutr.* 63 (2023) 5414–5429. <https://doi.org/10.1080/10408398.2021.2019672>.
- [2] L. Rani, M. Kumar, D. Kaushik, et al., A review on the frying process: methods, models and their mechanism and application in the food industry, *Food Res. Int.* 172 (2023) 113176. <https://doi.org/10.1016/j.foodres.2023.113176>.
- [3] P. E. S. Munekata, G. Rocchetti, M. Pateiro, et al., Addition of plant extracts to meat and meat products to extend shelf-life and health-promoting attributes: an overview, *Curr. Opin. Food Sci.* 31 (2020) 81–87. <https://doi.org/10.1016/j.cofs.2020.03.003>.
- [4] S. Dua, Z. F. Bhat, S. Kumar, Effect of oleuropein on the oxidative stability and storage quality of *Tabaq-Maz*, fried mutton ribs, *Food Biosci.* 12 (2015) 84–92. <https://doi.org/10.1016/j.fbio.2015.08.002>.
- [5] H. H. Gao, X. D. Wang, Y. W. Zhang, et al., Effect of temperature, pH, metal ions, and oil type on Chinese quince proanthocyanidins' thermal stability, antioxidant activity, and inhibition of heterocyclic amine formation during simulated frying, *Food Control* 161 (2024) 110406. <https://doi.org/10.1016/j.foodcont.2024.110406>.
- [6] P. H. Deng, S. Teng, Y. Zhou, et al., Effects of basic amino acids on heterocyclic amines and quality characteristics of fried beef patties at low NaCl level, *Meat Sci.* 215 (2024) 109541. <https://doi.org/10.1016/j.meatsci.2024.109541>.
- [7] Q. Q. Yang, Z. R. Wang, X. H. Chen, et al., Evaluation of bitter compounds in *Zanthoxylum schinifolium* Sieb. et Zucc. by instrumental and sensory analyses, *Food Chem.* 390 (2022) 133180. <https://doi.org/10.1016/j.foodchem.2022.133180>.
- [8] S. Zhang, H. X. Zhang, S. Q. Chen, et al., Widely targeted metabolomic deciphers the vertical spatial distribution of flavor substances in *Houttuynia cordata* Thumb, *J. Food Compos. Anal.* 117 (2023) 105102. <https://doi.org/10.1016/j.jfca.2022.105102>.
- [9] D. D. Pu, Y. M. Shan, L. L. Zhang, et al., Identification and inhibition of the key off-odorants in duck broth by means of the sensomics approach and binary odor mixture, *J. Agr. Food Chem.* 70 (2022) 13367–13378. <https://doi.org/10.1021/acs.jafc.2c02687>.
- [10] Y. R. Wang, H. Y. Zhang, J. R. Cui, et al., Dynamic changes in the water and volatile compounds of chicken breast during the frying process, *Food Res. Int.* 175 (2024) 113715. <https://doi.org/10.1016/j.foodres.2023.113715>.
- [11] K. X. Cheng, L. Teng, M. Yan, et al., Effect of cumin on flavor and protein oxidation of roast lamb with different roasting time, *Food Sci. Anim. Prod.* 2 (2024) 9240054. <https://doi.org/10.26599/FSAP.2024.9240054>.
- [12] M. Y. Liu, H. T. Luo, Q. Xiao, et al., Effect of *Latilactobacillus sakei* and *Staphylococcus xylosus* on the textural characteristics of dry fermented sausages, *Food Biosci.* 59 (2024) 103972. <https://doi.org/10.1016/j.fbio.2024.103972>.
- [13] J. Chen, H. W. Ye, H. Li, et al., Effects of temperature fluctuations on the quality and characteristic volatile compounds of large yellow croaker (*Pseudosciaena crocea*) during cold chain logistics, *Food Sci. Anim. Prod.* 2 (2024) 9240057. <https://doi.org/10.26599/FSAP.2023.9240057>.
- [14] W. L. Li, L. T. Zheng, Y. Xiao, et al., Insight into the aroma dynamics of Dongpo pork dish throughout the production process using electronic nose and GC × GC-MS, *LWT-Food Sci. Technol.* 169 (2022) 113970. <https://doi.org/10.1016/j.lwt.2022.113970>.
- [15] J. G. Ruan, Z. C. Wu, J. B. Xu, et al., Effects of replacement partial sodium chloride on characteristic flavor substances of bacon during storage based on GC × GC-MS and non-targeted metabolomics analyses, *Food Chem.* 428 (2023) 136805. <https://doi.org/10.1016/j.foodchem.2023.136805>.
- [16] A. A. Zhong, W. Chen, L. Hu, et al., Characterisation of key volatile compounds in fermented sour meat after fungi growth inhibition, *LWT-Food Sci. Technol.* 165 (2022) 113662. <https://doi.org/10.1016/j.lwt.2022.113662>.
- [17] J. Shi, Y. Q. Nian, D. D. Da, et al., Characterization of flavor volatile compounds in sauce spareribs by gas chromatography-mass spectrometry and electronic nose, *LWT-Food Sci. Technol.* 124 (2020) 109182. <https://doi.org/10.1016/j.lwt.2020.109182>.
- [18] A. Miyagi, Y. Ogaki, Chemical processes in peanut under thermal treatment, *J. Food Meas. Charact.* 8 (2014) 305–315. <https://doi.org/10.1007/s11694-014-9191-6>.
- [19] F. Ježek, J. Kameník, B. Macharáčková, et al., Cooking of meat: effect on texture, cooking loss and microbiological quality: a review, *Acta Vet. Brno* 88 (2019) 487–496. <https://doi.org/10.2754/avb201988040487>.
- [20] Z. C. Wu, J. M. Liu, J. G. Ruan, et al., Formation mechanism of texture characteristics of pork belly during stewing: focusing on the effects of myofibrillar protein modification, *Int. J. Food Sci. Technol.* 59 (2024) 2013–2024. <https://doi.org/10.1111/ijfs.16570>.
- [21] M. A. Ghani, C. Barril, D. J. Bedgood, et al., Measurement of antioxidant activity with the thiobarbituric acid reactive substances assay, *Food Chem.* 230 (2017) 195–207. <https://doi.org/10.1016/j.foodchem.2017.02.127>.
- [22] A. Dhami, A. Singh, D. Palariya, et al., α -Pinene rich bark essential oils of *Zanthoxylum armatum* Dc. from three different altitudes of

- uttarakhand, india and their antioxidant, *in vitro* anti-inflammatory and antibacterial activity, J. Essent. Oil Bear. Plant. 22 (2019) 660–674. <https://doi.org/10.1080/0972060X.2019.1630015>.
- [23] Z. X. Song, J. X. Fang, D. D. Wang, et al., Inhibition of LPS-induced skin inflammatory response and barrier damage via MAPK/NF- κ B signaling pathway by *Houttuynia cordata* Thunb fermentation broth, Foods 13 (2024) 1470. <https://doi.org/10.3390/foods13101470>.
- [24] Y. Liu, H. H. Ren, K. H. Li, *Litsea cubeba* essential oil: extraction, chemical composition, antioxidant and antimicrobial properties, and applications in the food industry, J. Food Sci. 89 (2024) 4583–4603. <https://doi.org/10.1111/1750-3841.17236>.
- [25] D. Zhang, J. M. Liu, J. G. Ruan, et al., Combination of millet pepper and garlic water extracts improves the antioxidant capability of myofibrillar protein under malondialdehyde-induced oxidative modification, LWT-Food Sci. Technol. 174 (2023) 114472. <https://doi.org/10.1016/j.lwt.2023.114472>.
- [26] M. G. Yu, T. Li, S. Y. Wan, et al., Sensory-directed establishment of sensory wheel and characterization of key aroma-active compounds for spicy tallow hot pot seasoning, Food Chem. 405 (2023) 134904. <https://doi.org/10.1016/j.foodchem.2022.134904>.
- [27] Y. X. Jin, X. Y. Yuan, J. F. Liu, et al., Inhibition of cholesterol biosynthesis promotes the production of 1-octen-3-ol through mevalonic acid, Food Res. Int. 158 (2022) 111392. <https://doi.org/10.1016/j.foodres.2022.111392>.
- [28] R. Liang, S. Y. Lin, D. Chen, et al., Differentiation of *Penaeus vannamei* from different thermal processing methods in physico-chemical, flavor and sensory characteristics, Food Chem. 378 (2022) 132092. <https://doi.org/10.1016/j.foodchem.2022.132092>.
- [29] L. J. Cheng, X. Li, Y. T. Tian, et al., Mechanisms of cooking methods on flavor formation of Tibetan pork, Food Chem.: X 19 (2023) 100873. <https://doi.org/10.1016/j.fochx.2023.100873>.
- [30] L. Wang, C. Li, S. Al-Dalali, et al., Characterization of key aroma compounds in traditional beef soup, J. Food Compos. Anal. 114 (2022) 104839. <https://doi.org/10.1016/j.jfca.2022.104839>.
- [31] L. Y. Xia, M. Qian, F. Cheng, et al., The effect of lactic acid bacteria on lipid metabolism and flavor of fermented sausages, Food Biosci. 56 (2023) 103172. <https://doi.org/10.1016/j.fbio.2023.103172>.
- [32] X. Y. Wu, J. Li, S. P. Wang, et al., 2-Undecanone protects against fine particle-induced kidney inflammation via inducing mitophagy, J. Agr. Food Chem. 69 (2021) 5206–5215. <https://doi.org/10.1021/acs.jafc.1c01305>.
- [33] J. H. Song, X. R. Li, P. F. Jiang, et al., Dynamic water migration and flavor analysis of sea cucumber in the process of Sichuan pepper seasoning soak, Food Chem. 459 (2024) 140411. <https://doi.org/10.1016/j.foodchem.2024.140411>.
- [34] S. Surendran, F. Qassadi, G. Surendran, et al., Myrcene-what are the potential health benefits of this flavouring and aroma agent?, Front. Nutr. 8 (2021) 699666. <https://doi.org/10.3389/fnut.2021.699666>.
- [35] J. J. Tang, Z. X. Zhang, S. L. Zheng, et al., Changes of main nutrient components and volatile flavor substances in processing of canned bamboo shoots, Fermentation 7 (2021) 293. <https://doi.org/10.3390/fermentation7040293>.
- [36] J. C. Bi, Y. Li, Z. Yang, et al., Effect of different cooking times on the fat flavor compounds of pork belly, J. Food Biochem. 46 (2022) e14184. <https://doi.org/10.1111/jfbc.14184>.