Food Chemistry: X 26 (2025) 102210

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x

Guiding chili variety selection for Zao chili in Guizhou: Based on a systematic study of sensory, physicochemical, and volatile characteristics

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ARTICLE INFO

Keywords:
Correlation analysis
Fermented chili
Key aroma substances
Processing adaptability
Product quality

ABSTRACT

This work investigated the influence of seven chili varieties in Guizhou on the quality of Zao Chili (ZC), a local traditional fermented chili product. The physical and chemical indicators, volatile components, and product quality of the seven chili varieties and the ZCs were analyzed. Significant differences in physical and chemical properties among the chili varieties substantially affected the quality of ZCs. Chaotian chilies are harder and spicier, have a higher seed/skin ratio and crude fibre content, and lower fruit weight, water content, and reducing sugar content than Erjingtiao chilies. The Erjingtiao chili FQB3 had the highest reducing sugar content (55.296 g/100 g). The ZC produced by FQB3 had the highest comprehensive sensory score (89.7), characterized by high total acid and amino acid nitrogen content and low crude fibre content. There were 181 volatile compounds in the ZCs, including 32 common compounds and 79 differential compounds. More volatile compounds were found in the ZC derived from Erjingtiao chili. The results combined with the OAV analysis indicated that the aroma profile of ZC could be classified into six attributes, comprising 14 key substances, such as β-damascenone and benzaldehyde. In conclusion, the Erjingtiao chili fulfils ZC's processing requirements. These results will serve as a guide in the assessment of ZC quality, the selection of chili processing varieties, and the stabilization of product quality.

1. Introduction

Guizhou is one of the most essential chili production areas in China, with a cultivation area of more than 3.33 billion square meters (Zhang et al., 2024), the largest in the country. Due to its unique “microclimate” conditions, Guizhou has bred wide local characteristic chili varieties with “harmonious spiciness and warm taste,” of which ten characteristic varieties of Guizhou chili have been registered as National Geographical Indications, providing a rich raw material base for Guizhou's characteristic chili products. In China, according to the shape of the fruit, Chaotian chili can be classified into Finger-shaped, Cone-shaped and Round-shaped. Xian chili can be divided into Erjingtiao-shaped, Thin linear-shaped and Screw-shaped. Differences among food raw material varieties determine their processing uses (Mori et al., 2015). Currently, researchers have conducted studies on different varieties of rice (Okada & Yamasaki, 2019), peas (Chen, Lin, et al., 2023), fruits (Portu et al., 2023), etc., in terms of nutrition, functional composition, and processing adaptability. Studies have mainly been conducted in chili on the differences in nutritional and physical properties between varieties and between different processed products (Loizzo et al., 2015). Research on the processing suitability of chili is still in its infancy and is gradually attracting researchers' attention.

Zao chili (ZC) is a unique Guizhou fermented chili pepper food with typical national characteristics and vital historical deposits. It has become one of the soul seasonings of the unique taste of “Guizhou cuisine”, with the perfect fusion of heat and acidity (Fu et al., 2024) and crisp texture, which is very popular with consumers. The crispiness and chili morphology are essential indicators of the quality of ZC and are closely related to the water content, textural characteristics, and crude fibre of the chili fruit. Therefore, in addition to the differences caused by the process, production conditions, and fermentation microorganisms, chili varieties are one of the most important factors influencing the quality of ZC. There are many ZC producers in Guizhou. However, most of them limited themselves to selecting the fruit shape and color of chili

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https://doi.org/10.1016/j.fochx.2025.102210
Received 23 November 2024; Received in revised form 20 January 2025; Accepted 20 January 2025
Available online 23 January 2025

for sensory selection and then entering the subsequent production process without specifying the chili varieties and related physicochemical properties. This results in significant differences between batches of ZC in terms of quality and taste (Chen, Huang, et al., 2024) and the phenomena of excessive water content, skin and flesh separation, and soft and rotten texture, which affect the value of the commodities. In recent years, research on Guizhou fermented chili products has focused on the analysis of volatile and functional components (Xiao et al., 2023; Zheng et al., 2022) and the succession of microbial communities, metabolite changes, and extension of storage time during fermentation (Chen, Zhang, et al., 2024; Ryu et al., 2021). Therefore, selecting raw material varieties that can withstand high-quality ZC processing is an effective measure for producers to stabilize and improve product quality at source. However, there were few reports on screening suitable raw materials for ZC. The effects of different chili varieties on the quality and flavor of ZC have yet to be thoroughly investigated.

This study systematically analyzed and evaluated the sensory characteristics, physicochemical properties, and volatile compositions of different chili varieties and their ZC products in Guizhou. The main aroma compounds of ZC were extracted by calculating the overtly volatile aroma (OAV) values through the threshold of substances and their contents. Meanwhile, the main differential volatile components among different ZCs were determined by statistical methods such as principal component analysis (PCA) and orthogonal partial least squares discriminant analysis (OPLS-DA). The relationships between chili raw material and ZC quality indicators were evaluated using the Spearman correlation. The visual network diagrams of nutritional, sensory, and aroma qualities were constructed to determine the critical indicators of raw chili materials suitable for ZC processing. This study aimed to provide theoretical guidance and technical support for selecting chili varieties for ZC processing and their comprehensive quality evaluation. Research on the processing suitability of chilis holds significant guiding implications for the stabilization of ZC quality.

2. Materials and methods

2.1. Materials

Seven different varieties of fresh red chili (FRC) were obtained from the experimental planting base of the Chili Pepper Research Institute of Guizhou Academy of Agricultural Sciences. FRCs were all ripe and free from pests, diseases, and molds, with specific sample information as shown in Table 1 and Fig. 1. Ginger, garlic, and salt were purchased from the supermarket of Guiyang City, Guizhou Province. The reference standards of capsaicin (≥98 % purity) and dihydrocapsaicin (≥98 % purity) were procured from EXTRASYNTHESE (French) and stored at −18 °C. The analytical grades were anthrone, sucrose, formaldehyde, and caustic soda, which were procured from Shanghai Yi En Chemical Technology Co. High-performance liquid chromatography (HPLC)-grade tetrahydrofuran, methanol were obtained from Sigma-Aldrich (Milan, Italy).

Table 1
Information about chili samples from different chili varieties.

No.	Variety name	Type	Shape	Source origin
FQA9	Qianla 10	Chaotian chili	Round	Fuquan, Guizhou, China
FQB3	Layan 11	Xian chili	Erjingtiao	
FQB5	Layan 101	Chaotian chili	Finger	
ZYQ8	Qianjiao 8	Xian chili	Erjingtiao	Zunyi, Guizhou, China
MJC6	Chaotian chili 6	Chaotian chili	Cone	Majiang, Guizhou, China
DFZJ	Dangfangzhoujiao	Xian chili	Thin-linear	Dafang, Guizhou, China
GYJ3	Longxing 3	Xian chili	Screw	Guiyang, Guizhou, China

2.2. Zao chili (ZC) preparation and collection

The experiment was conducted according to the local standard of Guizhou Province (DB 52/T 982, 2015) for treating FRCs. The FRCs were selected to be intact and free of pests, diseases, molds, and rotting. Then, they were de-stalked, washed, drained, and chopped into small pieces of approximately 0.5 cm^2. Subsequently, they were placed into a clean ceramic altar with 10 % salt added based on the mass proportion of chilies, and one-fifth of the space was reserved. 30 mL of edible oil was poured onto the surface of the chilies. The altar was sealed with water and stored in a fermentation chamber at 28 °C for 30 days. The water around the altar was replaced every 7 d. After the fermentation, samples were stored at −80 °C for subsequent analysis.

2.3. Detection of essential substances

2.3.1. Seed/skin ratio and fruit shape index

Ten chili fruits were randomly collected for each variety. Fruit characteristics such as fruit length, fruit outer diameter, fruit weight, seed weight, and flesh thickness were measured and recorded using calipers and an electronic analytical balance, and the measured values were averaged. Each chili variety's seed/skin ratio and fruit shape index (Tchokponhoué et al., 2020) were also calculated using eqs. (1) and (2), respectively.

$$\text{Seed}\Big/\text{skin ratio} = \frac{m_{Seed}}{m_{Total} - m_{Seed}} \times 100\% \quad (1)$$

$$\text{Fruit shape} = \frac{\text{Fruit length}}{\text{Fruit outer diameter}} \quad (2)$$

2.3.2. Hardness and color

Hardness determination (Mondal et al., 2022): Ten randomly selected chili samples of each variety were tested three times on a texture tester (FTC, 1LC-S1000N, America). A 6 mm diameter TMS6 cylindrical probe was used for Texture Profile Analysis (TPA) with the following parameters: pre-test rate 60 mm/min; test rate 60 mm/min; post-test rate 60 mm/min; test depth 60 %; trigger force 0.2 N; load range 25 N.

Color determination: Ten samples of chili were randomly obtained from each variety for determination. The upper, middle, and lower parts of each sample were measured once using a colorimeter (HunterLab, USP2194 UltraScan PRO, America) and expressed as L* (light/dark), a* (red/green), and b* (yellow/blue), respectively. The ZCs were broken up, mixed in a blender, and put into transparent sealed bags for color determination using the fresh fruit determination method.

2.3.3. Detection of chemical indexes

Water content was determined by direct drying according to the GB 5009.3, 2016. Total acid content was determined by the pH meter point titration method according to the GB 12456, 2021. Amino acid nitrogen content was determined by the acidometer method according to the GB 5009.235, 2016. Reducing sugar content was determined using the direct titration method of the GB 5009.7, 2016 with slight modifications. The spiciness value was determined according to the GB/T 21266, 2007. Fat was extracted using the Soxhlet method according to the GB 5009.6, 2016. Protein was determined using the Kjeldahl method in GB5009.5, 2016. Crude fibre content is determined by the GB/T 5009.10, 2003.

2.4. GC–MS analysis of the volatile composition in ZC

The detection method was slightly improved by referring to Li et al. (2023).Weight 5 g sample of ZC into a 20 mL headspace vial, and add 20 μL 2-octanol (1 μg/μL) as internal standard. Based on the qualitative

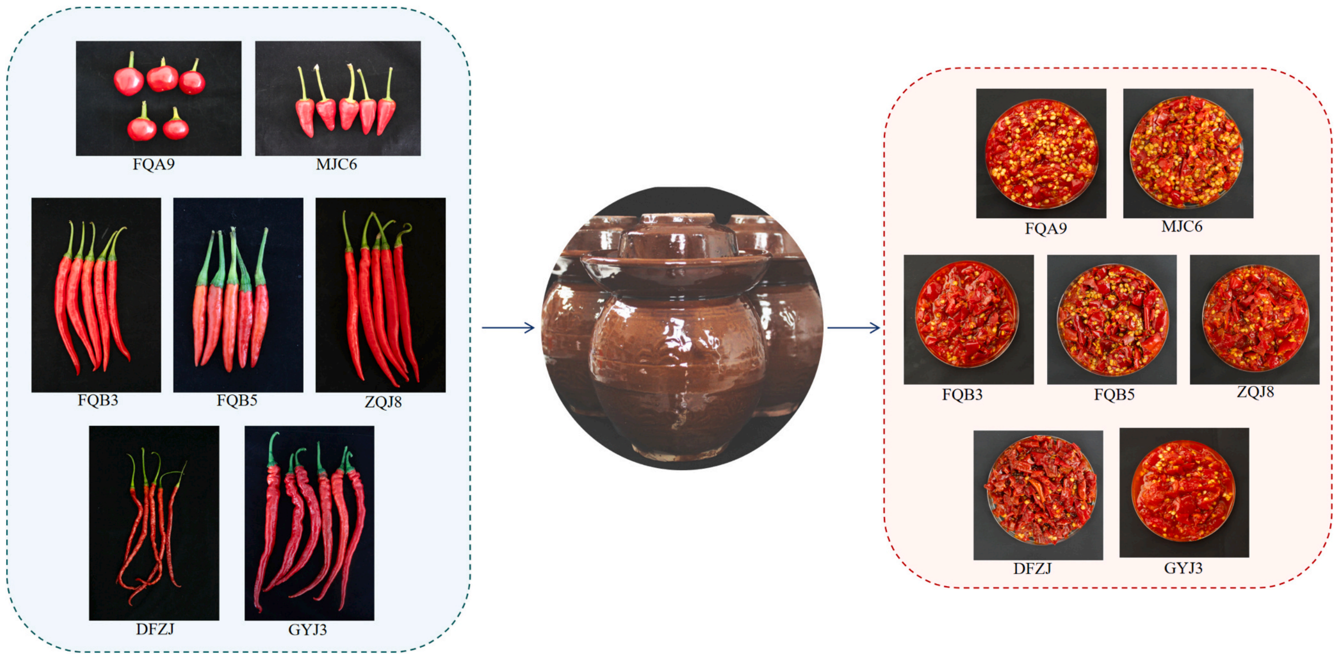

Fig. 1. Photos of seven types of fresh red chilis and their *Zao Chilis* counterparts. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

results, a semi-quantitative analysis of the volatile components was performed using the internal standard method (20 μL, 1 μg/μL 2-octanol). The semi-quantitative analysis was calculated concerning Eq. (3) and Eq. (4).

$$C_i\ (\mu g/g) = \frac{A_i \times m_B}{B \times m} \tag{3}$$

$$OAV = \frac{C_i}{C_{io}} \tag{4}$$

Ci: concentration of identified compounds (μg/g), OAV: Odor activity value, A_i: peak area of substance i, B: peak area of internal standard, m_B: amount of internal standard added (g), m: sample mass (g), C_{io}: aroma threshold of identified compounds.

2.5. Sensory evaluation of ZC

The sensory evaluation was carried out using the method of Zhu et al. (2023). Twenty-five members underwent 10 days of sensory training (20 min per day), and ten sensory judges (half men and half women, aged (26–38) were selected from the candidates for sensory evaluation. Fermented and matured ZC samples were placed in tasting cups of 10 g ZC each, which were tightly sealed and randomly labeled with a three-digit code. Before tasting each sample, panelists rinsed their mouths with water, tasted the samples with chopsticks, and rated them according to the sensory evaluation criteria (Table 2). The panelists worked independently. The sensory assessment room was approximately 12 square meters, with a temperature of 22 °C and a humidity of 55 %, using 5500 K LED lights.

2.6. Statistical analysis

All results are expressed as mean ± standard deviation (n = 3). Analysis of variance (ANOVA) and Duncan's multiple extreme variance test were performed using IBM SPSS 26 software. PCA and OPLS-DA were performed using SIMCA 14.1 software. Correlation analyses such as Spearman and radar plots were plotted online using the CNS platform (https://cnsknowall.com/#/HomePage). The network model was visualized using Cytoscape 3.7.2 software.

Table 2
Sensory standards for *Zao Chilis*.

Indicators	Sensory Descriptions	Scores
Color (20 points)	Uniform and consistent, with the red color expected of a bright red chili and shiny	16–20
	Darker in color with some gloss	6–15
	Dark or deep red, with poor gloss	0–5
Morphology (30 points)	chili tissue with no skin separation, good integrity, moderate seed/skin ratio, and harmonious soup ratio	25–30
	chili tissue has little skin separation, good integrity, more or less seeds, and more or less soupy	16–24
	Some chili tissues have separated skin and flesh, poor integrity, too many or too few seeds, and too much or too little broth	6–15
	Much of the chili tissue is separated from the skin and flesh, and the tissue is soft and misshapen	0–5
Aroma (20points)	With the characteristic fermented odor of ZC, no off-flavors	16–20
	Fermented aroma is strong or light but poorly balanced, slightly off-flavored	6–15
	Disorderly odor, no characteristic ZC aroma, pronounced off-flavor	0–5
Taste (30 points)	Pure acidity, crunch ratio very good, no off flavors, medium spiciness	25–30
	Pure acidity, good crunch, no off-flavors, moderately spicy	16–24
	Heavier or lighter acidity, good crunch, slightly mixed flavor, more spicy	6–15
	Too much or too little acidity, soft texture, no fresh flavor, mixed flavor	0–5

3. Results and discussion

3.1. Physicochemical characterization of FRC

3.1.1. Fruit traits and physical indicators

As the primary raw material of ZC, the fruit traits and physical indexes of chili significantly impact the appearance and other characteristics. The overall data presented in Table 3 demonstrate significant differences in the fruit traits and physical indexes of the seven types of

Table 3
Physical indicators of FRCs.

No.	Fruit traits indicators					Physical indicators				
	Single-fruit mass (g)	Skin-flesh thickness (mm)	Seed weight (g)	Seed/skin ratio (%)	Fruit shape index	Water content (%)	Hardness (N)	L*	a*	b*
FQA9	14.005 ± 0.281^{d}	3.368 ± 0.065^{d}	2.235 ± 0.065^{e}	18.989 ± 0.501^{c}	0.842 ± 0.014^{a}	67.728 ± 0.000^{c}	9.994 ± 0.232^{f}	40.815 ± 0.996^{d}	42.647 ± 1.280^{b}	25.703 ± 1.796^{d}
FQB3	10.091 ± 0.215^{c}	1.593 ± 0.063^{c}	0.689 ± 0.063^{a}	7.076 ± 0.331^{a}	11.868 ± 0.266^{d}	80.374 ± 0.000^{e}	7.456 ± 0.105^{c}	37.571 ± 0.480^{c}	39.440 ± 0.950^{b}	22.323 ± 1.037^{bc}
FQB5	2.945 ± 0.14^{a}	0.983 ± 0.033^{a}	0.672 ± 0.033^{a}	31.834 ± 0.811^{e}	5.791 ± 1.266^{c}	67.232 ± 0.002^{b}	9.324 ± 0.164^{e}	35.673 ± 0.403^{b}	33.452 ± 2.192^{a}	20.222 ± 0.649^{b}
ZYQ8	14.605 ± 0.307^{e}	1.532 ± 0.031^{c}	0.914 ± 0.031^{b}	11.468 ± 0.650^{b}	8.019 ± 2.266^{d}	80.562 ± 0.002^{e}	7.792 ± 0.132^{c}	37.872 ± 0.473^{c}	42.617 ± 0.674^{b}	24.248 ± 0.585^{cd}
MJC6	4.84 ± 0.28^{b}	1.316 ± 0.028^{b}	0.897 ± 0.028^{b}	24.638 ± 1.223^{d}	2.171 ± 3.266^{b}	62.564 ± 0.002^{a}	8.710 ± 0.093^{d}	34.520 ± 0.344^{ab}	34.582 ± 0.491^{a}	17.028 ± 0.307^{a}
DFZJ	12.428 ± 0.169^{d}	1.267 ± 0.034^{b}	1.901 ± 0.034^{d}	19.264 ± 1.901^{c}	23.444 ± 4.266^{f}	76.408 ± 0.001^{d}	6.156 ± 0.111^{b}	33.918 ± 0.308^{a}	34.862 ± 0.476^{a}	15.592 ± 0.355^{a}
GYJ3	31.122 ± 0.822^{f}	1.073 ± 0.014^{a}	1.484 ± 0.014^{c}	9.646 ± 0.270^{ab}	11.876 ± 5.266^{e}	83.682 ± 0.001^{f}	5.325 ± 0.046^{a}	39.060 ± 0.425^{c}	42.345 ± 1.025^{b}	25.313 ± 0.685^{d}
Relative standard deviation (%)	49.049	48.885	61.418	50.677	84.966	11.010	17.744	6.890	18.604	10.828

Different lower case letters in the same column indicate significant differences ($p < 0.05$).

chili ($p < 0.05$). The relative standard deviations of all indicators were greater than 10 % except L*. The relative standard deviations of the fruit shape index and seed weight were as high as 84.966 % and 61.418 %, respectively. GYJ3 exhibited the highest quality of single fruit (31.122 g), significantly different from the other chilies ($p < 0.05$). The single-fruit mass of finger-shaped and conical-shaped Chaotian chilies was not more than 5 g. The FQA9 exhibited a higher skin-flesh thickness than the other chilies ($p < 0.05$) at 3.368 mm, more than twice that of the other varieties. No significant difference ($p < 0.05$) was noted in the skin-flesh thickness between FQB3 and ZYQ8.

The seed/skin ratio of chili strongly influences the sensory quality of ZC and is closely related to seed weight and quality of individual fruits. Chili seeds are rich in leucine and sulfur amino acids (Cvetković et al., 2022) and are food ingredients with high processing potential. The seed/skin ratio of the Chaotian chili was generally higher than that of the Xian chili. The finger-shaped Chaotian chili FQB5 exhibited the highest seed/skin ratio of 31.834, approximately 4.5 times higher than the Erjingtiao chili. Significant differences ($p < 0.05$) in seed/skin ratios among round, finger, and cone-shaped Chaotian chili. The Chaotian chili has a high content of seeds characterized by a high content of oil and protein, which is particularly suited to producing fried products such as oil chilies and chili powder.

The fruit shape index represents a pivotal indicator for the analysis of chili (Naegele et al., 2017). It is observed that elevated values lead to the development of fruits with greater elongated characteristics. The fruit shape index exhibited a significant difference ($p < 0.05$) among the Chaotian chilies, with FQA9 displaying the smallest value (0.077). No significant difference was observed between the FQB3 and ZYQ8 varieties of Xian chili, which exhibited the characteristics of the Erjingtiao chili. The DFZJ displayed the highest fruit shape index (23.444), with a thinner skin and flesh and a higher seed count, rendering it a suitable candidate for raw material for dried chili.

The water content of the chili fruits impacted the morphology of the ZC. The water content of Xian chili was found to be higher than that of Chaotian chili.The highest water content was GYJ3 (83.682 %), while the lowest was MJC6 (62.564 %). The water content of the Xian chili was found to be above 75 % in all cases, while the water content of the Chaotian chili was found to be below 70 % in all cases. These results were differed significantly from the other samples ($p < 0.05$). Hardness is an essential indicator of fruit quality and product morphology (Gwanpua et al., 2014). Chilies with higher hardness are more resistant to storage and are less likely to soften during fermentation, which indicates ZC with less exhibition of skin and flesh separation. The hardness of Chaotian chili was higher than that of Xian chili. The hardness of all the Chaotian chili was higher than 8.7 N, and the hardness of the Xian chili was lower than 7.8 N. The two Erjingtiao chilies, FQB3 and ZYQJ8, were identified as the two most resilient varieties of Xian chilies, with no statistically significant differences ($p > 0.05$) observed between them. All the other varieties showed significant differences ($p < 0.05$).

L*, a*, and b* were used to evaluate the color of chilies (Li et al., 2024). The highest L*, a*, and b* values were observed in FQA9, which also exhibited significantly different L* (40.815) and a* (42.647) values compared to the other varieties ($p < 0.05$). The a* values of DFZJ, FBQ5, and MJC6 were not higher than 35, which were not significantly different from each other ($p > 0.05$) but significantly lower than the other varieties ($p < 0.05$).

The seven varieties of chili exhibited notable differences in fruit traits, with less variation observed in physical parameters. To meet the requirements for raw materials in ZC, chili with relatively high skin thickness, hardness, a* value, and a medium seed/skin ratio are required. The FQA9 variety exhibits elevated skin thickness and hardness, accompanied by a high seed/skin ratio. This result is analogous to chili Guota 166 (Chen et al., 2022). According to the literature (Zhou et al., 2024), the characteristics of screw chilies include a thin exocarp, thick flesh, and crispy flesh, and they are primarily used as fresh food. In contrast, the screw chili GYJ3 exhibited higher epidermal thickness but lower hardness and higher water content, which is in agreement with the report. These characteristics render them unsuitable as raw materials for ZC processing. Studying various chili indicators can provide a scientific basis for selecting raw materials for ZC, thus improving its quality and market competitiveness.

3.1.2. Physicochemical indexes of FRC

The physicochemical indices of chilies have a direct and critical influence on the flavor quality of ZC. Overall (Table 4), the physicochemical indices of chili fruits varied significantly among varieties, with a relative standard deviation (RSD) greater than 10 %, and the RSD of the heat value was as high as 86.706 %.

Organic acids represent a significant source of aromatic compounds in the examined samples. The total acid content was an essential indicator of chili quality (Chen, Niu, et al., 2023). As demonstrated in the study by Ortiz et al. (2020), a positive correlation was identified between total acids and disease resistance in chili. The total acid content of Xian chilies was lower than that of Chaotian chilies, with MJC6 (0.233 g/100 g) exhibiting the highest content and GYJ3 (0.121 g/100 g) the lowest. This discrepancy may be attributed to the water content of the chilies, with higher water content levels displaying lower total acidity. It suggests that Chaotian chilies have better disease resistance than Xian

Table 4
Physicochemical indexes of different chili varieties.

No.	Fresh sample			Dry basis conversion		
	Total acid (g/100 g)	Amino acid nitrogen (g/100 g)	Reducing sugar (g/100 g)	Spiciness value	Fat (g/100 g)	Crude fibre (%)
FQA9	0.211 ± 0.008^{cd}	0.067 ± 0.003^{c}	49.378 ± 0.172^{e}	202.550 ± 0.331^{b}	12.426 ± 0.161^{c}	20.622 ± 0.063^{d}
FQB3	0.137 ± 0.001^{a}	0.053 ± 0.001^{a}	55.296 ± 0.174^{g}	162.709 ± 2.231^{e}	10.375 ± 0.060^{a}	17.927 ± 0.046^{b}
FQB5	0.195 ± 0.003^{c}	0.065 ± 0.001^{c}	46.334 ± 0.044^{d}	601.506 ± 2.387^{g}	12.670 ± 0.148^{cd}	23.695 ± 0.025^{e}
ZYQ8	0.161 ± 0.003^{b}	0.062 ± 0.001^{b}	53.896 ± 0.097^{f}	126.577 ± 0.923^{c}	11.596 ± 0.109^{b}	17.862 ± 0.028^{b}
MJC6	0.233 ± 0.008^{d}	0.080 ± 0.001^{d}	42.391 ± 0.114^{b}	188.897 ± 1.057^{d}	15.659 ± 0.141^{f}	27.547 ± 0.056^{f}
DFZJ	0.199 ± 0.015^{c}	0.083 ± 0.001^{d}	44.356 ± 0.100^{c}	65.777 ± 1.342^{a}	12.890 ± 0.132^{de}	20.395 ± 0.023^{c}
GYJ3	0.121 ± 0.008^{a}	$0.088 \pm 0.002e^{e}$	33.118 ± 0.119^{a}	105.851 ± 0.637^{f}	13.197 ± 0.161^{e}	16.667 ± 0.026^{a}
Relative standard deviation (%)	22.786	17.962	16.246	86.706	12.766	18.520

Different lower case letters in the same column indicate significant differences ($p<0.05$).

chilies due to low water content and high total acid, consistent with the study reported (Liu et al., 1998). Amino acid nitrogen is closely correlated with protein (Kim et al., 2017), indirectly indicating free amino acids. The amino acid nitrogen content of the different chilies ranged from 0.053 g/100 g to 0.088 g/100 g. GYJ3 exhibited the highest content and significantly differed from the other samples ($p < 0.05$). The amino acid nitrogen content of the Erjingtiao chilies (ZYQ8, FQB3) was found to be comparatively low, with a maximum content of 0.065 g/100 g. This result was significantly different from the amino acid nitrogen content of other chili varieties ($p < 0.05$). It has been demonstrated that reducing sugars significantly impacted the growth of microorganisms and were readily utilized in fermentation (Lu et al., 2024). Significant differences ($p < 0.05$) were observed in reducing sugars among the different chilies, with FQB3 (55.296 g/100 g) exhibiting the highest content and GYJ3 (33.118 g/100 g) the lowest. Overall, Xian chili exhibited a higher concentration of reducing sugars than Chaotian chili, which was consistent with the findings of Wei et al. (2024). Furthermore, the reducing sugar contents of FQB3 and ZYQ8 were higher than those of the other chilies ($p < 0.05$), indicating that Erjingtiao chilies may be more suitable as raw materials for fermented chilies. The spiciness values were positively correlated with the spiciness of ZC, with capsaicin identified as the primary source of spiciness (Liu, Deng, Li, et al., 2024). Significant differences were observed in the spiciness values of the different chilies ($p < 0.05$). The spiciness values of the Chaotian chili were generally higher than those of the Xian chili varieties, which agrees with the findings of Zhang, Hu, et al. (2022). The highest spiciness value of FQB5 (601.506) was 9.1 times higher than that of DFZJ. The fat and crude fibre contents were closely related to the flavor and texture of ZC. The crude fibre content of Chaotian chili was higher than that of Xian chili. MJC6 exhibited the highest fat (15.659 g/100 g)and crude fibre content (27.547 %), which differed significantly from the other samples ($p < 0.05$). The fat content of FQB3 (10.357 g/100 g) and the crude fibre content of GYJ3 (16.667 %) were relatively low and differed significantly from the other varieties ($p < 0.05$).

The results demonstrate significant differences between the physicochemical indexes of Chaotian and Xian chilies. The Chaotian chili exhibits elevated levels of total acid, spiciness, fat, and crude fibre, while water content and reducing sugar are present in relatively low quantities. Xian chili varieties exhibit significant inter-varietal differences. The water, amino acid nitrogen, and fat content of the Xian chili is higher than that of the Xian chili and the Erjingtiao chili. Erjingtiao chili displays minimal variation in physicochemical indexes, making it a suitable raw material for fermented chili due to its high sugar and low crude fibre content. This result is conducive to the enrichment of advantageous microorganisms and the increase of acid substances.

3.1.3. Correlation analysis among FRC quality indicators

The complex and meaningful relationships between physical characteristics and physicochemical attributes of diverse varieties of chilies are elucidated in Fig. 2. The Spearman's correlation coefficient analysis demonstrated that fruit weight (Fig. 2A) exhibited a highly positive correlation with several indexes, such as skin and pulp thickness, seed weight, fruit shape index, and water content ($p < 0.05$), with the highest correlation coefficient ($r = 0.777$) with seed weight. The results of correlation analysis suggest that an increase in fruit weight is accompanied by a thickening of the pulp, which provides more space and nutrients for the seeds to develop, increasing seed weight (Tilen et al., 2021). Additionally, there is a potential tendency for the fruit shape to become more elongated. However, fruit weight was significantly negatively correlated with seed/skin ratio, firmness, spiciness, and crude fibre ($p < 0.05$).

There was a positive correlation ($p < 0.05$) between hardness and spiciness value ($r = 0.911$), crude fibre ($r = 0.729$), total acidity, seed/skin ratio, and reducing sugar (Fig. 2B). In addition, there was a significant negative correlation ($p < 0.05$) between hardness and fruit shape index ($r = -0.890$), fruit weight, moisture content, and amino acid nitrogen Crude fibre constitutes a structural component of the plant cell wall, providing mechanical support to the cell. Correlations have been demonstrated between crude fibre and hardness (Maleki et al., 2016), which is consistent with the results of this study. Capsaicin is found in the cell vesicles (Cervantes-Hernández et al., 2019). It is better preserved in the intact cell wall. The above evidence explains that Chaotian chilies are spicier, harder, and contain more seeds than Xian chilies. Research shows that fermentation softens chilies (Han et al., 2025). This result is due to pectinase and cellulase in chilies, which break down pectin and cellulose during fermentation, softening the chilies (Xu et al., 2021). Furthermore, microbial metabolism produces enzymes that break down pectin, protein, and sugars in the chilies (Kazerooni et al., 2021).

The chili seed/skin ratio (Fig. 2C) was found to be correlated with the majority of the indicators, thereby demonstrating that this indicator plays an essential role in evaluating chili quality. The seed/skin ratio was found to be positively correlated with crude fibre ($r = 0.811$), total acid ($r = 0.764$), hardness, fat, and spiciness ($p < 0.05$) and negatively correlated with reducing sugar skin-flesh thickness, fruit weight, and water content ($r = -0.796$) ($p < 0.05$). Chili varieties with higher seed/skin ratios exhibited a grainy and pungent taste, attributable to their high seed content. In contrast, varieties with high skin-flesh ratios

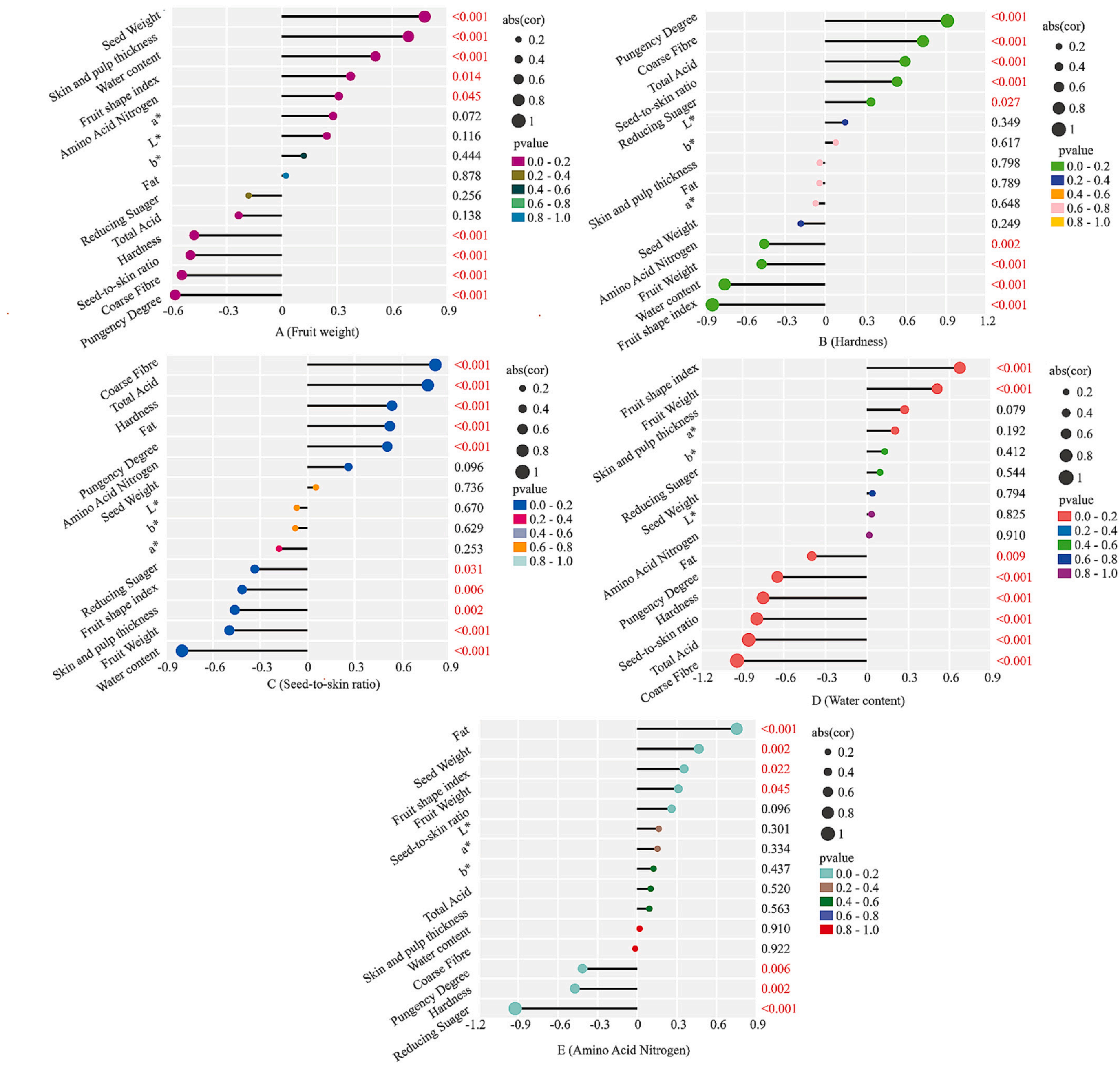

Fig. 2. Correlation of physicochemical indexes of fresh red chilis. The size of the circles in the chart indicates the strength of the correlation, with positive horizontal coordinates representing positive correlation and negative values representing negative correlation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

displayed low crude fibre, high water content, and a crisper, smoother taste. Xian chilies fit those characteristics. This phenomenon aligns with the observation that Chaotian chili is generally spicier than Xian chili and is consistent with the findings of Chen et al. (Chen, Huang, et al., 2024).

The water content (Fig. 2D) was found to be significantly and positively correlated ($p < 0.05$) with fruit weight ($r = 0.510$) and fruit shape index ($r = 0.637$) and negatively correlated ($p < 0.05$) with crude fibre, total acid, seed/skin ratio, firmness, spiciness, and crude fat. A significant negative correlation was observed between water content and fruit firmness ($r = -0.750$), which can be attributed to the influence of water content on cell structure and pectin substances, among other factors (Heristika et al., 2023). A higher water content results in cells that are full and loose in structure, thereby reducing the likelihood of pectin and other substances adhering tightly to the cells, reducing the hardness of chilies.

A significant positive correlation was observed between amino acid nitrogen (Fig. 2E) and fat ($r = 0.753$), seed weight, and fruit weight ($p < 0.05$), indicating that fruits with higher amino acid nitrogen typically exhibit higher fat content. The seeds of chilies are rich in protein, which is reflected in the prominence of amino acid nitrogen in the fruits, suggesting that chilies with a higher seed count have a higher fat and amino acid content, which is in line with the findings of Ananthan et al. (2018). Consequently, the Chaotian chili is well-suited to producing dried chili products.

By analyzing the correlation of the indicators, we clarified the complex relationship between the indicators of chili fruits. Chaotian chili was higher and positively correlated with crude fibre, total acid, spiciness, and hardness, while Xian chili was outstanding in terms of fruit weight, water content, and reducing sugar. These relationships contribute to a deeper understanding of chili quality characteristics and provide a scientific basis for agricultural improvement and food processing. For example, when choosing fresh chili varieties, it is necessary to consider varieties with a moderate seed/skin ratio and good taste. In contrast, for processing chili raw materials, choosing chili with an appropriate seed/skin ratio according to the product requirements is necessary to improve processing efficiency and product quality.

3.2. ZC quality characteristics analysis

3.2.1. Sensory characterization of ZC

Differences in raw food materials directly influence the organoleptic quality of processed products (Jacob et al., 2024). The results showed that ZC processed from different chili varieties varied considerably in color, morphology, odor, and taste (Fig. 3). Color scores often correlate with chili maturity and pigment content (e.g., carotenoids and anthocyanins) (Matsufuji et al., 2007). FQA9 scored up to 18.9, with a bright red color and glossy ZC, significantly different from the other groups ($p < 0.05$). The highest a* value for fresh fruit and the highest color score for the ZC were observed in FQA9, which further supports the hypothesis that the color of fresh fruit can directly impact the color of their products. FQB3 (16.545) and ZYQ8 (17.000) had a similar color performance with insignificant differences ($p>0.05$). The ZC made by FQB5 and DFZJ were characterized by a dark red hue and received lower scores of 5.636 and 3.636, respectively. Regarding morphology, the two groups of FQB3 and ZYQ8 had obvious advantages, with no skin/flesh separation of chili tissues and coordinated seed/skin ratios and soup ratios, which differed significantly from the other groups ($p < 0.05$). FQB5 (9.909) and DFZJ (10.364) scored lower with insignificant differences ($p>0.05$) but differed significantly from the other groups ($p < 0.05$). The analysis revealed that after processing, fresh fruits with thin flesh, high seed/skin ratio, or high water content are prone to problems such as skin/flesh separation. Chili aroma is related to the composition of volatile compounds (e.g., phenols, aldehydes, esters) (Rodríguez-Burruezo et al., 2010). The FQA9, FQB3, ZYQ8, and DF57 groups performed well, with high and non-significant differences in scores ($p>0.05$), with no participant achieving a score below 17 points. Erjingtiao chili had high aroma scores with distinctive fermented flavor and intense sourness. The Chaotian chili group (FQB5 and MCJ6) had lower odor scores of 15.455 and 13.818 due to more seeds and a high seed/skin ratio. Mouthfeel was influenced by the chemical composition and fermentation process of chili involving a spicy-sweet-bitter-sour balance. Erjingtiao chili (ZYQ8, FQB3) and Zhuzi chili (FQA9) made ZC popular with high scores of 28.455, 25.909, and 25.545, respectively, and the difference between ZYQ8 and the other groups was significant ($p < 0.05$). FQB5 (finger-shaped Chaotian chili) was scored at only 9.3 points due to the rough and uncrisp texture with many seeds and thin skin.

Overall, the Erjingtiao chilies demonstrated robust performance, with FQB3 and ZYQ8 scoring 89.727 and 89.545 points, respectively. The FQA9 was awarded 81.545 points, with 18.455 points allocated for color and 25.545 points for taste. The finger-shaped, conical-shaped Chaotian chili received low scores due to issues with the seed/skin ratio or the skin/flesh ratio, with scores of 40.273 points, respectively. The conical-shaped chili MJC6 is distinguished by its thick skin and flesh, earning it 67.273 points. Screw-shaped chili GYJ3 has a total score of 74.364, and the soup is observed to be layered due to its high water content. DFZJ obtained the lowest score of 44.727 among Xian chilies due to its thin skin and pulp thickness, high seed/skin ratio, and dark red color. The evaluation of sensory qualities is paramount in assessing the samples' overall quality. The results presented herein provide a basis for the selection of chili varieties and product improvement and facilitate

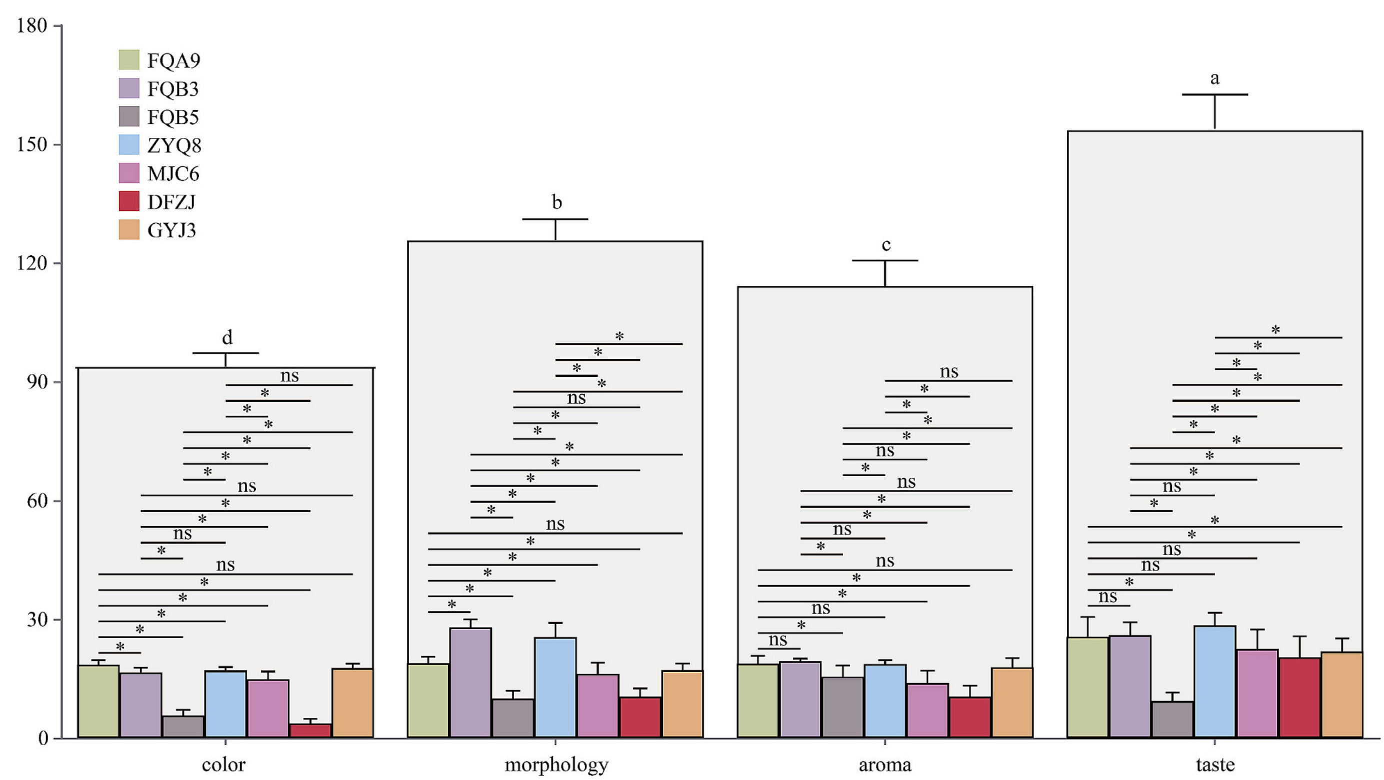

Fig. 3. Sensory scores of *Zao Chilis* from different cultivars. Different colors in the chart indicate different samples, error bars indicate a standard error. * means $p < 0.05$, ns means the difference is not significant.

the production of ZC products that better meet consumer needs. A comprehensive investigation into the correlation between chili varieties and the sensory quality of ZC products can facilitate a more accurate understanding of market demand, enhance product quality and competitiveness, and stimulate the advancement of related industries. Furthermore, this approach offers a valuable foundation for further research in chili processing technology and quality control, propelling innovation and progress within the industry.

3.2.2. Physicochemical indexes of ZC

The physicochemical properties of ZC produced from different chili varieties vary significantly (Fig. 4), which profoundly affects their flavor, texture, and culinary applications. From the perspective of microbial metabolism, the production of lactic acid and citric acid results in a decrease in pH and an increase in total acidity (Liu, Deng, Hou, et al., 2024; Wang et al., 2022). This result leads to a slightly acidic pH of 4.4–5.2 for each group of ZC. The ZCs produced by FQB3 and ZYQ8 exhibited the lowest pH levels of 4.403 and 4.643, respectively, and the highest total acid content, nearing 1.5 g/100 g, which was 2.2 times higher than that of GYJ3. These results differed significantly ($p < 0.05$) from the other groups. This finding indicates the high total acid content and adequate fermentation of Erjingtiao chili as a raw material for producing ZC. Free amino acids and peptides were produced during fermentation by microbial decomposition of fresh chili proteins (Yuan et al., 2024), increasing amino acid nitrogen content in all groups. The amino acid nitrogen content of Chaotian chili was higher than that of Xian chili before fermentation, and the content of all groups increased 3.6–6.9 times after fermentation. This result further confirms that fermentation favors the accumulation of amino acids, which is consistent with the findings of Li et al. (2024). The difference between Chaotian chilies (FQA9, FQB5) and Xian chilies (FQB3, DFZJ) was not significantly different from the other groups, with a content of around 0.37 g/100 g. All groups showed a decrease in reducing sugar content after fermentation, with FQB5 showing a smaller decrease of 57.986 %, significantly different from the other groups ($p < 0.05$). All the other groups demonstrated a minimum of 65 % decrease in reducing sugars, with ZYQ8 exhibiting the most significant decrease of 78.591 %. These results underscore the hypothesis that microorganisms utilize sugars for metabolism and fermentation during the fermentation process. A comparison of the pre-and post-fermentation changes in crude fibre content

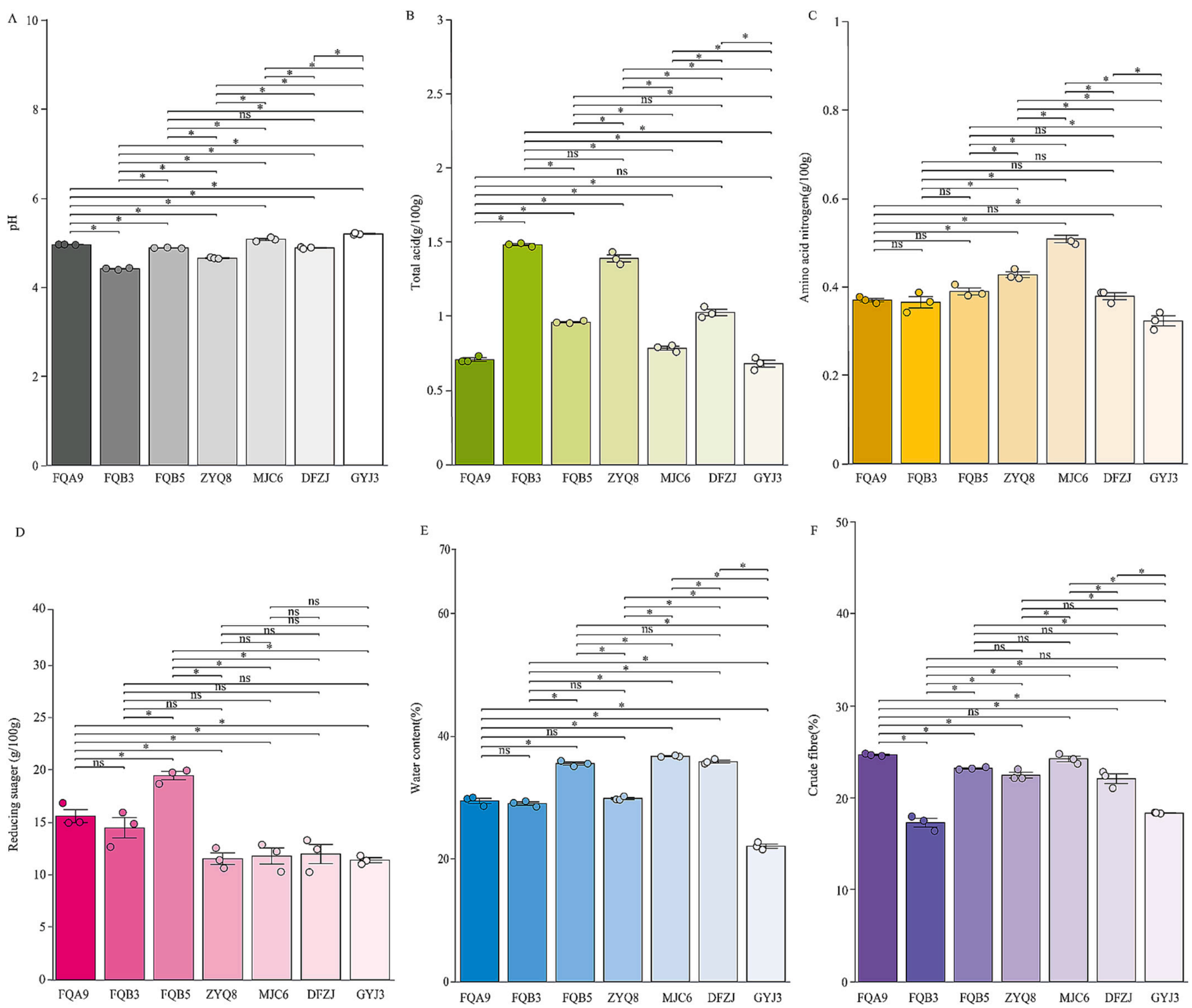

Fig. 4. Physicochemical indexes of *Zao Chilis* from different cultivars.(A) pH, (B) total acid, (C) amino acid nitrogen, (D) reducing suager, (E) water content, (F) crude fibre. Error bars indicate standard error and lower case letters represent variability. * means $p < 0.05$, ns means the difference is not significant.

revealed minimal disparities among the groups, except FQB3, FQB5, and MJ6, which exhibited a decline in fibre content post-fermentation. The FQB3 had a markedly reduced crude fibre content of approximately 9.093 %, contributing to enhanced palatability. During fermentation, microorganisms decomposed crude fibre and used sugar for growth and reproduction. The new substances produced during this process reduced the water content, as Shirai et al. (Shirai et al., 2001) found. The water content of the chili was reduced to less than 37 % after making ZC. The decrease in Xian chilies was higher than that of Chaotian chilies, with a decrease of 73.513 % in GYJ3. This result was attributed to the crushing of the chili fruits and the addition of salt during the process of ZC, which increased cellular osmotic pressure and exudation of cytosol.

In conclusion, the ZCs from FQB3 and ZYQ8 exhibited distinctive characteristics. The two groups of ZCs were characterized by high total acid content and amino acid nitrogen content, low crude fibre content, and moderate water content. This result was attributed to the high sugar content of Erjingtiao chili, which provided optimal conditions for microbial metabolism. Furthermore, understanding these differences can facilitate the selection of appropriate chili varieties to achieve the desired fermentation characteristics, enhance the quality and consumer acceptance of ZC, and provide a reference point for studying microbial action mechanisms and quality regulation. Furthermore, this understanding can inform the optimization and innovation of ZC production processes.

3.2.3. ZC volatile component analysis

3.2.3.1. Shared volatile components. GC–MS revealed 181 volatile compounds in all samples (Fig. 5A), including esters, alcohols, acids, ketones, aldehydes, alkenes, phenols, furan, alkanes, and other compounds. The highest content was esters and alcohols, which accounted for 31.492 % and 15.470 % of the total volatile components, respectively.

In the context of aroma composition analysis, the level of volatile components is not a reliable indicator of the substance's potential to significantly influence the aroma. The OAV is a more accurate measure of this effect. The higher the OAV of a volatile component, the greater the substance's contribution to a food product's aroma (Acree et al., 1984). An OAV>1.0 typically indicates that the substance contributes to the food product to a certain extent, whereas an OAV>10.0 suggests that the aroma component is considered to contribute significantly to the overall aroma (Du et al., 2011; Qian & Wang, 2005). Thirty-two volatile components were identified in 80 % of the samples, with 14 substances exhibiting an OAV>1.0. The 14 shared volatile components constitute the primary aroma of ZC, collectively imparting a distinctive flavor profile. β-damascenone was detected in all seven ZCs except FQA9. The highest concentration was observed in DFZJ, at 0.861 μg/g, significantly different from the other groups ($p < 0.05$). This result resulted in a significantly altered ZC odor. The β-damascenone content in FQB3 and ZYQ8, which exhibited higher odor scores, was 0.178 μg/g and 0.121 μg/g, respectively. These values were not significantly different ($p>0.05$). Previous research by Lee et al. (2018) has demonstrated that the β-damascenone content of fermented chilies increases with prolonged fermentation time. Among these, 1-hexanol, benzeneacetaldehyde, linalool, phenylethyl alcohol, and ethyl salicylate have been identified as the pivotal aroma substances of ZC (Liu, Hu, Deng, et al., 2024; Zhang et al., 2023). The two groups of ZCs (FQB3 and ZYQ8) that demonstrated superior performance in sensory evaluation and quality indexes exhibited certain similarities in the composition of volatile components. A joint analysis of these components revealed five substances with OAVs >45.0: 4-ethylphenol, 1-hexanol, benzeneacetaldehyde, β-damascenone, and linalool. The content of β-damascenone in the two ZCs was not significantly different ($p < 0.05$), with concentrations of 0.154 μg/g and 0.178 μg/g, respectively. Four substances were identified in the highest concentrations in the samples: 1-hexanol (0.890 μg/g), methyl salicylate (1.383 μg/g), and 4-ethyl-2-methoxyphenol (25.263 μg/g). These substances differed significantly from the other groups ($p < 0.05$). In order to facilitate a more intuitive comparison of the differences between the samples, a ZC aroma wheel was constructed using radar hierarchical maps for further illustration (Fig. 5B). The 14 essential aroma-presenting substances exhibited considerable variation among the samples. The aroma wheel of ZC was classified into six flavor groups according to their aroma-presenting properties, which were fruity, floral, pungent, fatty, fermented, and green. Four substances were identified as floral, with rose, iris, and valley aromas. Additionally, three were classified as fruity and two as irritating. The odors β-damascenone, ethyl caprylate, and ethyl salicylate were apple-like, while 4-ethylphenol exhibited a spicy, smoky odor.

3.2.3.2. Differential volatile components. The volatile compositions of ZCs made from different chili varieties exhibited considerable variation under identical processing and fermentation conditions. The volatile

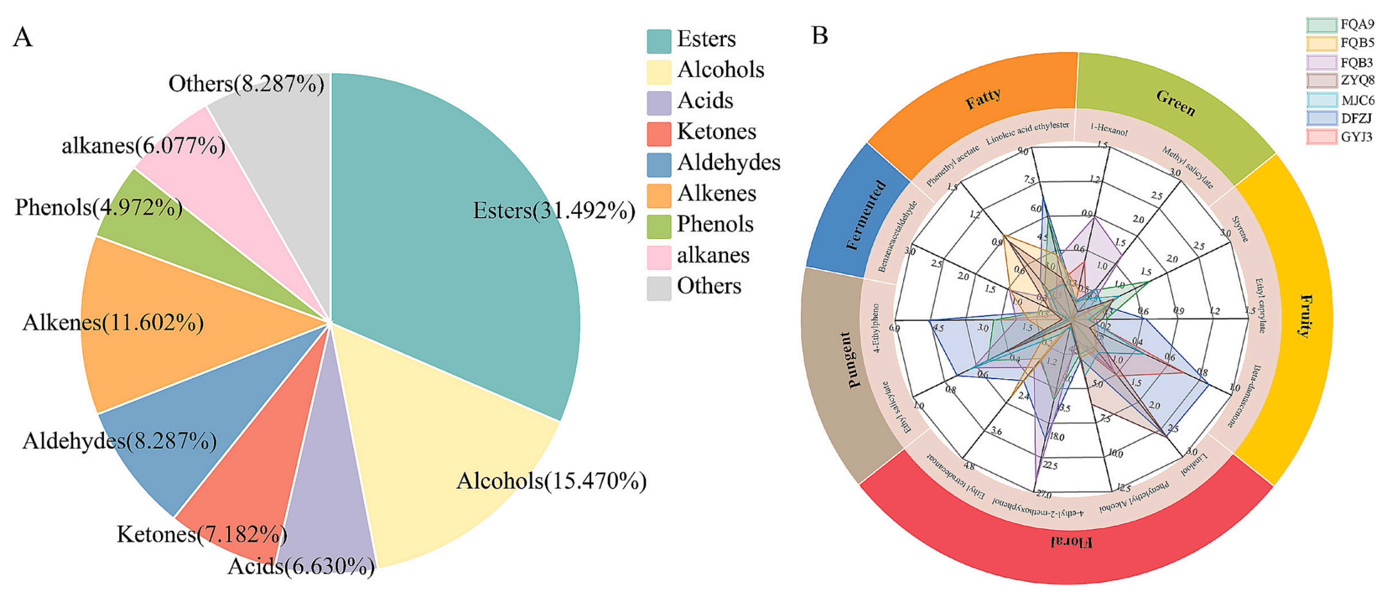

Fig. 5. Analysis of shared volatile compounds in *Zao Chilis*. (A) the volatile compounds classification and proportion, (B) the aroma wheel of the aroma-active compounds in ZC identified by the calculation of OAVs.

compositions of the seven ZCs were predominantly comprised of esters, phenolics, and alcohols. The Erjingtiao chilies (ZYQ8, FBQ3) displayed a more diverse range of volatile compositions, with 90 and 76 species, respectively (Table 5). Esters are primarily formed through the esterification of organic acids and alcohols (Wang et al., 2021) and play a significant role in fruits, wines, and fermented foods, which often impart fruity and floral aromas to the accumulation of esters with the prolongation of fermentation time has been demonstrated to enhance the flavor of the resulting fermented food (Cordente et al., 2021; Ye et al., 2021). The ZC samples exhibited the highest percentage of esters, which ranged from 8.502 % to 34.838 %. These results are due to the different initial ester content of different chili varieties (Koeda et al., 2023) and the synthesis of esters by microorganisms using the substrate to produce esters during fermentation (Xu et al., 2018). DFZJ demonstrated a relatively high esters content, comprising 26 distinct ester compounds, accounting for 34.838 % of the total volatile components. Erjingtiao chili exhibited intermediate ester contents but was more diverse, with more than 30 species.

Volatile phenolics constitute a class of aromatic compounds, and most evince spice, fruity, and smoky flavors. These compounds are predominantly found in fermented foods, including fruit wines and soy sauces (Ito & Matsuyama, 2021; Zhang, Ren, et al., 2022). Nine phenolics were identified in seven ZCs, with concentrations ranging from 3.447 to 28. Furthermore, 4-ethyl-2-methoxyphenol (floral, smoky, burnt) and 4-ethyl-2-methoxyphenol (roasted, smoky, burnt) were identified in all samples. Additionally, ethyl-2-methoxyphenol (floral, smoky) and 4-ethylphenol (roasted, smoky, burnt) were present. The highest percentage of 4-ethyl-2-methoxyphenol was observed in the FBQ3 samples, at 28.320 %, higher than that of esters. It has been demonstrated that the synthesis of 4-ethyl-2-methoxyphenol and 4-ethylphenol depends on microbial activity. The concentration of these compounds increases significantly following fermentation, imparting a sauce-like flavor and a distinctive fermentation aroma (de Castro et al., 2019). Consequently, volatile phenolics play a pivotal role in the complexity of ZC sauce aroma.

Twenty-nine distinct alcohol compounds were identified in the seven ZCs, with concentrations ranging from 5.095 % to 13.334 %. Five alcohol compounds were identified as being shared among the ZCs, namely 1-hexanol (leafy, green, and grassy), 1-heptanol (musty, sweet, woody), linalool (sweet, floral) (Hammock, Kopsell, & Sams, 2021), phenylethyl alcohol (floral, rose-like), and 1-nonanol (floral,orange--like). The proportion of linalool and phenylethyl alcohol was notably higher. The ZQJ8 exhibited the highest relative content of linalool and phenylethyl alcohol at 2.576 μg/g, 6.147 μg/g, significantly disparate from the remaining samples ($p < 0.05$).

PCA and OPLS-DA analyses of different ZC volatile compounds were conducted to investigate the differences among the samples. The PCA results demonstrated that the cumulative contribution of PC1 and PC2 was 42.15 %. The PCA score plot (Fig. 6A) showed a distinct distribution of all samples, and the repeatability of individual samples was good. This result indicates that the volatile components of different chili varieties vary greatly among their products under the same processing method, indicating that the chili raw material significantly affects ZC quality.

The OPLS-DA results are presented in the graph (Fig. 6B), where R_{2x} denotes the independent variable fitting index, R_{2y} denotes the dependent variable fitting index, and Q_2 denotes the prediction index of the model. Higher values indicate an approximately good model fit, and it is considered that R_2 and Q_2 exceeding 0.5 indicate an acceptable model fit result (Huang et al., 2018). The current test model demonstrates an $R_{2x} = 0.974$, $R_{2y} = 0.998$, and $Q_2 = 0.996$, indicating an optimal fit and high prediction accuracy. Furthermore, the distribution of the sample groups is observed to be dispersed across different quadrants, as demonstrated in Fig. 2B. After 200 replacement tests, the model's performance is evidenced by $R_2 = 0.177$, $Q_2 = -0.729$, and Q_2 being negative. The regression line intersecting the y-axis at a value less than 0 is a hallmark of model validation, thereby confirming the absence of overfitting. Variable importance projection (VIP) was employed as a screening criterion to evaluate the contribution of metabolites to the classification of the samples (Feng et al., 2022). The screening condition is typically utilized as VIP>1.0. A total of 79 differential metabolites with VIP > 1.0 were identified in the seven samples. Among these, 31 were identified as esters, followed by alkenes and ketones, which exhibited a lower threshold value.

A total of 24 differential volatiles contributing to the aroma were identified in the seven ZCs (Fig. 6C), with a combination of VIP > 1.0 and OAV > 1.0. The percentage for esters was found to be 37.501 %, while the percentage for both aldehydes and ketones was 16.673 %. The OAV varied considerably among the samples, with ethyl caprylate, ethyl linoleate, 4-ethylphenol, and styrene in seven samples. DFZJ exhibited the highest concentrations of ethyl caprylate and ethyl linoleate ($p < 0.05$), with OAV values of 32.879 and 14.248, respectively. Ethyl caprylate and styrene demonstrated high rankings in ZYQ8, with OAV values of 13.942 and 12.232, respectively. Xu et al. (2020) found that the fortified fermented chilies exhibited relatively high levels of ethyl caprylate and ethyl linoleate. Ethyl caprylate has a fruity flavor and is a fermentation, maturation, and aging marker. Ethyl linoleate is an ester compound formed from ethanol and linoleic acid, which lowers cholesterol and blood lipids (Jin et al., 2019). It has a waxy, creamy, fatty, coconut odor. The GYJ3 sample exhibited 16 volatiles with VIP > 1.0 and OAV > 1.0, of which 10 substances were significantly different from other samples ($p < 0.05$). Four substances were detected only in GYJ3: 4′-methylacetophenone (spice, OAV = 7.860), methional (cooked potato, OAV = 2348.926), 3-Octanone (herb, OAV = 28.393), and D-limonene (citrus, OAV = 54.593). This result indicates that the ZC flavor produced by GYJ3 was distinct from those observed in other varieties. Although the ZC produced from FQB3 and ZYQ8, which also belonged to the Erjingtiao chilies, exhibited a notable discrepancy in flavor ($p < 0.05$), the sensory evaluation scores of the two odors were higher, indicating that the Erjingtiao chili was a preferred raw material for the

Table 5
Types and relative contents of volatile compounds in different *Zao Chilis* samples.

Aroma component	FQA9		FQB3		FQB5		ZYQ8		MJC6		DFZJ		GYJ3	
	Kinds	Contents (%)	Kinds	Contents (%)	Kinds	Contents (%)	Kinds	Contents (%)	Kinds	Contents (%)	Kinds	Contents (%)	Kinds	Contents (%)
Esters	34	29.051	34	23.451	25	24.558	31	18.267	23	13.578	26	34.838	18	8.502
Alcohols	11	5.556	12	6.789	11	9.305	15	13.334	14	9.001	10	8.467	7	5.095
Acids	3	1.377	5	1.440	7	7.002	4	2.229	5	2.474	6	2.215	5	2.138
Ketones	1	0.217	7	1.597	2	0.495	6	2.191	5	3.295	3	1.936	3	1.657
Aldehydes	2	0.814	6	5.202	9	5.563	7	4.040	5	1.578	5	2.341	3	0.891
Alkenes	6	3.031	4	1.814	2	1.147	11	4.958	7	2.344	7	2.511	7	2.824
Phenols	5	16.805	4	28.320	6	4.757	6	3.447	2	1.298	3	24.268	4	15.496
alkanes	5	2.218	3	3.230	5	2.855	8	4.006	7	2.961	7	1.604	9	2.123
Others	5	1.779	1	0.846	4	2.798	2	2.411	3	0.656	1	0.907	8	2.470
Total	72	60.848	76	72.690	71	58.479	90	54.883	71	37.184	68	79.088	64	41.197

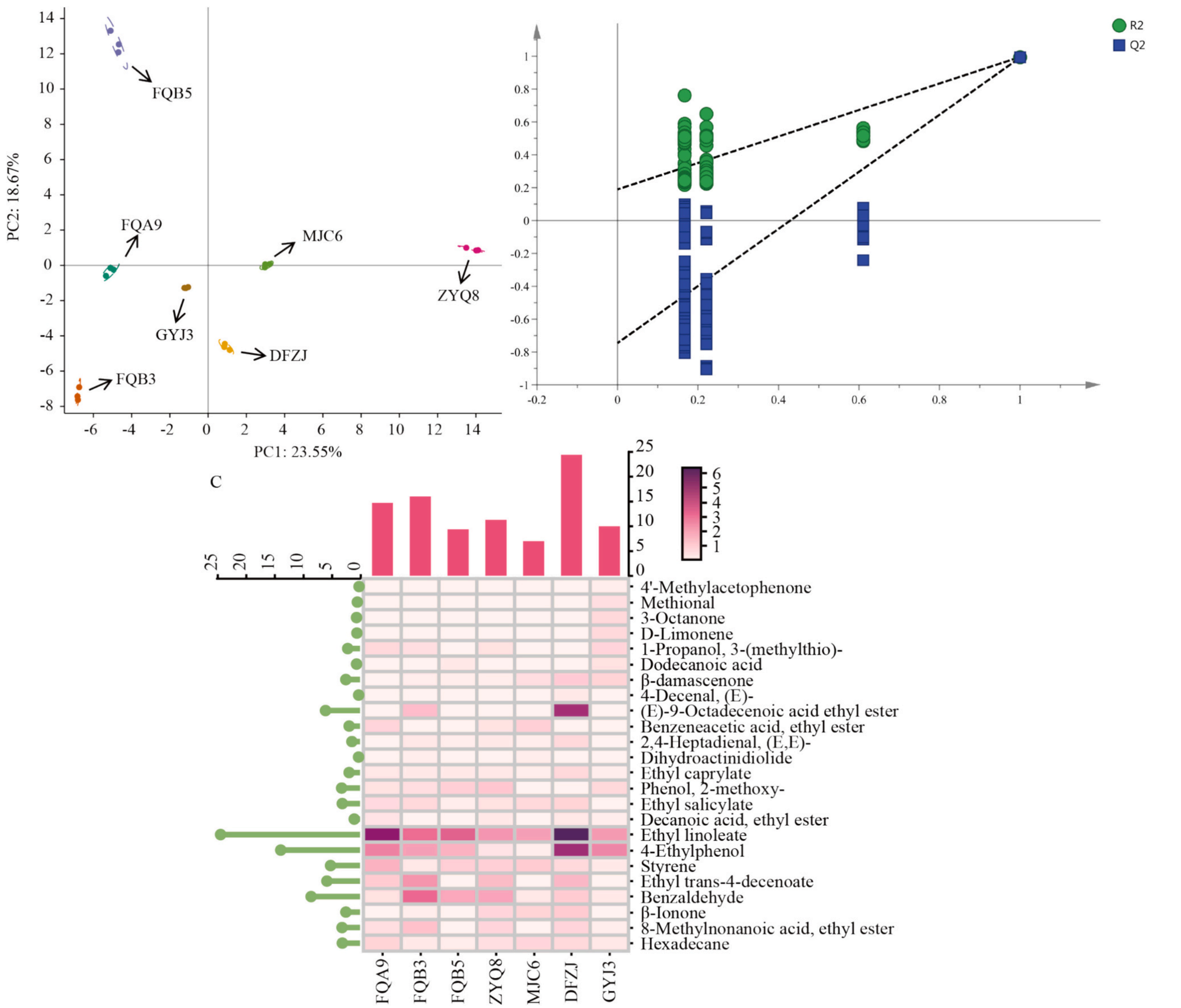

Fig. 6. The analyses of different *Zao Chilis* volatile compounds. (A)Principal component analysis of volatile compounds in *Zao Chilis*, (B) Results of 200 replacement tests, (C) the 24 different aroma-active compounds in ZC by calculating of OAVs.

fermentation of the ZC by consumers. β-damascenone is cleaved from neoxanthin to form a ketone, which is then reduced by an enzyme to an allenic triol. This latter compound is known to be a progenitor of β-damascenone and is responsible for significantly improving the fermented vegetable flavor (Catrileo et al., 2020; Kiczorowski et al., 2022.).

3.3. Correlation analysis between physicochemical indexes of FRC and quality indexes of ZC

To further elucidate the relationship between the raw materials of chilies and the quality and flavor of ZC, Spearman's analysis was employed to examine the correlation among the physico-chemical indexes of FRC, the physical characteristics indexes, and the quality indexes of ZC after fermentation (sensory indicators, physical and chemical indicators, and 24 critical volatile components). The results were then visualized using a neural network diagram (Fig. 7). A total of 220 correlations ($|r| \geq 0.6$, $p < 0.05$) were identified between the FRC indicators, the ZC indicators, and the volatile flavor substances. Of these, 45 demonstrated a strong correlation ($|r| \geq 0.8$, $p < 0.05$). A positive correlation was observed between ester substances and aldehydes, ketones. Of particular note is the strong correlation between ethyl salicylate and β-ionone ($r = 0.821$), which possesses a fruity aroma. Benzaldehyde is a class of aromatic compounds with a nutty aroma (Yoon et al., 2013). This substance was present in all ZCs, with a higher content observed in FQB3 (3.213 μg/g) and ZYQ8 (1.782 μg/g). indicating that it contributes to the flavor of the ZC. The GYJ3 contained the lowest amount of benzaldehyde (0.214 μg/g). There is a positive correlation between benzaldehyde and ZC total acid ($r = 0.832$) and a negative correlation between benzaldehyde and ZC-pH ($r = -0.901$). These results indicate that during ZC fermentation, the accumulation of total acid increased, and benzaldehyde gradually increased, enhancing the flavor of the ZC. The sensory evaluation and volatile composition analysis results indicated that FQB3 and ZYQ8 exhibited the highest overall quality, suggesting a correlation between benzaldehyde and the overall quality of the ZC. Furthermore, a correlation can be observed between the physical and chemical indicators. A significant positive correlation was observed between amino acid nitrogen and fat ($r = 0.747$, $p < 0.05$), indicating that fruits with higher amino acid nitrogen typically exhibit higher fat content, which is in line with the findings of Ananthan et al. (2018). The correlation between FRC-reducing sugars and ZC-total acid is significantly positive ($r = 0.819$, $p < 0.05$), while the correlation between FRC-reducing sugars and ZC-pH is significantly

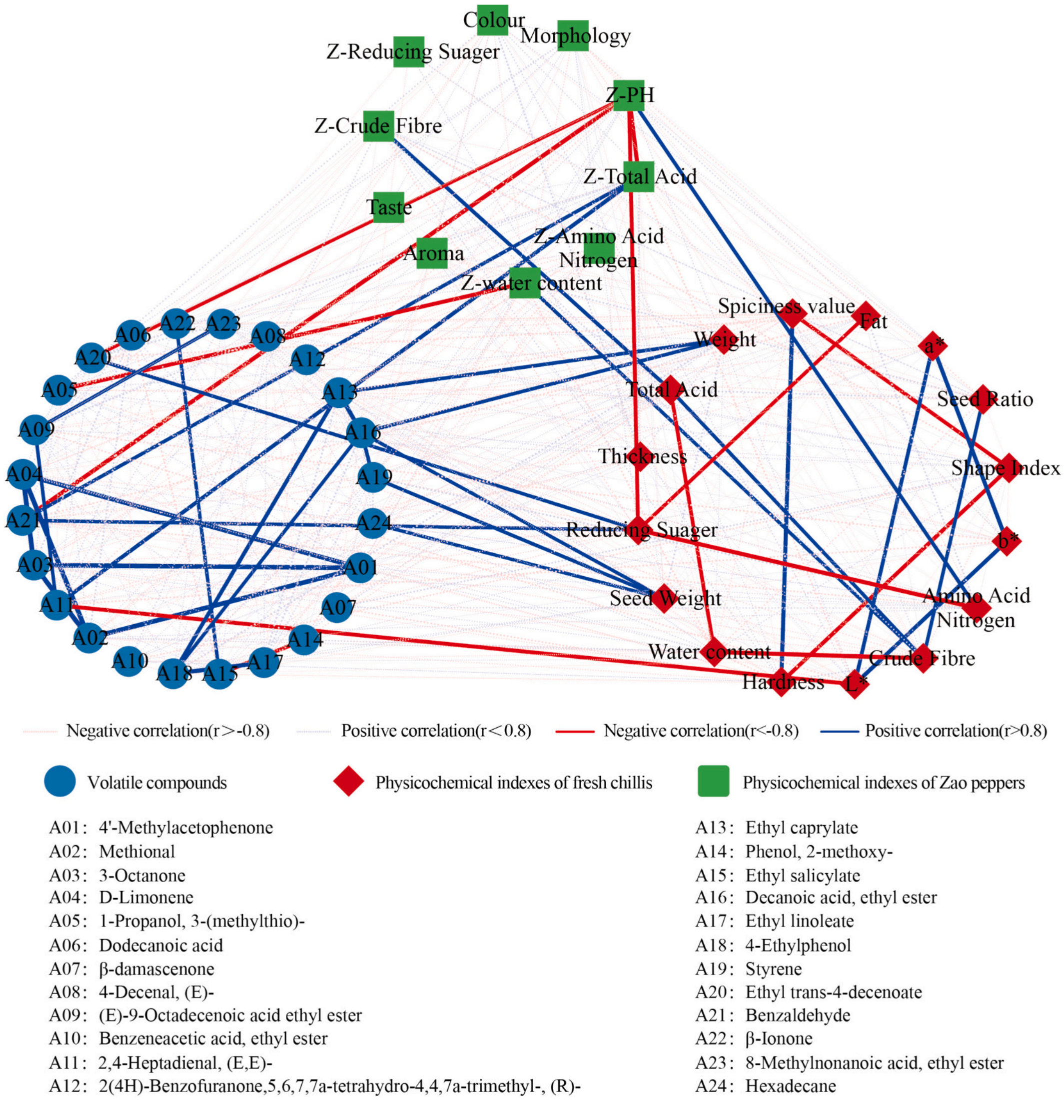

Fig. 7. Correlation diagram of fresh red chili physicochemical indexes, *Zao Chili* physicochemical indexes and *Zao Chili* volatile compounds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

negative ($r = -0.880$, $p < 0.05$). This result further indicates that the higher the reducing sugar content of the chili variety, the more readily microorganisms can use and metabolize it during fermentation, producing more acidic substances. Furthermore, the water content of ZC is positively correlated with the crude fibre of FRC ($r = 0.80$) and negatively correlated with reducing sugars ($r = -0.807$). This result is because, during the fermentation process, microorganisms utilize a proportion of the crude fibre, reducing the crude fibre content of ZC. Furthermore, crude fibre exhibits a certain degree of water absorption. Following degradation, the water in the chilies is released, increasing the water content of ZC. ZC produced from chili varieties with low reducing sugars exhibits a high water content. According to the characteristics of ZC products, there should not be too much soup, so the sensory score of chili varieties with low reducing sugars is relatively low. According to this correlation analysis, chili varieties with low crude fibre and high reducing sugar content should be selected as raw materials for ZC.

4. Conclusion

This study systematically analyzed and evaluated the sensory characteristics, physicochemical properties, and volatile components of seven chili varieties as well as their ZC products in Guizhou. The results showed that the physicochemical indexes of the Chaotian and Xian chili varieties differed significantly. Generally, Xian chili varieties had a higher sugar content than Chaotian chili varieties, rendering them more suitable for the production of fermented chili. The sensory scores and volatile compositions of the ZC made from the Erjingtiao chilies within the Xian chili group were superior to those of other varieties. Based on the results of GC - MS and other analyses, the aroma profiles of ZC were depicted. These findings provided theoretical guidance and technical support for screening chili varieties dedicated to ZC processing and for their comprehensive quality evaluation.

However, this study mainly focused on the representative chili varieties in Guizhou and had some limitations in variety coverage. Consequently, subsequent research should focus primarily on the key indicators proposed in this paper. Meanwhile, it is necessary to expand the sample of chili varieties and integrate microbiome, metabolomics, and other technologies to conduct a more comprehensive and accurate study, thereby promoting the improvement of the comprehensive quality of ZC.

CRediT authorship contribution statement

Xueya Wang: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Kuan Lu:** Writing – review & editing, Visualization. **Wenxin Li:** Methodology, Investigation. **Ju Chen:** Writing – review & editing. **Yong Yin:** Resources. **Xiaojing Sun:** Writing – review & editing. **Min Lu:** Writing – review & editing. **Jianwen He:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Declaration of competing interest

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

Acknowledgements

Guizhou Provincial Key Technology R&D Program: Qiankehe Support [2022] Key 016.

Guizhou Provincial Basic Research Program(Natural Science): Qiankehe Basic Research-ZK[2024] General 535.

Data availability

Data will be made available on request.

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