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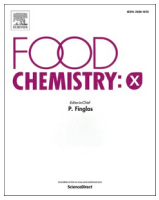

Effect of Chinese bayberry residue on quality of Chinese quinoa (*Chenopodium quinoa* Willd.) Rice wine

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ABSTRACT

Chinese bayberry residue (CBR) is a by-product of processing, which can be used as an auxiliary material during the processing of quinoa rice wine. In this study, the effects of CBR on the chemical profile, bioactive function, taste traits, and flavor of Chinese quinoa rice wine (CQRW) were investigated. The results showed that adding CBR increased the total phenolics, the total flavonoids, and antioxidant capacity. Malic acid content was the highest in Chinese rice wine (CRW), while the total content of components detected in HPLC-MS/MS was the highest in 10%CBR + CQRW. The CQRW exhibited the highest amino acid content, followed by 20%CBR + CQRW. *E*-tongue analysis results showed that 10%CBR + CQRW, 20%CBR + CQRW, and CQRW had the closest taste traits. Moreover, GC–MS analysis identified 72 aroma compounds in 10%CBR + CQRW sample, more than other samples. In summary, adding 10% CBR significantly improved the quality of CQRW.

1. Introduction

Quinoa, scientifically known as *Chenopodium quinoa* Willd., is an ancient grain native to the Andes Mountains in South America (Sharma, Kataria, & Singh, 2022). It was introduced to China in 1987 and is now extensively cultivated in the provinces of Shanxi, Yunnan and Qinghai (Tang & Tsao, 2017). Despite its ancient origins, quinoa is still considered a supergrain due to its exceptional nutritional value (Kataria, Sharma, & Dar, 2021). Surpassing regular grains in protein content, amino acids, vitamins, and minerals, quinoa offers remarkable antioxidant, anticancer, hypolipidemic, and antihypertensive properties (Bogdan, Kordialik-Bogacka, Czyzowska, Oracz, & Zyzelewicz, 2020; Nickel, Spanier, Botelho, Gularte, & Helbig, 2016). The Food and Agriculture Organization (FAO) of the United Nations recognizes quinoa as a "complete nutritional food" capable of fulfilling the basic nutritional requirements of the human body (Ruiz, Xiao, Boekel, Minor, & Stieger, 2016).

Huangjiu, a traditional Chinese fermented beverage, is made from grains, yeast, and Qu (a special saccharification starter in China). Characterized by its low alcohol content (<20% *v*/v), vibrant color, fragrant aroma, abundant nutrients, and potential health benefits, Huangjiu is highly popular among consumers (Varela et al., 2015; Xie et al., 2021; Yu, Ding, & Ye, 2012; Zhao, Wang, Zhao, Ma, & Sun, 2018). Quinoa, containing significant starch levels (58.1–64.2%), promotes the growth of fermenting microorganisms, such as yeast and mold, and facilitates ethanol synthesis (Lanza, 2013; Okamoto et al., 2020; Paucean et al., 2019; Varela et al., 2015). Consequently, it serves as an effective raw material for producing Huangjiu (Duan et al., 2023). During Huangjiu processing, the raw materials undergo gelatinization under high temperature and humidity, which not only reduces the content of bitter saponins in quinoa, improving the taste of its products (Li et al., 2022; Suarez-Estrella et al., 2021; Wei et al., 2016), but also enhances food safety by inactivating a toxic protein known as quinoin (He, Wang, Zhao, & Yang, 2022).

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As the by-product of bayberry processing, CBR retains significant quantities of functional components such as phenolics, anthocyanins, and dietary fiber, making it highly valuable for utilization (Zhu et al., 2020; Zhu et al., 2022). Consequently, CBR can be used as a fermentation aid in CQRW production. This application not only enhances the content of bioactive functional substances in CQRW but also improves the utilization rate of bayberry residue as a resource.

Although CBR contains biologically active substances and retains some economic value, CBR has not yet been introduced as an auxiliary material in the processing of CQRW before. The levels of phenolics, flavonoids, and antioxidant capacity during the CQRW fermentation process were dynamically monitored and analyzed in this study. Additionally, the overall quality of the prepared CQRW and the effects of adding CBR on CQRW quality were evaluated.

2. Materials and methods

2.1. Materials and reagents

Quinoa and rice were purchased from Jiaqi Agricultural Technonlogy Co., Ltd. (Taiyuan, China), and stored in a room-temperature dry warehouse. The CBR was acquired from ChengYouWangJiShanYuan Food Co., Ltd. (Guizhou, China), separated from the bayberry juice, lyophilized, crushed, and stored in a dryer (Jiancheng Biotechnology Co., Ltd. Nanjing, China). Highly active yeast (*Saccharomyces cerevisiae*) and Huangjiu Qu were purchased from Angel Yeast (Yichang, Hubei, China).

The 1,1-diphenyl-2-trinitrophenylhydrazine (DPPH) was purchased from Tengchun Biotechnology Development Co., Ltd. (Nanjing, China). Tripyridinyl triazine (TPTZ) was purchased from Jiancheng Biotechnology Co., Ltd. (Nanjing, China). Standards for phenolics (> 99.0%), organic acid (> 99.0%), and amino acids (> 99.0%) were purchased from Yuanye Biological Technology Co., Ltd. (Shanghai, China). All other reagents used were food grade or analytical grade or high performance liquid chromatography (HPLC) grade.

2.2. Preparation of Huangjiu samples

Rice and quinoa were each washed 1 to 2 times to remove dust. The rice (100 g) was soaked in water at room temperature for 12 h and then steamed at 100 °C for 50 min (Lv et al., 2015; Wei et al., 2016). After cooling to room temperature, it was mixed with traditional starter (Highly active yeast and Huangjiu Qu). The mixture was transferred to conical bottles and fermented for 12 days to produce CRW. Similarly, the quinoa (100 g) was soaked in water for 2 h at room temperature and steamed at 100 °C for 30 min. The subsequent steps were identical to those for CRW, resulting in the production of Chinese quinoa wine (CQW). To prepare CQRW, 50 g of rice and 50 g of quinoa were subjected to their respective gelatinization processes, cooled, thoroughly mixed with the starter, and then fermented.

Take 45 g rice and 45 g quinoa, subject them to different gelatinization processes, cool down, mix rice, quinoa, CBR (10 g), and starter evenly. Ferment the mixture to produce 10% CBR Chinese quinoa rice wine (10%CBR + CQRW). Using the same process, prepare 20% CBR Chinese quinoa rice wine (20%CBR + CQRW) and 30% CBR Chinese quinoa rice wine (30%CBR + CQRW), with respective increases in CBR content.

The starter amounts added during the fermentation process are as follows: 0.2% highly active yeast and 0.5% Huangjiu Qu. Fermentation was terminated after 12 days, with samples collected on days 0, 1, 2, 3, 6, 9, and 12. Subsequently, the supernatant was obtained by centrifuging at 6000*g* for 15 min and filtrating through a 0.22 μm membrane to remove bacteria and impurities. The wine samples were then stored in a refrigerator at 4 °C. The fermentation process had been optimized beforehand.

2.3. Determination of yeast count

Yeast count were measured by the dilution plate method, and the medium was YPD agar medium according to the national standard GB 4789.15–2016.

2.4. Chemical composition analysis

The alcohol content in Huangjiu adopted the method of GB 5009.225–2016 (China). An alcohol meter (0–20%, Glass factory, Hejian, China) was used to measure alcohol count, and the data was expressed as volume percent (vol%). The total sugar content of Huangjiu was detected by phenol-sulfuric acid method (Evstigneyev, 2017). The standard curve was linear at 490 nm, total sugar was expressed as g of glucose equivalents per liter of Huangjiu (g/L).

2.4.1. Determination of total phenolics content

The total phenolics content (TPC) in Huangjiu was measured by the Folin-Ciocalteu method (Zhu et al., 2020). Using an iMake microplate reader (D-Epoch, Bio Tek Instruments, Inc., USA) to measure absorbance at 760 nm, the standard curve was linear at 760 nm ($Y = 4.3893\ X + 0.0273$, $R^2 = 0.998$), and TPC was calculated according to the standard curve linear and expressed as mg of gallic acid equivalents per liter of Huangjiu (mg/mL).

2.4.2. Determination of total flavonoids content

The total flavonoids content (TFC) was determined by the aluminum chloride colorimetric assay (Duan et al., 2023). Using an iMake microplate reader to measure absorbance at 510 nm, the standard curve was linear at 510 nm ($Y = 1.2151\ X + 0.0032$, $R^2 = 0.999$). TFC was calculated according to the standard curve linear at 510 nm and expressed as mg of rutin equivalents per liter of Huangjiu (mg/mL).

2.4.3. Determination of total ester content

The total ester content in Huangjiu was determined using the colorimetric method (Ma et al., 2022). Using an iMake microplate reader to measure absorbance at 525 nm, the standard curve was linear at 525 nm ($Y = 0.3214\ X - 0.167$, $R^2 = 0.998$), and total ester was calculated according to the standard curve linear and expressed as mg of ethyl acetate equivalents per liter of Huangjiu (mg/mL).

2.5. Composition analysis of Huangjiu samples

Based on previous studies on Huangjiu, quinoa, and CBR, the quantitative analysis of myricetin, procyanidin, tartaric acid, malic acid, homogentisic acid, cyanidin-3-*O*-glucoside, chlorogenic acid, catechin, catechol, hydroxybenzene propanoic, vanillic acid, caffeic acid, epicatechin, rutin, *p*-coumaric acid, ferulic acid, and salicylic acid in CRW, CQW, CQRW, 10%CBR + CQRW, 20%CBR + CQRW, 30%CBR + CQRW were carried out by high performance liquid chromatography-mass spectrometry-mass spectrometry (HPLC-MS/MS) (Chen, Ren, Li, & Ma, 2020; Tang & Tsao, 2017; Zhu, Ren, et al., 2020).

For the HPLC-MS/MS, an Agilent 1260 Infinity II (Agilent Technologies, Germany) was coupled to an Agilent Technologies 6420 Triple Quad MS/MS (G6420) system equipped with an Agilent Phoroshell 120 EC-18 column (100 mm × 3 mm; 2.7 μm, Agilent, USA), an automatic sampler (G7129A), a binary pump (G1312B), and a column oven (G7130A). The HPLC-MS/MS was performed under the following conditions: electrospray ionization (ESI), capillary voltage 3.5–4.0 kV; nebulizer temperature, 45 psi; gas flow rate of 10 L/min with a temperature of 350 °C, MS mode is multiple reaction monitoring (MRM). Samples were filtered (0.22 μm) and analyzed by injecting 2.0 μL that were eluted through the column with a binary mobile phase that consisted of A (formic acid 0.1%) and B (acetonitrile (ACN) (Merck, Germany)), the flow rate was 0.3 mL/min with a gradient of 9.10 min which consisted of: 0–2 min, 90% A to 80% A; 2–6 min, 80% A to 10% A; 6–9

min, 10% A; 9–9.10 min, 10% A to 90% A. The components of Huangjiu samples were calculated by the standard curve in the Table S2, the total ion chromatogram of the standard is shown in Fig. S1, and the results were expressed as mg/L.

2.6. Quantitative analysis of amino acids in Huangjiu samples

The amino acids of Huangjiu samples were analyzed by HPLC-MS/MS according to the method reported by Zhang et al. (2021) with slight modification.

Each sub-sample was diluted with 0.5 M hydrochloricacid at the ratio of 1:10 (v:v) to extraction in tube. The tubes were vortexed for 20 min, sonicated in a 25 °C water bath for 20 min, and then centrifuged at 28489*g* for 20 min. Finally, dilute 250 μL of the extracted supernatant to 1 mL with acetonitrile. For the HPLC-MS/MS, an Agilent 1260 Infinity II (Agilent Technologies, Germany) was coupled to an Agilent Technologies 6420 Triple Quad MS/MS (G6420) system equipped with an Agilent Poroshell 120 HILIC-Z column (100 mm × 3 mm; 2.7 μm, Agilent, USA), an automatic sampler (G7129A), a binary pump (G1312B), and a column oven (G7130A).

The HPLC-MS/MS was performed under the following conditions: electrospray ionization (ESI), capillary voltage 3.5–4.0 kV; nebulizer temperature, 45 psi; gas flow rate of 10 L/min with a temperature of 350 °C, MS mode is MRM. Samples were filtered (0.22 μm) and analyzed by injecting 1.0 μL that were eluted through the column with a binary mobile phase that consisted of A (H_2O, pH = 3.0) and B (premixed ACN (90%)-H_2O (10%), pH = 3.0), the flow rate was 0.5 mL/min with a gradient of 9.10 min which consisted of: 0–7 min, 5% A to 45% A; 7–12 min, 45% A; 12–12.10 min, 45% A to 5% A. The amino acid of Huangjiu samples were calculated by the standard curve in the Table S3, the total ion chromatogram of the standard is shown in Fig. S1, and the results were expressed as mg/L.

2.7. In vitro antioxidant capacity

The in vitro antioxidant capacity of Huangjiu was evaluated using three assays.

2.7.1. DPPH radical scavenging capacity assay

The DPPH radical scavenging capacity (DPPH-RSC) was determined by the previous method of Zhu et al. (2020). The absorbance at 517 nm was measured using the iMake microplate reader. DPPH scavenging percentage value was calculated based on the following formula:

$$\mathrm{DPPH-RSC}(\%) = \left(1 - \frac{A_1 - A_2}{A_0}\right) \times 100\%$$

where A_0 was the absorbance (Abs) of the mixed solution of absolute ethanol and DPPH; A_1 was the mixed solution of sample and DPPH's Abs; A_2 was the Abs of the mixed solution of sample and absolute ethanol.

2.7.2. Hydroxyl radical scavenging capacity assay

Hydroxyl radical scavenging capacity (OH-RSC) was measured by the method of Ma et al. (2022). The absorbance at 526 nm was measured using the iMake microplate reader. Hydroxyl radical scavenging percentage value was calculated using the following formula:

$$\mathrm{OH-RSC}(\%) = \left(1 - \frac{A_1 - A_2}{A_0}\right) \times 100\%$$

where A_0 was the Abs of distilled water instead of Huangjiu, A_1 was the sample's Abs, and A_2 was the Abs of distilled water instead of H_2O_2 solution.

2.7.3. Ferric ion reducing antioxidant power assay

Ferric ion reducing antioxidant power (FRAP) reagent is a mixture (10:1:1, *v*/v/v) of acetate buffer (0.1 M, pH 3.6), TPTZ (10 mM), and ferric chloride (20 mM) (Sharma et al., 2022). Using an iMake microplate reader to measure absorbance at 593 nm, the standard curve was linear at 593 nm ($Y = 0.007\ X + 0.585$, $R^2 = 0.998$). The FRAP was expressed as mmol of per liter of Huangjiu (mmol/L).

2.8. Determination of taste trait of Huangjiu by E-tongue

Analysis was obtained from Huangjiu samples, using the Taste-Sensing System SA 402B (Intelligent Sensor Technology Co. Ltd., Atsugi, Japan). Huangjiu sample is a liquid sample, no sample pretreatment is required, and it can be analyzed directly on the equipment. E-tongue detection conditions: 30 mm KCl and 0.3 mm $C_4H_6O_6$ are prepared as a reference solution simulating the human oral cavity, and the sensor is activated in the reference solution 24 h in advance. Each sample is compared to a reference solution. According to the characteristics of the sample to be tested, the basic taste of sample is measured digitally such as: sweet, sour, bitter, astringent, salty, umami and richness. Sensor cleaning time is 6 min, sample determination time is 30 s, measurement aftertaste is 30 s. For this study 6 detecting sensors (AAE, CT0, CA0, C00, AE1, and GL1) and 2 reference electrodes were used. The "taste values" were calculated by multiplying sensor outputs for appropriate coefficients based on the Weber-Fechner law, which gives the intensity of sensation considering the sensor property for tastes (Guo, Zhang, Long, Fu, & Ren, 2023).

2.9. Analysis of volatile aroma compounds in Huangjiu

The volatile aroma compounds of Huangjiu samples were analyzed by headspace solid-phase microextraction-gas chromatography–mass spectrometry (HS-SPME-GC/MS) according to the method reported by Wang et al. (2020) with slight modification.

Firstly, an extraction head filled with 50/30 μm CAR/PDMS/DVB (Supelco, USA) was aged for 10 min at the inlet of the gas chromatograph at 250 °C. Secondly, 5.0 mL sample was placed in a 20 mL headspace bottle, and 20 μL of 50 mg/L 2-octanol was added as internal standard. Add 2 g of NaCl to the sample, equilibrate at 50 °C for 30 min in a water bath, then put it into the sample bottle, insert the aged extraction head and absorb at 50 °C for 30 min, and finally desorb 3 min at the inlet of 250 °C gas chromatograph.

GC–MS analyses were performed on a Pegasus HRT 4D Plus (LECO, USA) equipped with a DB-5 MS (30 m × 0.25 mm, 0.5 μm, Supelco, USA) column. At a split ratio of 10:1, the samples were injected. High-purity helium (He) was used as carrier gas, whose flow rate was 1.0 mL/min. For the heating program, the temperature was kept at 40 °C for 3 min, and raised to 230 °C with a speed of 10 °C/min, then maintained for 6 min. Ionization used EI + mode. The electron energy was set up at 70 eV, while the temperature of ion source was at 200 °C. The mass scan ranged from *m/z* 33 to 500. Based on comparing retention time and MS data with MS database NIST1, the matched components were identified. N-alkanes of C6-C26 were analyzed under the same chromatographic conditions as samples, and the retention index RI of each substance was calculated by instrument operation software. Volatile aroma compound content was calculated using the following formula:

$$\mathrm{C\ (mg/L)} = \frac{C_S}{A_S} \times A_f$$

where C_S was the 2-octanol concentration (50 mg/L); A_S was the peak area of 2-octanol; A_f was the peak area of each volatile compound in Huangjiu samples.

2.10. Statistical analysis

Three replications were performed and all the data were described as mean values ± standard deviation. The figures were plotted using Origin

2021 software (Chicago, IL, USA). Correlation analysis (Pearson correlation) and Analysis of variance (ANOVA) were conducted by IBM SPSS version 22.0 (Armonk, New York, NY, USA). As $p < 0.05$, it was considered to significant differences.

3. Results and discussion

3.1. Analysis of dynamic change of indexes in the fermentation process of Huangjiu

Different fermentation raw materials have a great influence on the quality of rice wine, such as alcohol content, taste, aroma and so on (Yang et al., 2020). Fig. 1 shows the changes in various indicators of Huangjiu with different raw materials during the fermentation process.

The alcohol content, a crucial measure of alcoholic beverages, is produced when yeast breaks down pyruvate via the EMP (Embden Meyerhof Parnas) pathway (Varela et al., 2015). It is directly related to the sugar content (can be converted from starch) and the yeast's growth rate during fermentation (Duan et al., 2018). When cooking at atmospheric pressure, rice starch gelatinizes easily (Lv et al., 2015), providing sufficient sugar for fermentation, resulting in CRW with the highest alcohol content (14.6 ± 0.1%) ($p < 0.05$) (Fig. 1a). However, high alcohol levels can alter tartaric and butyric acid concentrations and inhibit the growth of other aroma-producing microorganisms (Jin et al., 2021; Wang et al., 2020). Under the same cooking conditions, the degree of hydrolysis for quinoa starch was low, resulting in an alcohol content of only 10.6 ± 0.15% for CQW ($p < 0.05$). Except for those with a higher proportion of CBR (30%), the remaining Huangjiu samples showed no significant differences in alcohol content after fermentation ($p > 0.05$). These samples also had a total sugar content below 4 g/L at the end of fermentation (Fig. 1b), and the growth of yeast following a similar trend (Fig. 1c).

Phenolics and flavonoids are broad-spectrum bioactive substances in Huangjiu, playing a crucial role in maintaining redox homeostasis and serving as important indicators of its nutritional quality (Jin et al., 2021; Liu et al., 2020). The variation in phenolics and flavonoids in Huangjiu is primarily influenced by the fermentation materials and microbial metabolism. As shown in Fig. 1d, during the fermentation process, the trend of TPC in each sample was increased first and then flat. The TPC for the prepared CRW, CQW, CQRW, 10%CBR + CQRW, 20%CBR + CQRW, 30%CBR + CQRW were 0.611 ± 0.008, 1.059 ± 0.023, 0.831 ± 0.008, 0.877 ± 0.011, 1.023 ± 0.010, and 0.784 ± 0.012 mg/mL, respectively (Fig. 1d). These values significantly increased by 9.548 folds, 1.922 folds, 3.106 folds, 3.447 folds, 4.449 folds, and 3.482 folds ($p < 0.05$), respectively. Rice is rich in starch and B vitamins but contains low levels of phenolics and flavonoids. The CRW is mainly metabolized and synthesized by non-yeast microorganisms to increase TPC (TPC has the highest growth ratio and the lowest content) (Lu et al., 2021). The difference in TPC between the produced CQW and 20%CBR + CQRW was only 0.003 mg/mL, indicating that CBR played an important role in increasing TPC in Huangjiu (Table S1). This finding aligns with other studies demonstrating that microbial hydrolytic enzymes break down the cellulose backbone and phenolic structural branches during fermentation, resulting in higher levels of free phenolics and flavonoids (Chen, Ren, et al., 2020; Xie et al., 2021). The change in TFC during fermentation followed a similar trend to that of TPC, except in CQW and CQRW (Fig. 1e). Quinoa, rich in flavonoids, which are released by microbial enzymes during the initial day of fermentation, leading to an increase in TPC in CQW and CQRW (Chen, Ren, et al., 2020). During the middle stage of fermentation, the microbial activity capable of degrading flavonoids in Huangjiu intensified, resulting in a decrease in flavonoid content across all samples (Bogdan et al., 2020). However, this phenomenon was observed only in CQW and CQRW. Due to the presence of resistant starch, which serves as a substrate for bacterial flavonoid metabolism and promotes flavonoid synthesis, and CBR, which contains flavonoids, the TFC in other samples continued to increase (Paola Rodriguez-Castaño et al., 2019). Consequently, the TPC of 20%CBR + CQRW was the highest.

The antioxidant defense system in plants comprises both antioxidant enzymes and non-enzymatic antioxidants. However, the main protein components are typically inactivated during the production of Huangjiu raw materials (Cao et al., 2022; Sharma et al., 2022). As a result, the antioxidant capacity of Huangjiu is primarily derived from bioactive substances such as phenolics and flavonoids. During the fermentation process, the DPPH-RSC, OH-RSC, and FRAP of each sample increased first and then tended to be stable with the increase of fermentation time (Figs. 1g-i). The DPPH-RSC of CQW and 20%CBR + CQRW were highest (98.889 + 1.475%, 98.465 + 0.962%) ($p < 0.05$). The highest OH-RSC and FRAP of 20%CBR + CQRW were 95.350 + 0.616% and 2.606 + 0.010 mmol/L, respectively. This was due to the high content of phenolics and flavonoids in 20%CBR + CQRW.

The inclusion of CBR in the raw materials could enhance the alcohol content, phenolics, flavonoids, FRAP, and OH-RSC, demonstrating the effectiveness of CBR as a fermentation aid. With the appropriate addition of CBR, the nutritional and functional properties of Huangjiu were significantly improved.

3.2. Analysis of components of Huangjiu samples

3.2.1. Detection of components in Huangjiu

Fermentation increases bioactive substances, thus enhancing the nutritional quality of Huangjiu (Jin et al., 2021). The components in Huangjiu could be divided into two types: phenolic acids and analogs (homogentisic acid, chlorogenic acid, catechol, hydroxybenzene propanoic acid, vanillic acid, procyanidin, *p*-coumaric acid, ferulic acid, salicylic acid, tartaric acid, malic acid, caffeic acid), and flavonoids (flavonols (rutin and myricetin), anthocyanins (cyanidin-3-*O*-glucoside), and flavanonols (catechin and epicatechin)) (Huang, Cai, & Zhang, 2010). A total of 17 substances were detected in all samples, including 15 in CRW (no cyanidin-3-*O*-glucoside and procyanidin), 15 in CQW (no cyanidin-3-*O*-glucoside and caffeic acid), 16 in CQRW (no cyanidin-3-*O*-glucoside), 17 in 10%CBR + CQRW, 20%CBR + CQRW, and 30%CBR + CQRW (Table 1). The content of malic acid was the highest in CRW and lowest in CQW ($p < 0.05$), likely due to variations in the sugar content of the raw materials, as sugar metabolism produced malic acid. The sugar content in CRW is sufficient, and a large amount of pyruvic acid is converted into alcohol during alcoholic fermentation, affecting the TCA cycle (tricarboxylic acid cycle) and leading to the accumulation of malic acid (Duan et al., 2018). The contents of vanillic acid, caffeic acid, *p*-coumaric acid and ferulic acid of CQRW were significantly higher than other samples ($p < 0.05$). Additionally, the contents of tartaric acid, hydroxybenzene propanoic acid, epicatechin, and salicylic acid also increased significantly ($p < 0.05$), whereas rutin levels remained unchanged ($p > 0.05$).

The results indicated that using rice and quinoa together as fermentation materials promoted the decomposition of macromolecular compounds, thereby increasing the levels of phenolic acids and flavonoids in CQRW (Duan et al., 2023; Xie et al., 2021). Adding CBR significantly raised the levels of tartaric acid, chlorogenic acid, hydroxybenzene propanoic, myricetin, and salicylic acid ($p < 0.05$), while maintaining the stability of most substances in 10%CBR + CQRW and 20%CBR + CQRW (Xie et al., 2021). Furthermore, mixed fermentation with multiple raw materials, especially using CBR as an excipient, greatly enhanced the variety and contents of functional active substances in Huangjiu.

3.2.2. Correlation analysis of Huangjiu components and antioxidant ability

In order to verify the correlation between TPC/TFC/Total ester/DPPH-RSC/OH-RSC/FRAP and the components in Huangjiu, the correlation analysis was carried out with the data according to the method of Zhu, Jiang, et al. (2020). The results are shown in Fig. 2.

Fig. 2a (left) shows the intra-group correlation analysis of TPC/TFC/

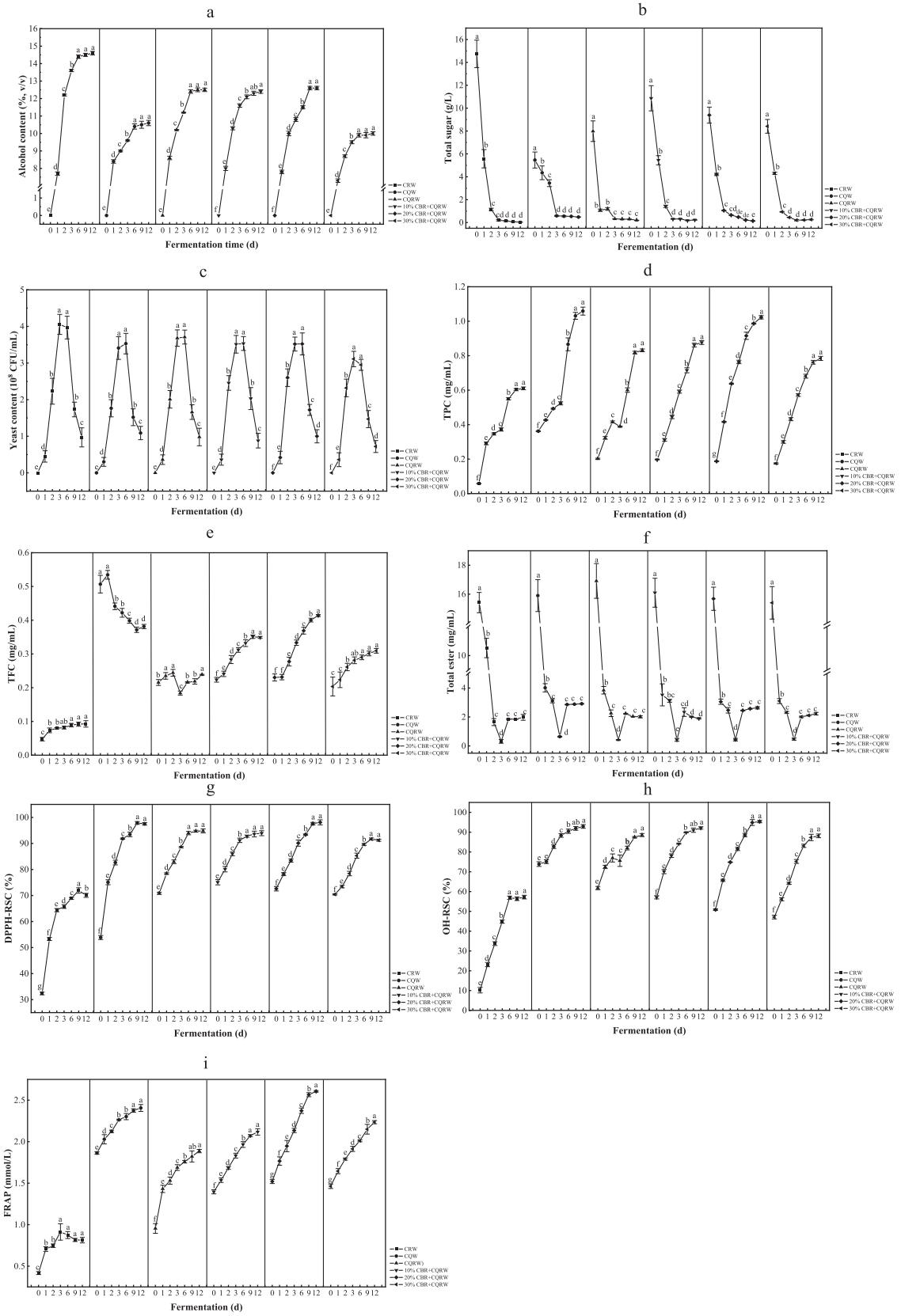

Fig. 1. Dynamic determination of alcohol content, total sugar content, yeast content, TPC, TFC, total ester, DPPH-RSC, OH-RSC, and FRAP of CRW, CQW, CQRW, 10%CBR + CQRW, 20%CBR + CQRW, 30%CBR + CQRW fermentation in 0, 1, 2, 3, 6, 9, 12 d. Alcohol content: (a). Total sugar content: (b). Yeast content: (c). TPC: (d). TFC: (e). Total ester: (f). DPPH-RSC: (g). OH-RSC: (h). FRAP: (i). Different lowercase letters mean significant difference ($p < 0.05$).

Table 1
The composition of the prepared CRW, CQW, CQRW, 10%CBR + CQRW, 20%CBR + CQRW, 30%CBR + CQRW were quantitatively identified (mg/L).

Num	RT (min) [1]	Compounds	CRW	CQW	CQRW	10%CBR + CQRW	20%CBR + CQRW	30%CBR + CQRW
1	1.551	Tartaric acid	0.9502 ± 0.0103 Eb	1.1642 ± 0.0106 Dd	1.3172 ± 0.0130 Ce	1.3511 ± 0.0067 Bd	1.3876 ± 0.0119 Ac	1.3884 ± 0.0062 Ac
2	1.641	Malic acid	38.6872 ± 0.0325 Aa	1.8371 ± 0.0122 Fb	7.5118 ± 0.0259 Cb	12.0184 ± 0.0172 Bb	6.0427 ± 0.0523 Db	5.6508 ± 0.0471 Eb
3	3.137	Homogentisic Acid	0.0225 ± 0.0018 Ffg	0.0988 ± 0.0014 Ae	0.0653 ± 0.0011 Dg	0.0788 ± 0.0003 Cf	0.0914 ± 0.0015 Bf	0.0617 ± 0.0014 Eef
4	5.979	Chlorogenic acid	0.0054 ± 0.0004 Agh	0.0049 ± 0.0002 Bi	0.0049 ± 0.0002 Bhi	0.0050 ± 0.0001 ABi	0.0051 ± 0.0001 ABi	0.0052 ± 0.0001 ABh
5	6.115	Cyanidin-3-*O*-glucoside	nd	nd	nd	0.0034 ± 0.0002 Ci	0.0107 ± 0.0007 Bhi	0.0236 ± 0.0012 Agh
6	6.149	Catechin	0.0031 ± 0.0001 Bh	0.0034 ± 0.0002 Ai	0.0035 ± 0.0002 Ai	0.0033 ± 0.0001 ABi	0.0024 ± 0.0001 Ci	0.0035 ± 0.0001 Ah
7	6.392	Catechol	0.0048 ± 0.0001 Dh	0.0565 ± 0.0005 Af	0.0027 ± 0.0003 Ei	0.0044 ± 0.0002 Di	0.0117 ± 0.0003 Bhi	0.0097 ± 0.0003 Ch
8	6.778	Hydroxybenzene propanoic	0.0444 ± 0.0006 Dd	0.0142 ± 0.0003 Fgh	0.0552 ± 0.0011 Bg	0.0676 ± 0.0004 Ag	0.0457 ± 0.0004 Cg	0.0337 ± 0.0003 Eg
9	6.852	Vanillic acid	0.0442 ± 0.0045 Fd	1.2580 ± 0.0012 Cc	1.6342 ± 0.0030 Ad	1.4744 ± 0.0066 Bc	1.0468 ± 0.0016 Dd	0.8323 ± 0.0010 Ed
10	6.914	Caffeic acid	0.0068 ± 0.0003 Bgh	nd	0.0189 ± 0.0002 Ah	0.0036 ± 0.0004 Ci	0.0038 ± 0.0003 Ci	0.0038 ± 0.0002 Ch
11	6.994	Epicatechin	0.0002 ± 0.0002 Dh	0.0007 ± 0.0001 Ci	0.0024 ± 0.0003 Ai	0.0024 ± 0.0002 Ai	0.0019 ± 0.0002 Bi	0.0017 ± 0.0002 Bh
12	7.247	Rutin	0.0269 ± 0.0020 Eef	18.7307 ± 0.0059 Aa	18.7319 ± 0.0095 Aa	17.8430 ± 0.0030 Ca	18.4227 ± 0.0024 Ba	10.1377 ± 0.0030 Da
13	7.322	Procyanidin	nd	0.0154 ± 0.0005 Agh	0.0117 ± 0.0003 Chi	0.0117 ± 0.0003 Chi	0.0136 ± 0.0004 Bhi	0.0045 ± 0.0005 Dh
14	7.491	*p*-Coumaric acid	0.0085 ± 0.0005 Egh	0.0198 ± 0.0004 Dg	0.0912 ± 0.0012 Af	0.0199 ± 0.0010 Dh	0.0245 ± 0.0009 Cghi	0.0385 ± 0.0005 Bfg
15	7.595	Ferulic acid	0.8433 ± 0.0021 Cc	0.0920 ± 0.0010 Ee	1.6994 ± 0.0014 Ac	0.8755 ± 0.0005 Be	0.2947 ± 0.0006 De	0.0616 ± 0.0004 Fef
16	7.757	Myricetin	0.0073 ± 0.0003 Cgh	0.0072 ± 0.0002 Chi	0.0070 ± 0.0001 Chi	0.0166 ± 0.0002 Bh	0.0348 ± 0.0002 Agh	0.0056 ± 0.0004 Dh
17	8.061	Salicylic acid	0.0410 ± 0.0010 Fde	0.0494 ± 0.0007 Ef	0.0623 ± 0.0006 Dg	0.0643 ± 0.0001 Cg	0.0766 ± 0.0002 Af	0.0708 ± 0.0006 Be
Total			40.6957 ± 0.0566 A	23.3522 ± 0.0352 E	31.2194 ± 0.0584 C	33.8434 ± 0.0373 B	27.5167 ± 0.0741 D	18.3332 ± 0.0633 F

[1] RT: Retention time. Uppercase letters and lowercase letters mark statistically significant differences with one-way ANOVA test of significance ($p < 0.05$) among samples and compounds, respectively. Nd indicates no detection.

Total ester/DPPH-RSC/OH-RSC/FRAP in Huangjiu samples and the intra-group correlation analysis of components in Huangjiu samples. There was a significant positive correlation between TPC and TFC and antioxidant capacity ($|\text{correlation coefficient}| > 0.45$, $p < 0.001$), indicating that the antioxidant capacity of rice wine was mainly manifested by phenolics and flavonoids (Ruiz et al., 2016). In addition, TPC and TFC showed a significant positive correlation with total esters, which explained that phenolics and flavonoids could synthesize esters during metabolic synthesis (Wei et al., 2016). The contents of TPC and TFC in Huangjiu samples after adding CBR were higher, and its volatile aroma might be better than other samples.

The correlation between the components in Huangjiu samples is also shown in Fig. 2a (right). There was a significant negative correlation between tartaric acid and malic acid, and a significant positive correlation with homogentisic acid, cyanidin-3-*O*-glucoside, vanillic acid, epicatechin, rutin, procyanidin, and salicylic acid ($p < 0.05$). Malic acid was significant negatively correlated with homogentisic acid, vanillic acid, epicatechin, rutin, procyanidin, and salicylic acid, and significant positively correlated with chlorogenic acid ($p < 0.05$). Homogentisic acid was significant negatively correlated with chlorogenic acid, and significant positively correlated with catechol, vanillic acid, rutin, procyanidin, and salicylic acid ($p < 0.05$). Chlorogenic acid was significant negatively correlated with vanillic acid, rutin, and procyanidin ($p < 0.05$). Catechol was significant negatively correlated with hydroxybenzene propanoic, caffeic acid, and ferulic acid, significant positively correlated with procyanidin ($p < 0.05$). Hydroxybenzene propanoic was significant positively correlated with caffeic acid, epicatechin, and ferulic acid ($p < 0.05$). Vanillic acid was significant positively correlated with epicatechin, rutin, procyanidin, and *p*-coumaric acid ($p < 0.05$). Caffeic acid was significant positively correlated with *p*-coumaric acid and ferulic acid ($p < 0.05$). Epicatechin was significant positively correlated with rutin, *p*-coumaric acid, and salicylic acid ($p < 0.05$). Ferulic acid was significant positively correlated with *p*-coumaric acid, myricetin was significant positively correlated with salicylic acid ($p < 0.05$). The above results suggested potential metabolic relationships among the components in Huangjiu samples. Metabonomics technology would be employed to analyze the secondary metabolites of the rice wine samples in greater detail.

According to the criteria of correlation coefficient and $p < 0.05$, the results showed 8 components including tartaric acid, malic acid, homogentisic acid, vanillic acid, epicatechin, rutin, procyanidin, and salicylic acid were significantly and closely associated with DPPH-RSC/OH-RSC/FRAP (Fig. 2b). There was a significant negative correlation between malic acid and DPPH-RSC/OH-RSC/FRAP ($p < 0.001$), while the other metabolites showed a significant positive correlation with these antioxidant indicators ($p < 0.001$). Therefore, despite having the highest content of malic acid, CRW did not exhibit the strongest antioxidant capacity. Phenolic compounds and flavonoids are powerful antioxidants, with more potential than vitamin C, vitamin E, or carotenoids (Ruiz et al., 2016).

The higher total content of components detected in Huangjiu samples, the stronger the antioxidant capacity, consistent with the findings of Jin et al. (2021). Mixed fermentation or the addition of CBR primarily enhanced the antioxidant capacity and also improved the nutritional quality of CQRW.

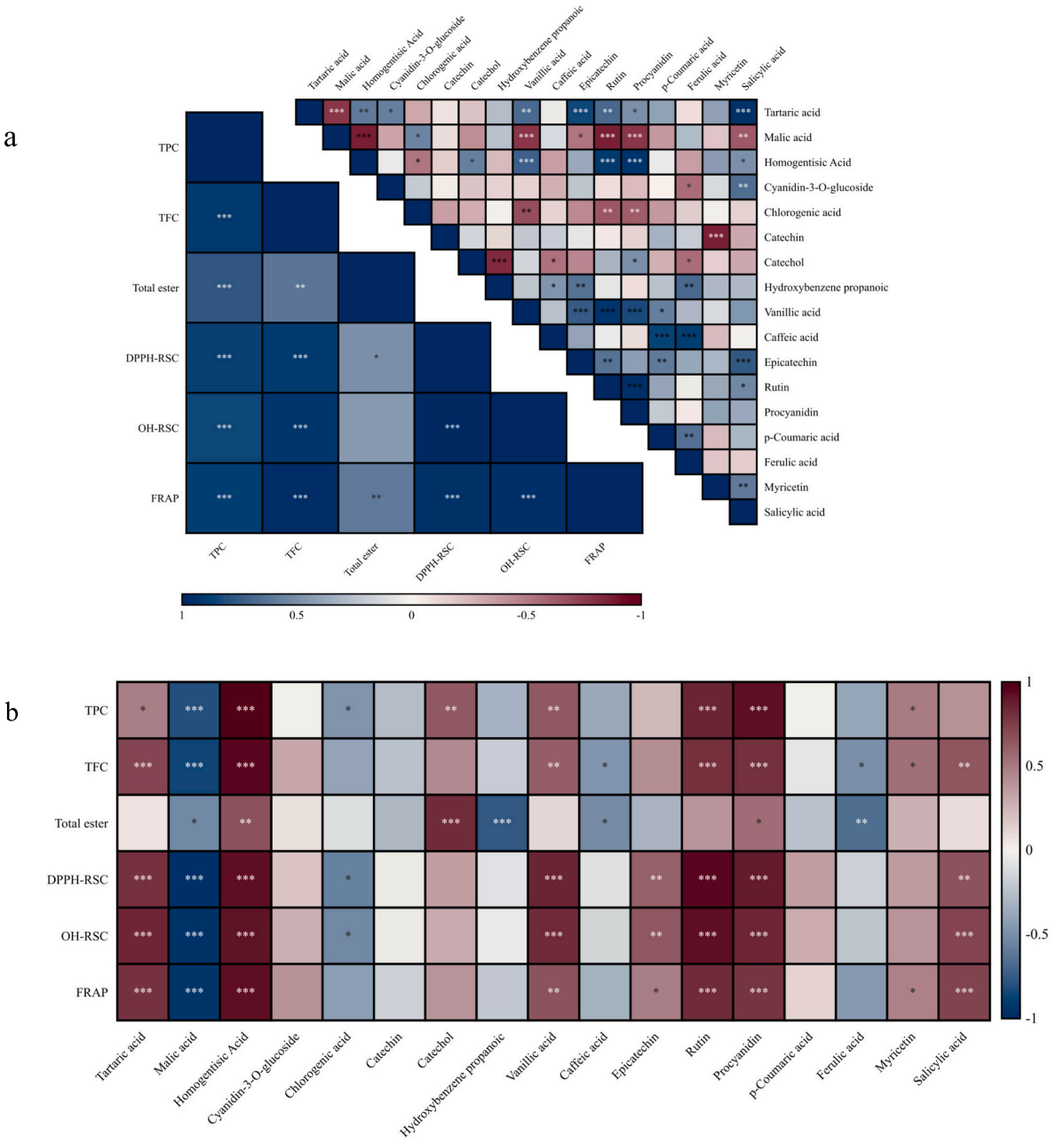

Fig. 2. Correlation analysis of basic index CRW, CQW, CQRW, 10%CBR + CQRW, 20%CBR + CQRW, 30%CBR + CQRW and correlation analysis of each component. (a): Correlation analysis of TPC, TFC, Total ester, antioxidants of the prepared Huangjiu samples (left, intra-group correlation analysis), correlation analysis of components in the prepared Huangjiu samples (right, intra-group correlation analysis) ($p < 0.05$, *; $p < 0.01$, **; $p < 0.001$, ***). (b): Correlation analysis of the data of TPC, TFC, Total ester, antioxidants and components of the prepared Huangjiu samples (inter-group correlation analysis) ($p < 0.05$, *; $p < 0.01$, **; $p < 0.001$, ***).

3.3. Detection of amino acid in Huangjiu

Huangjiu contains a rich array of amino acids, which are produced through the enzymatic hydrolysis of proteins in the raw material (Chen et al., 2020). Quinoa contains 11% more protein than rice and hydrolyzes more easily (Chen, Wu, et al., 2020; He et al., 2022; Ruiz et al., 2016). Therefore, the amino acid content of the sample (raw material including quinoa) was significantly higher than that of CRW (which contains only rice) ($p < 0.05$). Moreover, CQRW had the highest total amino acid content (Table 2). Phe, Leu, Ile, Met, Val, Thr, His, and Lys, which are essential amino acids for human, were higher in CQRW compared to other samples (the Leu content of CQRW was only lower than 10%CBR + CQRW) ($p < 0.05$) (Table 2). Among the samples, the extrusion and hulling process of rice led to the loss of most essential amino acids. Conversely, the preparation of quinoa rice wine preserved these amino acids, thanking to the inclusion of whole quinoa (Cao et al., 2022; Kuktaite et al., 2021).

The taste of amino acids is closely related to the R group of their side chains, which typically exhibit sour, sweet, bitter, salty, flavor, and aromatic qualities (Guo et al., 2023). According to the analysis of 17 amino acids listed in Table 2, 20%CBR + CQRW had the highest content of bitter amino acids, and CQRW had the highest content of aromatic amino acids, sweet amino acids, sour amino acids, and flavor amino acids ($p < 0.05$), and the taste of CQRW is more prominent. Duan et al. (2023) demonstrated that the type and content of amino acids significantly impact the aroma and taste of fermentation products ($p < 0.05$).

Table 2
The content of amino acid in prepared CRW, CQW, CQRW, 10%CBR + CQRW, 20%CBR + CQRW, 30%CBR + CQRW were determined (mg/L).

Num	RT [1] (min)	Compound	CRW	CQW	CQRW	10% CBR + CQRW	20% CBR + CQRW	30% CBR + CQRW
1	3.838	Phe	53.946 ± 1.242 ^{Dj}	62.930 ± 0.257 ^{Ck}	96.642 ± 0.400 ^{Az}	63.648 ± 0.383 ^{Cm}	76.472 ± 0.170 ^{Bk}	44.011 ± 0.750 ^{Em}
2	4.132	Leu	105.629 ± 0.837 ^{Fd}	137.533 ± 0.484 ^{Dd}	164.752 ± 0.296 ^{Bg}	177.552 ± 0.755 ^{Ac}	139.015 ± 0.778 ^{Cf}	136.184 ± 0.211 ^{Eb}
3	4.430	Ile	58.044 ± 0.394 ^{Di}	80.580 ± 0.299 ^{Bj}	89.779 ± 0.868 ^{Am}	90.620 ± 1.364 ^{Ak}	88.993 ± 0.867 ^{Aj}	68.158 ± 0.998 ^{Ci}
4	4.773	Met	68.024 ± 0.499 ^{Ch}	50.377 ± 0.707 ^{Ez}	80.009 ± 0.863 ^{An}	75.089 ± 0.901 ^{Bz}	67.433 ± 0.353 ^{Cz}	64.801 ± 0.595 ^{Dj}
5	5.300	Tyr	97.506 ± 0.249 ^{Ee}	92.755 ± 0.743 ^{Fi}	140.401 ± 0.843 ^{Ci}	142.882 ± 0.661 ^{Bg}	152.51 ± 1.310 ^{Ac}	115.067 ± 0.816 ^{De}
6	5.320	Val	105.524 ± 0.443 ^{Ed}	121.913 ± 0.450 ^{Df}	177.830 ± 0.538 ^{Ad}	170.525 ± 0.562 ^{Be}	142.421 ± 0.388 ^{Ce}	53.079 ± 0.583 ^{Fz}
7	5.527	Pro	128.408 ± 0.759 ^{Cb}	150.809 ± 0.453 ^{Bc}	178.568 ± 0.599 ^{Ad}	150.294 ± 0.758 ^{Bf}	151.609 ± 1.294 ^{Bc}	123.114 ± 0.695 ^{Dd}
8	6.662	Ala	139.998 ± 0.259 ^{Fa}	198.311 ± 0.274 ^{Da}	231.392 ± 0.790 ^{Ca}	173.795 ± 1.526 ^{Ed}	247.043 ± 1.435 ^{Aa}	233.36 ± 0.235 ^{Ba}
9	6.729	Thr	51.714 ± 1.524 ^{Dj}	26.263 ± 0.906 ^{Em}	128.421 ± 0.985 ^{Aj}	97.385 ± 0.949 ^{Bj}	95.686 ± 1.734 ^{Bi}	55.892 ± 1.361 ^{Ck}
10	7.114	Gly	73.970 ± 4.139 ^{Fg}	151.737 ± 0.403 ^{Dc}	225.692 ± 1.199 ^{Ab}	187.152 ± 1.393 ^{Bb}	167.856 ± 2.856 ^{Cb}	130.912 ± 1.972 ^{Ec}
11	7.281	Ser	73.303 ± 0.962 ^{Eg}	17.935 ± 0.179 ^{Fn}	159.437 ± 1.069 ^{Ah}	121.219 ± 1.030 ^{Bi}	115.137 ± 2.332 ^{Ch}	86.586 ± 1.414 ^{Dh}
12	7.630	Glu	109.733 ± 0.694 ^{Fc}	170.436 ± 0.904 ^{Cb}	202.66 ± 1.065 ^{Ac}	192.305 ± 1.603 ^{Ba}	166.848 ± 0.311 ^{Db}	130.898 ± 0.787 ^{Ec}
13	8.267	Asp	70.297 ± 0.890 ^{Fh}	118.125 ± 1.462 ^{Dg}	168.650 ± 0.493 ^{Af}	141.204 ± 0.627 ^{Bg}	128.227 ± 0.620 ^{Cg}	100.254 ± 0.746 ^{Ef}
14	9.253	His	43.114 ± 0.766 ^{Dk}	105.703 ± 2.148 ^{Bh}	121.397 ± 0.343 ^{Ak}	96.093 ± 0.378 ^{Cj}	96.040 ± 0.463 ^{Ci}	33.586 ± 1.516 ^{En}
15	9.504	Cys	1.773 ± 0.142 ^{Dz}	3.354 ± 0.359 ^{Co}	22.521 ± 0.666 ^{Ao}	10.390 ± 0.065 ^{Bo}	4.077 ± 0.865 ^{Cm}	4.335 ± 0.439 ^{Co}
16	9.566	Arg	94.743 ± 0.448 ^{Bf}	17.246 ± 0.342 ^{En}	12.142 ± 0.046 ^{Fp}	37.325 ± 2.562 ^{Dn}	116.047 ± 1.883 ^{Ah}	91.151 ± 1.001 ^{Cg}
17	9.882	Lys	107.749 ± 0.277 ^{Ecd}	130.649 ± 0.093 ^{De}	172.585 ± 1.800 ^{Ae}	135.325 ± 1.263 ^{Ch}	145.413 ± 0.630 ^{Bd}	101.201 ± 1.090 ^{Ff}
Amino acid separation								
Bitter amino acids [2]			558.505 ± 4.378 E^{a}	618.660 ± 4.722 ^{Da}	802.943 ± 3.336 ^{Bb}	778.645 ± 6.666 ^{Ca}	811.498 ± 2.859 ^{Aa}	541.235 ± 5.876 ^{Fb}
Aromatic amino acids [3]			69.797 ± 0.641 ^{CDe}	53.730 ± 1.066 ^{Ee}	102.530 ± 1.529 ^{Ae}	85.479 ± 0.966 ^{Be}	71.510 ± 1.218 ^{Ce}	69.135 ± 10.34 ^{De}
Sweet amino acids [4]			467.394 ± 7.643 ^{Fb}	545.055 ± 2.215 ^{Eb}	923.510 ± 4.642 ^{Aa}	729.846 ± 5.656 ^{Cb}	777.331 ± 9.651 ^{Bb}	629.864 ± 5.677 ^{Da}
Sour amino acids [5]			180.029 ± 1.584 ^{Fc}	288.561 ± 2.366 ^{Dc}	371.309 ± 1.559 ^{Ac}	333.510 ± 2.230 ^{Bc}	295.075 ± 0.931 ^{Cc}	231.152 ± 1.533 ^{Ec}
Flavor amino acids [6]			107.749 ± 0.277 ^{Ed}	130.649 ± 0.093 ^{Dd}	172.585 ± 1.800 ^{Ad}	135.325 ± 1.263 ^{Cd}	145.413 ± 0.630 ^{Bd}	101.201 ± 1.090 ^{Fd}
Total amino acids			1383.474 ± 14.523 ^{F}	1636.655 ± 10.462^{D}	2372.878 ± 12.864 ^{A}	2062.805 ± 16.780^{C}	2100.826 ± 18.289 ^{B}	1572.587 ± 15.210 ^{E}

[1] RT: Retention time. [2] Bitter amino acids: Phe, Leu, Ile, Tyr, Val, His, Arg. Aromatic amino acids [3]: Met, Cys. Sweet amino acids [4]: Pro, Ala, Thr, Gly, Ser. Sour amino acids [5]: Glu, Asp. Flavor amino acid [6]: Lys. Uppercase letters and lowercase letters mark statistically significant differences with one-way ANOVA test of significance ($p < 0.05$) among samples and compounds, respectively.

This result indicated that using quinoa as a fermentation material could enhance the aroma's richness and improve the taste of Huangjiu.

3.4. Taste traits analysis

3.4.1. Taste traits analysis the Huangjiu samples

High-quality Huangjiu typically features flavors such as sour, sweet, bitter, astringent, and fresh (Wang et al., 2020; Yu et al., 2022). The taste traits and intensity of six Huangjiu samples are presented in Fig. 3a. Due to the difference of fermentation raw materials, significant differences were observed in sourness, bitterness, astringency, aftertaste, umami, richness, saltness, and sweetness among the six samples.

Most of the acids in Huangjiu are produced by yeast, and a moderate amount of acids can enhance the taste while reducing the sweetness of Huangjiu (Li et al., 2022; Lv et al., 2015). The CQRW had the lowest sourness (−24.500 ± 0.029) ($p < 0.05$), CQW had the highest acidity (−8.857 ± 0.025) ($p < 0.05$), CRW was close to 10%CBR + CQRW and 20%CBR + CQRW. The CRW, which uses only rice as a raw material, is similar to traditional rice wine (Guo et al., 2023; Wang et al., 2020; Wei et al., 2016). Therefore, the sourness levels of CRW, 10%CBR + CQRW, and 20%CBR + CQRW fall within the normal range, enhancing the taste of rice wine.

The presence of bitterness is an essential characteristic of Huangjiu, and a suitable level of bitterness not only enhances the taste but also imparts a refreshing sensation to the wine (Lu et al., 2021; Yu et al., 2022). Compared with CRW, CQW had the lowest bitterness (4.007 ± 0.102), and other samples had little difference in bitterness, all of which were within the normal range. The astringency of Huangjiu is primarily caused by lactic acid, tyrosine, and others compounds (Yu et al., 2022). When CBR was added to the raw materials, the content of Tyr in the sample increased significantly (except in 30%CBR + CQRW) ($p < 0.05$) (Table 2, Fig. 3a). The astringency of all samples was within the normal range (Lu et al., 2021). The aftertaste of 20%CBR + CQRW is significantly higher than that of other samples ($p < 0.05$). A high aftertaste value can bring better taste (Guo et al., 2023). Duan et al. (2023) demonstrated that the umami taste was associated with Glu and Lys; CQRW, having the highest content of Glu and Lys, consequently exhibited the highest umami value. The complexity of the raw materials used could influence the richness of Huangjiu. Therefore, CQRW and 20% CBR + CQRW exhibited higher richness values compared to the other samples, indicating that the appropriate amount of CBR could enhance this aspect. In this study, CRW had the highest sweetness, CQW and 30%CBR + CQRW scored lower on sweetness, and the other samples had moderate sweetness scores. Comparing the taste traits of all the samples, CQW and 20%CBR + CQRW were judged to have the best taste. Appropriate amount of CBR can improve the taste quality of rice wine.

3.4.2. PCA analysis of Huangjiu taste traits

To compare the taste traits of Huangjiu brewed with different raw materials, principal component analysis (PCA) was performed (Melucci et al., 2016) on the taste traits value shown in Fig. 3a.

In Fig. 3b, PC1 (40.1%) and PC2 (36.6%), the first two principal components, explained most of the total variance (76.7%). The total variance was close to 80%, indicating that PC1 and PC2 had a good explanation for the samples and could be used for subsequent analysis (Ma et al., 2022). PC2 distinguished CRW, CQW, and CQRW, 10%CBR + CQRW, 20%CBR + CQRW, 30%CBR + CQRW. CRW and CQW were located at the negative end of PC2, while the other samples were positioned at the positive end. This indicated that there were significant differences in taste traits between CRW, CQW and the other samples ($p < 0.05$). PC1 distinguished 30%CBR + CQRW and CQRW, 10%CBR + CQRW, 20%CBR + CQRW. When the amount of CBR was 30%, the taste of CQRW changed significantly ($p < 0.05$), which might not be desirable for the preparation of Huangjiu. The CQRW, 10%CBR + CQRW, and 20%CBR + CQRW were positioned in the positive end of PC1 and PC2, and were closely related to astringency, richness, aftertaste-B, bitterness, and umami. This suggested that these samples shared similar taste characteristics. The taste traits of these three samples were identified as including astringency, richness, aftertaste-B, bitterness, and umami. The addition of 10% and 20% CBR improved the taste traits of CQRW.

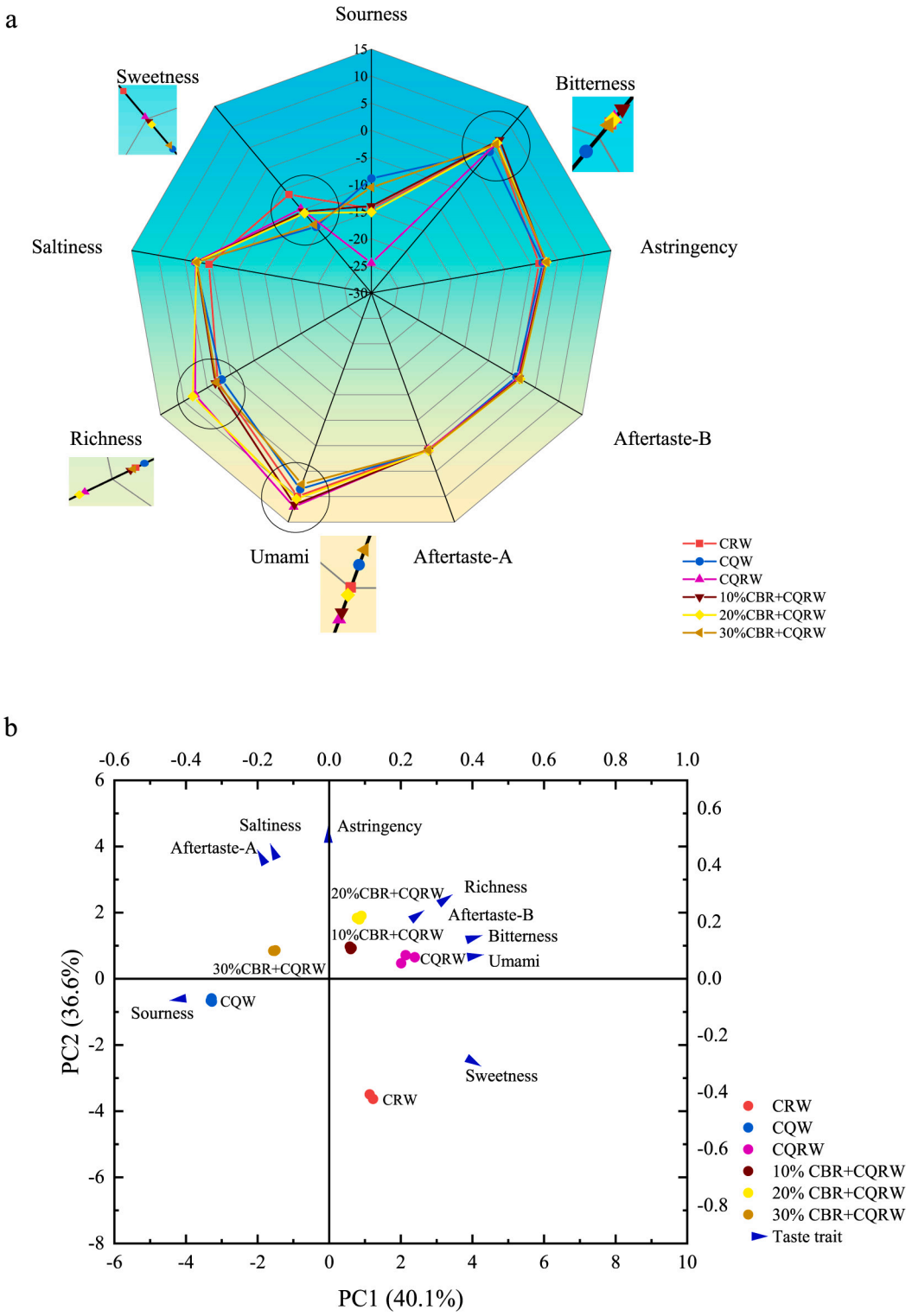

Fig. 3. Taste traits of the prepared CRW, CQW, CQRW, 10%CBR + CQRW, 20%CBR + CQRW, 30%CBR + CQRW analyzed by electronic tongue, and analysis of the correlation between the taste characteristics and amino acid content of the prepared Huangjiu samples. (a): Radar chart for the taste profiles of the prepared Huangjiu samples. (b): Principal component analysis (PCA) was used to analyzed the taste traits of the prepared Huangjiu samples. (c): Correlation analysis between taste traits and amino acid content of the prepared Huangjiu samples (inter-group correlation analysis) ($p < 0.05$, *; $p < 0.01$, **; $p < 0.001$, ***).

3.4.3. *Correlation analysis of Huangjiu amino acids and taste traits*

To verify the correlation between amino acids and taste traits of Huangjiu, correlation analysis was conducted using normalized data (Duan et al., 2023; Zhu, Jiang, et al., 2020). The intergroup correlation analysis was conducted based on the results of the intra-group correlation analysis of *E*-tongue and amino acids content (Fig. S2). The results are shown in Fig. 3c. Sourness was negatively correlated with all amino acids (no Arg). Bitterness and astringency showed a positive correlation

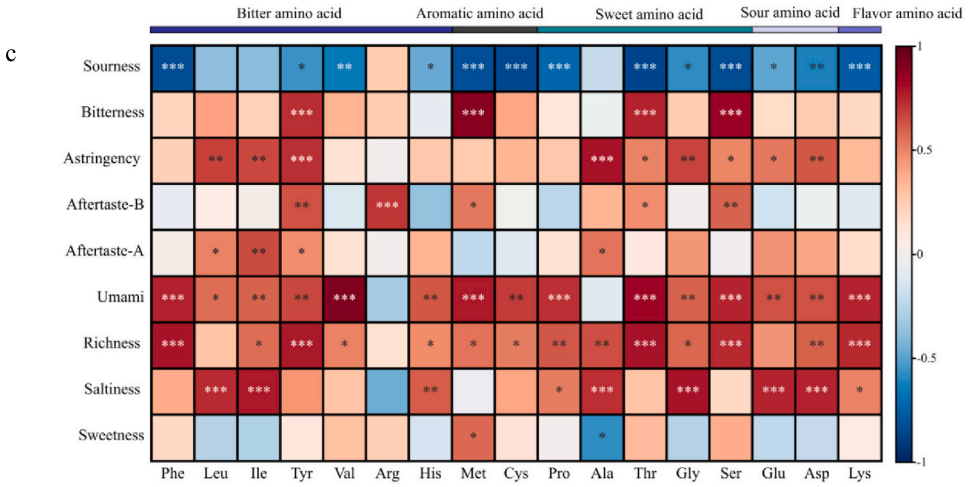

Fig. 3. (*continued*).

with most amino acids (except Arg, His and Ala). With the exception of Arg and Ala, umami showed a positive with other amino acids. The Lys, which is classified as an umami amino acid, had a significant impact on the umami value of Huangjiu due to its content ($p < 0.05$) (Chen, Wu, et al., 2020; Lu et al., 2021). The richness value was positively correlated with all amino acids, suggesting that higher amino acids levels in Huangjiu significantly influence its taste traits ($p > 0.05$). In Fig. 3c, saltiness was significantly correlated with Ile, Pro, Glu, and Asp ($p < 0.05$), aligning with the findings of Guo et al. (2023). There was a significant negative correlation between sweetness value and Ala (sweet amino acid) ($p < 0.05$). The change in amino acid content was closely associated with alterations in the taste characteristics of Huangjiu.

3.5. Analysis of aroma components of Huangjiu

The difference of fermentation raw materials influences the volatile compounds in Huangjiu (Yang et al., 2020; Yu et al., 2022). The main compounds and contents of Huangjiu with different raw materials were shown in Fig. 4 and Table 3. A total of 79 key volatiles were detected in 6 samples, including 26 esters, 16 higher alcohols, 12 aldehydes, 9 acids, 7 ketones, and 9 others. The 10%CBR + CQRW had the most easters, higher alcohols, aldehydes, acids, and ketones volatile compounds; CQRW had the most of others volatile compounds (Fig. 4a). With the increase of CBR, all kinds of volatile compounds in CQRW (with added CBR) showed a gradient decrease (Fig. 4a). Cluster analysis was used to analyze the volatile compounds of 6 Huangjiu samples. The 10%CBR + CQRW, 20%CBR + CQRW, and CQRW fall into the same category, indicating that both 10% and 20% CBR can enhance the aroma quality of CQRW (Fig. 4b). Table S4 lists the detection time and the characteristic aroma description of volatile compounds.

Yeast fermentation can promote the synthesis of certain ester compounds (Wei et al., 2016). Ester volatile compounds are produced by yeast and acetyl-CoA, influenced by various factors including fermentation factors (Wang et al., 2020). The CRW contained 18 ester compounds, with ethyl nonanoate, which imparts grape and rose aromas, being unique to CRW. The CQW had the highest number of ester compounds (23). However, its ester compounds content was 301.857 ± 6.118 mg/L, which is lower than that of other samples (except for 30% CBR + CQRW). When the fermentation materials included rice and quinoa, only one aromatic ester was absent, and the concentration of esters compound increased by 36.716% (compared with CQW). With the addition of 10% CBR, the type of ester compounds remained the same, but their concentration increased by 48.146% (compared to CQW). The results indicated that adding CBR as an excipient in CQRW enhanced the volatile aroma of Huangjiu esters.

The metabolism of sugar intermediates, or the transamination of aromatic amino acids via the *Ehrlich* pathway, produces the corresponding higher alcohols during alcoholic fermentation (Ma et al., 2022). Chen, Wu, et al. (2020) study showed that glutelin promoted the production of higher alcohols and ester was 11% and 99%, respectively. 1-Propanol showed weak ethanol and acetone flavor. 4-Methyl-1-pentanol showed wine flavor, and they were only detected in CRW and CQRW. The types (11) and contents (2080.046 ± 2.406 mg/L) of higher alcohols volatile compounds in CQW were lower than those in other samples ($p < 0.05$). When the raw material is solely quinoa, the absence of sugar and the lack of cooperative fermentation by lactic acid bacteria and yeast inhibit amino acid metabolism, reducing the content of higher alcohols (Wei et al., 2016). There was a difference in the type of higher alcohol compounds between CQRW and other samples with added CBR, which was 1-propanol. When the addition of CBR was 10%, the higher alcohols volatile compounds in Huangjiu was the most.

Aldehydes are typically produced by the oxidation of polyphenols or the conversion of alcohols (Li et al., 2022; Paucean et al., 2019). During fermentation, amylopectin can be preferentially utilized for the synthesis of aldehydes volatile compounds (Yang et al., 2020). The differences in starch types between quinoa and rice resulted in varying aldehydes volatile compounds contents in CRW and CQW. The 10%CBR + CQRW had the highest concentration of aldehydes volatile compounds (12). Additionally, a new aldehyde compound, 2-Methyl-3-phenylpropionaldehyde, was identified after adding CBR, which enhances the aroma of Huangjiu.

Saccharomyces cerevisiae can synthesize a variety of organic acids from sugars and other nutrients (Jin et al., 2021). Acetic acid is the most acids volatile compound, and its accumulation can lead to a deterioration in the quality of Huangjiu (Xie et al., 2021). The acetic acid content in CRW is comparable to that of traditional rice wine (Lv et al., 2015). Consequently, the sour volatile compounds in CRW and CQRW contribute positively to the aroma of rice wine.

Ketones volatile compounds usually have special aroma, 2-octanone shows fruity, fatty, grass flavor; 2-heptanone shows medicinal flavor; 2-undecanone shows fruity, cream, cheese flavor; 4-Methylacetophenone shows hawthorn, honey, alfalfa flavor; 2-nonanone shows fruity, sweet, wax, coconut flavor; 4-hydroxy-2-butanone shows aromatic odor. There were 6 ketones volatile compounds in 10%CBR + CQRW, and the highest content was 7.407 ± 0.235 mg/L ($p < 0.05$). Adding 10%CBR to the raw materials could increase the content of special aroma compounds in Huangjiu.

Other volatile compounds included furans, alkenes, naphthalene, and their derivatives, etc. And 9 others volatile compounds (except CRW) were identified in the Huangjiu samples, with the highest

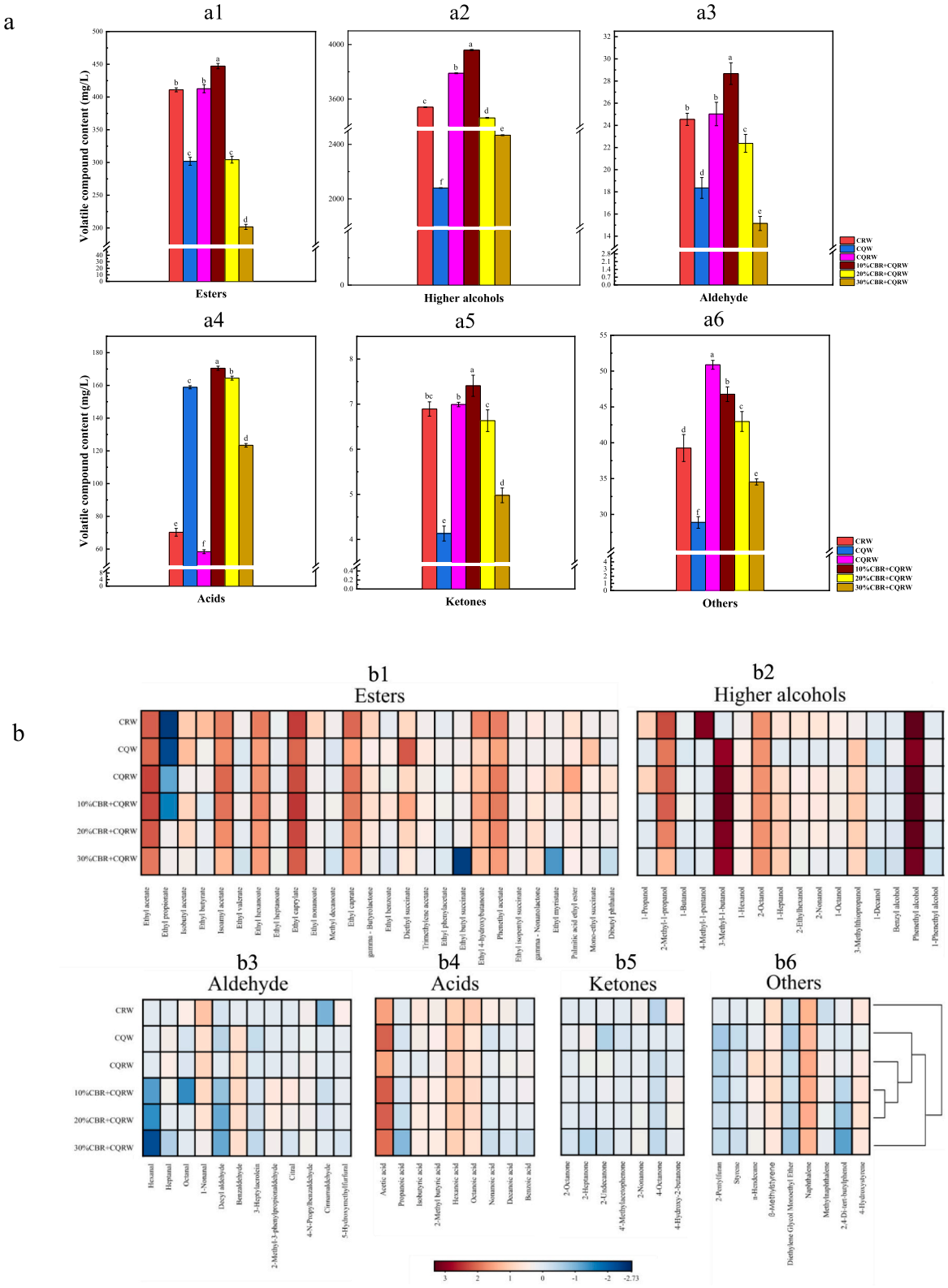

Fig. 4. Analysis of main volatile compounds in prepared CRW, CQW, CQRW, 10%CBR + CQRW, 20%CBR + CQRW, 30%CBR + CQRW. (a): Total analysis of total esters (a1), higher alcohols (a2), aldehydes (a3), acids (a4), ketones (a5), and others (a6) compound of the Huangjiu samples. (b) Heat map and cluster analysis of main volatile compounds in Huangjiu samples (esters (b1), higher alcohols (b2), aldehydes (b3), acids (b4), ketones (b5), and others (b6)). Different lowercase letters mean significant difference ($p < 0.05$).

Table 3
Concentration of main volatile compounds in the prepared CRW, CQW, CQRW, 10%CBR + CQRW, 20%CBR + CQRW, 30%CBR + CQRW (mg/L).

NO	Volatiles	CRW	CQW	CRQW	10% CBR + CQRW	20% CBR + CQRW	30% CBR + CQRW
	Esters	410.996 ± 3.002 ^{B}	301.857 ± 6.118^{C}	412.687 ± 4.336 ^{B}	447.188 ± 4.113 ^{A}	304.372 ± 5.201^{C}	201.699 ± 3.889 ^{D}
A1	Ethyl acetate	64.903 ± 0.551 ^{D}	55.436 ± 1.021 ^{E}	108.312 ± 0.715 ^{A}	100.513 ± 0.933 ^{B}	72.046 ± 0.786^{C}	40.315 ± 0.355 ^{F}
A2	Ethyl propionate	0.002 ± 0.001 ^{B}	0.003 ± 0.001 ^{B}	0.004 ± 0.001 ^{B}	0.013 ± 0.002 ^{A}	nd	nd
A3	Isobutyl acetate	5.756 ± 0.317 ^{B}	8.810 ± 0.559 ^{A}	nd	4.315 ± 0.103^{C}	4.221 ± 0.243^{C}	1.213 ± 0.131 ^{D}
A4	Ethyl butyrate	8.876 ± 0.422 ^{A}	0.901 ± 0.072 ^{B}	nd	0.423 ± 0.078 ^{E}	0.754 ± 0.025^{C}	0.631 ± 0.014 ^{D}
A5	Isoamyl acetate	33.751 ± 0.858^{C}	29.173 ± 0.750^{C}	55.953 ± 0.633 ^{A}	45.924 ± 0.456 ^{B}	27.784 ± 1.030^{C}	10.351 ± 0.231 ^{D}
A6	Ethyl valerate	nd	0.435 ± 0.075^{C}	0.551 ± 0.085 ^{B}	1.063 ± 0.023 ^{A}	0.597 ± 0.055 ^{B}	0.331 ± 0.056 ^{D}
A7	Ethyl hexanoate	35.306 ± 0.531 ^{A}	20.057 ± 0.089 ^{E}	25.219 ± 0.371^{C}	30.566 ± 2.153 ^{B}	22.981 ± 0.611 ^{D}	19.874 ± 0.691 ^{F}
A8	Ethyl heptanoate	0.857 ± 0.010 ^{B}	0.674 ± 0.024^{C}	0.562 ± 0.036 ^{D}	1.053 ± 0.041 ^{A}	0.844 ± 0.033 ^{B}	0.832 ± 0.055 ^{B}
A9	Ethyl caprylate	123.619 ± 0.615 ^{B}	58.005 ± 0.272 ^{F}	92.565 ± 0.355 ^{D}	135.223 ± 0.188 ^{A}	94.883 ± 0.358^{C}	69.135 ± 0.339 ^{E}
A10	Ethyl nonanoate	4.148 ± 0.746 ^{A}	nd	nd	nd	nd	nd
A11	Methyl decanoate	nd	0.409 ± 0.053 ^{D}	0.672 ± 0.022 ^{B}	0.935 ± 0.072 ^{A}	0.541 ± 0.016^{C}	0.315 ± 0.012 ^{E}
A12	Ethyl caprate	53.963 ± 1.010 ^{A}	15.714 ± 0.035 ^{F}	44.087 ± 0.277 ^{B}	37.465 ± 0.864^{C}	24.384 ± 0.156 ^{D}	19.893 ± 0.544 ^{E}
A13	gamma - Butyrolactone	4.433 ± 0.346 ^{A}	1.265 ± 0.221 ^{E}	2.526 ± 0.045^{C}	3.001 ± 0.233 ^{B}	1.985 ± 0.250 ^{D}	1.204 ± 0.472 ^{E}
A14	Ethyl benzoate	0.620 ± 0.046 ^{E}	1.396 ± 0.110 ^{B}	0.823 ± 0.034^{C}	2.315 ± 0.105 ^{A}	0.739 ± 0.036 ^{D}	0.412 ± 0.016 ^{F}
A15	Diethyl succinate	3.977 ± 0.140 ^{D}	72.847 ± 0.569 ^{A}	3.546 ± 0.301 ^{D}	16.351 ± 0.135 ^{B}	4.266 ± 0.333^{C}	2.135 ± 0.008 ^{E}
A16	Trimethylene acetate	nd	1.825 ± 0.011 ^{A}	1.211 ± 0.011 ^{D}	1.636 ± 0.084 ^{B}	1.315 ± 0.013^{C}	0.737 ± 0.035 ^{E}
A17	Ethyl phenylacetate	0.574 ± 0.044^{C}	nd	0.778 ± 0.016 ^{B}	0.913 ± 0.035 ^{A}	0.554 ± 0.056^{C}	0.435 ± 0.031 ^{D}
A18	Ethyl butyl succinate	nd	1.144 ± 0.132 ^{B}	1.876 ± 0.041 ^{A}	nd	nd	0.002 ± 0.002^{C}
A19	Ethyl 4-hydroxybutanoate	29.954 ± 0.035 ^{A}	4.953 ± 0.455 ^{E}	10.297 ± 0.764^{C}	18.832 ± 0.561 ^{B}	11.242 ± 0.325^{C}	8.664 ± 0.122 ^{D}
A20	Phenethyl acetate	35.744 ± 0.156 ^{B}	16.699 ± 0.546 ^{E}	38.036 ± 1.223 ^{A}	38.983 ± 0.435 ^{A}	28.905 ± 0.845^{C}	20.736 ± 0.651 ^{D}
A21	Ethyl isopentyl succinate	nd	1.062 ± 0.852 ^{A}	nd	nd	nd	nd
A22	gamma - Nonanolactone	1.780 ± 0.010^{C}	nd	1.855 ± 0.020 ^{B}	2.207 ± 0.036 ^{A}	2.930 ± 0.775 ^{A}	2.953 ± 0.035 ^{A}
A23	Ethyl myristate	nd	1.122 ± 0.100 ^{B}	4.091 ± 0.366 ^{A}	0.956 ± 0.026^{C}	0.756 ± 0.023 ^{D}	0.025 ± 0.006 ^{E}
A24	Palmitic acid ethyl ester	2.732 ± 0.165 ^{B}	1.700 ± 0.133^{C}	15.706 ± 0.465 ^{A}	2.984 ± 0.377 ^{B}	1.686 ± 0.161^{C}	1.269 ± 0.035 ^{D}
A25	Mono-ethyl succinate	nd	7.530 ± 0.022 ^{A}	1.454 ± 0.111 ^{B}	nd	nd	nd
A26	Dibutyl phthalate	nd	0.697 ± 0.016 ^{D}	2.530 ± 0.543 ^{A}	1.513 ± 0.192 ^{B}	0.957 ± 0.076^{C}	0.235 ± 0.047 ^{E}
	Higher alcohols	3540.501 ± 2.478^{C}	2080.046 ± 2.406 ^{F}	3789.026 ± 2.944 ^{B}	3959.347 ± 4.479 ^{A}	3461.786 ± 3.275 ^{D}	2467.366 ± 3.143 ^{E}
B1	1-Propanol	9.620 ± 0.123 ^{A}	nd	8.819 ± 0.242 ^{B}	nd	nd	nd
B2	2-Methyl-1-propanol	201.084 ± 0.546 ^{A}	86.018 ± 0.138 ^{D}	126.660 ± 0.476^{C}	135.662 ± 0.089 ^{B}	70.852 ± 0.585 ^{E}	21.170 ± 0.847 ^{F}
B3	1-Butanol	1.520 ± 0.122 ^{B}	0.767 ± 0.046 ^{D}	1.519 ± 0.181 ^{B}	1.736 ± 0.155 ^{A}	1.009 ± 0.044^{C}	0.678 ± 0.032 ^{E}
B4	4-Methyl-1-pentanol	1123.369 ± 0.651 ^{A}	nd	nd	nd	nd	nd
B5	3-Methyl-1-butanol	nd	766.788 ± 0.651 ^{E}	1453.051 ± 0.642 ^{B}	1633.166 ± 2.315 ^{A}	1241.977 ± 0.994^{C}	833.156 ± 0.317 ^{D}
B6	1-Hexanol	2.210 ± 0.110 ^{E}	2.981 ± 0.135 ^{B}	2.998 ± 0.022 ^{B}	3.135 ± 0.028 ^{A}	2.817 ± 0.061^{C}	2.632 ± 0.049 ^{D}
B7	2-Octanol	50.000	50.000	50.000	50.000	50.000	50.000
B8	1-Heptanol	4.770 ± 0.262 ^{E}	nd	5.972 ± 0.267 ^{D}	9.444 ± 0.364^{C}	12.810 ± 0.114 ^{A}	11.638 ± 0.397 ^{B}
B9	2-Ethylhexanol	4.492 ± 0.056 ^{A}	nd	2.483 ± 0.100^{C}	3.677 ± 0.042 ^{B}	2.330 ± 0.025 ^{D}	1.638 ± 0.048 ^{E}
B10	2-Nonanol	4.182 ± 0.182 ^{A}	nd	3.519 ± 0.149 ^{B}	3.465 ± 0.221 ^{B}	3.006 ± 0.023^{C}	1.349 ± 0.034 ^{D}
B11	1-Octanol	2.517 ± 0.067 ^{A}	1.419 ± 0.068 ^{D}	2.329 ± 0.058 ^{B}	2.331 ± 0.034 ^{B}	1.901 ± 0.017^{C}	1.127 ± 0.017 ^{E}
B12	3-Methylthiopropanol	1.985 ± 0.203 ^{D}	12.924 ± 0.388 ^{A}	10.028 ± 0.486 ^{B}	12.336 ± 0.416 ^{A}	10.707 ± 0.613 ^{B}	8.668 ± 0.421^{C}
B13	1-Decanol	nd	0.602 ± 0.013 ^{B}	0.914 ± 0.100 ^{A}	0.984 ± 0.065 ^{A}	0.956 ± 0.068 ^{A}	0.477 ± 0.022^{C}
B14	Benzyl alcohol	nd	1.507 ± 0.069 ^{A}	0.788 ± 0.054^{C}	0.993 ± 0.102 ^{B}	0.792 ± 0.010^{C}	0.566 ± 0.013 ^{D}
B15	Phenethyl alcohol	2134.752 ± 0.156 ^{A}	1155.560 ± 0.883 ^{F}	2118.609 ± 0.156 ^{B}	2100.965 ± 0.585^{C}	2061.793 ± 0.687 ^{D}	1533.645 ± 0.915 ^{E}
B16	1-Phenethyl alcohol	0.000	1.482 ± 0.016 ^{A}	1.337 ± 0.012 ^{B}	1.454 ± 0.063 ^{A}	0.836 ± 0.034^{C}	0.622 ± 0.032 ^{D}
	Aldehydes	24.546 ± 0.546 ^{B}	18.357 ± 0.939 ^{D}	25.027 ± 1.027 ^{B}	28.671 ± 0.975 ^{A}	22.379 ± 0.813^{C}	15.154 ± 0.639 ^{E}
C1	Hexanal	nd	nd	0.922 ± 0.062 ^{A}	0.057 ± 0.003 ^{B}	0.035 ± 0.004^{C}	0.006 ± 0.002 ^{D}
C2	Heptanal	nd	2.332 ± 0.156 ^{B}	2.847 ± 0.086 ^{A}	1.735 ± 0.023^{C}	1.347 ± 0.101 ^{D}	0.277 ± 0.066 ^{E}
C3	Octanal	2.538 ± 0.083 ^{A}	0.654 ± 0.030^{C}	0.788 ± 0.021 ^{B}	0.035 ± 0.008 ^{D}	nd	nd
C4	1-Nonanal	14.707 ± 0.186 ^{A}	5.716 ± 0.662 ^{D}	8.756 ± 0.423 ^{B}	7.334 ± 0.331^{C}	5.069 ± 0.068 ^{D}	2.164 ± 0.112 ^{E}
C5	Decyl aldehyde	0.745 ± 0.058 ^{A}	0.332 ± 0.024 ^{B}	nd	0.152 ± 0.025^{C}	0.075 ± 0.006 ^{D}	0.076 ± 0.015 ^{D}
C6	Benzaldehyde	1.178 ± 0.045 ^{D}	5.906 ± 0.011^{C}	6.649 ± 0.254 ^{B}	7.563 ± 0.198 ^{A}	6.307 ± 0.307 ^{B}	5.727 ± 0.201^{C}
C7	3-Heptylacrolein	0.949 ± 0.032 ^{A}	0.465 ± 0.023 ^{E}	0.834 ± 0.054 ^{B}	0.695 ± 0.051^{C}	0.583 ± 0.059 ^{D}	0.403 ± 0.013 ^{F}
C8	2-Methyl-3-phenylpropionaldehyde	nd	nd	nd	3.787 ± 0.156 ^{A}	3.062 ± 0.089 ^{B}	2.233 ± 0.027^{C}
C9	Citral	nd	nd	1.125 ± 0.049^{C}	3.668 ± 0.053 ^{A}	2.068 ± 0.076 ^{B}	0.698 ± 0.047 ^{D}
C10	4-N-Propylbenzaldehyde	1.910 ± 0.061 ^{A}	1.711 ± 0.012^{C}	1.907 ± 0.036 ^{A}	1.951 ± 0.052 A	1.943 ± 0.039 ^{A}	1.836 ± 0.029 ^{B}
C11	Cinnamaldehyde	0.101 ± 0.012 ^{D}	nd	nd	0.540 ± 0.042^{C}	0.798 ± 0.036 ^{B}	0.983 ± 0.067 ^{A}
C12	5-Hydroxymethylfurfural	2.418 ± 0.069 ^{A}	1.241 ± 0.020 ^{B}	1.200 ± 0.068 ^{B}	1.156 ± 0.033^{C}	1.093 ± 0.028^{C}	0.751 ± 0.061 ^{D}
	Acids	70.263 ± 2.387 ^{E}	158.846 ± 0.947^{C}	58.403 ± 1.181 ^{F}	170.456 ± 1.251 ^{A}	164.443 ± 1.213 ^{B}	123.381 ± 1.077 ^{D}
D1	Acetic acid	35.840 ± 1.338 ^{E}	132.205 ± 0.316^{C}	34.493 ± 0.891 ^{E}	140.964 ± 0.465 ^{A}	135.389 ± 0.463 ^{B}	100.154 ± 0.647 ^{D}
D2	Propanoic acid	nd	0.712 ± 0.012 ^{A}	nd	0.657 ± 0.035 ^{B}	0.475 ± 0.056^{C}	0.118 ± 0.022 ^{D}
D3	Isobutyric acid	3.818 ± 0.204 ^{A}	2.312 ± 0.023 ^{D}	nd	3.516 ± 0.210 ^{A}	3.180 ± 0.018 ^{B}	2.783 ± 0.036^{C}
D4	2-Methyl butyric acid	2.324 ± 0.013 ^{D}	2.411 ± 0.061^{C}	2.269 ± 0.043 ^{D}	2.587 ± 0.008 ^{B}	2.882 ± 0.005 ^{A}	2.866 ± 0.024 ^{A}
D5	Hexanoic acid	10.946 ± 0.546^{C}	13.587 ± 0.156 ^{A}	11.442 ± 0.120^{C}	12.009 ± 0.361 ^{B}	12.311 ± 0.243 ^{B}	10.338 ± 0.011 ^{D}
D6	Octanoic acid	11.465 ± 0.034 ^{A}	4.527 ± 0.274 ^{F}	5.126 ± 0.065 ^{E}	6.487 ± 0.086^{C}	7.032 ± 0.342 ^{B}	5.421 ± 0.085 ^{D}
D7	Nonanoic acid	2.534 ± 0.033 ^{A}	0.746 ± 0.019 ^{D}	1.118 ± 0.027 ^{B}	0.913 ± 0.010^{C}	0.767 ± 0.022 ^{D}	0.502 ± 0.033 ^{E}
D8	Decanoic acid	2.381 ± 0.011 ^{A}	0.944 ± 0.053 ^{E}	1.759 ± 0.046 ^{B}	1.456 ± 0.065^{C}	1.195 ± 0.059 ^{D}	0.664 ± 0.057 ^{F}
D9	Benzoic acid	0.954 ± 0.210 ^{E}	1.400 ± 0.033^{C}	2.195 ± 0.008 ^{A}	1.868 ± 0.011 ^{B}	1.213 ± 0.005 ^{D}	0.534 ± 0.063 ^{F}
	Ketones	6.892 ± 0.159 ^{BCE}	4.133 ± 0.166 ^{E}	6.993 ± 0.049 ^{B}	7.407 ± 0.235 ^{A}	6.634 ± 0.240^{C}	4.979 ± 0.163 ^{D}
E1	2-Octanone	nd	1.293 ± 0.025 ^{A}	0.900 ± 0.031 ^{D}	1.133 ± 0.033 ^{B}	1.031 ± 0.027^{C}	0.677 ± 0.019 ^{E}

(*continued on next page*)

Table 3 (*continued*)

NO	Volatiles	CRW	CQW	CRQW	10% CBR + CQRW	20% CBR + CQRW	30% CBR + CQRW
E2	2-Heptanone	nd	1.888 ± 0.061 ^{A}	1.633 ± 0.042 ^{B}	0.888 ± 0.052^{C}	0.804 ± 0.036^{C}	0.366 ± 0.023 ^{D}
E3	2-Undecanone	1.153 ± 0.011^{C}	0.288 ± 0.047^{F}	1.638 ± 0.043 ^{A}	1.356 ± 0.045 ^{B}	0.988 ± 0.005 ^{D}	0.536 ± 0.004 ^{E}
E4	4-Methylacetophenone	nd	0.663 ± 0.033 ^{A}	nd	nd	nd	nd
E5	2-Nonanone	2.062 ± 0.512 ^{A}	nd	1.279 ± 0.018 ^{E}	1.407 ± 0.043 ^{D}	1.586 ± 0.009^{C}	1.737 ± 0.044 ^{B}
E6	4-Octanone	0.323 ± 0.022 ^{D}	nd	0.554 ± 0.010 ^{A}	0.488 ± 0.007 ^{B}	0.486 ± 0.013 ^{B}	0.400 ± 0.011^{C}
E7	4-Hydroxy-2-butanone	3.355 ± 0.014 ^{A}	nd	0.989 ± 0.005 ^{D}	2.136 ± 0.055 ^{B}	1.739 ± 0.650 ^{BCE}	1.263 ± 0.062^{C}
	Others	39.270 ± 1.878 ^{D}	28.890 ± 0.808 ^{F}	50.878 ± 0.618 ^{A}	46.776 ± 1.020 ^{B}	42.967 ± 1.385^{C}	34.537 ± 0.423 ^{E}
F1	2-Pentylfuran	nd	0.207 ± 0.017 ^{E}	0.301 ± 0.008 ^{D}	0.357 ± 0.011^{C}	0.530 ± 0.006 ^{A}	0.463 ± 0.005 ^{B}
F2	Styrene	nd	0.439 ± 0.051 ^{D}	0.802 ± 0.024 ^{A}	0.778 ± 0.003 ^{A}	0.670 ± 0.006 ^{B}	0.522 ± 0.002^{C}
F3	n-Hendecane	1.535 ± 0.033 ^{E}	1.130 ± 0.031 ^{F}	6.804 ± 0.412 ^{A}	2.664 ± 0.036 ^{B}	2.030 ± 0.015^{C}	1.835 ± 0.123 ^{D}
F4	β-Methylstyrene	6.883 ± 0.292 ^{A}	3.894 ± 0.039 ^{D}	5.150 ± 0.015 ^{B}	6.678 ± 0.112 ^{A}	4.938 ± 0.229 ^{B}	4.056 ± 0.035^{C}
F5	Diethylene glycol monoethyl ether	0.479 ± 0.047 ^{A}	0.246 ± 0.005^{C}	0.467 ± 0.014 ^{A}	0.433 ± 0.022 ^{A}	0.309 ± 0.035 ^{B}	0.201 ± 0.006 ^{D}
F6	Naphthalene	24.352 ± 1.330^{C}	19.443 ± 0.505 ^{E}	30.157 ± 0.013 ^{A}	28.673 ± 0.786 ^{B}	27.182 ± 0.954 ^{B}	22.286 ± 0.153 ^{D}
F7	Methylnaphthalene	0.530 ± 0.045 ^{F}	1.045 ± 0.048 ^{E}	2.255 ± 0.054 ^{A}	1.966 ± 0.013 ^{B}	1.648 ± 0.011^{C}	1.336 ± 0.065 ^{D}
F8	2,4-Di-tert-butylphenol	1.449 ± 0.085 ^{A}	0.814 ± 0.101 ^{B}	1.402 ± 0.022 ^{A}	0.366 ± 0.031^{C}	0.177 ± 0.024 ^{D}	0.062 ± 0.003 ^{E}
F9	4-Hydroxystyrene	4.042 ± 0.046^{C}	1.671 ± 0.011 ^{F}	3.539 ± 0.056 ^{E}	4.862 ± 0.005 ^{B}	5.483 ± 0.109 ^{A}	3.776 ± 0.031 ^{D}

Uppercase letters mark statistically significant differences with one-way ANOVA test of significance among sample ($p < 0.05$).
Nd indicates no detection.

concentration of these compounds in CQRW. These compounds possessed distinctive aroma characteristics and had positive effects on the aroma of Huangjiu.

The CQRW and 10%CBR + CQRW exhibited the highest flavor quality. The mixed fermentation of quinoa and rice enhanced the variety of flavor substances in Huangjiu, and the addition of 10%CBR increased both the diversity and concentration of aroma compounds.

4. Conclusion

The CBR is a by-product of processing. Enhancing CBR utilization can mitigate environmental pollution and create economic value. Incorporating CBR during the CQRW brewing process enriched the phenolics and flavonoids in Huangjiu, thus enhancing its antioxidant capabilities. The addition of CBR led to increased total components detected and amino acid levels in Huangjiu. Additionally, 10%CBR + CQRW, 20%CBR + CQRW, and CQRW had the closest taste traits. Throughout the fermentation process, components such as amino acids and phenolic acids could produce volatile aroma compounds through metabolic pathways like the tricarboxylic acid cycle, *Ehrlich* pathway, and phenylpropanoid pathway. These metabolic processes, along with esterification, redox reactions, and enzymatic catalysis, contributed to the formation of volatile aroma compounds. The GC–MS analysis identified 72 aroma compounds in 10%CBR + CQRW sample, more than other samples. Consequently, adding CBR during CQRW fermentation enhanced the overall quality, with 10%CBR proving to be the most effective addition. The nutritional and functional roles of CQRW would be evaluated and prepared for industrial production.

CRediT authorship contribution statement

Jian Ma: Writing – original draft, Data curation, Conceptualization. **Wuyang Huang:** Writing – original draft, Resources, Methodology. **Yanhong Ma:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Jian Li:** Resources, Methodology, Formal analysis. **Naihong Feng:** Supervision, Funding acquisition, Formal analysis. **Bo Wen:** Software, Methodology. **Feihong Jia:** Visualization, Software. **Yu Wang:** Methodology, Investigation, Formal analysis. **Zhiqiang Gao:** Resources, Methodology, Investigation, Funding acquisition.

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.

The authors confirm that this manuscript has no conflicts of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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