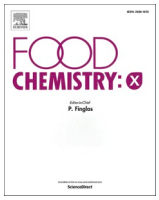
Food Chemistry: X 25 (2025) 102188

Contents lists available at ScienceDirect

Food Chemistry: X

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



Revealing the flavor differences of Sauvignon Blanc wines fermented in different oak barrels and stainless-steel tanks through GC-MS, GC-IMS, electronic, and artificial sensory analyses

Taoxian Zhang [a], Zusong Liao [b], Zhaohui Li [a], Yunqi Liu [b], Jingying Bi [c], Yanlin Liu [a], Yuyang Song [a,d,*], Yi Qin [a,d,e,*]

[a] College of Enology, Northwest A&F University, Yangling 712100, China
[b] Ningxia Xige Estate Co., Ltd, Wuzhong 751600, Ningxia, China
[c] College of Life Science and Technology, Ningxia Polytechnic, Yinchuan 750021, China
[d] National Forestry and Grassland Administration Engineering Research Center for Viti-Viniculture, Yangling 712100, China
[e] Shaanxi Key Laboratory for Viti-Viniculture, Yangling 712100, China

ARTICLE INFO

Keywords:
Sauvignon blanc wine
Oak barrels
Volatile compounds
Phenolic compounds
Aroma
Taste

ABSTRACT

The fermentation vessel significantly impacts the flavor characteristics of white wine. This study provides a comprehensive flavor analysis of Sauvignon Blanc wines fermented in oak barrels and stainless-steel tanks. Wines fermented in new barrels exhibited higher levels of malic and tartaric acids compared with those fermented in old barrels or steel tanks, resulting in a more sour taste. Fermentation in oak barrels increased the content of majority phenolic compounds in wine compared to fermentation in steel tanks. GC–MS analysis revealed that the primary differential compounds present in the wines from various oak barrels and steel tanks included ethyl acetate, ethyl lactate, furfural, ethyl octanoate, isoamyl alcohol, isobutyl alcohol, 1-propanol, and acetic acid. Moreover, GC-IMS identified furan, pyrazine, acetaldehyde, and valeraldehyde in wines from oak barrels, which enhanced aromatic complexity. This study provides essential insights to promote the quality and distinctiveness of Sauvignon Blanc wines.

1. Introduction

Sauvignon Blanc wines are widely appreciated for their multifaceted flavor profile, characterized by vegetal and tropical fruit aromas along with a refreshing acidity (Zhu et al., 2021). The choice of fermentation vessel is crucial in shaping the flavor characteristic of wines, with white wine fermentation typically employing stainless-steel tanks (Gil I Cortiella et al., 2020). Recently, there has been a growing trend to ferment white wine in oak barrels to enhance its aroma, taste, and overall quality (Di Renzo et al., 2023; Herrero et al., 2016). However, not all white grape varieties are suitable for oak-barrel fermentation, as it can obscure their varietal characteristics and disrupt the wine balance (Herrero et al., 2016). Although previous studies have highlighted the beneficial effects of oak-barrel fermentation on Chardonnay wines, the literature on its impact on the quality of Sauvignon Blanc wines is limited (Botha et al., 2020; Herjavec et al., 2007; Liberatore et al., 2010). In addition, most studies have focused on oak barrels of diverse origins and various toasting levels, neglecting the possible effects of distinct brands and utilization times of oak barrels on wine quality (Herrero et al., 2016; Liberatore et al., 2010).

Wines fermented in different oak barrels exhibit distinct chemical components, which affect the overall quality of the wine (Gil I Cortiella et al., 2020; Herrero et al., 2016). Acidity is widely recognized as a key sensory attribute of white wines, with appropriate acidity imparting freshness and vitality (Scutarașu et al., 2021).Organic acids serve as precursors to aromatic compounds, exerting a considerable influence on the taste and nutritional characteristics of wines (Hao et al., 2024). Phenolic compounds in wine are classified into two main groups: flavonoids and non-flavonoids (López-Solís et al., 2024). Flavanols and flavonols are the predominant flavonoids in white wines. Flavanols, including catechin and its derivatives, affect the wine's bitterness and astringency (Yang et al., 2024). Conversely, flavonols such as kaempferol, quercetin, myricetin, and their glycoside derivatives found in grape skins primarily contribute to the color of white wines (Obreque-

* **Corresponding authors at:** College of Enology, Northwest A&F University, Yangling, China.
E-mail addresses: yuyangsong@nwsuaf.edu.cn (Y. Song), qinyi@nwsuaf.edu.cn (Y. Qin).

https://doi.org/10.1016/j.fochx.2025.102188
Received 14 November 2024; Received in revised form 30 December 2024; Accepted 13 January 2025
Available online 17 January 2025
2590-1575/© 2025 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC license (http://creativecommons.org/licenses/by-nc/4.0/).

Slier et al., 2021). Moreover, cinnamic acids (caffeic, ferulic, and p-coumaric acids), benzoic acids (gallic, ellagic, and vanillic acids), and the aldehyde derivatives of these acids (vanillin and furfural) are primary non-flavonoid compounds, most of which are extracted from the oak barrels during fermentation (López-Solís et al., 2024; Obreque-Slier et al., 2021; Li & Duan, 2019).

The aroma of wine is a crucial sensory characteristic that significantly impacts consumer preference (Liu et al., 2023). Volatile compounds, including esters, higher alcohols, acids, aldehydes, and ketones, play a vital role in shaping the aroma profile of wines, contributing rich notes of fruity, floral, nutty, and dairy (Huang et al., 2023; Liu et al., 2023). Moreover, most volatile compounds are generated during fermentation (Huang et al., 2023). Gas chromatography–mass spectrometry (GC–MS) has matured over the years and has become the primary analytical technique for volatile compounds in wines, as it features the benefits of rapid separation with robust qualitative and quantitative capabilities (Bai et al., 2024; Rong et al., 2023). Gas chromatography–ion mobility spectrometry (GC-IMS) is a novel technology for food flavor analysis that has the advantages of simple pretreatment, short detection times, and high sensitivity, while enabling the visualization and comparison of volatile substance compositions in different samples (Li et al., 2024). Studies have increasingly combined GC–MS and GC-IMS to comprehensively analyze food flavor (Hao et al., 2024; Yin et al., 2023). Moreover, electronic sensors (e.g., E-nose and E-tongue) offer the benefits of easy and fast operation, while providing an objective assessment of the olfactory and taste profiles of samples without the need for expert human tasters (Hao et al., 2024). While previous research has extensively analyzed the volatile compounds related to wine flavor using GC–MS and isolated analytical techniques, our study provides a novel approach by combining GC–MS, GC-IMS, E-nose, and E-tongue to comprehensively evaluate the flavor characteristics of Sauvignon Blanc wines fermented in oak barrels.

This study aimed to investigate the differences in the flavor characteristics of Sauvignon Blanc wines fermented in various oak barrels (varied by brand and utilization time) and stainless-steel tanks. Initially, the physicochemical indices, monomeric phenols, and organic acid contents of Sauvignon Blanc wines from different vessels were characterized. Subsequently, the volatiles in the Sauvignon Blanc wines were examined using GC–MS and GC-IMS. Moreover, electronic sensory analysis (E-nose and E-tongue) and quantitative descriptive analysis (QDA) were conducted to assess the sensory properties of Sauvignon Blanc wines fermented in different vessels. Finally, partial least-squares regression (PLSR) analysis was used to characterize the association between volatile compounds and aroma attributes. Different detection methods were compared using multi-factor analysis (MFA). This investigation provides insights for optimizing fermentation practices in oak barrels to further enhance the quality and distinctiveness of Sauvignon Blanc wines.

2. Materials and methods

2.1. Sample collection

Sauvignon Blanc grapes were harvested in 2023 from Xige vineyards (coordinates: 38°04′30″ N, 105°53′28″ E). Following the harvest, the grapes were transported to the Xige Estate situated in Wuzhong City, Ningxia Province, China. There, they underwent sorting and destemming before being placed into an airbag press. Must preparations included the addition of Potassium metabisulfite at 30 mg/L and pectinase at 40 mg/L (Laffort Company, Bordeaux, France) with a soft pressing process employed for pressing. The free-run and light-pressure must were then moved to a 7.5-ton stainless-steel tank, where clarification occurred via cold-settling at 8 °C for 24 h. Subsequently, the clarified must was transferred to a different steel tank, and 330 mg/L of *Saccharomyces cerevisiae* (Excellence FTH, Lamothe–Abiet Company, France) was introduced to commence alcoholic fermentation.

Once the density of the grape must attained a range of 1.075 to 1.070 g/mL, it was transferred into new oak barrels (FN; Francois Freres Company, Saint-Romain, France), new oak barrels (TN; Taransaud, Merpins, France), 2-year-old oak barrels (FO; Francois Freres Company, Saint-omain, France), and a stainless-steel tank (S, used as control). Each barrel experiment was performed in duplicate. All fermenters were placed at an ambient temperature of 14–18 °C. The specific parameters of oak barrel are presented in Table S1. After the completion of fermentation (when the reducing sugar was below 2 g/L), wine samples were collected in triplicate (375 mL each from two identical oak barrels, which were mixed to produce the sample; 750 mL from the stainless-steel tank). Fermentation was completed on the 16th day after the initiation of fermentation.

2.2. Physicochemical parameter and organic acids detection

The total acidity, volatile acidity, and pH levels of Sauvignon Blanc wines were detected following to the National Standards of the People's Republic of China (GB/T 15038–2006). The total acidity was assessed using acid–base titration and represented as equivalents of tartaric acid. For the measurement of volatile acid, extraction was performed using water vapor distillation, followed by titration using acid–base titration techniques. The pH was measured using a pH meter (Hanna Instruments, Padua, Italy). The concentrations of reducing sugar, alcohol, glycerol, and organic acids (tartaric, succinic, lactic, malic, and citric acids) in the wines were measured as previously described with some modifications (Zhang et al., 2024) using a high-performance liquid chromatography system (LC-2050C, Shimadzu, Japan) equipped with an Aminex HPX-87H column (300 mm × 7.8 mm, Bio-Rad, USA). In brief, wine samples were diluted fourfold, filtered (0.22 μm), capped, and then transferred to 1.5 mL vials. The eluent was made up of 10 mmol/L H_2SO_4, flowing at a rate of 0.6 mL/min, while the column temperature was maintained at 60 °C for a duration of 35 min. Each sample had an injection volume of 20 μL and was analyzed for its chemical signals. A variable-wavelength ultraviolet detector with a photodiode array (Shimadzu, Kyoto, Japan) was used at a wavelength of 210 nm to detect organic acids and a refractive index detector (RID-20 A, Shimadzu, Kyoto, Japan) was used to detect sugars and alcohols. Data analysis was conducted using LabSolution software (Shimadzu, Kyoto, Japan), and the external calibration curves were established for quantitative analysis of compounds.

2.3. Color analysis of the wine samples

The CIELab parameters of the Sauvignon Blanc wines were determined based on a previous method (Xie et al., 2023). The L* (lightness), a* (red/green), and b* (yellow/blue) were determined using a wine color analyzer (W100, Hanon Advanced Technology Group Co., Ltd., Jinan, Shandong Province, China). The samples were tested in triplicate. The ΔE* (color difference) among wines fermented in oak barrels and steel tanks (FN, TN, FO versus S) was calculated using the following equation:

$$\Delta E* = \sqrt[2]{(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2}$$

2.4. Determination of monomeric phenols

Monomeric phenols in the Sauvignon Blanc wines were extracted following a previously described method (Huang et al., 2022). Briefly, 2 mL of the wine sample and 2 mL of ethyl acetate were added to a 5 mL centrifuge tube and shaken using a vortex mixer for 30 s. Then, the sample was centrifuged at 3500 rpm for 4 min, after which a rubber-tipped dropper was employed to transfer the collected supernatant into a 15 mL centrifuge tube. This process was repeated three times. The sample was evaporated using a rotary evaporator at 35 °C and then

dissolved in 2 mL of methanol to prepare the pretreated sample.

Monomeric phenols were determined based on a previous method (Huang et al., 2022) using a Waters UPLC I-Class equipped with an Acquity BEH C18 column (1.7 μm, 2.1 mm × 50 mm) and a chromatography workstation (Empower CDS, Waters, Milford, MA, USA). The chromatography column employed 1 % acetic acid as phase A and acetonitrile as phase B, with a flow rate of 0.5 mL/min, a column temperature of 35 °C, and an equilibration time of 3 min. The volume of the injection measured 2 μL, and a UV detector was utilized for measurements at a wavelength of 208 nm. Calibration curves of standards (Sigma-Aldrich, Milwaukee, WI, USA) were employed for quantification, with the corresponding equations detailed in Table S2.

2.5. Determination of the antioxidant capacity of wines

The antioxidant activity of Sauvignon Blanc wines was assessed using DPPH (1,1′-diphenyl-2-picryl-hydrazyl) and ABTS (2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)) radical scavenging assays. The DPPH radical scavenging activity was determined based on a previously described method (Xie et al., 2023), while the modified method of Bai et al. (2018) was used to determine the ABTS radical scavenging activity. Briefly, 0.1 mL of the wine sample was added to 3.9 mL of the DPPH stock solution (25 mg/L) and mixed thoroughly. After a 20-min reaction in the dark, the absorbance was measured at 517 nm. A solution of 15 % ethanol of the same volume was used as a control in place of the wine sample. The preparation method for the ABTS radical cation (ABTS·+) involved mixing 5 mL of a 7.0 mmol/L ABTS solution with 0.088 mL of a 140.0 mmol/L $K_2S_2O_8$ solution followed by incubation in the dark at room temperature for 12 to 16 h. Subsequently, the ABTS· + working solution was diluted with deionized water to achieve an absorbance of 0.70 ± 0.02 at 734 nm. Then, 0.1 mL of Sauvignon Blanc wine was mixed with 3.9 mL of the ABTS· + working solution, and the absorbance was recorded following a 10-min reaction in a light-shielded environment. For each sample, three replicates were performed. The results are reported as micromole Trolox equivalents (TE) per liter (μmol TE/L).

2.6. Volatile compounds analysis by GC–MS

The identification of volatile compounds in wines was carried out using headspace solid-phase microextraction (HS-SPME) coupled with GC–MS, following an established methodology (Huang et al., 2023). Briefly, 5.0 mL of the wine sample, 1.0 g of NaCl, and 10 μL of the internal standard (4-methyl-2-pentanol, 1.031 g/L) were put into a 20 mL glass vial, which was then positioned in a fully automatic oscillator at 40 °C for a duration of 30 min. Then, the SPME fiber (DVB/CAR/PDMS, Agilent Technologies, Santa Clara, CA, USA) was inserted in the headspace of the vial to extract at 40 °C for 30 min and preconditioned at 250 °C for 10 min before extraction, followed by desorption in the GC injector at 250 °C for 8 min.

GC–MS analysis of wine samples was conducted using GC (7890B, Agilent Technologies, USA) coupled with MS (5977B, Agilent Technologies, USA). Helium (99.999 %) was used as the carrier gas at a flow rate of 1.0 mL/min throughout the process. The column temperature was initially maintained at 50 °C for 1 min, then increased to 220 °C at a rate of 3 °C/min, followed by a 5-min hold. The injector temperature was set at 250 °C, and the ion source temperature was maintained at 230 °C. The MS was operated in positive electron ionization mode within a mass acquisition range of 35–350 *m/z*. Qualitative analysis was conducted by utilizing retention indices, mass spectra from pure standards, and the NIST14 standard library (National Institute of Standards and Technology, USA). For quantitative analysis, the external standard method was utilized. For each sample, three replicates were performed. To clarify the impact of specific volatile compounds on the overall flavor profile of wine, the odor activity value (OAV) was calculated according to previous methods (Huang et al., 2023)

2.7. Volatile compounds analysis by HS-GC-IMS

The volatile compounds in Sauvignon Blanc wines were identified by HS-GC-IMS (FlavourSpec®, G.A.S., Dortmund, Germany) following a previously described method (Hao et al., 2024) with slight modifications. Briefly, 5.0 mL of the sample was placed in a 20 mL headspace vial and incubated for 15 min under oscillating heat at 40 °C. Following incubation, 500 μL of the headspace gas was injected into the inlet using a heated syringe at 85 °C. The MXT-WAX capillary chromatography column (30 m × 0.53 mm, 1.0 μm, Restek, USA) was maintained at 60 °C with nitrogen serving as the carrier gas (purity ≥99.999 %). The carrier gas flow rate was initiated at 2 mL/min for 2 min, ramped up to 100 mL/min over the next 18 min, and held constant at 100 mL/min for 40 min. The compounds were identified with VOCal 0.4.03 software (G.A.S., Dortmund, Germany) by matching their retention index (RI) values and IMS migration time database search. The RIs were calculated using n-alkanes (C4–C9) as external references. Each sample type was conducted triplicate analyses.

2.8. E-nose and E-tongue analysis

The overall aroma profile of the Sauvignon Blanc wines was analyzed using an E-nose (PEN 3 plus, Airsense Analytics Co. Ltd., Schwerin, Germany) based on the method published by Lan et al. (2022). The performances of ten chemical sensors are listed in Table S3. The wine sample (5 mL) was placed in a 20 mL sample bottle and equilibrated at 25 °C for 10 min before the test. Every sample type was analyzed at least 3 times. The test conditions were set as follows: 200 s sensor cleaning time, 5 s auto-zero time, 5 s pre-sampling time, 100 s detection time, and 400 mL/min carrier gas flow rate.

The taste profile of the Sauvignon Blanc wines was assessed using an E-tongue sensor (Intelligent Sensor Technology, Inc., Kanagawa, Japan) based on a previous report (Hao et al., 2024). The E-tongue is equipped with five chemical sensors (Table S4). The reference solution contained 30 mM potassium chloride and 30 mM tartaric acid. The solution potential was set as the reference potential. The potential of the sample was measured, and the basic value for each sensory evaluation metric was determined by analyzing the potential difference of each sensor. Each sample type was analyzed four times and three stable datasets were collected for subsequent analysis.

2.9. Sensory analysis

The sensory evaluation was performed according to the methodology described by Bai et al. (2024). A total of 14 experienced tasters (seven males and seven females aged 20–30 years) from College of Oenology at Northwest A&F University, took part in the sensory evaluation of Sauvignon Blanc wines. Prior to the tests, each participant provided informed consent. The panel received comprehensive training in aroma identification using the “Le Nez du Vin” (Masterkit 54; France), which contained 54 common wine aromas. The panel achieved an accuracy rate of over 90 % in identifying wine aroma descriptors. Initially, the participants rated the wines on a 9-point scale based on appearance (limpidity, luster, and color density), aroma (purity, elegance, and intensity), and taste (sweetness, sourness, bitterness, astringency, alcohol, harmony, and aftertaste). Higher scores correspond to greater perceived intensity. Subsequently, each participant characterized the aroma attributes of the wines by providing five to six aroma descriptors and assessing the intensity of each descriptor on a 5-point scale. The intensity of an aroma was quantified using the M value, calculated as follows:

$$M = \sqrt{F \times I}$$

where F denotes the occurrence frequency of the aroma descriptor provided by the evaluation panel and I denotes the percentage of

average intensity to maximum intensity for the aroma descriptor.

2.10. Statistical analysis

The data are expressed as the mean ± standard deviation of three independent experiments. One-way analysis of variance (ANOVA) was conducted using SPSS (version 26.0; SPSS Inc., Chicago, IL, USA), with significant differences determined through Duncan's test ($p < 0.05$). SIMCA 14.1 software (Sartorius, Göttingen, Germany) was used to analyze the variable importance in projection (VIP) values. Characteristic fingerprints and difference plots were constructed using VOCal 0.4.03 software (G.A.S., Dortmund, Germany). Origin 2024b software (OriginLab Corporation, Northampton, MA, USA) was employed for histogram, heat-map, and radar plot analysis. Linear discriminant analysis (LDA) of E-nose data was were performed using Winmuster software (version 1.6.2.18; Airsense Analytics, Germany). PLSR analysis was performed on volatile compounds (X-matrix) and aroma attributes (Y-matrix) using Unscrambler 9.7 (Camo, Oslo, Norway). The volatile compound content was standardized before the PLSR analysis. PCA, MFA, and RV coefficient analysis were conducted using R software.

3. Results

3.1. Physicochemical properties of Sauvignon Blanc wines

The physicochemical properties of the Sauvignon Blanc wine fermented in various vessels are displayed in Table 1. The residual sugar, ethanol, and glycerol contents showed no significant differences across the samples from different vessels. The total acid and volatile acid content was relatively high in FN (7.20 ± 0.03; 0.71 ± 0.02), TN (7.22 ± 0.03; 0.72 ± 0.02), and FO (7.09 ± 0.02; 0.69 ± 0.03) wines compared to the S (6.95 ± 0.02; 0.65 ± 0.02) wine. In addition, FN, TN, and FO wines exhibited lower pH values than S wine. The levels of organic acids in wines also varied. FN and TN wines exhibited higher levels of malic and tartaric acids compared with FO and S wines. Additionally, FO wine contained higher concentrations of malic acid than S wine. Minimal differences in the quantities of citric, lactic, and succinic acids were observed among all groups.

Table 1 presents the color parameters of Sauvignon Blanc wines fermented in various vessels. FN, TN, and FO wines exhibited lower L* values and higher a* and b* values compared to S wine. Additionally, FN and TN wines displayed lower L* values and higher a* and b* values than FO wine. Furthermore, the ΔE* values for FN, TN, and FO wines were 1.09 ± 0.05, 1.01 ± 0.05, and 0.80 ± 0.04, respectively, which are all below 3.0.

Table 1
Physicochemical properties of Sauvignon Blanc wines.

Indexes	FN	TN	FO	S
Ethanol (% *v*/v)	15.14 ± 0.06a	15.20 ± 0.08a	14.97 ± 0.05a	14.96 ± 0.05a
Residual sugar (g/L)	1.66 ± 0.08a	1.65 ± 0.05a	1.75 ± 0.01a	1.76 ± 0.02a
Total acidity (g/L)	7.20 ± 0.03a	7.22 ± 0.03a	7.09 ± 0.02b	6.95 ± 0.02c
Volatile acidity (g/L)	0.71 ± 0.02ab	0.72 ± 0.02a	0.69 ± 0.03ab	0.65 ± 0.02b
pH	3.23 ± 0.01b	3.22 ± 0.01b	3.24 ± 0.01ab	3.26 ± 0.01a
Glycerol (g/L)	7.08 ± 0.07a	7.18 ± 0.04a	7.12 ± 0.06a	7.23 ± 0.06a
Citric acid (g/L)	0.35 ± 0.02a	0.37 ± 0.02a	0.35 ± 0.02a	0.35 ± 0.01a
Malic acid (g/ L)	1.33 ± 0.04a	1.34 ± 0.02a	1.16 ± 0.02b	1.08 ± 0.02c
Tartaric acid (g/L)	2.90 ± 0.02a	2.93 ± 0.03a	2.76 ± 0.02b	2.69 ± 0.04b
Succinic acid (g/L)	0.74 ± 0.03a	0.78 ± 0.02a	0.77 ± 0.02a	0.71 ± 0.04a
Lactic acid (g/L)	0.64 ± 0.04a	0.61 ± 0.03a	0.62 ± 0.03a	0.63 ± 0.02a
L*	97.99 ± 0.02c	98.04 ± 0.02c	98.22 ± 0.03b	98.94 ± 0.05a
a*	1.22 ± 0.02a	1.18 ± 0.02a	1.11 ± 0.01b	0.81 ± 0.02c
b*	3.13 ± 0.02a	3.03 ± 0.02b	2.98 ± 0.02b	2.79 ± 0.02c
ΔE*	1.09 ± 0.05a	1.01 ± 0.05a	0.80 ± 0.04b	–

Notes: different letters indicate significant differences among wine samples ($P < 0.05$). ΔE* represents the color differences of FN, TN, and FO wines compared to S wine.

3.2. Monomeric phenols contents

Ten monomeric phenols were identified in the wines, including seven flavonoids (epicatechin, catechin, rutin, quercetin, myricetin, kaempferol, and phlorizin) and three non-flavonoid compounds (p-

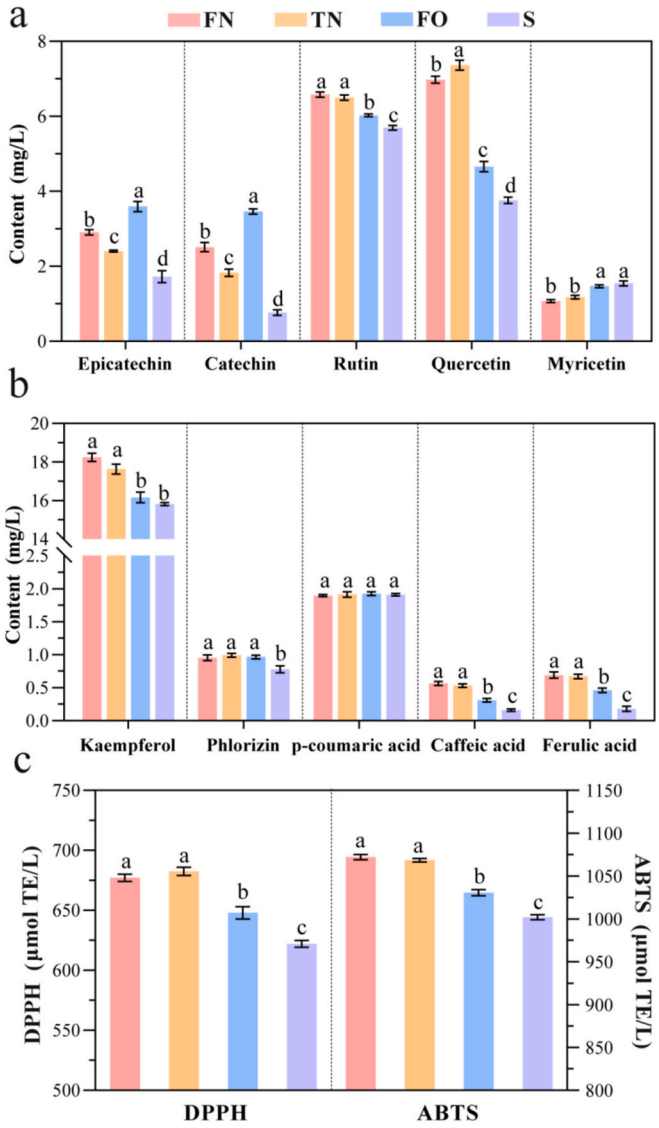


Fig. 1. Analysis of monomeric phenols and antioxidant capacity of Sauvignon Blanc wines. (a-b) Monomeric phenols contents. (c) Antioxidant capacity (DPPH and ABTS radical scavenging activities). Different letters indicate significant differences among wine samples ($p < 0.05$). Sample coding: FN, new Francois Freres oak barrel; TN, new Taransaud oak barrel; FO, two-year-old Francois Freres oak barrel; S, stainless-steel tank.

coumaric acid, caffeic acid, and ferulic acid) (Fig. 1a, b). The phenol content also varied depending on the fermentation vessel. Oak-barrel fermentation led to higher levels of epicatechin, catechin, rutin, quercetin, kaempferol, and phlorizin compared to fermentation in steel tanks (Fig. 1a, b). Specifically, wines fermented in new barrels displayed higher rutin, quercetin, and kaempferol contents than those fermented in old barrels. Conversely, wines fermented in old barrels exhibited higher concentrations of epicatechin and catechin compared to those fermented in new barrels. In addition, wines from old barrels demonstrated a higher myricetin content, although no significant difference was observed in comparison with steel-tank fermentation. In terms of non-flavonoid compounds, minimal differences were noted in the p-coumaric acid contents. In contrast, the levels of caffeic and ferulic acid were higher in wines fermented in oak barrels than in those fermented in steel tanks.

Variations in the content of phenolic compounds in wines can have a notable impact on their antioxidant activities. Therefore, the antioxidant properties of the wines were assessed using the DPPH and ABTS radical-scavenging methods. The DPPH radical scavenging activities of FN, TN, and FO wines were 9.03 %, 9.73 %, and 4.18 % higher, respectively, than those of S wine (Fig. 1c). Similarly, the ABTS radical scavenging activities of FN, TN, and FO wines were 7.22 %, 6.10 %, and 3.05 % higher, respectively, than those of S wine.

3.3. Volatile compounds

3.3.1. Volatile compounds identified by HS-SPME-GC–MS

To explore the aroma profiles, the volatile compounds present in Sauvignon Blanc wine fermented in various vessels were analyzed using HS-SPME-GC–MS. A total of 57 volatile compounds were detected in the wine samples, comprising 23 esters, 14 higher alcohols, 8 fatty acids, 7 terpenes, 3 volatile phenols, 1 aldehyde, and 1 mercaptan (Table S5). To reflect the differences in volatile components in oak barrels and steel tanks more intuitively, the volatile component data were standardized and visualized as a heat map. Cluster heat maps distinctly segregated the samples into two categories: FN and TN wines, and FO and S wines (Fig. 2a). The VIP values helped highlight the differences in volatile compounds in the wines fermented in various oak barrels and steel tanks. Specifically, VIP > 1 was a common screening criterion for differential compounds.

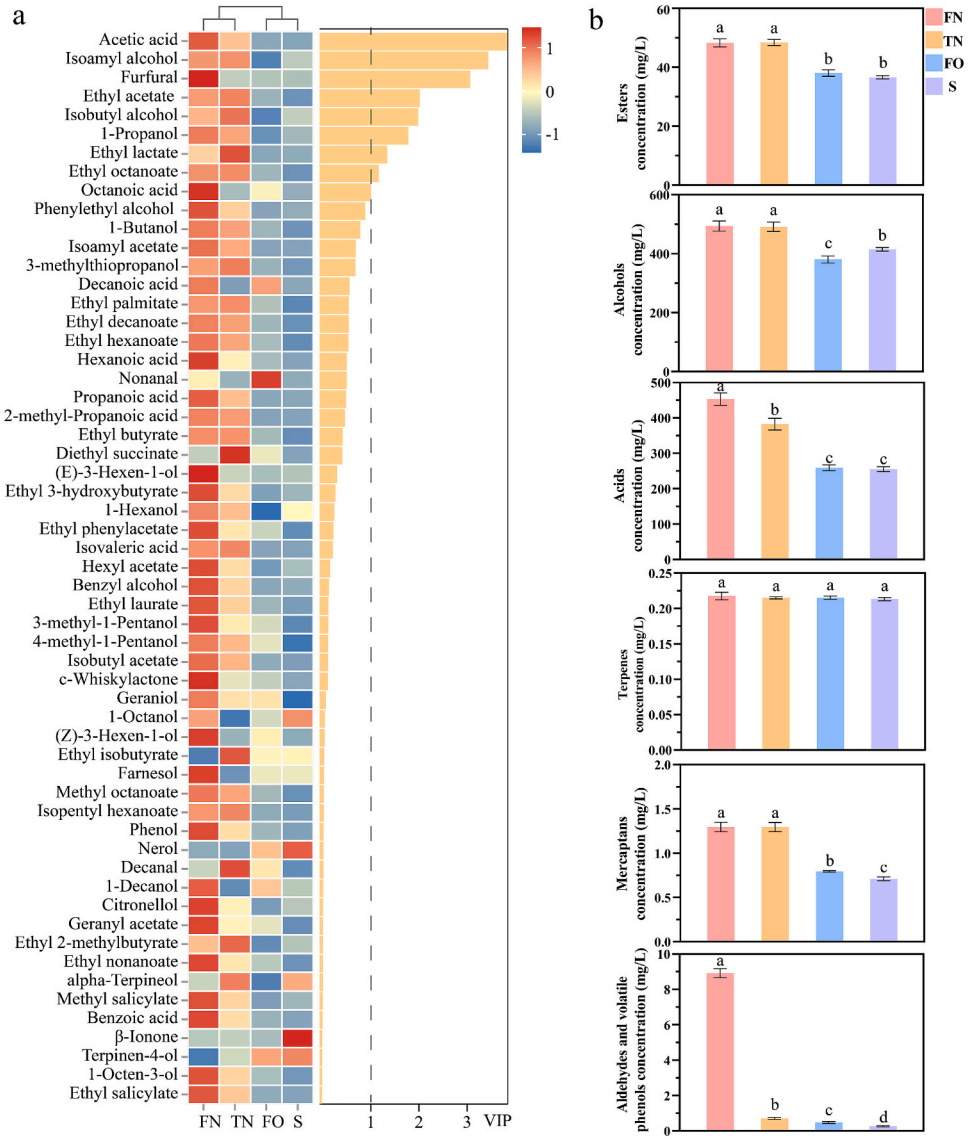


Fig. 2. Analysis of volatile compounds of the Sauvignon Blanc wines identified by HS-SPME-GC–MS. (a) Heatmap of volatile compound contents and variable importance in projection (VIP) values. (b) Different classes of volatile compounds concentrations. Different letters indicate significant differences among wine samples ($p < 0.05$).

Esters are the main aromatic components of wines and primarily impart fruity and floral aromas. The total ester concentrations in FN, TN, and FO wines were 31.99 %, 32.29 %, and 3.95 % higher, respectively, than that in S wine (Fig. 2b). Specifically, ethyl acetate, ethyl lactate, and ethyl octanoate, with VIP > 1, were identified as the key differential ester compounds (Fig. 2a). The levels of ethyl acetate, ethyl lactate, and ethyl octanoate in FN and TN wines significantly exceeded those in FO and S wines. Additionally, the FN and TN wines exhibited elevated concentrations of isoamyl acetate, ethyl palmitate, ethyl decanoate, ethyl hexanoate, and ethyl butyrate compared with the other wines.

Alcohols are the most abundant group of volatile compounds in wine. The total alcohol concentrations in FN and TN wines were 19.11 % and 18.42 % higher, respectively, than that in S wine (Fig. 2b). However, the total alcohol concentration of S wine was 8.98 % higher than that of FO wine. Isoamyl alcohol, isobutyl alcohol, and 1-propanol, with VIP > 1, were the key differential alcohol compounds (Fig. 2a). The levels of isoamyl alcohol, isobutyl alcohol, and 1-propanol in FN and TN wines notably exceeded those in FO and S wines. Moreover, higher phenylethyl alcohol and 1-butanol concentrations were observed in FN and TN wines.

Acids play a significant role in the sensory attributes of wines, aiding in the maintenance of the aromatic harmony. Compared with S wine, the total acid concentrations in FN and TN wines were 77.76 % and 49.96 % higher, respectively(Fig. 2b). Specifically, the levels of acetic acid in FN and TN wines were higher than those in FO and S wines. The highest octanoic acid content was observed for FN wine.

There was no significant difference in terpene content among the wine samples (Fig. 2b). The concentrations of mercaptans (3-methylthiopropanol) in FN, TN, and FO wines were 73.20 %, 82.61 %, and 11.83 % higher, respectively, compared with S wine (Fig. 2b). Furthermore, furfural levels followed the order FN > TN > FO; however, furfural was not detected in S wine (Table S4).

3.3.2. OAV of volatile compounds identified by HS-SPME-GC–MS

Odor activity values (OAVs) are employed to evaluate the contribution of volatile compounds to the overall aroma profile of wines, where volatile compounds with OAV > 1 are considered important contributors. In this study, 20 volatile compounds with OAV > 1 were observed in the Sauvignon Blanc wines (Table 2). Isoamyl acetate displayed the highest OAV among all wines, imparting a distinctive banana flavor. Furthermore, the OAVs of isoamyl acetate were notably elevated in FN and TN wines compared to those in FO and S wines, indicating an intensified contribution to the flavor. Ethyl hexanoate, ethyl octanoate, ethyl butyrate, ethyl decanoate, ethyl acetate, isobutyl alcohol, isoamyl alcohol, isobutyric acid, and isovaleric acid exhibited higher OAVs in FN and TN wines than in FO and S wines, conferring strong fruity, floral, sweet, acidic, and cheese-like odors to FN and TN. In contrast, c-whisky lactone, hexanoic acid, and octanoic acid showed higher OAVs in FN wine than in TN, FO, and S wines, imparting strong coconut, woody, and nutty odors to FN. Furthermore, the high OAV of nonanal in FO contributed to its strong raw green aroma. Similar OAVs were observed for decanoic acid, geraniol, and β-ionone for all wines, imparting fatty, lemon, and violet odors.

3.3.3. Volatile compounds identified by HS-GC-IMS

To further evaluate the aroma components of the Sauvignon Blanc wines fermented in various vessels, HS-GC-IMS was employed to examine the volatile compounds. Most signals were observed at drift times of 0.8–1.9 ms and retention times of 200–1200 s (Fig. 3a). The red vertical line denotes the reaction ion peak (RIP) at a drift time of 1.0 s, with each point on either side of the RIP signifying a volatile compound. A total of 47 signals were detected, comprising 38 known and 9 unknown components. The known components included 18 esters, 4 alcohols, 6 aldehydes, 2 furans, 1 pyrazine, and 7 other compounds (Table S6). Meanwhile, 4 dimers formed in the IMS drift tube are indicated by the letter D in the figure. Difference comparison topographic plots were generated using the topographic plot of S group as the reference (Fig. 3b). Compared with S group, the concentrations of certain compounds were higher (indicated by red hues) or lower (indicated by blue hues) in the FN, TN, and FO groups (Fig. 3b).

Fingerprint analysis revealed variations in the volatile compound composition of Sauvignon Blanc wines fermented in various vessels (Fig. 3c). The variations in the relative content of volatile compounds are visualized in the heatmap (Fig. 3d). The volatile compounds within the red box, including acetaldehyde, furan, ethyl (E)-2-butenoate, triethylamine, and 4 unknown components, were relatively high in the FN wine (Fig. 3c). The levels of volatile compounds in TN wine indicated in the yellow box (butyl ether, pyrazine, (E, E)-2,4-heptadienal, 1,3-butanediol, and (Z)-3-nonen-1-ol) were higher than those in FN, FO, and S wines. The levels of volatile compounds marked in the green box (ethyl octanoate M, butanoic acid, 3-methylbutyl ester M, butyl acetate, ethyl propanoate, acetic acid propyl ester, valeraldehyde, and ethyl 2-methylpropionate) were higher in FO wine than in the others. Moreover, GC-IMS identified fewer volatile compounds than GC–MS (Fig. 3e). Specifically, HS-GC-IMS detected a greater variety of aldehydes, furans, and pyrazines, whereas HS-SPME-GC–MS identified a greater variety of

Table 2
OAV (> 1) of volatile compounds in Sauvignon Blanc wines identified by HS-SPME-GC–MS.

Volatiles	Odor description	OAV			
		FN	TN	FO	S
Ethyl hexanoate	Green apple	22.88	21.94	18.15	16.73
Ethyl octanoate	Sweet, floral, banana	7.40	7.47	5.23	4.69
Ethyl decanoate	Fruity, fatty, pleasant	6.60	6.34	4.62	4.12
Ethyl acetate	Fruity, pineapple	2.16	2.21	1.69	1.59
Ethyl butyrate	Strawberry, apple, banana	43.95	43.80	35.80	33.45
Isoamyl acetate	Banana	532.60	512.60	440.8	440.13
Phenethyl acetate	Rose, sweet honey, raspberry	2.07	1.81	1.70	1.53
c-Whisky lactone	Coumarin, coconut, woody, nutty	13.25	11.95	11.80	11.50
Isobutyl alcohol	Alcohol, sweet	14.94	15.76	11.88	13.23
Isoamyl alcohol	Whiskey, nail polish	9.27	9.32	7.38	8.09
Hexanoic acid	Cheese, fatty	11.68	9.92	8.98	8.62
Acetic acid	Acid, fruit	2.13	1.79	1.18	1.17
Isobutyric acid	Fatty, earthy, caramel	2.04	2.00	1.60	1.60
Isovaleric acid	Cheese	30.21	30.30	27.19	27.13
Octanoic acid	Rancid, cheese, fatty acid	10.49	8.40	8.93	8.23
Decanoic acid	Fatty, rancid	1.47	1.22	1.43	1.23
Geraniol	Lemon, geranium	2.04	1.98	1.97	1.84
β-Ionone	Violet, sweet fruit flavor	1.13	1.13	1.13	1.14
3-methylthiopropanol	Boiled, vegetables	2.46	2.59	1.59	1.42
Nonanal	Raw green, spicy tangy	18.67	15.80	23.27	15.53

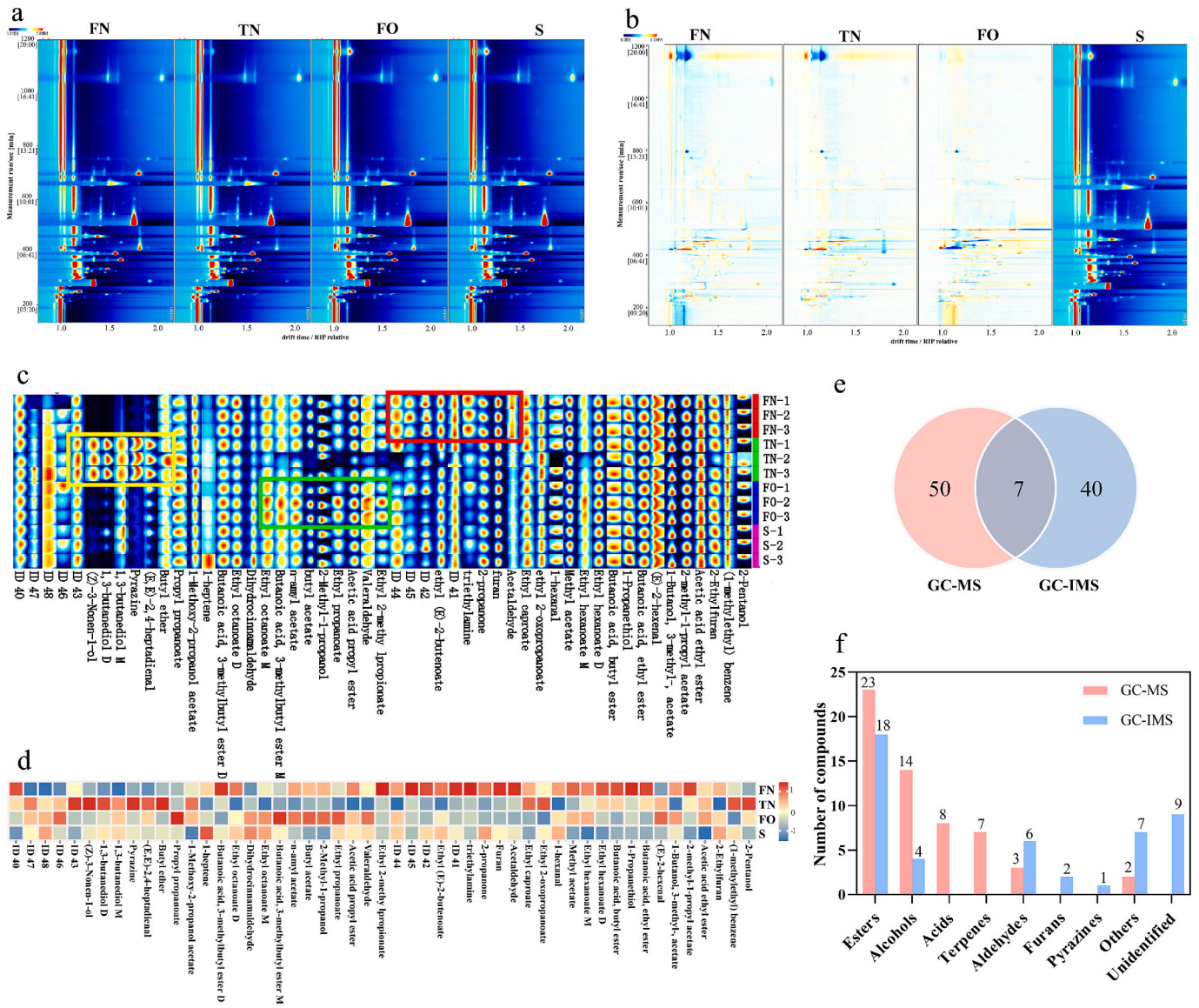


Fig. 3. Analysis of volatile compounds of the Sauvignon Blanc wines identified by HS-GC-IMS. (a) Topographic plots. Dots distributed on both sides of the RIP peak represent volatile compound. Colors represent the concentration of volatile compounds. White and red indicate low and high concentrations, respectively. The higher the concentration of the compound, the darker the color. (b) The difference comparison topographic plots. The compounds of FN, TN, and FO showing similar concentrations to those of S are marked in white, whereas those showing higher or lower concentrations than S are marked in red and blue, respectively. The higher/lower the concentration of the compound, the darker the red/blue color. (c) Fingerprint of volatile compounds. D and M denote the dimer and monomer forms of the compound, respectively. (d) Heatmap of volatile compound concentrations. (e)Venn diagram and (f) bar chart analysis the differences in the number of volatile compound species. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

esters, alcohols, acids, and terpenes (Fig. 3f).

3.4. Electronic sensory analysis

E-nose and E-tongue sensor devices were employed to analyze the sensory characteristics of Sauvignon Blanc wine fermented in various vessels. As shown in Fig. 4a, all four wine samples exhibited response values for W5S (sensitivity to nitrogen oxides), W1S (sensitivity to methane and short-chain alkanes), W1W (sensitivity to sulfides and terpenes), W2S (sensitivity to alcohols, aldehydes, and ketones), and W2W (sensitivity to organic sulfides and aromatic components). The response values of W5S and W1S for FN wine were higher than those for TN, FO, and S wines. The various wine samples displayed distinct response values for W1W, W2S, and W2W, and their intensities were ranked as follows: FN > TN > FO > S (Fig. 4a).

Linear discriminant analysis facilitates a more intuitive representation of aroma disparities among different wine samples by accentuating intergroup differences (Li et al., 2024). This model explained 94.28 % of the variance (LD1 = 79.17 %, LD2 = 2.34 %), providing a better explanation for the aroma distinctions among the four wine samples (Fig. 4b). The four wine samples were distinguishable, indicating that the aromatic characteristics of FN, TN, and FO wines were markedly different from those of S wine. The greatest separation was observed between FN and S wines, indicating substantial aroma differences between these samples. The results showed that the E-nose is an effective analytical tool for identifying aroma profiles and positively distinguishing wines fermented in different types of vessels.

In E-tongue analysis, the electric potential (EP) of each sensor correlates with the intensity of a respective taste. FN and TN wines exhibited the higher EP values related to sourness, and FO ranked higher than S (Fig. 4c). Among the four wines, FN displayed the highest levels of bitterness, after-bitterness, and after-astringency, followed by TN, FO,

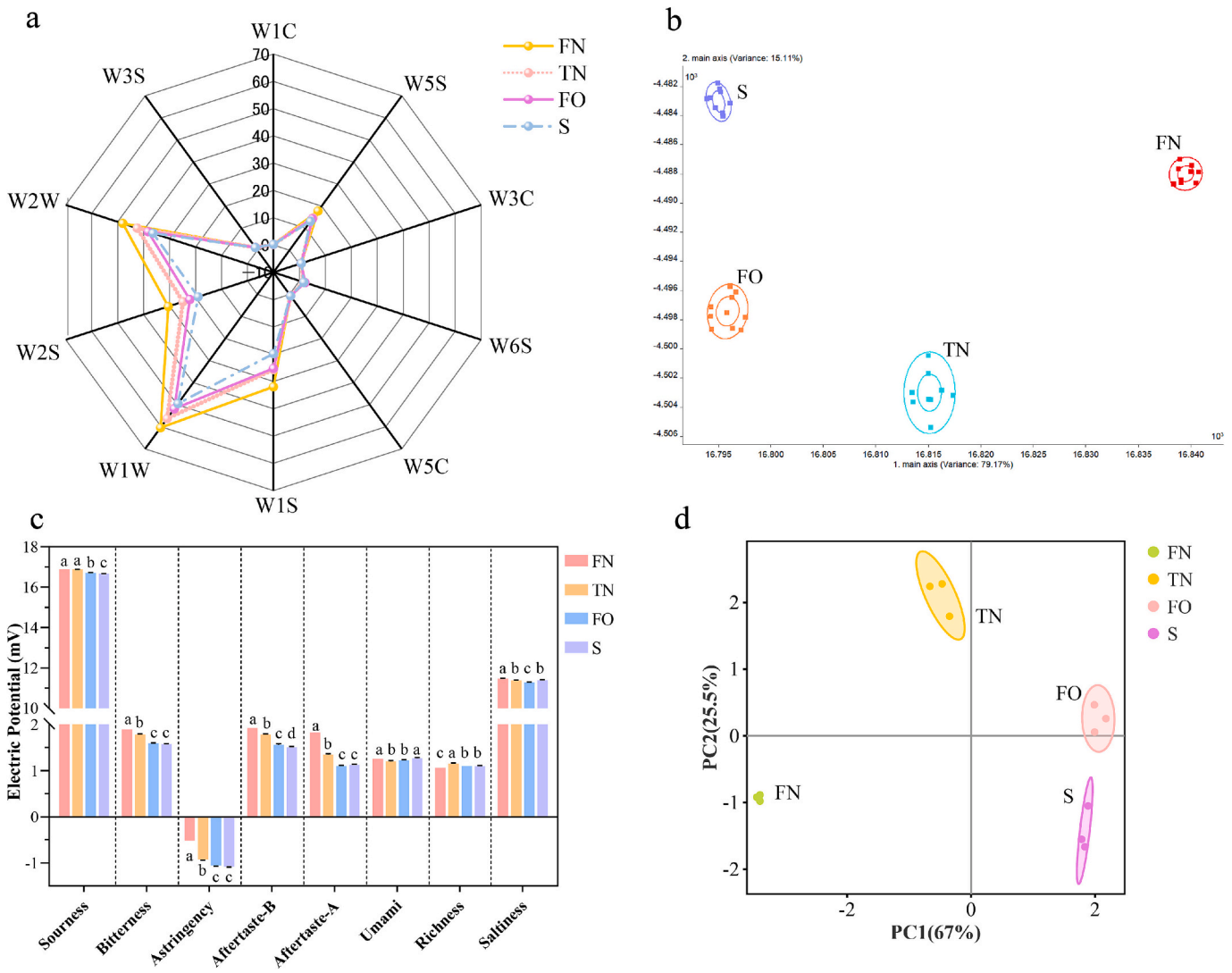


Fig. 4. Electronic sensory analysis of the Sauvignon Blanc wines. (a) Radar graph for the E-nose analysis. (b) linear discriminant analysis for the E-nose. (c) The electric potential of each E-tongue sensor. (d) PCA biplot graph for the E-tongue analysis.

and S. The EP of astringency was below 0, indicating weak astringency of all tested wines. In addition, compared to S wine, FN and FO wines exhibited stronger and weaker saltiness intensity, respectively. The taste profiles of the four Sauvignon Blanc wines were distinguishable by principal component analysis (PCA) (Fig. 4d), with FO and S wines exhibiting quite close clustering.

3.5. Artificial sensory analysis

QDA was performed to evaluate the sensory attributes of four Sauvignon Blanc wines (Fig. 5). There were no significant differences in the appearance scores (including limpidity, luster, and color density) between the wines fermented in the different oak barrels (Fig. 5a). The overall aroma quality (including intensity, purity, and elegance) was rated higher in wines fermented in oak barrels than in those fermented in steel tanks, with new barrels yielding superior results compared to old barrels. In terms of taste attributes, FN, TN, and FO wines received higher scores for body, sourness, harmony, and aftertaste than S wine, with FN and TN outperforming FO. Additionally, bitterness levels were similar across all four wines.

The radar plot of wine aroma descriptors revealed that FO and S wines released the most lemon, orange, grapefruit, peach, pineapple, banana, granadilla, and floral aromas (Fig. 5b). Moreover, the FN, TN, and FO wines featured aromas of cheese, roasted bread, hazelnuts, caramel, and honey, with the intensities ranked in the order of FN > TN > FO.

3.6. Correlation between volatile compounds and aromas attributes

Considering the potential for additive, synergistic, or masking effects among various volatile compounds, those with OAV > 0.1 may still significantly influence the overall flavor profile. The associations between the volatile compounds and aroma attributes were established using PLSR (Fig. 5c). Isoamyl acetate, isobutyl acetate, and ethyl hexanoate were highly correlated with a banana aroma, whereas ethyl laurate was highly correlated with a cheese aroma. Furfural and c-whisky lactone showed a strong correlation with roasted bread and hazelnut aromas. Acetic acid and hexyl acetate were linked to a honey aroma, whereas acetic acid and citronellol were associated with a lemon aroma. Moreover, floral aromas were found to be correlated with β-ionone and nonanal.

3.7. Comparison of the discriminative abilities of various detection methods by MFA

The different detection methods exhibit certain benefits and

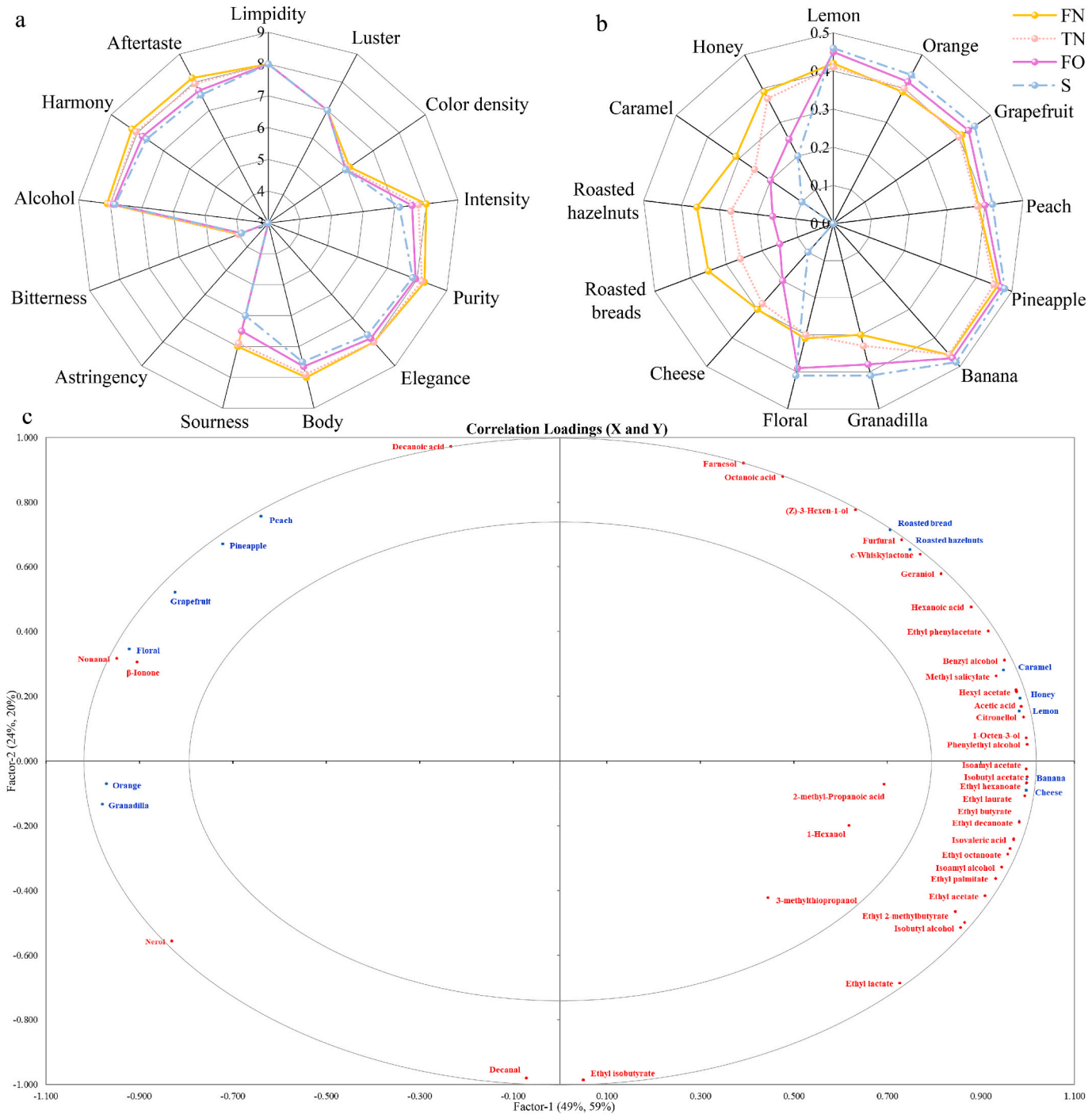


Fig. 5. Quantitative descriptive analysis and PLSR analysis of Sauvignon Blanc wines. (a) Sensory attributes; (b) Aroma attributes; (c) Correlation loadings between volatile compounds and aroma attributes.

limitations. Using the analyses presented earlier as a basis, we speculated that combining the GC–MS, GC-IMS datasets may offer a more comprehensive evaluation of the volatile characteristics of the Sauvignon Blanc wines. Therefore, the four methods (i.e., GC–MS, GC-IMS, and E-nose separately, and the combination of GC–MS and GC-IMS) were compared using MFA to evaluate their potential for distinguishing the flavor characteristics of Sauvignon Blanc wines fermented in various vessels.

In Fig. 6a, the centroid represents the resulting coordinates of MFA, and the points linked to the centroid indicate the coordinates of the projections formed by the variations. The closer these projections are to the centroid, the greater the similarity between the descriptions. The combination of GC–MS and GC-IMS was most proximate to the center of mass across all samples, indicating that the combination had a better distinguishing capability. The RV coefficients between the variable sets were computed using various detection methods (Fig. 6b). The RV coefficients of the GC–MS, GC-IMS, E-nose, and combination methods were 0.95, 0.89, 0.91, and 0.99, respectively.

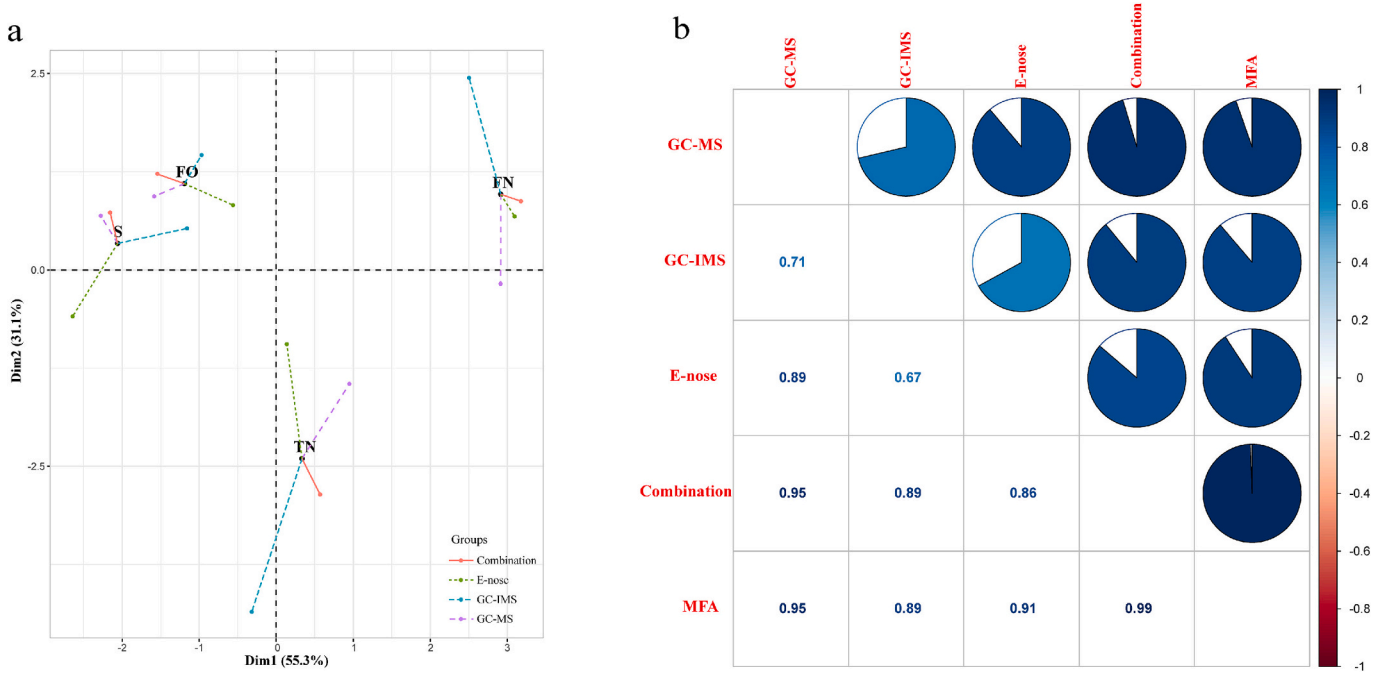


Fig. 6. Multi-factor analysis (MFA) of different detection methods. (a) Coordinates of the projected points of the variations of MFA; (b) RV coefficients between variable sets of detection methods. Combination: the combination of GC–MS and GC-IMS.

4. Discussion

4.1. Effects of fermentation in different vessels on the appearance and taste of Sauvignon Blanc wine

Color is the most visually straightforward characteristic of wines. In this study, the color parameters of Sauvignon Blanc wine fermented in various oak barrels or steel tanks exhibited differences in L*, a*, and b* values (Table 1). However, the ΔE* values for FN, TN, and FO wines were below 3.0 (when S was used as the reference), suggesting that the differences were not perceivable by the human eye (Bai et al., 2024; Martínez et al., 2001). This observation has been noted in a prior study on the fermentation of Sauvignon Blanc wines using vessels of various material (Gil I Cortiella et al., 2020). The color of white wine primarily originates from certain phenolic compounds found in grape skins (Obreque-Slier et al., 2021). However, white wine is typically pressed prior to fermentation, resulting in an extremely short maceration time for the skins, which further reduces color extraction (Nunes et al., 2017). Consequently, whether fermented in oak barrels or stainless-steel tanks, the impact of this procedural difference on color is negligible. Moreover, in the final sensory analysis, the appearances (including limpidity, luster, and color density) of the wines fermented in different vessels were scored similarly (Fig. 5a).

Acidity significantly affects the flavor profile of white wine, with higher acidity enhancing its overall organoleptic characteristics (Gawel et al., 2018). In this study, we observed increased levels of total and volatile acids in wines from oak barrels compared to those from steel tanks, consistent with the results of Herjavec et al. (2007), who studied the effect of oak-barrel fermentation on wine quality. This phenomenon can be attributed to the porosity of oak barrels, which allows for a controlled influx entrance of oxygen, thereby creating a micro-oxygenation environment for wines during fermentation. This process facilitates the conversion of ethanol to ethanal, ultimately resulting in the production of acetic acid and other volatile acids. In contrast, stainless-steel tanks are non-porous and do not promote this effect (Del Alamo-Sanza et al., 2017; Yan et al., 2024). Organic acids are fundamental constituents of wine and significantly influence its sour taste (Yan et al., 2024). Specifically, the contents of malic and tartaric acids in FN and TN wines were higher than those in FO and S wines. This may be attributed to differences in oxygen concentration in various vessels, which influence microbial metabolism (Yan et al., 2024). Malic and tartaric acids confer a mellow and fresh acid taste to Sauvignon Blanc wine (Hao et al., 2024). In the E-tongue analysis, FN and TN wines displayed higher sourness intensities compared to FO and S wines (Fig. 4c), which is consistent with the sensory evaluation results (Fig. 5a). This observation may be attributed to differences in the content of malic acid and tartaric acid in the wines. Additionally, FO wine had higher malic acid levels than S wine, leading to a stronger sourness perception in sensory evaluations (Fig. 5a).

Phenolic compounds in wine contribute significantly to its appearance and sensory characteristics, including color, flavor, and mouthfeel (Huang et al., 2022). This study found that fermentation in oak barrels resulted in higher levels of most phenolic compounds than fermentation in steel tanks (Fig. 1a, b). Given that the entire fermentation process lasts 16 days, there may be a transfer of certain phenolic compounds from the barrel to the wine (López-Solís et al., 2024). Specifically, rutin, quercetin, and kaempferol are present in higher concentrations in wines from new oak barrels than in those from old barrels, largely contributing to the color profile of white wines (Mattivi et al., 2006; Obreque-Slier et al., 2021). The epicatechin and catechin concentrations were higher in wines from old barrels than in those from new barrels, which may be attributed to oxidation, polymerization, and/or the adsorption of these molecules by the wood. These compounds significantly related to the astringency and bitterness of the wine (López-Solís et al., 2024). However, the wines fermented in old oak barrels with a high concentration of flavanols did not exhibit a higher level of astringency and bitterness than the other treatment groups in the E-tongue analysis (Fig. 4c). This observation is consistent with previous research and suggests that flavanols may work in conjunction with other components, such as phenolic acids, tyrosol, ethanol, pH, and polysaccharides, to generate bitterness (Estier & Marchal, 2024; López-Solís et al., 2024). Moreover, in the sensory evaluation, no significant differences in bitterness among the different wine samples were perceived (Fig. 5a), indicating that the E-tongue demonstrated superior sensitivity in detecting subtle differences (Potter et al., 2024).

4.2. Effects of fermentation in different vessels on the aroma of Sauvignon Blanc wine

The total ester, alcohol, and acid contents in FN and TN wines were significantly higher than those in S wine, whereas the levels of these compounds in FO wine were similar to those in S wine (Fig. 2b). This could be because the micro-oxygenation environment of new oak barrels may facilitate yeast cell reproduction, which, in turn, produces aroma-active compounds (Liu et al., 2023), whereas in old oak barrels, continuous use causes the wood pores to become clogged, resulting in reduced diffusion of oxygen into the barrel (Del Alamo-Sanza et al., 2017). Previous studies also showed that the levels of alcohols, esters, and acids in Chardonnay white wine fermented in oak barrels were higher than those fermented in steel tanks (Liberatore et al., 2010). There were no significant differences in the terpene concentrations among the wine samples, primarily because most terpene compounds contribute to varietal aromas (Huang et al., 2023). Ethyl hexanoate, ethyl octanoate, ethyl decanoate, ethyl acetate, ethyl butyrate, isobutyl alcohol, isoamyl alcohol, isobutyric acid, and isovaleric acid exhibited higher OAVs in FN and TN wines than in FO and S wines. This increase can be attributed to the micro-oxygenation environment present in new oak barrels, which significantly influence microbial metabolism. These compounds confer strong fruity, floral, sweet, and cheese aromas to wine (Liu et al., 2023). Moreover, isoamyl acetate, phenethyl acetate, c-whisky lactone, hexanoic acid, and octanoic acid showed higher OAVs in FN wine than in TN, FO, and S wines, providing strong banana, honey, coconut, woody, nutty, and cheese aromas to FN (Huang et al., 2023; Zhang et al., 2022). These differential compounds may primarily account for the varying response values of the E-nose, which effectively differentiated the various samples (Fig. 4a,b). However, in the sensory evaluation, FN and TN wines did not exhibit strong fruity and floral aromas, whereas S and FO wines did show these characteristics. This could be attributed to FN and TN wines containing increased levels of oak-related aromas, such as toast, hazelnut, and caramel, which might overshadow certain fruity and floral aromas (Lu et al., 2023; Nunes et al., 2017).

4.3. Comparison of volatile compounds detected by two methods

In this study, GC-IMS detected a smaller quantity of volatile compounds than GC–MS, while detecting a greater variety of aldehydes, furans, and pyrazines, similar to the findings reported by Hao et al. (2024). This may be because the many components in complex samples can lead to ion–molecule and ion–ion competitive reactions within the ionization chamber during analysis, limiting the selectivity of IMS and reducing the number of detected compounds (Chen et al., 2024). Additionally, variations in the enrichment and concentration levels of each group of volatile compounds occur during SPME, which alter the relative proportions of each group (Hao et al., 2024). The contents of acetaldehyde, furan, and ethyl (E)-2-butenoate were relatively high in FN wine, enhancing its fruity, floral, caramel, and toasted aromas (Yuan et al., 2023). The significant contents of pyrazine, (E, E)-2,4-heptadienal, 1,3-butanediol, and (Z)-3-nonen-1-ol in TN wine were responsible for its toasted, fruity, and nutty aromas (Liu et al., 2023; Ren et al., 2024). The content of butyl acetate, ethyl propanoate, and valeraldehyde were relatively high in FO, conferring fruity and almond aroma attributes to FO (Liu et al., 2023).

As an extension of PCA, MFA is well-suited for investigating the relationship between various analytical techniques applied to the same sample; it helps to resolve discrepancies by standardizing multiple datasets (Li et al., 2023). In our work, the MFA results indicated that the combination of GC–MS and GC-IMS had better distinguishing ability for Sauvignon Blanc wines from various oak barrels and steel tanks than either of the individual methods. However, the distinguishing ability of GC–MS was close to the combination of GC–MS and GC-IMS for S wine. This may be because S wine contained less aldehydes, furans, and pyrazines, to which GC-IMS was more sensitive (Hao et al., 2024). Consequently, GC–MS showed a good distinguishing ability for S wine. RV coefficients are particularly useful for the dimension with the largest explained variance. According to the previous literatures, RV coefficients greater than 0.7 indicate a good level of differentiation (Moelich et al., 2017). In this study, GC–MS, GC-IMS, and E-nose all displayed a good level of differentiation. However, the RV coefficients of the combination of GC–MS and GC-IMS were the highest, further demonstrating that this combination is a better method in distinguishing Sauvignon Blanc wines from various oak barrels and steel tanks.

In summary, wines fermented in oak barrels exhibited rich fruit and floral aromas and enhanced notes of cheese, roasted bread, hazelnuts, caramel, and honey compared to wines fermented in steel tanks. The intensity and elegance of the aromas imparted to wine by the old barrels were lower than those of the new barrels. Moreover, the brand of the oak barrel used for fermentation has a subtle influence on the flavor profile of Sauvignon Blanc wine.

5. Conclusions

This study comprehensively analyzed the flavor profiles of Sauvignon Blanc wines fermented in various oak barrels and stainless-steel tanks using GC–MS, GC-IMS, and electronic sensory. The findings revealed that new oak barrels elevated malic and tartaric acid levels, contributing to enhanced sourness, while also increasing the production of esters, higher alcohols, acids, and aldehydes, which enriched the wine's aroma profile. Ethyl acetate, ethyl lactate, furfural, ethyl octanoate, isoamyl alcohol, isobutyl alcohol, 1-propanol, and acetic acid were the key differential compounds among the various oak barrels and steel tanks. GC-IMS further identified furan, pyrazine, acetaldehyde, and valeraldehyde in wines from oak barrels, which enhanced the complexity of the aroma. Fermentation in oak barrels increased the contents of most phenolic compounds compared to fermentation in steel tanks; however, in the sensory evaluation, participants did not perceive distinct differences in astringency and bitterness among the various wine samples. Sensory evaluations indicated that wines fermented in oak barrels exhibited rich fruit and floral flavors and featured more aromas of cheese, roasted bread, hazelnuts, caramel, and honey than wines fermented in steel tanks. The intensity and elegance of the aromas imparted to wine by old oak barrels were lower than those by new oak barrels. Additionally, the brand of the oak barrel used for fermentation had a subtle influence on the flavor profile of Sauvignon Blanc wine. MFA indicated that the combination of GC–MS and GC-IMS could provide a more comprehensive solution for exploring volatile characteristics in Sauvignon Blanc wines from different oak barrels and steel tanks. These results provide a foundation and guidance for winemakers in selecting barrels to enhance the desirable flavor attributes of Sauvignon Blanc wines. Because the study focuses exclusively on Sauvignon Blanc, the results may not be directly applicable to other grape varieties.

Ethical statement

The sensory evaluation was conducted in accordance with The Code of Ethics of the World Medical Association (Helsinki Declaration) and approved by the Northwest A&F University. We declare that we will protect the rights and privacy of all participants during the study process, obtain the consent of participants, and will not force participants to participate in the study. Do not release participant data without the participant's knowledge. Participants could withdraw from the study at any time. Consent to conduct the sensory evaluations described in this study was obtained from all members of the tasting panel. The panel members also confirmed that they consented to the use of their personal information and the publication of pertinent data.

CRediT authorship contribution statement

Taoxian Zhang: Writing – original draft, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Zusong Liao:** Resources, Investigation. **Zhaohui Li:** Investigation. **Yunqi Liu:** Investigation. **Jingying Bi:** Investigation. **Yanlin Liu:** Resources, Methodology. **Yuyang Song:** Supervision, Investigation, Formal analysis. **Yi Qin:** Writing – review & editing, Validation, Resources, Methodology, Funding acquisition, 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

This research was Supported by Ningxia Hui Autonomous Region Key R&D Project (2022BBF01003, 2021BEF03004), Changji State Science and Technology Support High-Quality Industrial Development Project (2022Z03), Innovative Talent Program for Intellectual Aid in Xinjiang (2024), the Earmarked Fund for CARS (CARS-29-jg-3).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2025.102188.

Data availability

Data will be made available on request.

References

Bai, S., Cui, C., Liu, J., Li, P., Li, Q., & Bi, K. (2018). Quantification of polyphenol composition and multiple statistical analyses of biological activity in Portuguese red wines. *European Food Research and Technology, 244*(11), 2007–2017. https://doi.org/10.1007/s00217-018-3112-6

Bai, Y., Chen, Q., Liu, X., Yue, W., Tian, X., & Han, F. (2024). Effect of exogenous organic acids on chemical compositions and sensory attributes of fortified sweet wines from dehydrated grapes. *Food Chemistry, 445*, Article 138745. https://doi.org/10.1016/j.foodchem.2024.138745

Botha, A., Du Toit, W., Brand, J., Kidd, M., & Groenewald, N. (2020). The effect of different oak products used during fermentation and ageing on the sensory properties of a white wine over time. *Foods, 9*(9), 1220. https://doi.org/10.3390/foods9091220

Chen, J., Wang, W., Jin, J., Li, H., Chen, F., Fei, Y., & Wang, Y. (2024). Characterization of the flavor profile and dynamic changes in Chinese traditional fish sauce (Yu-lu) based on electronic nose, SPME-GC-MS and HS-GC-IMS. *Food Research International, 192*, Article 114772. https://doi.org/10.1016/j.foodres.2024.114772

Del Alamo-Sanza, M., Cárcel, L. M., & Nevares, I. (2017). Characterization of the oxygen transmission rate of oak wood species used in cooperage. *Journal of Agricultural and Food Chemistry, 65*(3), 648–655. https://doi.org/10.1021/acs.jafc.6b05188

Di Renzo, M., Letizia, F., Di Martino, C., Karaulli, J., Kongoli, R., Testa, B., … Iorizzo, M. (2023). Natural Fiano wines fermented in stainless steel tanks, oak barrels, and earthenware Amphora. *Processes, 11*(4), 1273. https://doi.org/10.3390/pr11041273

Estier, T., & Marchal, A. (2024). Towards an understanding of bitterness in white wines: Contribution of 27 compounds assessed by LC-HRMS and sensory analysis. *Food Chemistry, 451*, Article 139503. https://doi.org/10.1016/j.foodchem.2024.139503

Gawel, R., Smith, P. A., Cicerale, S., & Keast, R. (2018). The mouthfeel of white wine. *Critical Reviews in Food Science and Nutrition, 58*(17), 2939–2956. https://doi.org/10.1080/10408398.2017.1346584

Gil I Cortiella, M., Úbeda, C., Covarrubias, J. I., & Peña-Neira, Á. (2020). Chemical, physical, and sensory attributes of sauvignon blanc wine fermented in different kinds of vessels. *Innovative Food Science & Emerging Technologies, 66*, Article 102521. https://doi.org/10.1016/j.ifset.2020.102521

Hao, Y., Li, J., Zhao, Z., Xu, W., Wang, L., Lin, X., Hu, X., & Li, C. (2024). Flavor characteristics of Shanlan rice wines fermented for different time based on HS-SPME-GC-MS-O, HS-GC-IMS, and electronic sensory analyses. *Food Chemistry, 432*, Article 137150. https://doi.org/10.1016/j.foodchem.2023.137150

Herjavec, S., Jeromel, A., Da Silva, A., Orlic, S., & Redzepovic, S. (2007). The quality of white wines fermented in Croatian oak barrels. *Food Chemistry, 100*(1), 124–128. https://doi.org/10.1016/j.foodchem.2005.09.034

Herrero, P., Sáenz-Navajas, M. P., Avizcuri, J. M., Culleré, L., Balda, P., Antón, E. C., … Escudero, A. (2016). Study of Chardonnay and Sauvignon blanc wines from D.O.Ca Rioja (Spain) aged in different French oak wood barrels: Chemical and aroma quality aspects. *Food Research International, 89*, 227–236. https://doi.org/10.1016/j.foodres.2016.08.002

Huang, R., Jiang, J., Su, Y., Yu, H., Shen, L., Liu, Y., Qin, Y., & Song, Y. (2023). Microbial community succession and volatile compounds changes during spontaneous fermentation of Cabernet Sauvignon (Vitis vinifera L.) under rain-shelter cultivation. *Food Chemistry, X, 17*, Article 100618. https://doi.org/10.1016/j.fochx.2023.100618

Huang, R., Yu, H., Dong, C., Shen, L., Qin, Y., Liu, Y., Jiang, J., & Song, Y. (2022). Correlations between microbial diversity, monomeric phenols, and biological parameters during spontaneous fermentation of Cabernet Sauvignon grapes obtained from rain-shelter cultivation. *LWT, 171*, Article 114146. https://doi.org/10.1016/j.lwt.2022.114146

Lan, T., Wang, J., Yuan, Q., Lei, Y., Peng, W., Zhang, M., Li, X., Sun, X., & Ma, T. (2022). Evaluation of the color and aroma characteristics of commercially available Chinese kiwi wines via intelligent sensory technologies and gas chromatography-mass spectrometry. *Food Chemistry: X, 15*, Article 100427. https://doi.org/10.1016/j.fochx.2022.100427

Li, A., Feng, X., Yang, G., Peng, X., Du, M., Song, J., & Kan, J. (2024). Impact of aroma-enhancing microorganisms on aroma attributes of industrial Douchi: An integrated analysis using E-nose, GC-IMS, GC–MS, and descriptive sensory evaluation. *Food Research International, 182*, Article 114181. https://doi.org/10.1016/j.foodres.2024.114181

Li, S.-Y., & Duan, C.-Q. (2019). Astringency, bitterness and color changes in dry red wines before and during oak barrel aging: An updated phenolic perspective review. *Critical Reviews in Food Science and Nutrition, 59*(12), 1840–1867. https://doi.org/10.1080/10408398.2018.1431762

Li, X., Zhang, Y., Hengchao, E., He, X., Li, J., Zhao, X., & Zhou, C. (2023). Characteristic fingerprints and comparison of volatile flavor compounds in Morchella sextelata under different drying methods. *Food Research International, 172*, Article 113103. https://doi.org/10.1016/j.foodres.2023.113103

Liberatore, M. T., Pati, S., Nobile, M. A. D., & Notte, E. L. (2010). Aroma quality improvement of Chardonnay white wine by fermentation and ageing in barrique on lees. *Food Research International, 43*(4), 996–1002. https://doi.org/10.1016/j.foodres.2010.01.007

Liu, S., Lou, Y., Li, Y., Zhao, Y., Laaksonen, O., Li, P., Zhang, J., Battino, M., Yang, B., & Gu, Q. (2023). Aroma characteristics of volatile compounds brought by variations in microbes in winemaking. *Food Chemistry, 420*, Article 136075. https://doi.org/10.1016/j.foodchem.2023.136075

López-Solís, R., Osorio-Umaña, P., Medel-Marabolí, M., & Obreque-Slier, E. (2024). Comparative analysis of the evolution of phenolic profiles during wood aging of a Carménère wine using novel products or procedures aimed at re-using oak barrels. *Food Bioscience, 57*, Article 103623. https://doi.org/10.1016/j.fbio.2024.103623

Lu, H.-C., Cheng, B.-H., Lan, Y.-B., Duan, C.-Q., & He, F. (2023). Modifications in aroma characteristics of 'Merlot' dry red wines aged in American, French and Slovakian oak barrels with different toasting degrees. *Food Science and Human Wellness*, 1–21. https://doi.org/10.26599/FSHW.2022.9250032

Martínez, J. A., Melgosa, M., Pérez, M. M., Hita, E., & Negueruela, A. I. (2001). Note. Visual and instrumental color evaluation in red wines. *Food Science and Technology International, 7*(5), 439–444. https://doi.org/10.1106/VFAT-5REN-1WK2-5JGQ

Mattivi, F., Guzzon, R., Vrhovsek, U., Stefanini, M., & Velasco, R. (2006). Metabolite profiling of grape: Flavonols and anthocyanins. *Journal of Agricultural and Food Chemistry, 54*(20), 7692–7702. https://doi.org/10.1021/jf061538c

Moelich, E. I., Muller, M., Joubert, E., Næs, T., & Kidd, M. (2017). Validation of projective mapping as potential sensory screening tool for application by the honeybush herbal tea industry. *Food Research International, 99*, 275–286. https://doi.org/10.1016/j.foodres.2017.05.014

Nunes, P., Muxagata, S., Correia, A. C., Nunes, F. M., Cosme, F., & Jordão, A. M. (2017). Effect of oak wood barrel capacity and utilization time on phenolic and sensorial profile evolution of an Encruzado white wine. *Journal of the Science of Food and Agriculture, 97*(14), 4847–4856. https://doi.org/10.1002/jsfa.8355

Obreque-Slier, E., Herrera-Bustamante, B., & López-Solís, R. (2021). Ripening-associated flattening out of inter-varietal differences in some groups of phenolic compounds in the skins of six emblematic grape wine varieties. *Journal of Food Composition and Analysis, 99*, Article 103858. https://doi.org/10.1016/j.jfca.2021.103858

Potter, R. I., Warren, C. A., Lee, J., & Ross, C. F. (2024). Comparative assessment of Riesling wine fault development by the electronic tongue and a sensory panel. *Journal of Food Science, 89*(5), 3006–3018. https://doi.org/10.1111/1750-3841.17036

Ren, A., Zhang, Y., Bian, Y., Liu, Y., Zhang, Y., Ren, C., Zhou, Y., Zhang, T., & Feng, X. (2024). Pyrazines in food samples: Recent update on occurrence, formation, sampling, pretreatment and analysis methods. *Food Chemistry, 430*, Article 137086. https://doi.org/10.1016/j.foodchem.2023.137086

Rong, Y., Xie, J., Yuan, H., Wang, L., Liu, F., Deng, Y., … Yang, Y. (2023). Characterization of volatile metabolites in Pu-erh teas with different storage years by combining GC-E-nose, GC–MS, and GC-IMS. *Food Chemistry: X, 18*, Article 100693. https://doi.org/10.1016/j.fochx.2023.100693

Scutarașu, E. C., Teliban, I. V., Zamfir, C. I., Luchian, C. E., Colibaba, L. C., Niculaua, M., & Cotea, V. V. (2021). Effect of different winemaking conditions on organic acids compounds of white wines. *Foods, 10*(11), 2569. https://doi.org/10.3390/foods10112569

Xie, Q., Tang, Y., Wu, X., Luo, Q., Zhang, W., Liu, H., Fang, Y., Yue, X., & Ju, Y. (2023). Combined ultrasound and low temperature pretreatment improve the content of anthocyanins, phenols and volatile substance of Merlot red wine. *Ultrasonics*

Sonochemistry, 100, Article 106636. https://doi.org/10.1016/j.ultsonch.2023.106636

Yan, Y., Zou, M., Tang, C., Ao, H., He, L., Qiu, S., & Li, C. (2024). The insights into sour flavor and organic acids in alcoholic beverages. *Food Chemistry, 460*, Article 140676. https://doi.org/10.1016/j.foodchem.2024.140676

Yang, Y., Ye, Z., Qin, Y., Pathirana, S., Araujo, L. D., Culley, N. J., & Kilmartin, P. A. (2024). Effects of post-fermentation addition of green tea extract for sulfur dioxide replacement on Sauvignon Blanc wine phenolic composition, antioxidant capacity, colour, and mouthfeel attributes. *Food Chemistry, 447*, Article 138976. https://doi.org/10.1016/j.foodchem.2024.138976

Yin, H., Wang, L., Su, H., Liang, Y., Ji, P., Wang, X., & Xi, Z. (2023). Effects of ultraviolet and infrared radiation absence or presence on the aroma volatile compounds in winegrape during veraison. *Food Research International, 167*, Article 112662. https://doi.org/10.1016/j.foodres.2023.112662

Yuan, X., Zhou, J., Zhang, B., Shen, C., Yu, L., Gong, C., Xu, Y., & Tang, K. (2023). Identification, quantitation and organoleptic contributions of furan compounds in brandy. *Food Chemistry, 412*, Article 135543. https://doi.org/10.1016/j.foodchem.2023.135543

Zhang, B., Tang, C., Yang, D., Liu, H., Xue, J., Duan, C., & Yan, G. (2022). Effects of three indigenous non-Saccharomyces yeasts and their pairwise combinations in co-fermentation with Saccharomyces cerevisiae on volatile compounds of Petit Manseng wines. *Food Chemistry, 368*, Article 130807. https://doi.org/10.1016/j.foodchem.2021.130807

Zhang, T., Liao, Z., Li, Z., Liu, Y., Liu, Y., Song, Y., & Qin, Y. (2024). Dynamic changes in dissolved oxygen concentration, microbial communities, and volatile compounds during industrial oak-barrel fermentation of Sauvignon Blanc wine. *Food Research International, 197*, Article 115250. https://doi.org/10.1016/j.foodres.2024.115250

Zhu, W., Benkwitz, F., & Kilmartin, P. A. (2021). Volatile-based prediction of Sauvignon Blanc quality gradings with static headspace–gas chromatography–ion mobility spectrometry (SHS–GC–IMS) and interpretable machine learning techniques. *Journal of Agricultural and Food Chemistry, 69*(10), 3255–3265. https://doi.org/10.1021/acs.jafc.0c07899