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INFLUENCE OF DIFFERENT AGEING METHODS ON PHYSICOCHEMICAL, PHYTOCHEMICAL, CHROMATIC AND ANTIOXIDANT QUALITIES OF TOMATO WINE

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Abstract

Bottle ageing requires space, energy and time and may be expensive. In this study, tomato wines made with tomato pH 3.40 (Wine A), 3.20 (Wine B), and 4.11 (Wine C) were treated with ultrasound of frequency 33 kHz and their qualities were compared with wines aged in bottles at 10±2°C and 15±2°C for 90 days. The physicochemical properties of the ultrasonic-treated and bottle-aged wines were very comparable. Ultrasonic-treated wines generally recorded significantly higher ($P<0.05$) lycopene, β-carotene, total phenolic, total flavonoid and anthocyanin content than the bottle-aged wines. Typically, the ultrasound-treated wines had higher ($P<0.05$) total antioxidant activity and lower reducing power, but comparable DPPH scavenging activity as the bottle-aged samples. Significantly higher L, b*, ΔE*, C*, H*, A420, ($P<0.05$) and lower a* ($P>0.05$) were found for bottle-aged wines than the ultrasonic-treated ones. Cluster analysis using a dendrogram indicated that Wine B treated with ultrasound was much closer to its bottle-aged counterpart than Wines A and C. This means that ultrasonically treated Wine B may have qualities much more similar to its corresponding bottle-aged sample..*

Keywords
Tomato wine, bottle-aged wine, ultrasound-treated wine, total flavonoid, DPPH scavenging activity

Introduction

Ageing is an indispensable phase in winemaking, probably because wine undergoes many changes during this stage, including physicochemical, phytochemical, aromatic, and colour changes. These changes help to produce wine of desirable colour, flavour and other physicochemical properties (Ribereau-Gayon et al., 2006). The factors which influence wine ageing include the storage container (Ribereau-Gayon et al., 2006), temperature, humidity, light, and vibration (Jackson, 2008). Therefore, it is important to control these factors to produce wine of acceptable quality.

Wines are usually stored in bottles and wood under specific temperature and humidity conditions over a given period of time. The ageing duration for fruit wines may usually range from three (3) to six (6) months (Gnoumou et al., 2022; Kocher and Pooja, 2011; Puertolas et al., 2009; Selli et al., 2002), but for wines made from grapes it may last for several months (Chung et al., 2008; Lopes et al., 2009; Recamales et al., 2006; Torchio et al., 2011). However, 33 months ageing duration was reported for Chinese rice wine (Shen et al., 2012). Ageing requires space, energy and time. Therefore, ageing wine for a longer time may be expensive.

Many alternative ways of ageing wine, including pulsed electric field (PEF), AC electric field, irradiation, ultrasound (US) and high hydrostatic pressure processing (HHPP) have been studied. Ultrasonic-treated rice wine (Chang and Chen, 2002), wines treated with different dosages of irradiation (Chang, 2003), wines treated with different intensities of the electric field at different periods (Zeng et al., 2008), PEF-treated wine (Puertolas et al., 2009), hydrostatic high pressure (HHP)-treated red wine (Tao et al., 2012), ultrasonicated mulberry wine and pressurized mulberry wine subjected to HHP treatment (Tchabo et al., 2017), HHP-treated white wine (Valdes et al., 2021), and HHP-raspberry wine (Cao et al., 2022) have been reported.

Any alternative ageing process should give a wine of comparable properties to normal ageing to ensure consumer acceptability. Many physical processes of wine ageing have involved wines made from many fruits excluding tomatoes. Meanwhile, during the major season in Ghana, substantial quantities of tomatoes go to waste, and wine production promises to be an avenue for wastage reduction. Reduction in tomato waste could help to limit the number of times the land is tilled and this can reduce the negative effect on the environment.

Among the many physical processes used in ageing wine, the most promising is ultrasonic processing (Garcia Martin and Sun, 2013). Against this background, the study compared the effect of ultrasonic (US) treatment (33 kHz for 30 min) and bottle ageing (at 10±2°C and 15±2°C for 90 days) on the physicochemical, phytochemical, chromatic, and antioxidant qualities of tomato wine.

Materials and Methods

Tomato wine production

Tomato wine was produced as described by Owusu et al. (2015) briefly, tomato must, ameliorated with table sugar, was batch fermented in a 5-L Erlenmeyer flask. A 24-year-old yeast inoculum of size 3.8% was used to ferment tomato must of volume 4.5 L. Three kinds of tomato musts of pH 4.11, 3.40, and 3.20 were used in the study. The original tomato must recorded a pH of 4.11, and this was adjusted to two other pH levels. The musts were batch fermented in an incubator at temperatures of 15±2°C (Jackson, 2008). The wines produced from the must pH 4.11, pH 3.40 and pH 3.20 were designated as Control, Wine A and Wine B, respectively. After fermentation, the wine was separated from the pomace and stored at 7°C for two months for particles to settle down. It was then kept frozen until needed for analysis.

Determination of tomato wine properties

The wine pH was determined according to the method of AOAC (1984), titratable acidity (TA) was determined as described by Sadler and Murphy (2010), the total soluble solids (TSS) of tomato wine was measured with the Abbe Refractometer (WAY-2S, Germany) equipped with temperature compensation mechanism, the reducing sugar (RS) was estimated using the dinitrosalicyclic (DNS) method (Miller, 1972), and ethanol content (EC) was determined by the method described by (Caputi et al., 1968). The anthocyanin content was measured by the method proposed by Di Stefano et al. (1989), total phenolic (TP) content was assayed using the Folin-Ciocalteu reagent according to the method of (Singleton and Rossi, 1965), and the total flavonoid (TF) content was determined by the method of Zhishen et al. (1999). The method described by Hussain et al. (2006) was used to determine the ascorbic acid content of the tomato wines, β-carotene and lycopene were extracted following the method described by Fish et al. (2002) and the values determined by the formula proposed by Nagata and Yamashita (1992). The total antioxidant activity (TAA) was measured using the method of Prieto et al. (1999), DPPH scavenging activity was assayed using the method of Liu and Yao (2007), and reducing power (RP) was assessed by the method of Oyaizu (1986). The colour of the tomato wines was determined with an automatic colour difference meter (DC-P3, Beijing, China) with a 2cm path length after calibration with the black and white reference tiles. Browning index (A_{420}) was measured as increased absorbance at 420 nm (A_{420}) (Jackson, 2008), and clarity determined as absorbance at 660 nm (A_{660}) (Cao et al., 2007).

Ageing

The tomato wines were subjected to bottle and ultrasonic ageing. In the bottle ageing process, the wines were put in 250 mL brown bottles, 0.027 g/L potassium metabisulphite was added, and the bottles were tightly capped and sealed. They were incubated at 10±2°C and 15±2°C for 90 days, and samples were taken for analysis on days 0 and 90. An ultrasonic probe frequency of 33 KHz was used for sonication. The probe was immersed in an ultrasonic bath of dimensions 45cm x 36.5cm x 31cm, containing a water level of about 5cm. The samples of volume 170 mL contained in a robust polythene bag were processed at a constant power of 600 W, and a varied pulsed duration of 10s on and 5s off. The sonication time utilized for the process was 30 min. After sonication, the various parameters were determined.

Data Analysis

The statistical analysis was performed with SPSS Version 17.0, and the results are presented in figures. One-way analysis of variance (ANOVA) was used to compare the means of triplicate measurement of all parameters. Means were separated using Duncan's Multiple Range Test.

Results and Discussion

Physicochemical properties of tomato wines

The physicochemical properties (EC, reducing sugar, TSS, pH, and TA) of the ultrasonically treated wine and wine aged in bottles for 90 days are shown in Figure 1 to 3. Ethanol influences the aroma, taste and microbiological stability of wines (Jackson, 2008). There was no significant difference ($P>0.05$) in EC between ultrasonically treated wines AU15 and CU15, their untreated and their bottle-aged counterparts (Figure 1a). Similar results were reported where gamma irradiation of rice wine did not give any difference in its EC compared to the control (Chang, 2003). High-power ultrasound could not influence the EC of wine significantly (Zhang et al., 2016). The PEF-treated wine and the control gave the same ethanol content (Puertolas et al., 2009). The ultrasonically treated wines AU15 and CU15 were thus of comparable EC to those aged in bottles. Wine BU15 gave a slight reduction in EC, which was not significant. This is similar to the results reported for wines treated with an AC electric field (Zeng et al., 2008). Wine B was the only one in which storage temperature significantly influenced its EC. Guava wine stored at 15°C exhibited a significant decrease in EC, and the final wine at the end of 3 months had an EC of 12.6±0.2 (%v/v) (Kocher and Pooja, 2011). A reduction in the EC of ultrasonically treated kiwi was reported (Zhang et al., 2022). The RS content of wine affects its microbial stability, and in wines of higher pH, increased levels of RS increase their microbial instability (Jackson, 2008). In wine, BU15, the RS content was significantly lower after the ultrasonic treatment, and this was comparable to the results of Wines BN10 and BN15. The results show that after the ultrasonic treatment, wine BU15 may be more microbial stable than the untreated sample B15 (Jackson, 2008). The treatment of wine with PEF led to a decrease in its RS content (Puertolas et al., 2009). The RS content for ultrasonic-treated wines, AU15, remained the same as the untreated wine. This agrees with the results found for the total sugar content of wines treated with the AC electric field (Zeng et al., 2008). The effect of storage temperature on the RS content was significant ($P<0.05$) for Wine C. All the

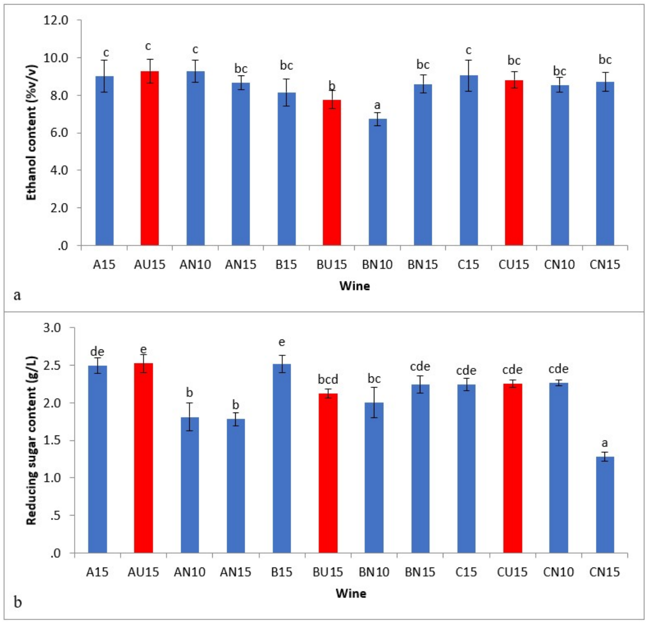

Figure 1. (a) Ethanol content, (b) Reducing sugar content of tomato wine before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15^{o}C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15^{o}C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10^{o}C; AN15, BN15, and CN15-A, B, and C aged at 15^{o}C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

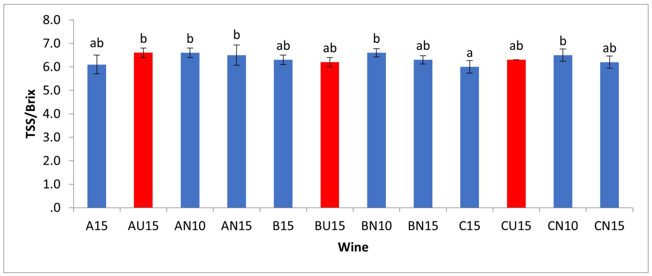

Figure 2. Total soluble solids of tomato wine before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15^{o}C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15^{o}C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10^{o}C; AN15, BN15, and CN15-A, B, and C aged at 15^{o}C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

ultrasonic-treated wines did not show a statistically significant difference in their TSS contents (Figure 2) compared with the untreated and bottle-aged samples. In a similar study, it was reported that sonication did not significantly influence the TSS of sonicated blueberry wine (Zhao et al., 2023).

The pH of the ultrasonic-treated wines and the bottle-aged wines remained the same as the untreated (Figure 3a). Zhang et al. (2016), in a similar study, reported that ultrasound treatment did not change the pH of red wine. It was also reported that HHP, PEF and US-treated wines did not show significant differences in pH compared to the control (Van et al., 2021). The pH of ultrasonic-treated rice wine showed a slight increase, while that of ultrasonic-treated maize wine remained the same as the untreated (Chang and Chen, 2002), and the present results are partly in line with it. In other studies, a slight increase in pH was observed after treatment of wine with HHP (Valdes et al., 2021), but there was a slight reduction in pH of blueberry wine treated with ultrasound (Zhao et al., 2023). However, in the case of blueberry wine stored in bottles for 8 months, there was a slight reduction in pH (Varo et al., 2023). The TA for ultrasonic-treated wines was slightly lower than the untreated wines and the bottle-aged wines, though no statistically significant difference ($P>0.05$) was observed (Figure 3b). Thus, the treated wines recorded TA values similar to the bottle-aged wines. A reduction in TA for PEF-treated wine was reported (Puertolas et al., 2009). In a rice wine maturation process, Chang (2003) found that the acidity of irradiated wines remained the same as the untreated. The TA of red wine obtained after ultrasonic treatment remained the same as the control (Zhang et al., 2016).

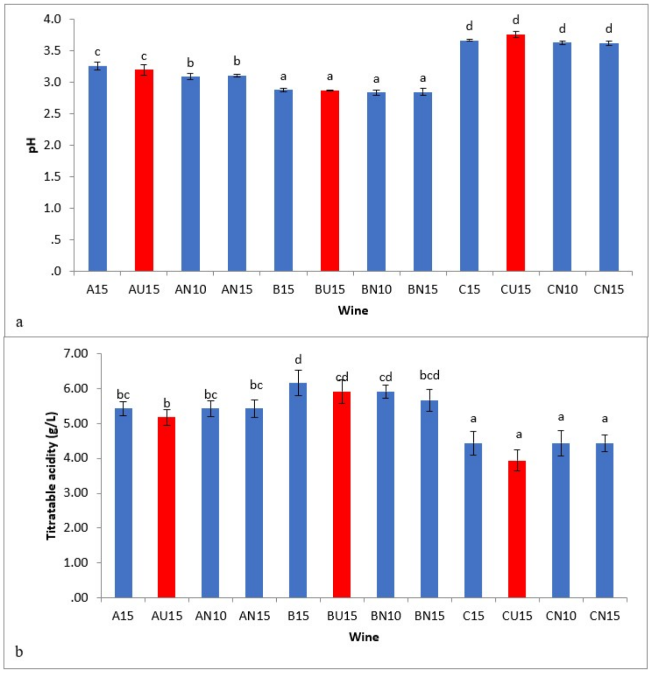

Figure 3. (a) pH and (b) titratable acidity (TA) of tomato wines before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15^{o}C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15^{o}C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10^{o}C; AN15, BN15, and CN15-A, B, and C aged at 15^{o}C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

Bioactive compounds of tomato wines

The ascorbic acid content of all ultrasonic-treated wines and those aged in bottles was significantly ($P<0.05$) lower than the untreated wines (Figure 4a). During sonication, oxidation of ascorbic acid might have taken place, and this could account for this observation (Hart and Henglein, 1985). Almost all the bottle-aged wines also showed significant reduction in their ascorbic acid contents. The ascorbic acid retention was generally better for bottle-aged wines than the ultrasonically aged ones. The present results are comparable to those reported for guava wine stored at 15°C for 3 months (Kocher and Pooja, 2011). Reduction in ascorbic acid content in a

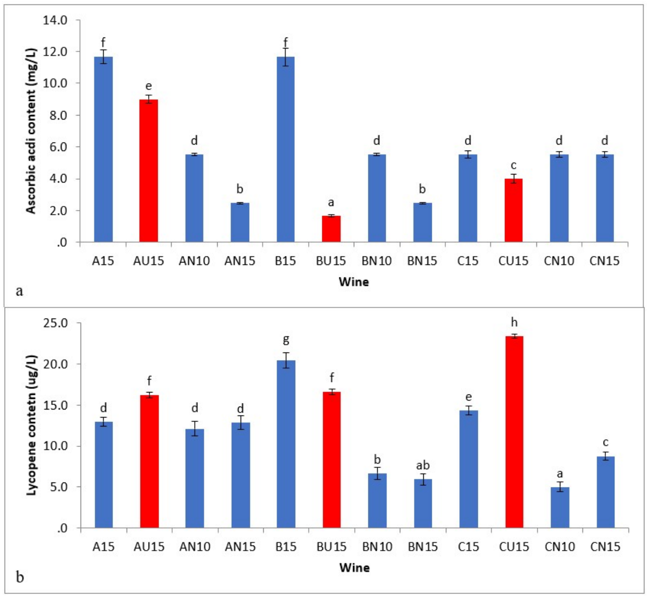

Figure 4. (a) Ascorbic acid and (b) Lycopene content of tomato wines before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15°C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15°C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10°C; AN15, BN15, and CN15-A, B, and C aged at 15°C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

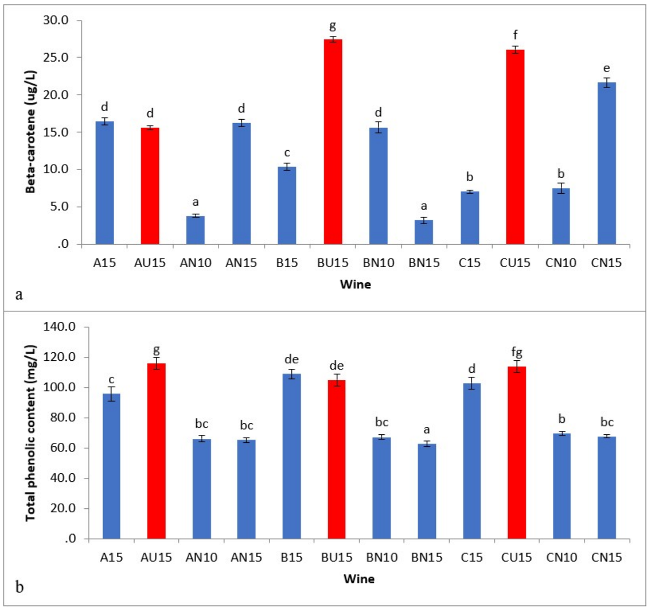

Figure 5. (a) β-carotene and (b) Total phenolic content of tomato wines before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15°C; AU15, BU15, and CU15-Wines A, B, and C respectively°C made at 15°C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10°C; AN15, BN15, and CN15-A, B, and C aged at 15°C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

model wine stored for 693 days was also reported (Wallington et al., 2013). During bottle ageing, the ascorbic acid content of Wine A was affected significantly ($P<0.05$) by storage temperature. The lycopene content of the tomato wines treated with ultrasound gave significantly higher values ($P<0.05$) compared to the wines aged in bottles (Figure 4b). In addition, the β-carotene content of the ultrasonic-treated wines BU15 and CU15 was significantly higher ($P<0.05$) compared with the corresponding untreated wines and the bottle-aged wines (Figure 5a). The enhancement of the lycopene and the β-carotene contents of the wines with the ultrasonic treatment may be due to the increased extraction of carotenoids through the generation of high pressure during sonication (Jambrak, 2011). High-pressure treatment (400 MPa/25°C/15 min) of tomato puree led to an increase in extractable carotenoids and lycopene (Sánchez-Moreno et al., 2006), and the present results are comparable to this. During bottle ageing, the lycopene content of Wine C was significantly influenced by the storage temperature (Figure 4b). The ultrasonic treatment significantly enhanced ($P<0.05$) the concentration of total phenolics of Wines A15 and C15 (Figure 5b). This is similar to the results reported for PEF-treated wines (Puertolas et al., 2010, 2009) but contrary to the results obtained for ultrasonic-treated blueberry wine (Zhao et al., 2023), and sonicated red wine (Zhang et al., 2016). The results obtained for Wines A15 and C15 were significantly higher than the corresponding bottle-aged wines. However, even though the total phenolic content of the ultrasonic-treated wine BU15 did not differ from its untreated it recorded a significantly higher value ($P<0.05$) than its bottle-aged counterparts. In the case of wines aged in bottles, while Wines B and C gave significant reduction ($P<0.05$) in total phenolics Wine A did not. A significant reduction in the phenolic content of guava wine stored at 15°C for 3 months was reported (Kocher and Pooja, 2011). Zhang et al. (2016) noticed a reduction in the phenolic content of red wine after ultrasound treatment. Lukic et al. (2020) also reported a reduction in total phenolics after ultrasonic treatment of white wine. Except for Wine B15, storage temperature did not influence the total phenolic content of the tomato wines. The influence of storage temperature on white wine phenolic content was reported (Recamales et al., 2006). The flavonoid content of ultrasonic-treated wines was higher ($P<0.05$) than the untreated and bottle-aged samples (Figure 6a). (Lukic et al., 2020), however, reported a reduction in the TF content of white wine after sonication. The storage temperature effect on the flavonoid content of the wines was not significant. The anthocyanin content of all ultrasonically treated wines was significantly higher than that of the untreated and bottle-aged samples (Figure 6b). Similar results were reported for PEF-treated wines (Puertolas et al., 2010, 2011, 2009) and ultrasonically treated blueberry wine (Li et al., 2020). However, decreased levels of anthocyanin were found for red wines after HHPP treatment (Tao et al., 2012), and also for blueberry wine after sonication (Zhao et al., 2023). The storage temperature effect on anthocyanin content ($P<0.05$) was found for only Wine B15.

Antioxidant activity of tomato wines

Generally, the TAA of all ultrasonic-treated wines was significantly higher ($P<0.05$) than the untreated and bottle-aged

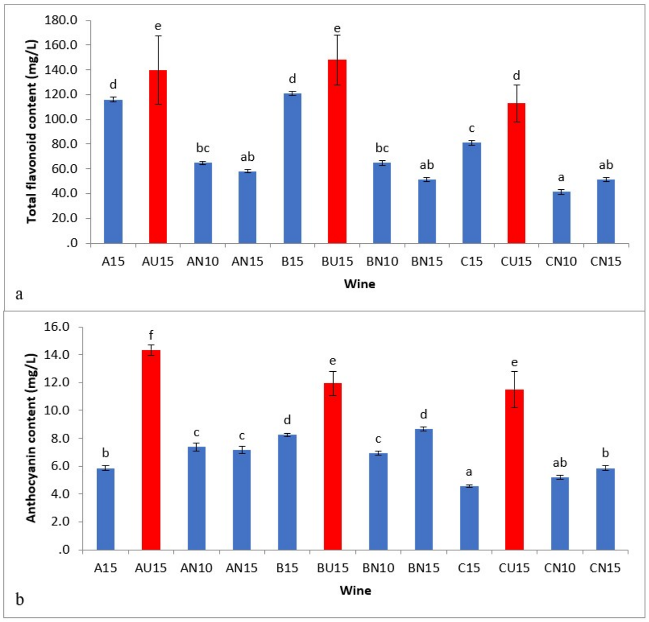

Figure 6. (a) Flavonoid and (b) anthocyanin content of tomato wines before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15°C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15°C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10°C; AN15, BN15, and CN15-A, B, and C aged at 15°C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

wines (Figure 7a). The storage temperature had a statistically significant effect ($P<0.05$) on the TAA of all the wines. Ultrasonic treatment of blueberry wine (Li et al., 2020) and rose wine (Van et al., 2021) led to improvement in their antioxidant qualities, in line with the results of the current study. Ultrasonic treatment enhanced most of the bioactive compounds, especially beta-carotene, lycopene, flavonoids, anthocyanins, and phenolics (Figure 4 to 6), and this could account for the improvement in the TAA of the ultrasonically treated wines. The DPPH scavenging activity of all ultrasonic-treated samples was not different ($P<0.05$) from the untreated wines (Figure 7b), and this is consistent with previous findings (Bhat et al., 2011). Also, the DPPH scavenging activity of ultrasonically treated Wine AU15 and CU15 was not different ($P<0.05$) from that of AN10 and CN10, respectively. Storage temperature significantly affected the DPPH scavenging activity of only Wine A. The reducing power (RP) of Wines A15 and C15 was not different ($P>0.05$) from that of their ultrasonic-treated counterparts (Figure 8). The only ultrasonic-treated wine that gave a RP value comparable to wines aged in bottles was AU15. Generally, the bottle-aged samples gave significantly higher RP values than the ultrasonic-treated samples, and this reduction might have been caused by free radicals that were formed during sonication. There was a statistically significant effect of storage temperature on the RP of only wine A.

Colour properties of tomato wines

The colour characteristics of the tomato wines aged in bottles and those aged with ultrasonic treatment were assessed using

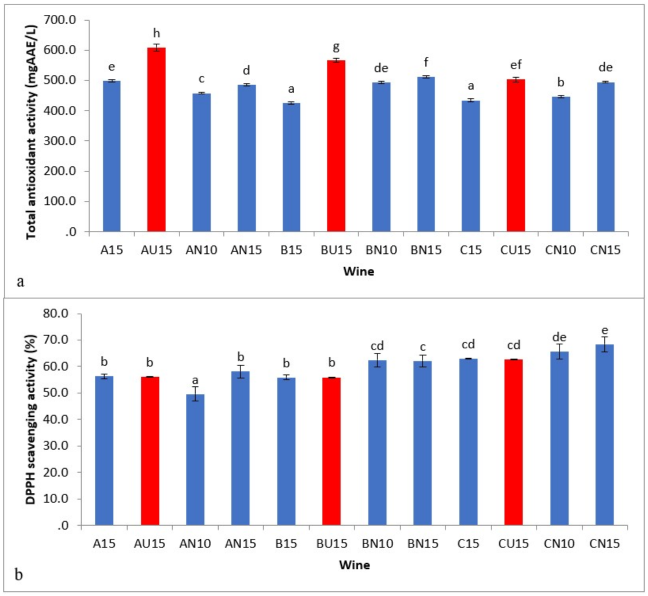

Figure 7. (a) Total antioxidant activity and (b) DPPH scavenging activity of tomato wines before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15°C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15°C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10°C; AN15, BN15, and CN15-A, B, and C aged at 15°C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

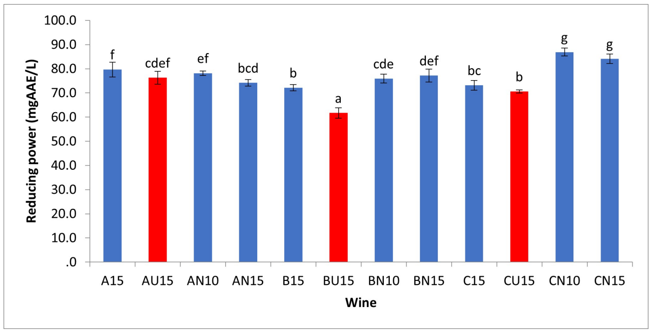

Figure 8. Reducing power of tomato wines before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15°C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15°C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10°C; AN15, BN15, and CN15-A, B, and C aged at 15°C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

lightness (L*), redness (a*), yellowness (b*), chroma (C*), hue (H*) and colour difference (ΔE*). The L* values of untreated wines A15 and C15 were significantly higher ($P<0.05$) than those of their corresponding ultrasonic-treated ones (Figure 9a). This means that the ultrasonic-treated wines became darker than the untreated wines. This is in line with the findings reported for PEF-treated Cabernet Sauvignon red wines (Puertolas et al., 2010) and ultrasonically treated white wine (Lukic et al., 2020). Ultrasonic-treated wine BU15, however, recorded a higher L* value than its untreated counterpart. This agrees with the results for red wine treated with an ultrasound frequency of 45 kHz (Zhang et al., 2016), HHPP red wine (Tao et al., 2012), and high-power pulsed microwave-treated blueberry wine (Liu et al., 2024). In addition, all the bottle-aged wines gave significantly higher L* values ($P<0.05$) than

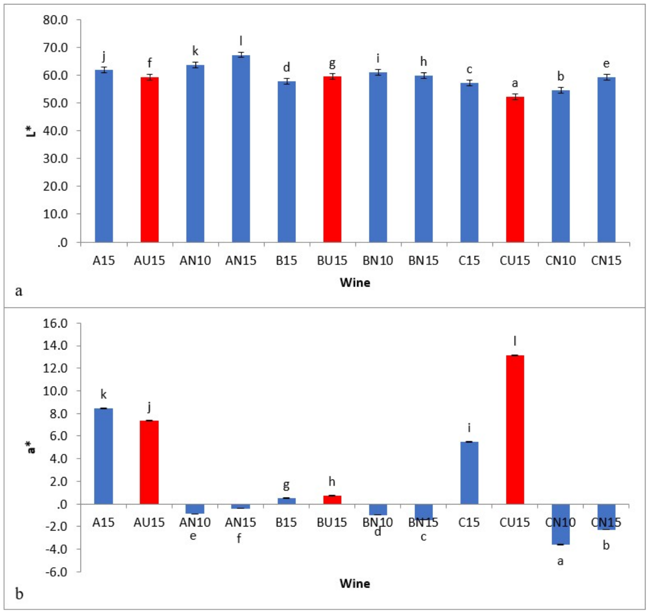

Figure 9. (a) Lightness, L* and (b) redness/greenness, a* of tomato wine before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15°C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15°C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10°C; AN15, BN15, and CN15-A, B, and C aged at 15°C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

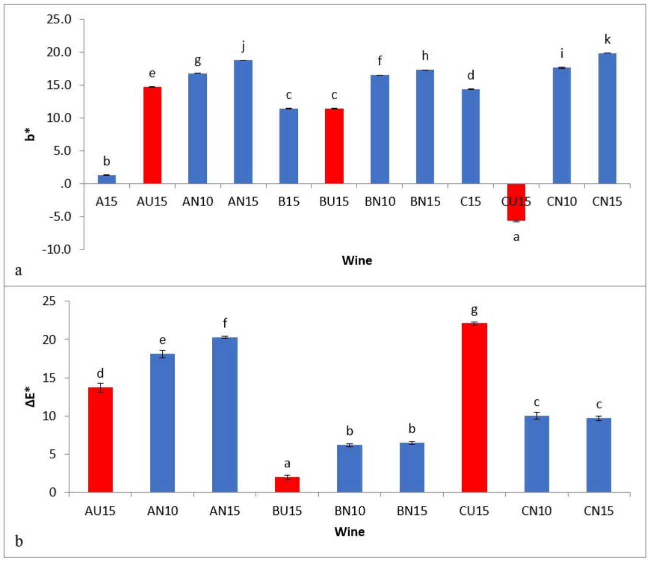

Figure 10. (a) Yellowness/blueness, b* and (b) Total colour difference, ΔE^* of tomato wines before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15°C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15°C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10°C; AN15, BN15, and CN15-A, B, and C aged at 15°C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

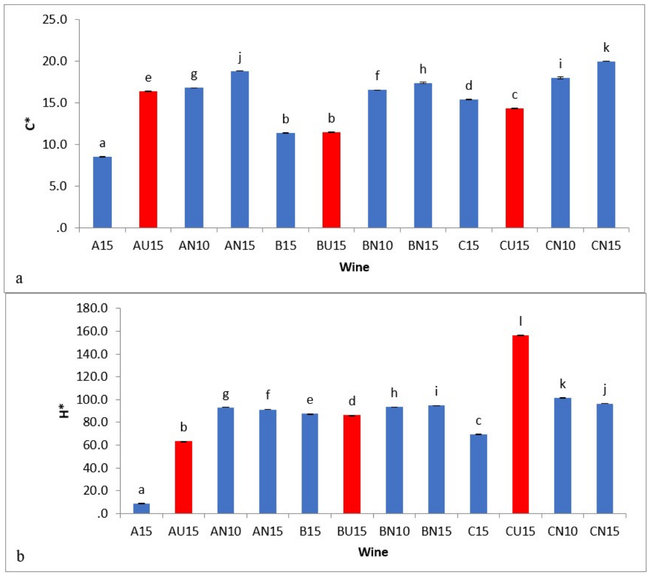

Figure 11. (a) Chroma, C* and (b) Hue, H* of tomato wines before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15°C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15°C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10°C; AN15, BN15, and CN15-A, B, and C aged at 15°C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

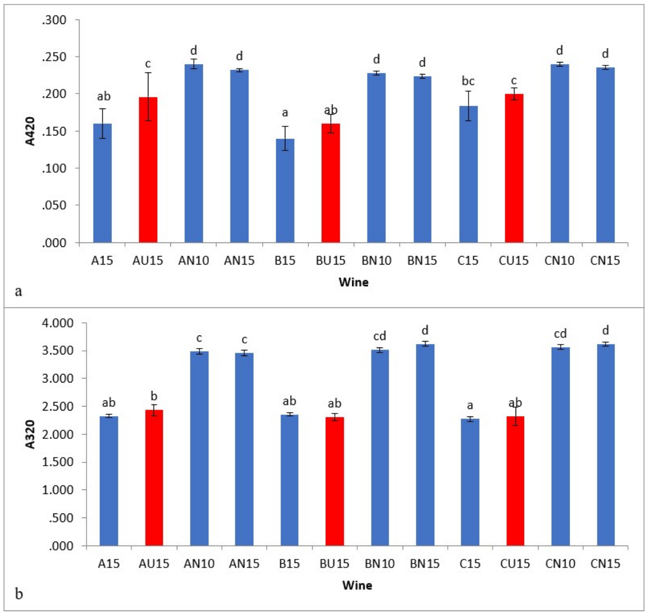

Figure 12. (a) Browning index, A_{420} and (b) Hydroxycinnamic index, A_{320} of tomato wine before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15°C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15°C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10°C; AN15, BN15, and CN15-A, B, and C aged at 15°C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

the ultrasonic-treated ones. This may be due to an increase in cloud levels (A_{660}) (Figure 13) of the bottle-aged wines, which might have led to precipitation of unstable suspended particles, thus increasing L* values. Storage temperature exerted a significant influence ($P<0.05$) on the L* values of the wines, and most wines recorded higher values at 15°C than at 10°C. Lightness, L* for the wines was closely related to the titratable acidity (TA) and the hue, H* (Figure 14). Therefore, the H* and TA might have contributed to the L* values obtained. Reduced TA and increased H* may lead to reduced L*. The a* values of sonicated wines, BU15 and CU15, were significantly higher ($P<0.05$) than the untreated samples (Fig-

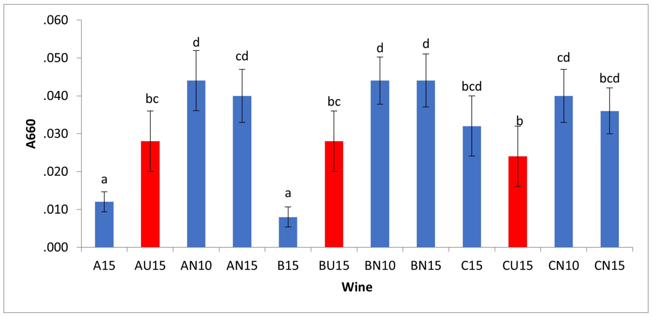

Figure 13. Clarity index (A_{660}) of tomato wines before and after ageing. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15°C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15°C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10°C; AN15, BN15, and CN15-A, B, and C aged at 15°C. Different alphabets on the bars indicate a significant difference ($p<0.05$)

ure 9b). This is in line with the results reported for red wine treated with an ultrasound frequency of 45 kHz (Zhang et al., 2016). Thus, after ultrasonic treatment, those wines became redder than the untreated ones. Also, all the ultrasonic-treated wines gave significantly higher a* values ($P<0.05$) than those aged in bottles. This observation conforms to that which was made by Garcia Martin and Sun (2013), Wu et al. (2022), and Liu et al. (2024). Storage temperature had a significant effect on a* values of the wines. The sonicated wines recorded significantly higher lycopene content than those aged in bottles (Figure 4b). In addition, sonication significantly ($P<0.05$) increased the anthocyanin content of the wines. Cluster analysis results from the dendrogram (Figure 14) indicated that a* of the wines were more related to lycopene than anthocyanin. Therefore, the increase in a* values for the sonicated tomato wines may be due to the different enhancement levels of the lycopene and anthocyanin contents of the wines (Gerster, 1997; Martin-Alvarez, 2009; Nguyen and Schwartz, 1999). In the ultrasonically treated wine, AU15 recorded a higher b* value (yellower) than A15, and this was significant ($P<0.05$). This agrees with previous findings for red wine treated with HHPP (Tao et al., 2012), red wine sonicated at a frequency of 45 kHz (Zhang et al., 2016), ultrasonic-treated white wine (Lukic et al., 2020), and high-power pulsed microwave-treated blueberry wine (Liu et al., 2024). All ultrasonically treated wines gave significantly lower b* values ($P>0.05$) than those aged in bottles. This supports the findings of a previous study (Garcia Martin and Sun, 2013). Storage temperature influenced the b* value of all the wines significantly ($P<0.05$). The dendrogram (Figure 14) indicates that after ageing, b* was clustered with A_{320} and C*. This shows that these variables may contribute to the variation in the b* values obtained for the various wines. A correlation between hydroxycinnamic acid and per cent yellow colour in *Tempranillo* wine was reported (Martin-Alvarez, 2009). The total colour difference, ΔE* of the ultrasonic-treated and bottle-aged tomato wines, using the untreated samples as the reference, is shown in Figure 10b. Except for ultrasonically treated wine CU15, all other treated wines gave lower ΔE* values than the bottle-aged samples. The ΔE* value greater than 3 was suggested to give perceptible colour differences in various products (Li et al., 2020; Martínez et al., 2001). This means that after the application of the two ageing methods, the only wine that may not be visually differentiated from the untreated is BU15. The ΔE* values of most of the ultrasonically treated and all bottle-aged wines were greater than three units, which conforms to the results obtained for wines aged for 66 weeks (Garcia-Puente et al., 2006), and ultrasonic-treated white wine (Lukic et al., 2020). This is an indication that the wines could be differentiated from the untreated wines visually (Li et al., 2020; Martínez et al., 2001). While ultrasonic treatment increased ($P<0.05$) the chroma (C*) value of A15, it decreased that of C15 (Figure 11a). Liu et al. (2024), in a previous study, reported a decrease in C* during storage of blueberry wine. Lowered C* value for a red wine processed with HHPP was reported (Tao et al., 2012). The bottle-aged samples recorded higher C* values ($P<0.05$) than the ultrasonic-treated samples. This shows that after bottle ageing, the wines became more vivid than those treated with ultrasound. A reduction in C* value after 18 weeks of storage of wine was reported (Garcia-Puente et al., 2006). Storage temperature affected the C* values of all the wines significantly ($P<0.05$). The hue (H*) of all the tomato wines treated with ultrasound and those aged in bottles was higher than the untreated samples (Figure 11b). The only treated wine that recorded higher H* than the bottle-aged samples was CU15. This is similar to previous results on ultrasonically treated white wine (Lukic et al., 2020) and high-power pulsed microwave-treated blueberry wine (Liu et al., 2024). The H* values show that after ageing, most wines moved towards 90°C and thus became yellower. The ultrasonically treated wines and those aged in bottles gave higher A_{420} values than the untreated wines (Figure 12a). The ultrasonically treated wines gave significantly lower A_{420} values ($P>0.05$) than the samples aged in bottles. During ultrasonic treatment of samples, cavitation formation removes oxygen, and this may account for the reduced browning experienced in ultrasonically treated samples than those aged in bottles (Knorr et al., 2004). Tomato wines aged at 10°C generally gave slightly higher A_{420} values than those at 15 °C, though the differences were not significant. Reddy and Reddy (2009) reported lower browning at lower storage temperatures than at higher storage temperatures in mango wine. In normal ageing, the A_{420} value of wine increases throughout the process (Jackson, 1994). In white wines, the major non-flavonoid phenolic compounds are the hydroxycinnamic acids, which are responsible for their colour (Ugliano and Henschke, 2009). The A_{320} values of all the tomato wines were significantly higher for all bottle-aged wines than the ultrasonic-treated wines (Figure 12b). Correlation between hydroxycinnamic acid and percent yellow colour in *Tempranillo* wine was reported (Martin-Alvarez, 2009). During ageing, an increase in hydroxycinnamic acid may be observed (Rentzsch et al., 2009). The ultrasonic-treated samples AU15 and BU15 gave higher A_{660} values ($P<0.05$) than their corresponding untreated samples, but all the ultrasonic-treated samples gave

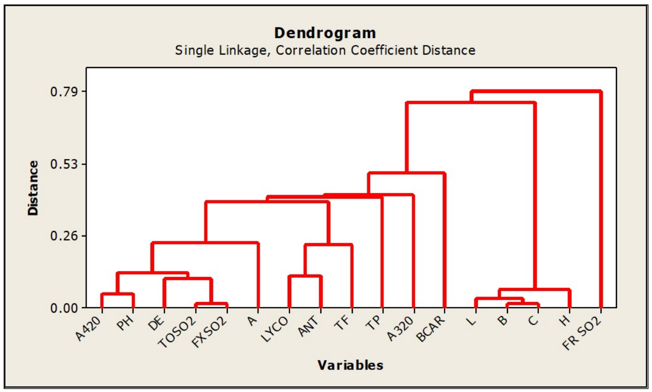

Figure 14. Dendrogram of tomato wines made at 15°C showing the relationship among their colour parameters after ageing at 10°C and 15°C. A_{420}-Browning index, DE-Dry extract, $TOSO_2$ –Total Sulphur dioxide, FXSO2-Fixed Sulphur dioxide, A-Red, LYCO-Lycopene, ANT-Anthocyanin, TF-Total flavonoid, TP-total phenolics, A320-Hydrocyanamic index, L-Lightness, B-Yellow, C-Chroma, H-Hue, $FRSO_2$-Free Sulphur dioxide

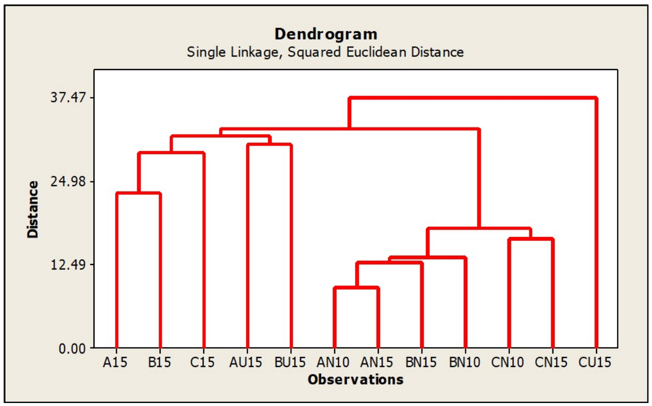

Figure 15. Dendrogram for aged tomato wines. A15, B15, C15-Untreated Wines A, B, and C respectively made at 15 °C; AU15, BU15, and CU15-Wines A, B, and C respectively made at 15°C and treated with ultrasonic frequency 33 kHz for 30 min; AN10, BN10, CN10-A, B, and C aged at 10°C; AN15, BN15, and CN15-A, B, and C aged at 15°C

lower values than the bottle-aged ones (Figure 13). Similar findings, where cantaloupe melon juice gave a higher clarity (A_{660}) value than the untreated, were reported (Fonteles et al., 2012).

Multivariate analysis of tomato wines

The dendrogram (Figure 15) shows the relative positions of the various wines and their separation after ageing. The untreated wines were separated from each other, with C15 well separated from the other two wines. The bottle-aged wines were separated from their untreated counterparts. The ultrasonic-treated wines were also separated from the untreated ones, but the separation was better for CU15 than AU15 and BU15. Similar results on the separation of ultrasonically treated wine and untreated wine were reported in a previous study (Zhang et al., 2016). Moreover, the ultrasonic-treated wines were also separated from the bottle-aged ones, with the separation for wines AU15 and CU15 being smaller than that for BU15. Similar results where wine samples were separated into untreated, high hydrostatic pressure treatment for 0.25 and 0.5 h, and high hydrostatic pressure treatment for 1 and 2 h were reported (Tao et al., 2012). The results show that ultrasonically-treated wine BU15 may have properties more similar to its counterpart aged in bottles.

Conclusion

Bottle and ultrasonic ageing of tomato wines were compared. The results showed that the ultrasonically treated tomato wines generally had comparable physicochemical qualities to the bottle-aged wines. The phytochemical composition of ultrasonic-treated tomato wine, and hence its antioxidant activity, was better than the bottle-aged wines. Therefore, it is better to use the ultrasonic frequency of 33 kHz to age tomato wine than to age it in a bottle. In future research, issues such as the linkage of ultrasonic treatment of tomato wine with its sensory qualities and scaling up of ultrasonic treatment of tomato wine for industrial application will be considered

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Conflict of interest

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

Data availability

Data will be made available on request.

References

AOAC (1984). *Official Methods of Analysis*. Association of Official Analytical Chemists, Washington, D.C., 4th edition.

Bhat, R., Ameran, S., Voon, H., Karim, A., and Tze, L. (2011). Quality attributes of starfruit (averrhoa carambola l.) juice treated with ultraviolet radiation. *Food Chemistry*, 127:641–644.

Cao, H., Wang, Z., Ma, H., Zhong, H., and Ma, X. (2007). Study on processing technology for strawberry clear juice. *Food Science*, 28(4):117–120.

Cao, Z., Li, Y., Yu, C., Li, S., Zhang, X., and Tian, Y. (2022). Effect of high hydrostatic pressure on the quality of red raspberry wine. *Journal of Food Processing and Preservation*, 46:E16030.

Caputi, A., Masao, U., and Brown, T. (1968). Spectrophotometric determination of ethanol in wine. *American Journal of Enology and Viticulture*, 19:160–165.

Chang, A. (2003). The effects of gamma irradiation on rice wine maturation. *Food Chemistry*, 83:323–327.

Chang, A. and Chen, F. (2002). The application of 20 khz ultrasonic waves to accelerate the ageing of different wines. *Food Chemistry*, 79:501–506.

Chung, H.-J., Son, J.-H., Park, E.-Y., Kim, E.-J., and Lim, S.-T. (2008). Effect of vibration and storage on some physicochemical properties of a commercial red wine. *Journal of Food Composition and Analysis*, 21:655–659.

Di Stefano, R., Cravero, M., and Gentilini, N. (1989). Metodi per lo studio dei polifenoli dei vini. *L'enotecnico I. Maggio*, pages 83–89.

Fish, W., Perkins-Veazie, P., and Collins, J. (2002). A quantitative assay for lycopene that utilises reduced volumes of organic solvents. *Journal of Food Composition and Analysis*, 15(3):309–317.

Fonteles, T. V., Costa, M. G. M., de Jesus, A. L. T., de Miranda, M. R. A., Fernandes, F. A. N., and Rodrigues, S. (2012). Power ultrasound processing of cantaloupe melon juice: Effects on quality parameters. *Food Research International*, 48(1):41–48.

Garcia Martin, J. and Sun, D. (2013). Ultrasound and electric fields as novel techniques for assisting the wine aging process. the state-of-the-art research. *Trends in Food Science and Technology*, 33:40–53.

Garcia-Puente, R., Alcalde-Eon, C., Santos-Buelga, C., Rivas-Gonzalo, J., and Escribano-Bailón, M. (2006). Behaviour and characterization of the colour during red wine making and maturation. *Analytica Chimica Acta*, 563:215–222.

Gerster, H. (1997). The potential role of lycopene for human health. *Journal of American College of Nutrition*, 16(2):109–126.

Gnoumou, J., Soro, D., Gnagne, B., and Koffi, E. (2022). Study of the stability during aging of mixed cashew and papaya wine produced with palm wine sediment. *Food and Nutrition Science*, 13:181–194.

Hart, E. and Henglein, A. (1985). Free radical and free atom reactions in the sonolysis of aqueous iodide and formate solutions. *Journal of Physical Chemistry*, 89:4342–4347.

Hussain, I., Ishaq, M., Rehman, I., Ahmad, I., and Shakirullah, M. (2006). Comparative studies of vitamin c contents in different processed and unprocessed milk samples. *Journal of Chemical Society of Pakistan*, 28(3):236–240.

Jackson, R. (1994). Post-fermentation treatments and related topics. *Wine Science: Principles and Applications*, pages 277–337.

Jackson, R. (2008). *Wine Science: Principles and Applications*. Elsevier Inc., USA, 3rd edition.

Jambrak, A. (2011). Experimental design and optimization of ultrasound treatment of food products. *Journal of Food Processing and Technology*, 2(3):1–3.

Knorr, D., Zenker, M., Heinz, V., and Lee, D.-U. (2004). Applications and potential of ultrasonics in food processing. *Trends in Food Science and Technology*, 15:261–266.

Kocher, G. and Pooja (2011). Status of wine production from guava (psidium guajava l.): A traditional fruit of india. *African Journal of Food Science*, 5(16):851–860.

Li, X., Zhang, L., Peng, Z., Zhao, Y., Wu, K., Zhou, N., Yan, Y., Ramaswamy, H., Sun, J., and Bai, W. (2020). The impact of ultrasonic treatment on blueberry wine anthocyanin color and its in vitro antioxidant capacity. *Food Chemistry*, 333(4):127–455. `https:www.doi.org/10.1016/j.foodchem.2020.127455`.

Liu, Q. and Yao, H. (2007). Antioxidant activities of barley seed extracts. *Food Chemistry*, 102:732–737.

Liu, S., Li, S., Li, S., Wang, Y., Fan, L., and Zhou, J. (2024). Effects of high-power pulsed microwave on the enhanced color and flavor of aged blueberry wine. *Food Science and Biotechnology*, 33:33–45.

Lopes, P., Silva, M., Pons, A., Tominaga, T., Lavigne, V., Saucier, C., Darriet, P., Teissedre, P.-L., and Dubourdieu, D. (2009). Impact of oxygen dissolved at bottling and transmitted through closures on the composition and sensory properties of a sauvignon blanch wine during bottle storage. *Journal of Agriculture and Food Chemistry*, 57:10261–10270.

Lukic, K., Brncic, M., Curko, N., Tomasevic, M., Tusek, A., and Ganic, K. K. (2020). Quality characteristics of white wine: The short- and long-term impact of high-power ultrasound processing. *Ultrasonic Sonochemistry*, 68:105–194. `https:www.doi.org/10.1016/j.ultsonch.2020.105194`.

Martin-Alvarez, P. (2009). Statistical techniques for the interpretation of analytical data. In Moreno-Arribas, M. and Polo, M., editors, *Wine Chemistry and Biochemistry*, pages 677–713. Springer Science + Business Media, LLC.

Martínez, J., Melgosa, M., Pérez, M., Hita, E., and Negueruela, A. (2001). Visual and instrumental colour evaluation in red wines. *Food Science and Technology International*, 7:439–444.

Miller, G. (1972). Use of dinitrosalicylic acid reagent for the determination of reducing sugars. *Analytical Chemistry*, 31:426–428.

Nagata, M. and Yamashita, I. (1992). Simple method for the simultaneous determination of chlorophyll and carotenoids in tomato fruit. *Nippon Shakuhin Kogyo Gakkaish*, 39(10):925–928.

Nguyen, M. and Schwartz, S. (1999). Lycopene: Chemical and biological properties. *Food Technology*, 53(2):38–45.

Owusu, J., Ma, H., Wang, Z., Afoakwa, N. A., Cunshan, Z., and Amissah, A. (2015). Effect of ph and temperature on antioxidant levels of tomato wine. *Journal of Food Biochemistry*, 39(1):91–100.

Oyaizu, M. (1986). Studies on products of browning reaction: Antioxidative activities of products of browning reaction prepared from glucosamine. *Journal of Nutritional Science and Vitaminology*, 44:307–315.

Prieto, P., Pineda, M., and Anguilar, M. (1999). Spectrophotometric quantification of antioxidant capacity through the formation of a phosphomolybdenum complex: Specific application to the determination of vitamin e. *Analytical Biochemistry*, 269:337–341.

Puertolas, E., Hernandez-Orte, P., Sladana, G., Alvarez, I., and Raso, J. (2010). Improvement of the winemaking process using pulsed electric fields at pilot-plant scale. evolution of chromatic parameters and phenolic content of carbernet sauvignon red wines. *Food Research International*, 43:761–766.

Puertolas, E., Saldana, G., Alvarez, I., and Raso, J. (2011). Experimental design approach for the evaluation of anthocyanin content of rosé wines obtained by pulsed electric fields. influence of temperature and time of maceration. *Food Chemistry*, 126:1482–1487.

Puertolas, E., Saldana, G., Condon, S., Alvarez, I., and Raso, J. (2009). A comparison of the effect of macerating enzymes and pulsed electric fields technology on phenolic content and colour of red wine. *Journal of Food Science*, 74(9):C647–C652.

Recamales, A., Sayago, A., González-Miret, M., and Hernanz, D. (2006). The effect of time and storage conditions on the phenolic composition and colour of white wine. *Food Research International*, 39:220–229.

Reddy, L. and Reddy, O. (2009). Production, optimization, and characterization of wine from mango (Mangifera Indica Linn.). *Natural Product Radiance*, 8(4):426–435.

Rentzsch, M., Wilkens, A., and Winterhalter, P. (2009). Nonflavonoid phenolic compounds. In Moreno-Arribas, M. and Polo, M., editors, *Wine Chemistry and Biochemistry*, pages 509–527. Springer-Verlag, New York.

Ribereau-Gayon, P., Glories, Y., Maujean, A., and Dubourdieu, D. (2006). *Handbook of Enology Volume 2: The Chemistry of Wine and Stabilization and Treatments*. John Wiley & Sons Ltd., Chichester, England, 2nd edition.

Sadler, G. and Murphy, P. (2010). *Food Analysis*, pages 219–238. Springer-Verlag, New York. Editor: Nielsen, S.S.

Selli, S., Canbas, A., and Unal, U. (2002). Effect of bottle colour and storage conditions on browning of orange wine. *Nahrung*, 46(2):64–67.

Shen, F., Li, F., Liu, D., Xu, H., Ying, Y., and Li, B. (2012). Ageing status characterization of chinese rice wines using chemical descriptors combined with multivariate data analysis. *Food Control*, 25:458–463.

Singleton, V. and Rossi, J. (1965). Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *American Journal of Enology and Viticulture*, 16:144–158.

Sánchez-Moreno, C., Plaza, L., De Ancos, B., and Cano, M. (2006). Impact of high-pressure and traditional thermal processing of tomato purée on carotenoids, vitamin c, and antioxidant activity. *Journal of the Science of Food and Agriculture*, 86:171–179.

Tao, Y., Sun, D.-W., Górecki, A., Błaszczak, W., Lamparski, G., Amarowicz, R., Fornal, J., and Jelínski, T. (2012). Effects of high hydrostatic pressure processing on the physicochemical and sensorial properties of a red wine. *Innovative Food Science and Emerging Technologies*, 16:409–416.

Tchabo, W., Ma, Y., Kwaw, E., Zhang, H., Li, X., and Afoakwah, N. (2017). Effects of ultrasound, high pressure, and manosonication processes on phenolic profile and antioxidant properties of a sulfur dioxide-free mulberry (morus nigra) wine. *Food Bioprocess Technology*, 10:1210–1223.

Torchio, F., Segade, S., Gerbi, V., Cagnasso, E., and Rolle, L. (2011). Changes in chromatic characteristics and phenolic composition during winemaking and shelf-life of two types of red sweet sparkling wines. *Food Research International*, 44:729–738.

Ugliano, M. and Henschke, P. (2009). Yeast and wine flavour. In Moreno-Arribas, M. and Polo, M., editors, *Wine Chemistry and Biochemistry*, pages 313–388. Springer-Verlag, New York.

Valdes, M., Ramirez, R., Martinez-Cañas, M., Frutos-Puerto, S., and Moreno, D. (2021). Accelerating aging of white and red wines by the application of hydrostatic high pressure and maceration with holm oak (quercus ilex) chips, influence on physicochemical and sensory characteristics. *Foods*, 10(4):899. `https://doi.org/10.3390/foods10040899`.

Van, W. S., Hong, L., and Silva, F. (2021). Nonthermal high-pressure processing, pulsed electric fields, and ultrasound preservation of five different table wines. *Beverage*, 7(4):69. `https://doi.org/10.3390/beverages7040069`.

Varo, M., Martın-Gomez, J., Merida, J., and Serratosa, M. (2023). Blueberry wine aging: Influence of bottle storage time on color, anthocyanin monomers, and antioxidant activity. *Journal of Food Biochemistry*, 1:7588560.

Wallington, N., Clark, A., Prenzler, P., Barril, C., and Scollary, G. (2013). The decay of ascorbic acid in a model wine system at low oxygen concentration. *Food Chemistry*, 141(3):3139–3146.

Wu, Z., Li, X., Zeng, Y., Cai, D., Teng, Z., Wu, Q., Sun, J., and Bai, W. (2022). Color stability enhancement and antioxidation improvement of sanhua plum wine under circulating ultrasound. *foods*, 11(16):24–35. `https://doi.org/10.3390/foods11162435`.

Zeng, X., Yu, S., Zhang, L., and Chen, X. (2008). The effects of ac electric field on wine maturation. *Innovative Food Science and Emerging Technologies*, 9:463–468.

Zhang, Q.-A., Shen, Y., Fan, X.-H., and Martín, J. F. G. (2016). Preliminary study of the effect of ultrasound on the physicochemical properties of red wine. *CYTA – Journal of Food*, 14(1):55–64.

Zhang, Y., Qiu, Q., Xu, Y., Zhu, J., Yuan, M., and Chen, M. (2022). Fast aging technology of novel kiwifruit wine and dynamic changes of aroma components during storage. *Food Science and Technology*, 43:E98422. `https://doi.org/10.1590/fst.98422`.

Zhao, Y., Zeng, Y., Li, X., Yuan, K., Li, Y., Tian, L., Sun, J., and Bai, W. (2023). Modeling and application of sensory evaluation of blueberry wine based on principal component analysis. *Current Research in Food Science*, 6(1):100–403. `https://doi:10.1016/j.crfs.2022.11.022`.

Zhishen, J., Mengchneg, T., and Jianming, W. (1999). The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals. *Food Chemistry*, 64:555–559.