Food Science and Biotechnology (2024) 33:33–45
https://doi.org/10.1007/s10068-023-01325-x

RESEARCH ARTICLE

Effects of high power pulsed microwave on the enhanced color and flavor of aged blueberry wine

Siyuan Liu[1,2] · Shuangjian Li[1,2] · Siyuan Li[2] · Ying Wang[2,3] · Linlin Fan[2,3] · Jianzhong Zhou[1,2,3]

Received: 12 January 2023 / Revised: 12 April 2023 / Accepted: 26 April 2023 / Published online: 12 May 2023

Abstract

A new method of high-power pulsed microwave (HPPM) was applied to accelerate the aging of blueberry wine. The color changes of blueberry wines during aging were investigated through Chemical Wine Age and CIE-LAB measurement. Results showed that the blueberry wines treated by HPPM at low frequencies (50 and 100 Hz) exhibited improved color characteristics with L^* value reaching 47.04 at 100 Hz, an increased maturity of wine body, and a shortened chemical wine age from 90 days to 75 days. Moreover, the aroma changes determined by GC-MS showed that HPPM accelerated the formation of esters in blueberry wine, which were increased by 18.44% and 56.97% respectively under the conditions of 50 and 150 Hz. The formation of acid substances was reduced compared with the original wine, with contents of acetic acid, caproic acid, and octanoic acid of 29.46 μg/mL, 15.60 μg/mL, 17.74 μg/mL, respectively, displaying an enhanced wine flavor.

Keywords High-power pulsed microwave · Blueberry · Artificial aging · Anthocyanin

Introduction

Blueberry is a perennial deciduous or evergreen shrub of *Vaccinium* in the cuckoo family. It is a small round fruit about 0.2 to 0.6 inches across, usually brightly colored ranging from blue to purple. This fruit is juicy, sour and sweet, delicious, and has a unique flavor. It is an excellent source of amino acids, sugar, acid, vitamins, dietary fiber, anthocyanins and other nutrients. It possesses plenty of health care functions, such as anti-aging, reducing cardiovascular disease and type 2 diabetes, vascular protection, anti-arteriosclerosis, and alleviating visual fatigue (Kalt et al., 2020; Yan et al., 2023; Zhang et al., 2023). Blueberries are favored by people of all ages. They often eaten fresh or frozen. However, they are easily contaminated with bacteria during storage and transportation owing to their juicy and thin properties. Since food safety is a high priority for all of the world and significantly affects all citizens, many policies regarding food products and circulation have been implemented such as by the European Union (EU) ((Bondoc 2016a, 2016b). Meanwhile, the European Food Safety Authority (EFSA) has recommended blueberry producers to use good agricultural, hygiene and manufacturing practices in order to reduce the external contamination ((Bondoc 2016c, 2016d). One of the effect ways is processing of blueberry fruits into other products with added values. For example, the production of blueberry wine by alcoholic fermentation can not only retain the nutritional value of fresh blueberry fruit, but also facilitate a long-term preservation.

In general, the freshly fermented fruit wine tastes sour and astringent, the wine body is turbid, and the stability is poor (Baiano et al., 2016). Therefore, young fruit wine needs to be stored for a period of time to improve its characteristics. Accordingly, aging is an important stage to improve the quality of fruit wine, which can weaken the astringent taste of fruit wine and form a stable wine body with complete color, aroma and flavor. The traditional aging method is mainly oak barrel aging (Ma et al., 2022). This method can

Siyuan Liu and Shuangjian Li have contributed equally to this work.

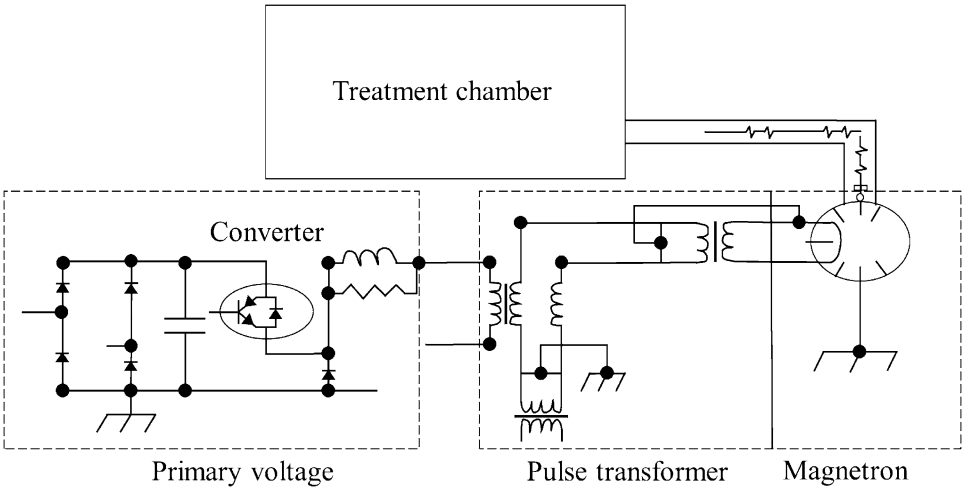
✉ Linlin Fan
fanlinlin@jaas.ac.cn

✉ Jianzhong Zhou
zjzluck@126.com

[1] College of Food Science and Technology, Shanghai Ocean University, Shanghai 201306, China

[2] Institute of Agro-product Processing, Jiangsu Academy of Agricultural Sciences, Nanjing 210014, China

[3] Key Laboratory of Cold Chain Logistics Technology for Agro-product, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China



Scheme 1 The working path of HPPM.

improve the quality of fruit wine, but it needs a long aging cycle and high cost. Researchers attempt to develop artificial aging technology and methods to accelerate the aging of fruit wine, shorten the aging time, and improve the quality of fruit wine in a short time (García Martín and Sun, 2013). At present, many physical methods for fruit wine aging are available, such as oak aging, ultrasonic aging, pulsed electric field aging, microwave aging, ultra-high-pressure aging, and cold and hot aging (Alcarde et al., 2014; Darra et al., 2013; Li and Duan, 2019). Fresno et al. (Fresno et al., 2019) found that the ultrasonic treatment has a certain protective effect on total anthocyanins of wines, but the color intensity decreases significantly. It is noted that the manual aging through non-thermal processing is a feasible method to shorten the aging time, improve the quality of fruit wine, and reduce the production cost.

High-power pulsed microwave (HPPM) has been developed as an innovative non-thermal technology (Peng et al., 2020; Xie et al., 2015). It can generate short and periodic high-frequency pulse microwave which is one of the electromagnetic waves with frequencies ranging from 300 MHz to 300 GHz. As one of the non-thermal physical technologies, HPPM has gained increasing attention due to its better maintenance of food texture and nutrients. It was reported that the pulsed electric field caused the ionization of molecules and decreased activation energy required for the reaction, accelerating the chemical reaction rates in wines when used for aging (Yang et al., 2016). The electromagnetic waves itself have positive effects on ethanol and water molecules in wines (Ma et al., 2022). It can increase the molecular orientation, facilitate mutual polarization between molecules, and promote the combination of ethanol and water to form more hydrogen bonds, promoting the result of natural wine aging.

HPPM has instantaneous high energy and intermittent action to avoid the negative influence of the thermal effect. The electromagnetic waves produced by HPPM is expected to accelerate the molecular cleavage, rearrangement, polymerization, esterification and other reactions to produce new color substances or flavor substances during aging. Scheme 1 showed the working path of HPPM. However, HPPM technology has not been applied to the fruit wine aging. In this work, HPPM was used as a new method to accelerate the aging of blueberry wine. The effects of HPPM on the color changes of blueberry wine during aging were examined, as well as the flavor substances of blueberry wine after aging were analyzed.

Materials and methods

Materials and reagents

Blueberries (*Rabbiteye*) were provided by Nanjing Shuangji Agricultural Development Co., Ltd.; *Saccharomyces cerevisiae* (LAVIN DV 10) and tanning (food grade)was purchased from Shanghai Kangxi Food and Beverage Co., Ltd.; pectinase (food grade, 30,000 u/mL) was from Shanghai Xiangyang Biology Co, Ltd.; sugar (food grade) was purchased from local supermarket; potassium sulfite (food grade) was from Nanjing Jiebaike Biotechnology Co., Ltd.; and gelatin (food grade) was from Beijing Cuifeng Technology Co., Ltd.

Blueberry wine fermentation

The fresh blueberry fruits were washed and crushed. Then, the pulp was added with 0.1% pectinase, 15% white granulated sugar, 0.15 g/kg potassium pyrosulfite, and 0.2 g/kg yeast, mixed evenly and placed into a tank for fermentation. The fermentation temperature was set to (20–23 °C), and the mixture was stirred once a day in 5 days during fermentation. After fermentation, the mixture was filtered to remove the residue and added with tannin (0.15 g/L) and gelatin

(0.6 g/L) for clarification. The wine was obtained after filtration with the precision paperboard after 7 days, and it was packed into a brown wine bottle for aging treatments. A total sugar of 4.5 g/L and an alcohol content of 11.8% (v/v) were considered as basic indicators of blueberry wine after fermentation.

High-power pulsed microwave (HPPM) treatment

A total of 300 mL of blueberry wine samples was placed into 500 mL glass containers each time for HPPM treatments. Briefly, the wine was placed into the cavity, under the conditions of a pulse power of 750 kW and a pulse width of 1.5 µs. Different frequencies (50, 100, 150, 200, 250 Hz) were selected for HPPM treatment. After treatment, the blueberry wine was placed back into the bottle, sealed with an oak stopper, and stored in the dark at room temperature for testing.

Determination of chemical aging of blueberry wine

Chemical wine age was determined based on the changes of anthocyanins during aging. The changes in anthocyanins-related colors in blueberry wine were analyzed by UV–vis spectrophotometry. Anthocyanins-related parameters in blueberry wine were detected based on the methods of Atanasova et al. (Atanasova et al., 2002) with a slight modification.

Blueberry wine color (BWC): A total of 50 µL of 10% acetaldehyde solution was added to 5 mL of blueberry wine sample. Acetaldehyde was used to reduce the pigment bleached by SO_2, and the resultant was set in the dark for 45 min. The distilled water (5 mL) with 50 µL of 10% acetaldehyde was taken as the reference solution. The absorbance value of the sample was measured at 520 nm.

Color due to pigments derivatives resistant to SO_2 (CDR SO_2): Dissolving potassium pyrosulfite in solution can increase the content of SO_2 in blueberry wine. A total of 75 µL of 20% potassium pyrosulfite solution was added to 5 mL of blueberry wine sample or 5 mL distilled water, and the absorbance at 520 nm was tested after standing in the dark for 10 min.

Chemical age of blueberry wine (CABW): The chemical age of blueberry wine was calculated by the Eq. (1).

$$\mathrm{CABW} = \left(\mathrm{CDR\ SO_2} / \mathrm{BWC}\right) \tag{1}$$

Determination of color density and tint

The color characteristics of blueberry fruit wine were determined by spectrophotometry (MAPADA, China), and the absorbance values of the samples were measured at 420 nm, 520 and 620 nm (Wang et al., 2019). The color density and tint were expressed as CD and T, which were calculated as Eqs. (2) and (3).

$$\text{Color Density (CD)} = \mathrm{OD_{420nm}} + \mathrm{OD_{520\ nm}} + \mathrm{OD_{620\ nm}} \tag{2}$$

$$\text{T int (T)} = \mathrm{OD_{420\ nm}} / \mathrm{OD_{520\ nm}} \tag{3}$$

Determination of CIE-LAB color

The Lab value of blueberry fruit wine was determined by a color difference instrument (3nh, China). The sample was measured in transmission mode. The color parameters L^* (light and dark), a^* (red and green), and b^* (yellow and blue) were obtained following the instructions of the instrument. The hue angle (h_{ab}), saturation chroma (C^*) and chromatic aberration (ΔE) were calculated by the following Eqs. (4, 5 and 6).

$$\mathrm{h_{ab}} = \arctan\left(\mathrm{b^*} / \mathrm{a^*}\right) \tag{4}$$

$$\mathrm{C^*} = \sqrt{\left(\mathrm{a^{*2}} + \mathrm{b^{*2}}\right)} \tag{5}$$

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{6}$$

L^* indicates brightness, $L^* > 0$ indicates partial brightness, and $L^* < 0$ indicates partial darkness; a^* indicates red and green, $a^* > 0$ indicates partial red, and $a^* < 0$ indicates partial green; b^* indicates yellow blue, $b^* > 0$ indicates yellowish, and $b^* < 0$ indicates bluish; h_{ab} represents the hue angle, and different hues indicate different colors; C^* indicates saturation chroma.

Volatile compound analysis

Solid–phase microextraction gas chromatography–mass spectrometry (SPME–GC–MS) was conducted to detect the changes in aroma components in blueberry wines (Niimi et al., 2020).

Solid phase microextraction: 5.0 mL of the sample was placed into a 20 mL headspace bottle, and was added 20 µL of 2-octanol (50 mg/L) as the internal standard. The aged 50/30 umcar/PDMS/DVB fiber (Supelco, USA) was inserted into the headspace of the sample bottle for absorption at 50 °C for 30 min. After collecting the absorbed extraction head, it was inserted into the gas chromatography sample inlet for desorption at 250 °C for 3 min. At the same time, the instrument was started to collect data.

Gas chromatography: The TG-5MS (30 m × 0.25 mm ×0.25 µm, Agilent, USA) elastic quartz capillary column was applied. The flow rate of carrier gas (purity 99.999%)

was 1.2 mL/min. Non-split injection was adopted. The temperature of the injection port was 250 °C, and the temperature rise was programmed as follows: the initial temperature was kept at 40 °C for 2 min, and then, it was increased to 280 °C at 6 °C/min for 14 min.

Mass spectrum conditions: The ion source was EI source, and the transmission line temperature was 280 °C. The ion source temperature was 300 °C, the electronic energy was 70 eV, and the scanning range (m/z) was 40–550 amu under full scan acquisition mode.

Analysis: The volatile components of blueberry fruit wine were analyzed through computer retrieval and comparison with the standard mass spectra provided by NIST105 and Wiley7.0 mass spectrometry libraries. The data processing system of NIST spectrum library workstation was used to analyze according to the peak area normalization method, and the volatile identifications were semi-quantified by using 2-octanol (20 uL, 50 μg/mL) as an internal standard.

Statistical analysis

All tests were performed in triplicate and data were expressed as mean ± standard deviation, ANOVA with Duncan's test was applied for data comparison (IBM SPSS 19.0, Chicago, USA). Differences with $p < 0.05$ were considered statistically significant. Mapping and correlation analysis were performed using origin 2020b (OriginLab, Northampton, Massachusetts, USA).

Results and discussion

Impact of HPPM treatment on CABW

Chemical wine age is an important indicator to evaluate the aging degree of fruit wine. Free anthocyanins converted into stable anthocyanin derivatives with metabolites and polyphenols formed in the fermentation process during aging. More anthocyanin derivatives are formed with longer aging time, and the changes in anthocyanins reflected the chemical age of wines. The relevant parameters of chemical wine age of blueberry wine with HPPM treatment during storage, including the blueberry wine color (BWC), the color due to pigments derivatives resistant to SO_2 (CDR SO_2) and the chemical age of blueberry wine (CABW).

The BWC value is related to the combination between anthocyanins and phenolic acids or flavanols. Adding acetaldehyde to blueberry wine can release anthocyanins bound with SO_2. Acetaldehyde will combine with SO_2 to form polymers, while heavy sulfite anthocyanins will decompose to generate acetaldehyde sulfite compounds. These phenomena will release the combination of SO_2 and anthocyanins. They can also convert colorless chalcone form anthocyanins into red salt ion form anthocyanins, which can enhance the color of blueberry wine. As shown in Fig. 1(A), the BWC value of blueberry wine treated with HPPM on day 0 increased compared with that of the original wine. Specifically, the BWC value of blueberry wine treated under the condition of 100 Hz was significantly increased, which due to the combination of anthocyanins and some phenolic acids. New color compounds likely formed owing to the molecular rearrangement and polymerization resulted by HPPM. BWC values of all groups showed a downward trend during 90 days of storage. Gambuti et al. (Gambuti et al., 2015) also found SO_2 was able to modulate reactions initiated by micro-oxygenation, since micro-oxygenated wines with lower concentration of ethyl-bridged compounds and pyranoanthocyanins. But high concentration of SO_2 (40 mg/L of free SO_2) compared to standard concentration (25 mg/L of free SO_2) slowed down decrease of flavan-3-ols and particularly anthocyanins (Ćurko et al., 2021).

SO_2 plays important antioxidant and antibacterial roles in the fermentation and aging of fruit wine. CDR SO_2 value is the chromaticity value of anthocyanin derivatives that are resistant to SO_2 bleaching. The SO_2 added to the blueberry wine will exist in the form of sulfite ion in the wine body, and it can combine with free anthocyanins to form colorless and unstable heavy sulfite anthocyanins. Meanwhile, the free anthocyanins and some anthocyanin derivatives in the blueberry wine will be decolorized immediately. Since some anthocyanin derivatives occupied at position 4 are stable to SO_2 (Sun et al., 2019), CDR SO_2 value is used to indicate the color stability of fruit wine during aging. As shown in Fig. 1(B), the CDR SO_2 value during aging for 0–30 days gradually increased, indicating that the ability of blueberry wine to resist SO_2 bleaching was enhanced. This finding was consistent with the research results of Li et al. (Li et al. 2020b). However, the CDR SO_2 values of all groups showed a downward trend during the storage process after 30 days. HPPM showed no effects on the change process of CDR SO_2.

The changes in anthocyanins during the aging process were used as the basis for evaluating the chemical age of fruit wine. Free anthocyanins could combine with the polyphenols and metabolites during fermentation to form more stable anthocyanin derivatives during aging. Therefore, the content of anthocyanin derivatives increased over the aging time. The CABW value was defined as the ratio of CDR SO_2 value to BWC value. As shown in Fig. 1(C), the CABW value of blueberry wines under low frequency (50, 100 and 150 Hz) treatment and with a storage for 75 days was higher than that of the original wines stored for 90 days. It suggested that HPPM treatment shorten the time and accelerated the blueberry wine aging. HPPM may polarize the polar molecules in the wine body through its instantaneous high energy

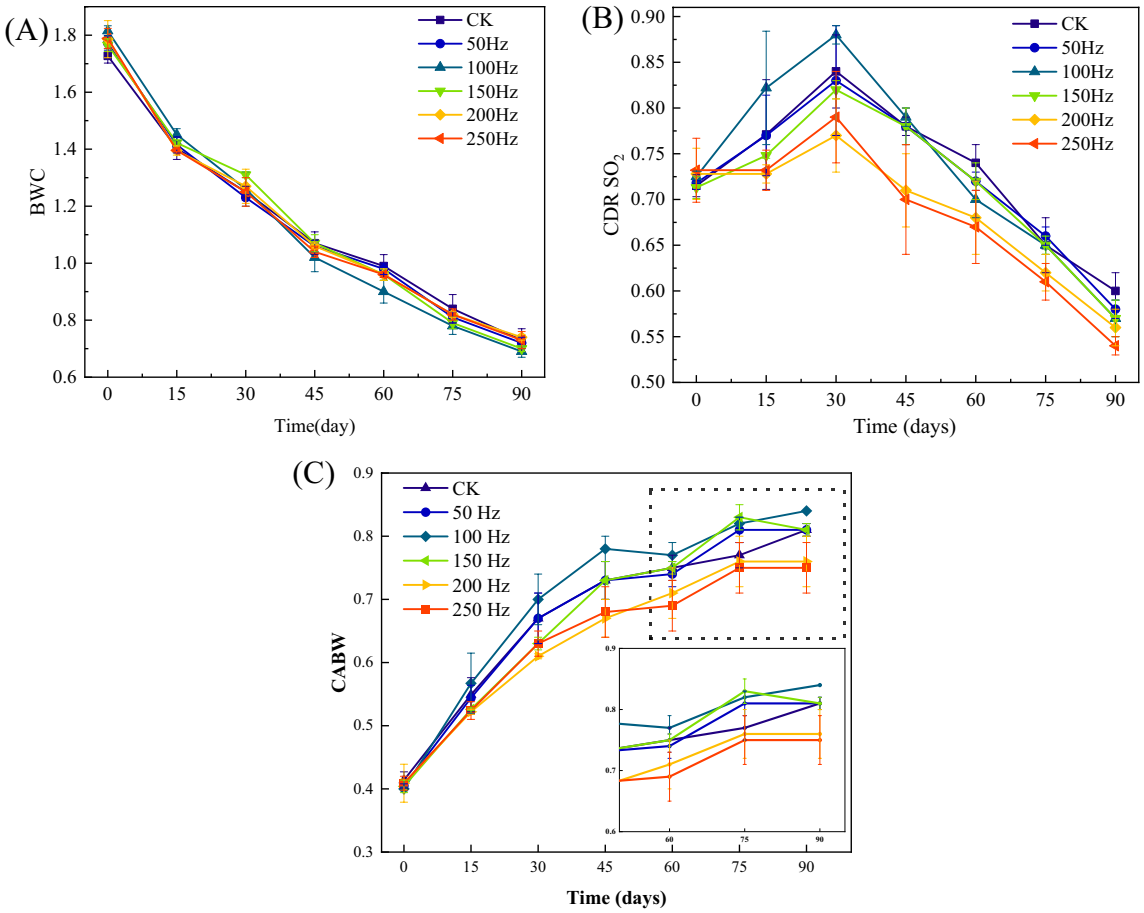


Fig. 1 The changes in chemical age of blueberry wine. (**A**) Effects of different HPPM frequencies on blueberry wine color (BWC). (**B**) Effects of different HPPM frequencies on color due to pigments derivatives resistant to SO_2 (CDR SO_2). (**C**) Effects of different HPPM frequencies on chemical aging of blueberry wine (CABW).

and microwave magnetic field to form more hydrogen bonds between ethanol and water. At the same time, it is conducive to the recombination of insoluble molecules. As a result, the wine body presents the result of natural aging. Lukić et al. (Lukic et al., 2019) found that ultrasonic treatment under appropriate conditions can accelerate the aging reaction of wine and shorten the aging cycle. Similarly, HPPM can also shorten the aging time of blueberry wine.

In summary, the free anthocyanins gradually decreased and the polymerized anthocyanins continued to increase during the aging process of blueberry wine treated with HPPM. As a result, the chemical wine age gradually increased. Notably, HPPM treatment can improve the color value of blueberry wine under specific conditions and shorten the aging cycle, which may present a potential contribution in the aging process.

Effect of HPPM treatment on CD (color density) and T (tint) values

The CD value was defined as the color density of blueberry wine at different wavelengths (λ_{420nm}, λ_{520nm}, and λ_{620nm}), and it is related to the formation of anthocyanin derivatives. As shown in Fig. 2(A), the CD value showed a decreasing trend during storage. The HPPM treatment condition at a high frequency (200 and 250 Hz) slowed down the decline in CD value of blueberry wine. It was possibly due to that HPPM promoted the generation of anthocyanin derivatives.

The T value of blueberry wine reflects the maturity of the wine body. After the blueberry wine was brewed, the free anthocyanins in the wine body account for a high proportion. As aging time extended, the free anthocyanins in the blueberry wine body gradually reacted with other phenolic substances to form polymerized anthocyanins, leading to the changes in the color of the wine body and an increase in the

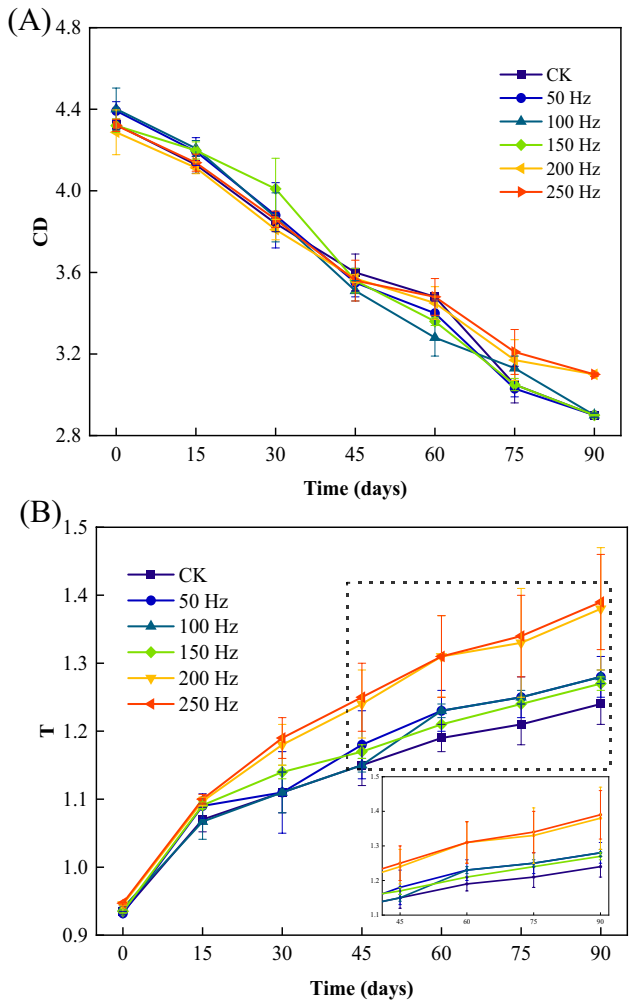


Fig. 2 Effects of different HPPM frequencies (50, 100, 150, 200, 250 Hz) on CD values and T values of blueberry wine. (**A**) shows the CD values and (**B**) shows the T values

color stability. As shown in Fig. 2(B), the T value showed a gradual increasing trend during storage, which was similar to the finding of Liu et al. (Liu et al., 2018) and consistent with other research results. After 90 days of storage, the T value of the blueberry wine treated with high frequency (200 and 250 Hz) of HPPM was significantly higher than that of the original wine ($p < 0.05$). It indicated that HPPM treatment accelerated the conversion of free anthocyanins to polymerized state and improved the T value of blueberry wine. Meanwhile, the T value was greater when the frequency of HPPM was higher.

We also found that the T value of blueberry wine treated with HPPM at lower frequency (50 and 100 Hz) after 60 days of storage (T = 1.23) was higher than that of the original wine after 75 days of storage (T = 1.17). Meanwhile, the T value of blueberry wine treated with HPPM at 200 and 250 Hz after 45 days of storage was higher than that of the original wine after 90 days of storage. These results suggested that HPPM shortens the time required for blueberry wine to mature. Since HPPM has microwave characteristics, it can increase the internal energy of the molecules in the blueberry wine body, accelerate the chemical reaction speed, and thus speed up the maturation of the blueberry wine body.

Impact of HPPM treatment on the appearance color of blueberry wine

The color change of fermented fruit wine during aging is affected by many factors, such as pH value, storage temperature, oxidation and chemical structure ((Li et al. 2020a). L^*, a^*, b^*, h_{ab}, C^*, and ΔE are commonly used to evaluate the color characteristics of fruit wines (Pathare et al., 2012). The color characteristics of blueberry wine treated with HPPM at different frequencies during storage were measured, and the results were shown in Table 1. In the case of untreated blueberry wine, the L^*, b^*, h_{ab} and ΔE values gradually increased, and a^* and C^* values gradually decreased during storage for 90 days. In addition, the color change of blueberry wine after HPPM treatment was consistent with that of natural blueberry wine.

Specifically, the L^* value (brightness from light to dark) showed an upward trend with the extension of time during storage. After 90 days of storage, the L^* value of blueberry wine treated with HPPM was higher than that of the original wine. The L^* value of the blueberry wine treated at 100 Hz was significantly increased. The value reached 47.04, implying that the color of the blueberry wine gradually became brighter. The a^* value (from red to green) showed a downward trend during storage, that is, the red tone of the blueberry wine gradually decreased. But no significant difference was observed between the blueberry wine and the original wine treated with different HPPM frequencies. The b^* value (from yellow to blue) and h_{ab} value (hue angle) showed an upward trend during storage, suggesting the yellow tone in the blueberry wine gradually increased. Among them, the blueberry wine treated at 250 Hz showed significantly increased b^* and h_{ab} values. The C^* value (saturation) tended to decrease during storage. At the same time, the decline rate of C^* value of blueberry wine after HPPM treatment was lower than that of original wine, indicating that HPPM slowed down the decline in C^*.

The ΔE value (color difference) of this experiment was calculated with reference to the original wine. In the storage process, the ΔE value of blueberry wine maintained a proportional relationship with the increase in HPPM frequency. After 90 days of storage, the ΔE value of blueberry wine treated with high frequency (200 and 250 Hz) was significantly higher than that of other groups. The difference

Table 1 Effects of different HPPM frequencies on the color characteristics of blueberry wine

Time (days)	Frequency	L^*	a^*	b^*	h_{ab}	C^*	ΔE
0 day	Untreated	26.03 ± 0.09^{a}	56.38 ± 0.10^{a}	37.85 ± 0.07^{a}	0.59 ± 0.01^{a}	67.91 ± 0.12^{a}	0
	50 Hz	25.73 ± 0.11^{bc}	56.14 ± 0.06^{b}	37.61 ± 0.17^{a}	0.59 ± 0.00^{a}	67.58 ± 0.14^{ab}	0.47 ± 0.19^{ab}
	100 Hz	25.87 ± 0.09^{ab}	56.06 ± 0.02^{bc}	37.90 ± 0.18^{a}	0.60 ± 0.00^{a}	67.67 ± 0.12^{ab}	0.42 ± 0.02^{b}
	150 Hz	25.63 ± 0.07^{cd}	56.05 ± 0.04^{bc}	37.59 ± 0.27^{a}	0.59 ± 0.00^{a}	67.49 ± 0.18^{b}	0.63 ± 0.15^{ab}
	200 Hz	25.63 ± 0.13^{bcd}	55.88 ± 0.15^{cd}	37.75 ± 0.17^{a}	0.59 ± 0.00^{a}	67.44 ± 0.22^{b}	0.67 ± 0.20^{ab}
	250 Hz	25.48 ± 0.09^{d}	55.83 ± 0.05^{d}	37.61 ± 0.12^{a}	0.59 ± 0.00^{a}	67.31 ± 0.11^{b}	0.82 ± 0.13^{a}
15 days	Untreated	26.39 ± 0.49^{a}	53.63 ± 0.23^{a}	37.80 ± 0.97^{a}	0.61 ± 0.01^{a}	65.61 ± 0.66^{a}	3.14 ± 0.04^{a}
	50 Hz	26.76 ± 0.50^{a}	53.86 ± 0.06^{a}	38.93 ± 0.83^{a}	0.63 ± 0.01^{a}	66.46 ± 0.46^{a}	3.23 ± 0.03^{a}
	100 Hz	26.12 ± 0.86^{a}	53.67 ± 0.38^{a}	37.64 ± 0.25^{a}	0.61 ± 0.02^{a}	65.57 ± 1.32^{a}	2.75 ± 0.08^{a}
	150 Hz	26.75 ± 0.20^{a}	53.84 ± 0.20^{a}	39.03 ± 0.16^{a}	0.63 ± 0.00^{a}	66.50 ± 0.24^{a}	2.9 ± 0.13^{a}
	200 Hz	27.22 ± 0.38^{a}	54.02 ± 0.11^{a}	39.58 ± 0.52^{a}	0.63 ± 0.01^{a}	66.97 ± 0.40^{a}	3.42 ± 0.06^{a}
	250 Hz	27.13 ± 0.37^{a}	53.92 ± 0.24^{a}	39.54 ± 0.56^{a}	0.63 ± 0.00^{a}	66.86 ± 0.52^{a}	3.39 ± 0.05^{a}
30 days	Untreated	27.78 ± 0.63^{b}	51.75 ± 0.28^{a}	37.07 ± 0.50^{b}	0.621 ± 0.02^{b}	63.675 ± 1.30^{b}	5.39 ± 0.10^{c}
	50 Hz	28.47 ± 0.07^{b}	51.75 ± 0.86^{a}	38.83 ± 0.34^{ab}	0.64 ± 0.04^{ab}	64.74 ± 2.82^{ab}	6.13 ± 0.15^{b}
	100 Hz	28.48 ± 0.42^{b}	51.77 ± 0.33^{a}	36.80 ± 0.89^{b}	0.62 ± 0.03^{b}	63.62 ± 1.65^{b}	5.67 ± 0.80^{bc}
	150 Hz	28.29 ± 0.25^{b}	52.25 ± 0.07^{a}	39.69 ± 0.22^{ab}	0.65 ± 0.00^{ab}	65.62 ± 0.19^{ab}	5.05 ± 0.02^{c}
	200 Hz	29.75 ± 0.06^{a}	52.49 ± 0.18^{a}	42.00 ± 0.61^{a}	0.69 ± 0.00^{a}	68.03 ± 0.12^{a}	7.89 ± 0.05^{a}
	250 Hz	30.56 ± 0.03^{a}	52.33 ± 0.12^{a}	42.03 ± 0.81^{a}	0.69 ± 0.00^{a}	67.99 ± 0.02^{a}	8.12 ± 0.20^{a}
45 days	Untreated	31.37 ± 0.90^{b}	50.6 ± 0.43^{a}	37.48 ± 0.14^{b}	0.64 ± 0.03^{b}	62.99 ± 1.37^{ab}	8.18 ± 0.85^{b}
	50 Hz	32.40 ± 0.33^{ab}	50.39 ± 0.49^{a}	39.54 ± 0.29^{ab}	0.66 ± 0.04^{ab}	64.09 ± 2.41^{ab}	9.49 ± 0.49^{b}
	100 Hz	33.62 ± 0.49^{a}	49.94 ± 0.90^{a}	37.29 ± 0.20^{b}	0.64 ± 0.01^{ab}	62.33 ± 1.37^{b}	9.54 ± 0.98^{b}
	150 Hz	31.43 ± 0.52^{b}	50.19 ± 0.96^{a}	38.98 ± 0.04^{ab}	0.66 ± 0.01^{ab}	63.55 ± 1.39^{ab}	8.41 ± 0.39^{b}
	200 Hz	33.65 ± 0.79^{a}	50.81 ± 0.12^{a}	43.78 ± 0.35^{a}	0.71 ± 0.04^{a}	67.12 ± 2.07^{a}	12.95 ± 0.07^{a}
	250 Hz	32.72 ± 0.25^{ab}	49.99 ± 0.29^{a}	43.09 ± 0.56^{ab}	0.71 ± 0.03^{a}	66.03 ± 1.42^{ab}	11.85 ± 0.06^{a}
60 days	Untreated	35.47 ± 0.23^{b}	48.01 ± 0.62^{a}	39.82 ± 0.14^{abc}	0.67 ± 0.02^{a}	61.51 ± 1.69^{ab}	12.79 ± 0.40^{c}
	50 Hz	35.43 ± 1.17^{b}	47.56 ± 0.20^{a}	38.98 ± 2.03^{abc}	0.69 ± 0.03^{a}	61.52 ± 1.14^{ab}	12.94 ± 0.82^{c}
	100 Hz	37.61 ± 1.13^{a}	46.76 ± 0.83^{a}	37.89 ± 0.89^{c}	0.68 ± 0.01^{a}	60.19 ± 1.12^{b}	14.32 ± 1.36^{bc}
	150 Hz	35.77 ± 0.96^{ab}	47.84 ± 0.47^{a}	38.25 ± 0.90^{bc}	0.67 ± 0.00^{a}	61.25 ± 1.71^{ab}	13.11 ± 0.28^{c}
	200 Hz	37.25 ± 0.53^{ab}	48.36 ± 0.10^{a}	44.70 ± 4.20^{a}	0.74 ± 0.05^{a}	65.93 ± 2.76^{a}	15.86 ± 1.89^{a}
	250 Hz	36.74 ± 0.85^{ab}	48.11 ± 0.35^{a}	44.43 ± 3.98^{ab}	0.74 ± 0.04^{a}	65.55 ± 2.85^{a}	16.53 ± 0.90^{a}
75 days	Untreated	39.28 ± 2.05^{b}	45.62 ± 1.40^{a}	36.9 ± 1.74^{a}	0.68 ± 0.04^{a}	58.71 ± 0.83^{a}	17.2 ± 2.34^{b}
	50 Hz	40.92 ± 0.45^{ab}	44.77 ± 0.62^{a}	39.25 ± 2.28^{a}	0.72 ± 0.03^{a}	59.56 ± 1.63^{a}	19.07 ± 0.73^{ab}
	100 Hz	42.71 ± 1.64^{a}	43.64 ± 1.24^{a}	38.99 ± 1.04^{a}	0.73 ± 0.00^{a}	58.51 ± 1.61^{a}	21.05 ± 1.99^{a}
	150 Hz	39.94 ± 0.81^{ab}	44.08 ± 0.88^{a}	38.62 ± 0.78^{a}	0.72 ± 0.01^{a}	58.61 ± 1.11^{a}	18.64 ± 0.30^{ab}
	200 Hz	38.05 ± 1.00^{b}	44.49 ± 0.32^{a}	43.70 ± 4.55^{a}	0.77 ± 0.06^{a}	62.46 ± 62.46^{a}	18.47 ± 0.77^{ab}
	250 Hz	41.23 ± 0.26^{ab}	44.86 ± 0.61^{a}	44.18 ± 5.18^{a}	0.77 ± 0.05^{a}	63.04 ± 4.06^{a}	20.73 ± 1.05^{ab}
90 days	Untreated	44.84 ± 0.52^{b}	42.05 ± 0.27^{ab}	37.72 ± 1.40^{b}	0.73 ± 0.02^{b}	56.49 ± 1.13^{a}	23.68 ± 0.58^{b}
	50 Hz	45.19 ± 0.80^{ab}	42.16 ± 0.52^{ab}	39.07 ± 2.52^{ab}	0.75 ± 0.03^{ab}	57.51 ± 1.76^{a}	23.37 ± 0.30^{b}
	100 Hz	47.04 ± 1.29^{a}	40.88 ± 1.13^{b}	38.6 ± 0.96^{ab}	0.76 ± 0.00^{ab}	56.22 ± 1.47^{a}	25.09 ± 0.96^{ab}
	150 Hz	45.73 ± 0.81^{ab}	41.92 ± 0.65^{ab}	39.09 ± 0.58^{ab}	0.75 ± 0.01^{ab}	57.32 ± 0.65^{a}	24.97 ± 0.93^{ab}
	200 Hz	45.07 ± 0.15^{ab}	43.07 ± 0.50^{a}	46.45 ± 6.01^{ab}	0.82 ± 0.06^{ab}	63.47 ± 4.65^{a}	26.41 ± 0.21^{a}
	250 Hz	45.46 ± 0.76^{ab}	42.86 ± 1.02^{a}	46.9 ± 5.20^{a}	0.83 ± 0.05^{a}	63.6 ± 4.48^{a}	26.14 ± 0.27^{a}

between blueberry wine and original wine was greater when the ΔE value was large.

In general, the blueberry wine treated with different HPPM frequencies can improve the L^*, a^*, b^*, h_{ab}, and C^* values compared with the original wine after 90 days of storage. Moreover, in the light of the results of CABW, CD, T value and color characteristics of blueberry wine, the frequency of 50 Hz had a better color protection effect, as it caused a relatively small color difference. Therefore, the color of blueberry wine was relatively stable. Zhang et al. (Zhang et al., 2015) found that L^*, a^*, and b^* were increased after ultrasonic treatment with different powers,

which was consistent with the results of the current experiment. It was noted that the physical method could stabilize the color of wines relating to anthocyanins. However, many kinds of anthocyanins and their derivatives were present in blueberry wines, and the generation pathway and mechanism of derivatives during the aging process of blueberry wine needed further studies.

The correlations of different indicators without or with HPPM treatment at 50, 100, 150, 200 and 250 Hz was further integrated and summarized. Compared with the untreated samples (Fig. 3(A)), the correlation between some indexes including b^* and L^*, h_{ab}, ΔE, CABW and T values of blueberry wine was significantly increased after HPPM treatment (Fig. 3(B)), accompanied by the values close to 1 or − 1. These results suggested that an appropriate HPPM treatment could slow down the color loss of blueberry wine during storage. Moreover, in the light of the results, the HPPM frequency of 50 Hz and the treatment time of 20 min was considered as the conditions to improve the color of blueberry wines.

Volatile profiles analysis

The flavor substances of untreated blueberry wine stored for 45 and 90 days and blueberry wine treated with HPPM at 50, 150, and 250 Hz were analyzed to evaluate the effect of HPPM on the aroma of blueberry wine. The results were shown in Table 2. A total of 51 aromatic compounds were determined, including 10 alcohols, 18 esters, 6 aldehydes and ketones, 7 terpenes, and 10 acids. Among all compounds of blueberry wine, the alcohol content was the highest, followed by esters.

Esters

Esters mainly come from the fermentation of blueberry fruit and alcohol. Most of the fermentation-derived compounds were esters and alcohols. At the same time, esters provided fruit aroma for blueberry wine (Cai et al., 2020; Chen et al., 2013). Table 2 showed that the esters with high content in blueberry wine were composed of ethyl acetate, ethyl hexanoate, ethyl octanoate, ethyl benzoate and diethyl succinate. Among them, the content of ethyl acetate in blueberry wines treated with HPPM at 50 and 150 Hz was higher than that of the original wine after 45 days of storage, and the highest content reached 327.03 μg/mL at 150 Hz. Meanwhile, the content of ethyl octanoate was higher than that of the original wine under the treatment conditions of 150 and 250 Hz, and the highest content reached 216 μg/mL at 150 Hz. Moreover after 90 days of storage, the content of diethyl succinate in blueberry wine treated by HPPM under different conditions was higher than that of the original wine, and the highest content reached 110.10 μg/mL at 50 Hz. Compared with the contents of total ester in the original wine, those in blueberry wine after HPPM treatment at 50 and 150 Hz after 45 days of storage were 625.56 μg/mL and 828.99 μg/mL, respectively. These values were 528.13 μg/mL higher than those of the original wine. Although HPPM has intermittent action, it will still produce some thermal effects. The characteristics of microwave electromagnetic field in HPPM also promoted the oxidation and esterification of blueberry wine. Moreover, the amyl acetate in blueberry wine treated by HPPM under different conditions was higher than that in the original wine during the storage period of 90 days. These results indicated that the effect of HPPM on the esters of blueberry wine was positive and stable.

Alcohols

Alcohols are metabolites formed by yeast through sugar catabolism or decarboxylation reaction and amino acid deamination (Anton et al., 2014). Alcohols with appropriate concentration can set off the ester aroma and promote the harmony. They are important aroma substances in fruit wine. As shown in Table 2, in addition to ethanol, the main alcohols in blueberry wine are isoamyl alcohol, *n*-hexanol, and phenylethanol. Among them, phenylethanol is an important alcohol in blueberry wine, which has the aroma of rose and is produced by amino acid and glucose metabolism during the alcohol fermentation of blueberry wine (Synos et al., 2015). After 45 days of storage, the total alcohol in the blueberry wine treated by HPPM was lower than that of the original wine. It was presumably due to that HPPM accelerated the esterification reaction in the blueberry wine. After 90 days of storage, the content of phenylethanol in the blueberry wine treated by HPPM was higher than that of the original wine, and the highest content of phenylethanol was 396.22 μg/mL in the wine treated at 250 Hz. Isoamyl alcohol gradually disappeared during storage.

Aldehydes, ketones and terpenes

Aldehydes and ketones have special aroma, and can make the aroma of the wine tend to merge aldehydes and ketones in blueberry wine (Zhong et al., 2021). The contents of nonanal, furfural and 3-hydroxy-2-butanone increased gradually during storage (Thuaytong and Anprung, 2011). During the storage of blueberry wine, the terpene compounds such as linalool gradually decreased from 79.66 μg/mL to 13.21 μg/mL with the storage time. Meanwhile, after 45 days of storage, the terpene content of blueberry wine treated by HPPM under different conditions was lower than that of the original wine. This may be because the hydrolysis of terpenoids was accelerated by HPPM treatment, resulting in less terpenoids in the system, and some of the bound terpenoids

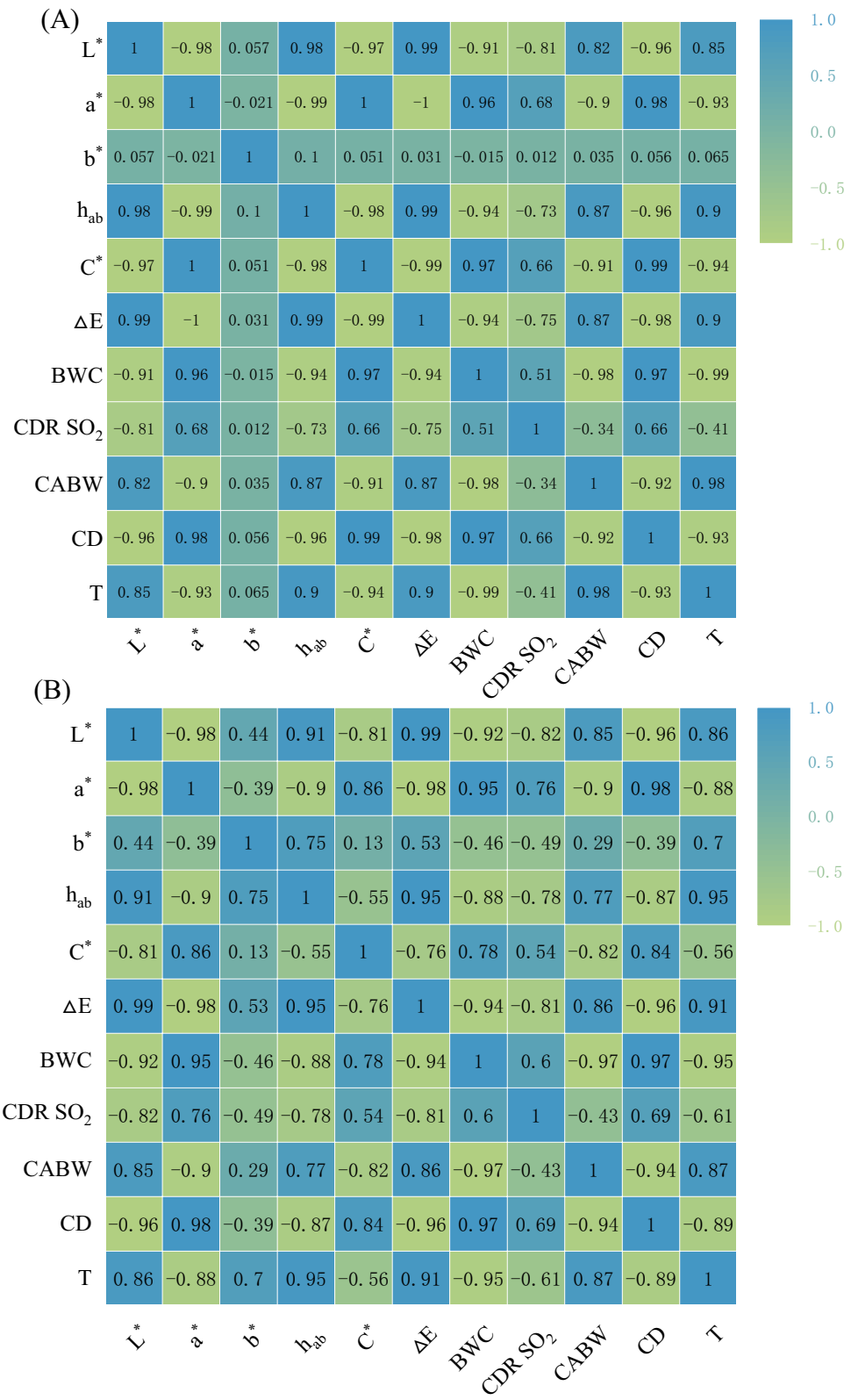


Fig. 3 The correlation of different indicators in blueberry wine. (**A**) The samples without treatment; (**B**) The samples with HPPM treatment. The value close to 1 or − 1 shows the greater correlation between the indexes

Table 2 The flavor composition changes of blueberry wine after 45 and 90 days storage

Chemical compound	Content (μg/mL)							
	45 days				90 days			
	Untreated	50 Hz	150hz	250hz	Untreated	50 Hz	150 Hz	250 Hz
Esters								
Ethyl acetate	44.31 ± 0.81^{e}	201.23 ± 0.69^{b}	327.03 ± 1.35^{a}	24.02 ± 0.53^{g}	87.82 ± 0.61^{c}	69.42 ± 0.59^{d}	32.79 ± 0.26^{f}	44.34 ± 0.46^{e}
Ethyl butyrate	3.61 ± 0.31^{d}	3.03 ± 0.20^{d}	2.72 ± 0.47^{d}	3.02 ± 0.26^{d}	7.21 ± 0.27^{b}	5.92 ± 0.26^{c}	9.38 ± 0.34^{a}	6.79 ± 0.18^{bc}
Ethyl 2-methylbutyrate	4.52 ± 0.59^{c}	5.90 ± 0.32^{c}	6.03 ± 0.71^{c}	5.42 ± 0.30^{c}	5.88 ± 0.24^{c}	5.60 ± 0.59^{c}	7.50 ± 0.28^{b}	9.87 ± 0.09^{a}
Amyl acetate	13.92 ± 1.17^{c}	16.70 ± 0.25^{b}	19.19 ± 0.55^{a}	17.17 ± 0.81^{b}	6.24 ± 0.24^{de}	12.13 ± 0.24^{c}	7.54 ± 0.24^{d}	5.38 ± 0.41^{e}
Ethyl hexanoate	127.58 ± 1.9^{a}	123.26 ± 0.83^{b}	110.56 ± 0.62^{c}	111.37 ± 0.23^{c}	84.04 ± 0.70^{d}	60.94 ± 0.91^{f}	82.25 ± 0.38^{d}	76.06 ± 0.59^{e}
Ethyl L(-)-lactate;	ND^{d}	1.62 ± 0.26^{c}	ND^{d}	1.47 ± 0.17^{c}	ND^{d}	3.63 ± 0.08^{a}	ND^{d}	2.91 ± 0.42^{b}
Methyl octanoate	4.31 ± 0.59^{a}	2.18 ± 0.27^{c}	2.60 ± 0.35^{bc}	2.13 ± 0.16^{c}	4.33 ± 0.16^{a}	2.18 ± 0.29^{c}	3.32 ± 0.09^{ab}	2.85 ± 0.14^{bc}
Ethyl octanoate	139.39 ± 2.06^{c}	117.51 ± 0.72^{d}	216.32 ± 1.10^{a}	169.45 ± 0.91^{b}	15.00 ± 0.19^{g}	35.47 ± 0.40^{f}	49.52 ± 0.36^{e}	52.75 ± 2.97^{e}
Ethyl 2-furoate	2.85 ± 0.89^{ab}	1.61 ± 0.28^{bc}	1.28 ± 0.16^{cd}	1.89 ± 0.40^{bc}	ND^{d}	ND^{d}	3.64 ± 0.25^{a}	3.29 ± 0.29^{a}
Methyl benzoate	5.18 ± 0.28^{a}	1.30 ± 0.36^{c}	1.89 ± 0.13^{c}	1.78 ± 0.18^{c}	ND^{d}	ND^{d}	ND^{d}	2.81 ± 0.32^{b}
Ethyl decanoate	10.52 ± 0.71^{b}	4.86 ± 0.15^{cd}	4.06 ± 0.47^{cde}	3.28 ± 0.32^{e}	11.76 ± 0.18^{a}	3.84 ± 0.13^{de}	5.00 ± 0.25^{cd}	5.15 ± 0.17^{c}
Ethyl benzoate	56.60 ± 2.26^{a}	57.54 ± 1.03^{a}	51.36 ± 0.30^{bc}	51.93 ± 0.43^{b}	ND^{d}	4.00 ± 0.33^{c}	ND^{d}	ND^{d}
Diethyl succinate	63.58 ± 0.80^{e}	51.89 ± 0.85^{f}	65.81 ± 0.67^{e}	51.97 ± 0.40^{f}	84.00 ± 0.66^{d}	110.10 ± 1.23^{a}	96.94 ± 0.29^{b}	89.76 ± 0.17^{c}
Methyl salicylate	2.47 ± 0.51^{c}	2.57 ± 0.26^{c}	2.88 ± 0.49^{bc}	1.96 ± 0.32^{c}	4.51 ± 0.12^{a}	4.06 ± 0.39^{ab}	4.57 ± 0.29^{a}	4.42 ± 0.56^{a}
Phenylethyl acetate	4.34 ± 0.41^{bc}	1.88 ± 0.18^{d}	3.57 ± 0.20^{cd}	2.99 ± 0.29^{d}	4.93 ± 0.26^{b}	6.02 ± 0.17^{a}	ND^{f}	3.15 ± 0.16^{d}
Ethyl palmitate	11.39 ± 0.38^{a}	4.99 ± 0.28^{c}	2.60 ± 0.35^{d}	1.84 ± 0.21^{d}	8.45 ± 0.12^{b}	5.87 ± 0.31c	11.16 ± 0.50^{a}	10.93 ± 0.97^{a}
Ethyl hydrogen succinate	29.54 ± 0.11^{a}	19.73 ± 0.33^{b}	7.09 ± 0.32^{c}	ND^{f}	ND^{f}	4.01 ± 0.20^{e}	6.06 ± 0.23^{d}	5.45 ± 0.47^{d}
Dibutyl phthalate	4.01 ± 0.30^{b}	7.77 ± 0.57^{a}	4.00 ± 0.49^{bc}	ND^{c}	ND^{c}	ND^{c}	ND^{c}	ND^{c}
Total	528.13 ± 1.00^{c}	625.56 ± 0.33^{b}	828.99 ± 0.42^{a}	451.68 ± 1.11^{d}	324.18 ± 0.81^{ef}	333.19 ± 5.88^{e}	319.68 ± 3.29^{f}	325.89 ± 3.76^{ef}
Alcohols								
2-Methyl-3-hexanol	6.13 ± 0.54^{a}	ND^{b}	ND^{b}	ND^{b}	ND^{b}	ND^{b}	ND^{b}	ND^{b}
Isobutanol	16.67 ± 0.97^{b}	ND^{c}	ND^{c}	ND^{c}	ND^{c}	ND^{c}	18.05 ± 0.43^{a}	ND^{c}
3-Methyl-1-butanol;	513.49 ± 3.44^{c}	528.64 ± 1.23^{b}	548.69 ± 1.60^{a}	492.59 ± 1.68^{d}	ND^{f}	372.18 ± 1.07^{e}	ND^{f}	ND^{f}
1-Hexanol	58.04 ± 0.81^{a}	57.54 ± 0.85^{a}	55.56 ± 0.59^{a}	51.64 ± 0.91^{a}	57.12 ± 1.55^{a}	41.62 ± 5.75^{b}	58.01 ± 0.32^{a}	57.95 ± 1.78^{a}
Trans-3-caren-2-ol	16.08 ± 0.60^{a}	8.00 ± 0.46^{c}	7.40 ± 0.66^{c}	9.32 ± 0.50^{b}	ND^{d}	ND^{d}	ND^{d}	ND^{d}
1-Octanol	3.21 ± 0.66^{a}	2.34 ± 0.3^{ab}	2.25 ± 0.22^{ab}	1.57 ± 0.26^{b}	ND^{c}	ND^{c}	ND^{c}	ND^{c}
1-Nonanol	ND^{c}	1.20 ± 0.25^{b}	ND^{c}	ND^{c}	9.32 ± 0.06^{a}	1.03 ± 0.21^{b}	ND^{c}	ND^{c}
3-Methylthiopropanol	3.68 ± 0.24^{a}	1.61 ± 0.30^{b}	1.84 ± 0.27^{b}	ND^{c}	ND^{c}	ND^{c}	ND^{c}	ND^{c}
Phenethyl alcohol	537.72 ± 1.97^{a}	479.58 ± 0.74^{c}	494.13 ± 1.17^{b}	469.33 ± 1.33^{d}	360.45 ± 0.69^{f}	293.55 ± 0.38^{g}	361.90 ± 2.18^{f}	396.22 ± 1.97^{e}
Total	1155.03 ± 4.85^{a}	1078.90 ± 0.35^{c}	1109.86 ± 0.31^{b}	1024.45 ± 3.67^{d}	426.89 ± 0.92^{f}	708.39 ± 6.99^{g}	437.96 ± 1.44^{f}	454.17 ± 3.75^{e}
Aldehydes and ketones								
Acetaldehyde	ND^{c}	ND^{c}	ND^{c}	ND^{c}	ND^{c}	29.37 ± 0.31^{b}	34.38 ± 0.36^{a}	ND^{c}
3-Hydroxy-2-butanone	ND^{f}	ND^{f}	2.43 ± 0.49^{d}	14.48 ± 0.57^{a}	5.40 ± 0.16^{c}	4.70 ± 0.37^{c}	7.58 ± 0.20^{b}	1.2 ± 0.19^{e}
1-Nonanal	5.34 ± 0.55^{c}	0.70 ± 0.14^{e}	2.55 ± 0.30^{de}	4.57 ± 0.34^{cd}	6.76 ± 0.27^{bc}	10.53 ± 1.84^{a}	6.63 ± 0.31^{bc}	8.82 ± 0.14^{ab}
Furfural	ND^{d}	3.48 ± 0.29^{c}	ND^{d}	ND^{d}	ND^{d}	4.83 ± 0.12^{b}	ND^{d}	8.15 ± 0.18^{a}
4-Propyl-benzaldehyde,	ND^{d}	ND^{d}	NDd	ND^{d}	ND^{d}	15.55 ± 0.70^{b}	22.49 ± 0.36^{a}	4.59 ± 0.38^{c}
4-Ethylbenzaldehyde	14.98 ± 0.71^{a}	9.68 ± 0.26^{b}	6.28 ± 0.46^{c}	6.09 ± 0.46^{c}	ND^{d}	ND^{d}	ND^{d}	ND^{d}
Total	20.32 ± 1.26^{e}	13.86 ± 0.11^{f}	11.25 ± 0.66^{g}	25.14 ± 0.22^{c}	12.15 ± 0.12^{fg}	64.97 ± 1.21^{b}	71.08 ± 0.10^{a}	22.76 ± 0.53^{d}

Table 2 (continued)

Chemical compound	Content (μg/mL)							
	45 days				90 days			
	Untreated	50 Hz	150hz	250hz	Untreated	50 Hz	150 Hz	250 Hz
Terpene								
Myrcene	ND^{c}	ND^{c}	ND^{c}	ND^{c}	6.06 ± 0.24^{a}	3.54 ± 0.17^{b}	ND^{c}	ND^{c}
DL-Limonene	ND^{c}	ND^{c}	ND^{c}	ND^{c}	18.75 ± 0.23^{a}	12.60 ± 0.23^{b}	18.20 ± 0.27^{a}	18.84 ± 1.07^{a}
2-Vinyltoluene	7.46 ± 0.39^{a}	4.36 ± 0.35^{b}	4.23 ± 0.26^{b}	ND^{c}	ND^{c}	ND^{c}	ND^{c}	ND^{c}
2,6-Dimethyl-styrene	ND^{e}	ND^{e}	ND^{e}	ND^{e}	8.46 ± 0.13^{a}	1.44 ± 0.20^{d}	3.14 ± 0.22^{c}	7.62 ± 0.35^{b}
Linalool	79.66 ± 0.77^{a}	68.65 ± 2.73^{b}	68.03 ± 0.65^{b}	64.84 ± 0.62^{b}	13.21 ± 0.24^{c}	11.08 ± 1.29^{c}	11.16 ± 1.44^{c}	ND^{d}
β-Citronellol	5.65 ± 0.24^{a}	3.57 ± 0.36^{b}	4.30 ± 0.19^{b}	4.39 ± 0.52^{b}	ND^{c}	ND^{c}	ND^{c}	ND^{c}
α-Terpineol	ND^{d}	ND^{d}	NDd	ND^{d}	32.04 ± 0.55^{a}	23.89 ± 0.39^{c}	29.26 ± 0.10^{b}	29.81 ± 0.05^{b}
Nerolidol	ND^{c}	2.03 ± 0.15^{b}	2.67 ± 0.47^{a}	ND^{c}	ND^{c}	ND^{c}	ND^{c}	ND^{c}
Total	92.76 ± 1.40^{a}	78.62 ± 2.89^{b}	79.24 ± 0.27^{b}	68.09 ± 0.00^{c}	78.51 ± 0.92^{b}	52.54 ± 0.65^{e}	61.77 ± 1.49^{d}	56.27 ± 1.47$_{e}$
Acid								
Acetic acid	83.58 ± 0.77^{a}	24.51 ± 0.54^{f}	22.00 ± 0.46^{fg}	18.67 ± 0.67^{g}	52.79 ± 2.77^{c}	29.46 ± 0.23^{e}	40.25 ± 0.38^{d}	60.89 ± 1.17^{b}
2-Methyl butyric acid	ND^{d}	ND^{d}	ND^{d}	ND^{d}	4.81 ± 0.18^{ab}	3.88 ± 0.17^{c}	5.38 ± 0.45^{a}	4.59 ± 0.39^{bc}
Valeric acid	2.54 ± 0.57^{a}	2.30 ± 0.41^{a}	3.16 ± 0.21^{a}	2.96 ± 0.32^{a}	ND^{b}	ND^{b}	ND^{b}	ND^{b}
Caproic acid	21.02 ± 0.56^{a}	16.94 ± 1.90^{b}	16.72 ± 0.58^{b}	14.29 ± 0.43^{b}	20.94 ± 0.36^{a}	15.60 ± 0.75^{b}	21.82 ± 0.43^{a}	20.47 ± 0.56^{a}
Octanoic acid	37.03 ± 1.22^{a}	27.99 ± 0.26^{c}	24.76 ± 2.30^{d}	19.01 ± 0.63^{e}	ND^{f}	17.74 ± 0.42^{e}	ND^{f}	33.19 ± 0.34^{b}
Nonanoic acid	3.31 ± 0.61^{a}	0.78 ± 0.16^{c}	2.00 ± 0.24^{b}	3.00 ± 0.28^{a}	ND^{c}	ND^{c}	ND^{c}	ND^{c}
Decanoic acid	6.44 ± 0.43^{a}	5.31 ± 0.34^{a}	3.63 ± 0.41^{b}	2.98 ± 0.29^{b}	5.74 ± 0.18^{a}	3.80 ± 0.41^{b}	2.43 ± 0.49^{b}	5.48 ± 0.50^{a}
Vanillic acid	2.45 ± 0.49^{a}	1.26 ± 0.25^{b}	1.38 ± 0.19^{b}	ND^{c}	ND^{c}	ND^{c}	ND^{c}	ND^{c}
Benzoic acid;	9.15 ± 0.66^{a}	5.78 ± 0.25^{c}	7.20 ± 0.44^{b}	3.50 ± 0.23^{d}	ND^{e}	3.92 ± 0.21^{d}	ND^{e}	5.44 ± 0.46^{c}
Palmitic acid	ND^{d}	ND^{d}	ND^{d}	ND^{d}	ND^{d}	3.54 ± 0.17^{c}	11.83 ± 0.17^{a}	6.33 ± 0.35^{b}
Total	165.52 ± 3.20^{a}	84.86 ± 3.29^{c}	80.84 ± 0.24^{c}	64.40 ± 1.05^{d}	84.28 ± 2.77^{c}	77.94 ± 0.75^{c}	81.73 ± 0.26^{c}	136.38 ± 1.99^{b}

were further released, whose aglycones can enhance the flavor of the wine (Liu et al., 2019).

Acids

Proper reduction of acids can reduce the acidity and astringency of fruit wine and improve the taste (Noguerol-Pato et al., 2012). In blueberry wine, the main acids detected were acetic acid, caproic acid, and octanoic acid. After 45 days of storage, the total acid content of blueberry wine treated with different HPPM frequencies was lower than that of the original wine. This finding indicated that HPPM could slow down the formation of acids in blueberry wine. The acetic acid, caproic acid, and octanoic acid in the blueberry wine treated by HPPM under different conditions were lower than those in the original wine, which were 29.46 μg/mL, 15.60 μg/mL, 17.74 μg/mL, respectively.

In this work, a new method of high-power pulsed microwave (HPPM) was used to accelerate the aging of blueberry wine. Low-frequency HPPM treatment has positive effects on the aging process of blueberry wine. The CABW value of blueberry wine decreased from 90 days to 75 days and the T value reduced from 75 days to 60 days under the condition of HPPM with a lower frequency (50 and 100 Hz) and treatment time of 20 min. HPPM promoted the formation of esters in blueberry wine at the early stage of aging as well. After 45 days of storage, the content of total esters of blueberry wine treated with HPPM at 50 and 150 Hz was increased by 18.44% and 56.97%, respectively, compared with those of the original wine. Furthermore, HPPM reduced the formation of acid substances of blueberry wine, and improved the flavor of wine. Overall, this work confirms the potential application of HPPM in the aging of blueberry wine as a new physical processing technology.

Acknowledgements We appreciate all individuals who made their efforts on this study. This work was supported by Jiangsu Agricultural Science and Technology Innovation Fund [CX(22)2026] and Jiangsu Provincial Key R&D Program [Grant number BE2020380 and BE2021322].

Declarations

Conflict of interest We declare that we have no conflict of interest.

References

Alcarde AR, Souza LM, Bortoletto AM. Formation of volatile and maturation-related congeners during the aging of sugarcane

spirit in oak barrels. Journal of the Institute of Brewing 120: 529-536 (2014)
Anton MJ, Suarez Valles B, Garcia Hevia A, Picinelli Lobo A. Aromatic profile of ciders by chemical quantitative, gas chromatography-olfactometry, and sensory analysis. Journal of Food Science 79: S92-S929 (2014)
Atanasova V, Fulcrand H, Cheynier V, Moutounet M. Effect of oxygenation on polyphenol changes occurring in the course of wine-making. Analytica Chimica Acta 458: 15-27 (2002)
Baiano A, Scrocco C, Sepielli G, Del Nobile MA. Wine Processing: A Critical Review of Physical, Chemical, and Sensory Implications of Innovative Vinification Procedures. Critical Reviews in Food Science and Nutrition 56: 2391-407 (2016)
Bondoc, I. European regulation in the veterinary sanitary and food safety area, a component of the European policies on the safety of food products and the protection of consumer interests: A 2007 retrospective Part One: The role of European institutions in laying down and passing laws specific to the veterinary sanitary and food safety area. Universul Juridic, Supliment, 12-15 (2016a)
Bondoc, I.European regulation in the veterinary sanitary and food safety area, a component of the European policies on the safety of food products and the protection of consumer interests: A 2007 retrospective. Part Two: Regulations. Universul Juridic, Supliment, 16-19 (2016b)
Bondoc, I.European regulation in the veterinary sanitary and food safety area, a component of the European policies on the safety of food products and the protection of consumer interests: A 2007 retrospective. Part Four: Decisions. Universul Juridic, Supliment, 24-27 (2016c)
Bondoc, I. European regulation in the veterinary sanitary and food safety area, a component of the European policies on the safety of food products and the protection of consumer interests: A 2007 retrospective. Part Three: Directives. Universul Juridic, Supliment, 20-23 (2016d)
Cai W, Tang F, Guo Z, Guo X, Zhang Q, Zhao X, Ning M, Shan C. Effects of pretreatment methods and leaching methods on jujube wine quality detected by electronic senses and HS-SPME-GC-MS. Food Chemistry 330: 127330 (2020)
Chen S, Xu Y, Qian MC. Aroma characterization of chinese rice wine by gas chromatography-olfactometry, chemical quantitative analysis, and aroma reconstitution. Journal of Agricultural and Food Chemistry 61: 11295-302 (2013)
Ćurko N, Ganić KK, Tomašević M, Gracin L, Jourdes M, Teissedre P-L. Effect of enological treatments on phenolic and sensory characteristics of red wine during aging: Micro-oxygenation, sulfur dioxide, iron with copper and gelatin fining. Food Chemistry 339: 127848 (2021)
Del Fresno JM, Morata A, Escott C, Loira I, Cuerda R, Suarez-Lepe JA. Sonication of Yeast Biomasses to Improve the Ageing on Lees Technique in Red Wines. Molecules 24: 635 (2019)
El Darra N, Grimi N, Maroun RG, Louka N, Vorobiev E. Pulsed electric field, ultrasound, and thermal pretreatments for better phenolic extraction during red fermentation. European Food Research and Technology 236: 47-56 (2013)
Gambuti A, Han G, Peterson AL, Waterhouse AL. Sulfur Dioxide and Glutathione Alter the Outcome of Microoxygenation. American Journal of Enology and Viticulture 66: 411-423 (2015)
García Martín JF, Sun D-W. Ultrasound and electric fields as novel techniques for assisting the wine ageing process: The state-of-the-art research. Trends in Food Science & Technology 33: 40-53 (2013)
Kalt W, Cassidy A, Howard LR, Krikorian R, Stull AJ, Tremblay F, Zamora-Ros R. Recent Research on the Health Benefits of Blueberries and Their Anthocyanins. Advances in Nutrition 11: 224-236 (2020)
Li S-Y, Duan C-Q. 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: 1840-1867 (2019)
Li X, Zhang L, Peng Z, Zhao Y, Wu K, Zhou N, Yan Y, Ramaswamy HS, Sun J, Bai W. The impact of ultrasonic treatment on blueberry wine anthocyanin color and its In-vitro anti-oxidant capacity. Food Chemistry 333: 127455 (2020a)
Li X, Zhang L, Peng Z, Zhao Y, Wu K, Zhou N, Yan Y, Ramaswamy HS, Sun J, Bai W. The impact of ultrasonic treatment on blueberry wine anthocyanin color and its In-vitro anti-oxidant capacity. Food Chemistry 333: 127455 (2020b)
Liu S, Zhang X, You L, Guo Z, Chang X. Changes in anthocyanin profile, color, and antioxidant capacity of hawthorn wine (Crataegus pinnatifida) during storage by pretreatments. LWT - Food Science and Technology 95: 179-186 (2018)
Liu F, Li S, Gao J, Cheng K, Yuan F. Changes of terpenoids and other volatiles during alcoholic fermentation of blueberry wines made from two southern highbush cultivars. LWT - Food Science and Technology 109: 233-240 (2019)
Lukic K, Brncic M, Curko N, Tomasevic M, Valinger D, Denoya GI, Barba FJ, Ganic KK. Effects of high power ultrasound treatments on the phenolic, chromatic and aroma composition of young and aged red wine. Ultrasonics Sonochemistry 59: 104725 (2019)
Ma T, Wang J, Wang H, Zhao Q, Zhang F, Ge Q, Li C, Gamboa GG, Fang Y, Sun X. Wine aging and artificial simulated wine aging: Technologies, applications, challenges, and perspectives. Food Research International 153: 110953 (2022)
Niimi J, Guixer B, Splivallo R. Odour active compounds determined in the headspace of yellow and black plum wines (Prunus domestica L.). LWT - Food Science and Technology 130: 109702 (2020)
Noguerol-Pato R, Gonzalez-Alvarez M, Gonzalez-Barreiro C, Cancho-Grande B, Simal-Gandara J. Aroma profile of Garnacha Tintorera-based sweet wines by chromatographic and sensorial analyses. Food Chemistry 134: 2313-25 (2012)
Pathare PB, Opara UL, Al-Said FA-J. Colour Measurement and Analysis in Fresh and Processed Foods: A Review. Food and Bioprocess Technology 6: 36-60 (2012)
Peng Y, Sun K, Yuan Y, Shen Y, Campbell JC, "2020 IEEE Photonics Conference (IPC)," ed.^eds. (2020).
Sun J, Luo H, Li X, Li X, Lu Y, Bai W. Effects of low power ultrasonic treatment on the transformation of cyanidin-3-O-glucoside to methylpyranocyanidin-3-O-glucoside and its stability evaluation. Food Chemistry 276: 240-246 (2019)
Synos K, Reynolds AG, Bowen AJ. Effect of yeast strain on aroma compounds in Cabernet franc icewines. LWT - Food Science and Technology 64: 227-235 (2015)
Thuaytong W, Anprung P. Bioactive compounds and prebiotic activity in Thailand-grown red and white guava fruit (Psidium guajava L.). Food Science and Technology International 17: 205-12 (2011)
Wang H, Ni ZJ, Ma WP, Song CB, Zhang JG, Thakur K, Wei ZJ. Effect of sodium sulfite, tartaric acid, tannin, and glucose on rheological properties, release of aroma compounds, and color characteristics of red wine. Food Science and Biotechnology 28: 395-403 (2019)
Xie X, Li K, Shen Y, Li Q, Zang J, Beling A, Campbell JC. Photonic Generation of High-Power Pulsed Microwave Signals. Journal of Lightwave Technology 33: 3808-3814 (2015)
Yan Y, Pico J, Gerbrandt EM, Dossett M, Castellarin SD. Comprehensive anthocyanin and flavonol profiling and fruit surface color of 20 blueberry genotypes during postharvest storage. Postharvest Biology and Technology 199: 112274 (2023)
Yang N, Huang K, Lyu C, Wang J. Pulsed electric field technology in the manufacturing processes of wine, beer, and rice wine: A review. Food Control 61: 28-38 (2016)

Zhang Q-A, Shen Y, Fan X-H, García Martín JF. Preliminary study of the effect of ultrasound on physicochemical properties of red wine. CyTA - Journal of Food 14: 55-64 (2015)

Zhang Y, Dai J, Ma X, Jia C, Han J, Song C, Liu Y, Wei D, Xu H, Qin J, Yang S. Nano-emulsification essential oil of Monarda didyma L. to improve its preservation effect on postharvest blueberry. Food Chemistry 417: 135880 (2023)

Zhong W, Liu S, Yang H, Li E. Effect of selected yeast on physico-chemical and oenological properties of blueberry wine fermented with citrate-degrading Pichia fermentans. LWT - Food Science and Technology 145: 111-261 (2021)