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Impact of high-intensity ultrasound on phenolic content and quality of black tea wine

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Abstract

Tea is the most popular non-alcoholic beverage in Turkiye and worldwide. Black tea, a product of tea leaves fermentation, is the most consumed form of tea in Turkiye. Although a significant amount of tea is produced and consumed globally, there are limited alternative products developed in this field apart from traditional black tea. The objective of this study was to produce tea wine with a high phenolic content from the highly popular and widely consumed black tea in Türkiye. The study aimed to evaluate the influence of ultrasound treatment on the physicochemical properties and overall quality of tea wine, with a particular focus on its impact on phenolic content. The results indicated that ultrasound treatment significantly affected physicochemical properties of tea wine such as total acidity, volatile acidity, total soluble solids, reducing sugar ($p<0.05$). Ultrasound treatment after brewing increased the total phenolic content (TPC) of tea infusions by 49%. The TPC levels of the samples decreased after fermentation but no significant change occurred in TPC levels duration of two months aging. The color parameters of tea wine were also affected from ultrasound treatment, fermentation process and aging. The L^* value of tea wines significantly decreased to 66.41 in samples treated with 50% ultrasound for 8 minutes. Ultrasound treatment was found to influence sensory attributes, with increased amplitude and duration having a negative impact on taste. While there is limited research in the literature on tea-flavored, wine-based beverages, also known as tea wine, our project seeks to produce tea wine using a standardized process. We employed ultrasound, a new food preservation technique, to create an alcoholic drink with high phenolic content from brewed black tea, suitable for year-round production. It is expected that the findings highlighted the potential of tea in the production of diverse products, contributing to the expansion of tea consumption into new areas.

Keywords: Black tea, Tea wines, Phenolic compounds, Ultrasound, Functional beverages

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INTRODUCTION

Tea (*Camellia sinensis*), a plant native to Southeast Asia, is cultivated in 30 countries worldwide, including Türkiye. For the past 80 years, tea has been an economically significant crop in Türkiye, which ranks third globally in per capita tea consumption. Tea, the second most consumed non-alcoholic beverage after water, is also an essential part of Turkish culture.

Turkish tea is renowned globally for its unique flavor, which is attributed to the distinctive climatic conditions of its growing region. Black tea is the most produced and consumed type in Turkey. It contains a range of beneficial compounds, including phenolic compounds, free amino acids, alkaloids, and volatile aroma compounds. Among its polyphenols, epigallocatechin gallate (EGCG), theaflavin, and thearubigin exhibit potent antioxidant properties, with studies highlighting their anti-cancer and strong antiviral activities (Elmas et al., 2019). In black tea production process, catechins are oxidized and polymerized into theaflavins and thearubigins. These compounds play a crucial role in determining the tea's color, flavor, and brightness. Furthermore, the concentration of specific theaflavins has been strongly associated with tea taster evaluations and quality ratings (Erol et al., 2010).

In Turkiye, black tea is traditionally brewed before consumption. During the brewing process, phenolic compounds from the tea leaves such as theaflavins and thearubigins are released into the water, which shapes the sensory characteristics such as taste, color, and aroma (Erol et al., 2010). To enhance the extraction efficiency of phenolic compounds from foods, modern technologies such as supercritical fluid extraction, pressurized liquid extraction, high hydrostatic pressure, microwave, and ultrasound are increasingly employed (Alara et al., 2021). Ultrasound-assisted extraction, is considered as a promising non-conventional technology for extracting compounds as typically uses less solvent, requires shorter extraction times, and achieves higher yields while preserving thermo-sensitive compounds by minimizing their degradation (Yusoff et al., 2022). Therefore, the application of ultrasound emerges as a promising technique to enhance the release of phenolic compounds during tea brewing. Raghunath & Mallikarjunan (2020) demonstrated that applying ultrasound during the black tea brewing process significantly enhanced the total phenolic and flavonoid content, as well as the antioxidant activity of the tea.

Although Turkiye is a prominent global tea producer, innovation in tea-based products beyond traditional production methods remains limited. While industrial initiatives are underway to expand tea's applications, there is a continued demand for alternative and novel products. One such innovative creation is tea wine, a fermented beverage that blends the flavors of tea and wine into a unique functional drink (Xu et al., 2024). Tea wine is produced by fermenting tea leaf extracts or brewed tea with sugar and yeast, offering a distinctive aroma and a rich profile of polyphenolic compounds, which have made it increasingly popular among consumers (F. Wu et al., 2024).

This study aimed to develop a phenolic-rich tea wine as a new functional product using black Turkish tea. The research focused on optimizing the production process and increasing the phenolic content of the tea wine through ultrasound treatment. The effects of ultrasound at different intensities and durations on the physicochemical properties and phenolic content of the tea wine were explored, with the goal of creating a product that offers both health benefits and sensory appeal.

MATERIALS AND METHODS

Materials

Black tea, specifically 'Çaykur Siftings Tea,' a specialty tea available exclusively in the Rize province, was obtained from Çaykur (Turkiye). The sugar, wine yeast, and lemon needed for the production of tea wine were purchased from a local retail store. Folin−Ciocalteu reagent and all other chemicals used in the analysis were purchased from Merck (St. Louis, MO, USA).

Production of tea wine with ultrasound-assisted method

5 g of black tea leaves were weighed and placed into a stainless-steel teapot. Boiling water (0.5 L at 100 °C) was poured over the tea leaves, and the mixture was allowed to brew for 10 min. After the infusion time, the tea infusion was transferred to a 500-mL beaker, and the sonicator probe was immersed to ensure maximum exposure to sonic waves. Ultrasound treatment was applied to the tea infusions at amplitudes of 50% and 70% for durations of 4, 6, and 8 min. All sonication treatments were performed using an ultrasonicator (Bandelin Sonoplus, Germany) equipped with a titanium alloy flat-tip probe with a diameter of 13 mm. The samples were left at room temperature for 30 minutes to facilitate mass transfer. Subsequently, the ultrasonicated black tea infusions were filtered to separate the tea leaves from the infusion. Sugar (80 g) and yeast (1 g) were then added to the black tea infusions, and the mixture was stirred at 600 rpm for 10 minutes to ensure complete dissolution. Finally, the prepared tea infusion was transferred to a fermentation container and incubated at 25 °C for three months. After fermentation, the broth was extracted, clarified, filtered, and pasteurized at 65 °C for 10 minutes to produce the final tea wine. The samples were coded based on the ultrasound amplitude and treatment duration. Samples treated at 50% amplitude were labeled as U50-4, U50-6, and U50-8 for 4, 6, and 8 minutes, respectively, while those treated at 70% amplitude were designated as U70-4, U70-6, and U70-8.

Physicochemical analysis

Tea wine density was determined using pycnometer according to Turkish Standards 522. The following formula was used to calculate tea wine density:

$$\text{density of tea wine} = \frac{\text{mass of pycnometer full of tea wine} - \text{mass of pycnometer}}{\text{volume of pycnometer}}$$

Total soluble solids, alcohol, and ash content of tea wine was measured according to OIV Compendium of International Methods of Analysis of Wine and Musts (OIV, 2023). pH of tea wine samples was measured with a pH meter (HI2002, Hanna Instruments, USA) at room temperature.

Total acidity was determined by mixing 25 mL of tea wine with a few drops of 2% phenolphthalein solution and titrated with N/3 NaOH (Y. Y. Huang et al., 2021). The titration was stopped when the sample turned a violet color, and the amount of NaOH consumed was used to calculate the total acidity of the tea wine. The amount of NaOH used indicates the total acidity in terms of tartaric acid, expressed as g/L.

To determine the volatile acidity of the tea wines, 20 mL of the sample was mixed with 35 mL of distilled water and distilled for 30 minutes until a sufficient amount of liquid was collected. Subsequently, 1–2 drops of phenolphthalein were added to the distillate, and it was titrated with 0.1N NaOH. The amount of alkali consumed was multiplied by 0.375 and 0.306 to calculate the volatile acidity in terms of acetic acid and sulfuric acid, expressed as g/L (Aktan and Yıldırım, 2012).

The reducing sugar content was determined according to Neto et al. (2015) in this method, 25 mL tea wine sample was diluted with 250 mL of distilled water. The sample was then filtered, and titration was performed. 5 mL of Fehling A and 5 mL of Fehling B solutions were added into 25 mL of distilled water and then the mixture was heated to boiling. After boiling for 2 minutes, 2–3 drops of methylene blue were added, and titration was carried out by adding tea wine dropwise to the mixture over a flame, until the color changed from blue to copper red. The volume of titrant used was then used to calculate the reducing sugar content.

$$\text{reducing sugar } \left(\frac{\text{g}}{100}\text{ml}\right) = \frac{\text{Factor} \times \text{dilution factor}}{\text{volume of titrant}} \times 100$$

Total phenolic analysis

The total phenolic content of tea wine samples was evaluated as expressed by Stevanato et al. (2004). 1 mL of tea wine was added to 75 mL of distilled water. Then, 5 mL of Folin-Ciocalteu reagent was introduced, and the mixture was shaken thoroughly to ensure proper mixing. After a 3-minute incubation, 10 mL of saturated Na_2CO_3 solution was added, and the volume was adjusted to 100 mL with distilled water. The mixture was vortexed to achieve homogeneity and left to stand for 1 hour. Absorbance was measured at 720 nm using a UV-Vis spectrophotometer (Shimadzu, Japan). The obtained absorbance values were evaluated using a standard calibration curve (Başoğlu and Uylaşer, 2016). For the calibration curve, gallic acid solutions with concentrations of 50, 100, 200, 300, and 400 mg/L were prepared, and absorbance readings were recorded. The calibration curve was constructed based on these absorbance values (Cemeroglu, 2013).

Color analysis

The color analysis of the tea wines was performed by direct reading on a Konica Minolta CR-5 colorimeter (Konica Minolta Sensing, Netherlands). The color values (L, a, b) of the product were measured, and the total color difference (ΔE) was calculated using the following formula:

$$\Delta E = \sqrt{(L - L_0)^2 + (a - a_0)^2 + (b - b_0)^2}$$

where, ΔE represents color difference; L_0, a_0, and b_0 represent lightness, redness and yellowness values of tea infusions before fermentation and L, a, and b represent lightness, redness and yellowness values of tea wine after fermentation.

Sensory analysis

The sensory characteristics of the tea wine were evaluated using a hedonic scale. Sensory analysis was conducted by 11 panelists' ages at 18 or older. The product's taste, aroma, fragrance, color, acidity, turbidity, bitterness, and overall liking were assessed. A scoring system ranging from 1 to 5 was used for the sensory characteristics of the product. In this scoring system, 1 indicates very poor, 2 indicates poor, 3 indicates average, 4 indicates acceptable, and 5 indicates very good.

Statistical analysis

The effect of ultrasound application on the physicochemical properties and phenolic compound content of tea wines during production was analyzed using a one-way ANOVA test at a 95% confidence level, performed with OriginLab (Origin Pro 8.5, MA, USA) software. The significance of differences between groups was determined using the Tukey test.

RESULTS AND DISCUSSIONS

Influence of ultrasound process parameters on the physico-chemical properties of tea wine

Density and alcohol concentration

The density and alcohol concentration results of tea wine are shown in Table 1. After fermentation, the density of these beverages was found to range between 987.3 and 991.7 g/mL. Among the samples, the control (brewed tea before fermentation) had the highest density, while the sample treated with ultrasound at 50% amplitude for 6 min. after fermentation exhibited the lowest density. This difference is attributed to the alcohol content generated during fermentation, as alcohol's lower density compared to water reduces the overall density of beverages with higher alcohol levels. The highest alcohol content was observed in samples treated with ultrasound at 50% amplitude for 6 and 8 minutes, while the lowest was found in samples without ultrasound treatment. Table 1 indicates that the alcohol content of the tea wines formed through fermentation ranged from 5.87% to 9.52%.

Ultrasound application was found to influence alcohol production during fermentation. Previous studies on wine production from black tea have reported achieving alcohol levels of up to 14% by volume (Chen et al., 2023). The lower alcohol content in the current samples may result from the low alcohol tolerance of the yeast used or the absence of bioreactors providing optimal conditions for controlled fermentation. Enhancing the alcohol content in tea wine could involve using a yeast strain with higher alcohol tolerance and adjusting sugar levels.

Acidity

The total acidity values, expressed as tartaric acid, for tea wine are presented in Table 1. Acidity is a key indicator of wine quality, as it enhances flavor and inhibits the growth of harmful microorganisms during fermentation. The acidity of both ultrasound treated and untreated tea wines ranged from 7.87 to 9.41 g/L. The lowest acidity was observed in the control sample without ultrasound treatment, while the highest was found in the sample treated with ultrasound at 50% amplitude for 8 min. Among the samples, only the U50-8 sample showed a statistically significant difference in acidity compared to the others ($p<0.05$) following ultrasound treatment. An increasing trend in wine titratable acidity was also observed in a previous study when ultrasound treatment time was extended (Ifrim et al., 2024). Patel et al., (2010) reported that the total acidity of *Sauvignon Blanc* wine, expressed as tartaric acid, ranges from 7.86 to 8.85 g/L. Similarly, the titratable acidity of *Cabernet Sauvignon* wines was found to vary between 6.10 and 7.33 g/L in another study (Berbegal et al., 2023). In contrast, studies on tea wines have shown a wide range of results. Xu et al., (2023) reported that the total acidity of wines produced from Ziyan tea fermentation ranged from 0.99 to 2.76 g/L, depending on the fermentation duration. For rice tea wine, a traditional Asian beverage, Wang et al. (2023) reported a total acidity of 6.08 g/L. Kumar et al. (2020) noted that in tea-flavored wines prepared by brewing tea in apple juice, total acidity ranged from 0.86% to 1.02% malic acid during a six-month fermentation period. Huang et al. (2024) investigated the effects of low-temperature plasma, high-temperature high-pressure, and UV treatments on the physicochemical properties of tea wine. They observed significant variations in the titratable acidity of tea wines depending on the treatment, with acidity ranging from 4.0 to 4.8 g/L.

Volatile acidity

During alcoholic fermentation, volatile acids are produced, with acetic acid being a major component. The quantity of volatile acids formed depends on the composition of the must (acids, sugars, and nitrogenous compounds), the yeast strain used, and the fermentation conditions (Burin et al., 2015; Mangas et al., 2023). The results of volatile acid analysis after three months of fermentation for tea wine are summarized in Table 1.

In ultrasound-treated and untreated tea wines, volatile acid concentrations ranged from 0.20 to 0.50 g/L (expressed as acetic acid). Overall, fermentation and ultrasound treatment had no significant effect on volatile acid levels ($p>0.05$). However, the U70-6 sample, among the ultrasound-treated beverages, showed significantly higher levels of volatile acids ($p<0.05$). Due to their high sensory threshold, volatile acids generally have a limited impact on wine aroma. However, excessive levels of volatile acidity, generated during alcoholic fermentation, is particularly harmful to the quality of wine. In the tea wine, volatile acid levels remained below the acceptable limit of 0.72 g/L of acetic acid (Ribéreau-Gayon et al., 2006). For comparison, volatile acid levels were reported to be 0.03% (as acetic acid) in wines made by fermenting tea brewed in apple juice (Kumar et al., 2020). Furthermore, research showed that increasing the power and duration of ultrasound treatment during the tea-based aromatization of Chardonnay wines resulted in elevated volatile acid levels (Liang et al., 2023). Similarly, Merlot red wines pretreated with higher ultrasound power exhibited increased levels of volatile acidity which is consistent with our findings (Xie et al., 2023).

pH

Grapes, one of the most commonly used fruits in winemaking, possess naturally acidic properties, with acidity levels varying by variety. Puertas et al. (2008) reported a pH of 3.84 for free-run juice derived from Tempranillo grapes. Similarly, Jiang & Zhang (2010) found that juice from Cabernet Sauvignon grapes grown in China's Loess Plateau had a pH of 3.1, while Chardonnay grape juice had a pH of 3.1 (Szövényi et al., 2024). However, tea does not naturally exhibit acidic properties, making it more susceptible to spoilage during fermentation compared to grapes. To reduce this risk, lemon juice was added to the tea-based wine before fermentation, adjusting the pH to 3.86. Fermentation was then carried out under these conditions. The pH values of the resulting wine, after a three-month fermentation period, are presented in Table 1. The pH of the tea wines was found to range from 3.90 to 4.14. While the U50-8 sample exhibited a slightly higher pH, the ultrasound treatment overall did not have a significant effect on the pH of the tea wine. Gómez Gallego et al. (2013) observed that the pH of Moravia Dulce wine ranged from 3.67 to 3.83, Rojal wine from 3.69 to 3.85, and Tortosi wine from 3.80 to 3.87 (Tetik and Selli, 2018). While the composition of tea-based wine differs from that of traditional grape wine, it was notable that the control sample without ultrasound treatment and the U70-6 group had pH values similar to those of Rojal wine. The tea wine demonstrated acidic characteristics, with pH levels close to those of standard grape wines. The results of this study are consistent with findings in the literature. For instance, in a study on Ziyan tea wine, Lin et al. (2024) reported that the pH decreased during aerobic fermentation but showed no significant change once anaerobic fermentation began.

Total soluble solids

The impact of ultrasound application on the total soluble solids (TSS) content of tea wine was investigated, and the resulting TSS values are presented in Table 1. The TSS content of the wines ranged from 0.35% to 0.76%. The lowest TSS levels were observed in the U70-8 and U50-8 samples, while the highest levels were found in the control group and in the U70-6 wines treated with ultrasound at 70% amplitude for 6 minutes. The observed variations in TSS content are believed to be linked to yeast activity during fermentation. Lin et al. (2024) reported a significant decrease in TSS content, from 15% to 8%, in Ziyan tea wines after 12 days of fermentation due to yeast activity. Similarly, Zou et al. (2023) found that TSS content in tea wines decreased significantly over a 20-day fermentation period, attributing the decrease to the role of tea in supporting yeast sugar consumption. These results suggest that ultrasound treatment influences the production and consumption of compounds, such as sugars, during fermentation, likely due to the activity of yeast, which leads to changes in total soluble content.

Ash

The ash content of tea wines is presented in Table 1. Ultrasound treatment was found to increase the ash content, with the highest values observed in the samples treated with ultrasound at 70% amplitude. Among these, the U70-6 samples exhibited the highest ash content, while the control samples, which were obtained without ultrasound treatment, had the lowest. The elevated ash content in the samples treated with 70% ultrasound amplitude may be attributed to the fragmentation of tea leaves due to the high ultrasound power, leading to the formation of small particles that were not fully separated during the filtration process. Additionally, it was observed that these small tea leaf particles contributed to increased turbidity.

Reducing sugar

Table 1 presents the reducing sugar content of the tea wines. In tea wines, the reducing sugar content ranged from 4.6 to 8.3 g/L. Since tea does not contain the necessary nutrients for yeast fermentation, sucrose was added to facilitate the process. At the beginning of fermentation, the brewed tea contained no reducing sugar; however, the added sucrose was converted into reducing sugar by the *Saccharomyces cerevisiae* yeast during fermentation, resulting in an increase in reducing sugar levels. Upon examining the reducing sugar content of the tea wine, it was found that ultrasound treatment significantly ($p<0.05$) impacted the reducing sugar levels after three months of fermentation. In the control samples without ultrasound treatment, the reducing sugar level was 4.6 ± 0.3 g/L, whereas the level increased to 8.3 ± 0.1 g/L in the ultrasound-treated brewed teas. Ultrasound treatment was shown to increase the reducing sugar content in the tea wine. The highest reducing sugar levels were observed in the samples treated with ultrasound at 70% amplitude. The reducing sugar content was 8.3 ± 0.1 g/L in the samples treated for 6 minutes with ultrasound at 70% amplitude, and 6.6 ± 0.5 g/L in the samples treated for 8 minutes. Previous studies have also highlighted that ultrasound treatment increases the reducing sugar content in alcoholic beverages like wine (Martínez-Pérez et al., 2020). For example, in wines produced from Monastrell red grapes, ultrasound treatment resulted in an increase in reducing sugar content from 1.8 g/L to 2.1 g/L (Martínez-Pérez et al., 2020). Additionally, Joshi & Kumar (2017) found that in tea wines made with different sugar sources, such as sucrose (3.14 g/L), apple concentrate (6.09 g/L), and honey (6.91 g/L), the reducing sugar content varied depending on the sugar source.

Total Phenolic Content

The amount of phenolic compounds in tea wines is presented in mg GAE/L in Figure 1. The total phenolic content (TPC) was measured both before fermentation, after brewing the tea, and in the ultrasound-treated brewed teas. The phenolic content before fermentation is expressed as "initial" in both the control (untreated) and ultrasound-treated samples in Figure 1. The TPC of the brewed black tea (315.71 ± 6.06 mg GAE/L) is consistent with the study conducted by Bagheri et al. (2021). It was observed that ultrasound treatment increased the transfer of phenolic compounds from the tea leaves into the water. The amplitude and duration of ultrasound significantly ($p<0.05$) affected the transfer of phenolic compounds (Figure 1). After ultrasound treatment, the phenolic content significantly ($p<0.05$) increased in all samples. The highest phenolic content was found in the samples treated with ultrasound at 50% amplitude for 4 min (U50-4). Ultrasound treatment enhances the extraction process by causing cavitation bubbles to collapse, which breaks cell walls and releases active compounds. This process reduces particle size, accelerates mass transfer through diffusion, and increases extraction efficiency (Ozsefil & Ziylan-Yavas, 2023). Borah et al. (2024) reported that ultrasound duration increased the extraction efficiency of polyphenolic compounds from green tea leaves in the aqueous phase with increasing temperature. Similarly, Both et al. (2014) found a 15% increase in polyphenol extraction using ultrasound-assisted methods compared to conventional methods for black tea, while a 49% increase in TPC was noted in the U50-4 tea wine.

Although ultrasound treatment increased TPC, no linear correlation was established between the amplitude and the transfer of phenolic compounds. The highest TPC was obtained at 50% amplitude, while a decrease in TPC was observed at 70% amplitude. Generally, there was no statistically significant difference between the total phenolic content at 50% and 70% amplitudes. However, in the samples treated for 8 minutes, the phenolic content was significantly lower at 70% amplitude. Similarly, increasing ultrasound treatment duration did not result in a linear increase in phenolic transfer. This may be due to the formation of larger cavitation bubbles during ultrasound treatment, the effects of decomposition, or the increased formation of hydroxyl radicals under high ultrasonic power, which may react with phenolic compounds and lead to their degradation (Afroz Bakht et al., 2019; Ozsefil

& Ziylan-Yavas, 2023; Z. L. Wu et al., 2008). Qiao et al. (2013) investigated the effect of ultrasound treatment on the stability of phenolic acids in different solvents, finding that ultrasound power and frequency, as well as the liquid volume, significantly affected the degradation of phenolic compounds. Based on the obtained data, the optimal amplitude and duration for producing tea wines with high phenolic content were determined to be 50% and 4 minutes, respectively.

The phenolic compound content of tea wines was analyzed after three months of fermentation, and the results are presented in Figure 1. A significant reduction ($p<0.05$) in phenolic content was observed across all samples following fermentation. The lowest phenolic content was recorded in the control sample at 106.43 mg GAE/L, while the highest was found in the U50-8 sample, which contained 204.29 mg GAE/L. The U50-4 sample showed the second-highest phenolic content. The degradation of phenolic compounds over time is a well-documented phenomenon. Šilarová et al. (2017) studied the degradation of catechins and other green tea phenolic compounds during a six-month storage period and found that the most significant degradation occurred within the first three weeks. During fermentation, the activity of yeasts likely contributes to the observed reduction in phenolic content. The degradation or biotransformation of phenolic compounds due to microbial activity is a common occurrence during the fermentation of phenolic-rich foods. For instance, Valero-Cases et al. (2017) reported that fermentation of pomegranate juice with various lactic acid bacteria led to the complete degradation of epicatechin and catechin. However, bacterial activity also resulted in the formation of new catechin-derived phenolic compounds and a decrease in ellagic acid content. Similarly, Chen et al. (2023) found that increasing the yeast concentration during fermentation significantly reduced the total phenolic content in tea wines. To evaluate changes in phenolic compounds during storage, an analysis was conducted after two months of storage following fermentation. The results revealed no significant changes in the total phenolic content during this storage period.

Color parameters in tea wine

Color is one of the most critical quality parameters in wine production and a key factor influencing consumer preferences (Fairchild, 2018). Grapes, pears, apples, strawberries, and raspberries are commonly used in winemaking, with phenolic compounds and anthocyanins from these fruits playing a significant role in determining the color of the wine. The development of wine color begins during fermentation and continues throughout storage, as the phenolic compounds in the fruit interact to produce a stable color profile.

Tea is a beverage naturally rich in phenolic compounds, which also contribute to the color development of tea wines. The results of color analysis conducted after a 3-month fermentation period for tea wine are shown in Table 2. The analysis revealed that ultrasound treatment significantly influenced the color properties of the beverages.

The brightness (L^*) values decreased significantly in samples treated with ultrasound at 50% amplitude, indicating a darker product. The brightness value of the beverage treated with ultrasound at 50% amplitude for 8 minutes (U50-8) was measured at 66.41 ± 1.14. This reduction in brightness is attributed to the increased extraction of phenolic compounds from tea leaves facilitated by ultrasound. The enhanced phenolic content in ultrasound-treated tea samples (Figure 1) likely contributed to the observed decrease in brightness. However, no significant statistical difference ($p>0.05$) in brightness was found in the U70-8 sample.

Ultrasound treatment also caused a significant increase ($p<0.05$) in the redness (a^*) values of the beverages. The highest redness value, 14.8, was observed in the U50-8 sample, while the untreated control group exhibited the lowest redness. Similarly, the yellowness (b^*) values were significantly higher in the ultrasound-treated samples, with the U50-8 sample showing the highest yellowness value. Among all the samples, the U50-8 beverages exhibited the most significant overall color change (ΔE) due to ultrasound treatment.

After a 2-month storage period following fermentation, the color properties of the tea wines are presented in Table 3. During storage, the brightness (L^*) values decreased further, indicating a continued darkening of the beverages. Additionally, the redness (a^*) values declined, while the yellowness (b^*) values increased over time. The most pronounced color changes during storage were observed in the ultrasound-treated U50-8 samples, whereas the untreated control group exhibited the least changes.

These findings highlight the substantial impact of ultrasound treatment and storage duration on the color attributes of tea wines, emphasizing the role of phenolic compounds in defining and maintaining color stability.

Sensory analysis

Phenolic compounds not only play a crucial role in determining the color of tea but also significantly contribute to its sensory characteristics. During brewing, these compounds transfer from the tea leaves to the water, imparting attributes such as bitterness and astringency, or enhancing aroma and flavor, depending on their concentration and composition.

The sensory evaluation of black tea wine was conducted by 11 panelists. The wines were assessed for taste, aroma, clarity, color, acidity, aroma, astringency, and overall acceptability. The results, displayed in a radar chart (Figure 2), revealed that tea wine samples without ultrasound treatment received the highest overall acceptability scores (>4). Ultrasound treatment was found to influence sensory attributes, with increased amplitude and duration having a negative impact on taste. Among the samples, U50-4 was the most favored in terms of taste, followed by the control sample, while U70-8 was the least preferred.

Astringency levels were highest in the U70-8 sample, followed by U70-6, U50-8, U50-6, U50-4, and the control group. The main contributors to taste and astringency in the beverages include phenolic compounds, free amino acids, sugars, organic acids, and caffeine (Alasalvar et al., 2012). The highest phenolic content was observed in the U50-4 sample, highlighting the significant role of black tea's phenolic compounds in shaping the sensory profile of tea-flavored aromatized wine. The specific type of phenolic compound also affects the resulting taste and aroma. For instance, oligomeric or polymeric flavan-3-ols exhibit less bitterness and astringency compared to their monomeric counterparts (Kraujalyte et al., 2016). Conversely, tannic acid, theaflavin, and thearubigin are known to be responsible for the astringent taste in black tea (Alasalvar et al., 2012). Additionally, caffeine has been reported to contribute to astringency (Xu et al., 2018).

The pronounced astringency observed in the U70-8 sample may not solely be due to its phenolic content but rather to the ultrasound treatment at 70% amplitude, which caused increased fragmentation of tea leaves. This likely facilitated the release of astringent compounds such as tannic acid, theaflavin, thearubigin, or caffeine into the liquid phase. Supporting this, Kowalski et al. (2019) demonstrated that ultrasound-assisted brewing of black tea increased flavonoid content by 29%, polyphenol content by 34%, and caffeine content by 51%.

In terms of clarity, the control sample was rated the highest, followed by the U50-4 sample. Clarity was influenced by the amplitude and duration of ultrasound application. The reduction in clarity and the appearance of turbidity were attributed to the fragmentation of tea leaves during ultrasound treatment, which resulted in the formation of small particles suspended in the liquid.

Tablo 1. Physico-chemical parameters of tea wine treated with ultrasound before fermentation

	Density	Total soluble solids (%)	Ash (%)	Reducing sugar (g/L)	Alcohol concentration (%)	pH	Total acidity (g/L)	Volatile acid (g/L)
Control	1018.2 ± 0.4[a]	0.73 ± 0.21[a]	0.08 ± 0.01[a]	4.6 ± 0.3[a]	5.87 ± 0.27[a]	3.90 ± 0.01[a]	7.87 ± 0.07[a]	0.31 ± 0.01[a]
U50-4	990.4 ± 0.3[b]	0.56 ± 0.13[b]	0.18 ± 0.02[b]	5.5 ± 0.8[a]	6.88 ± 0.28[b]	4.02 ± 0.06[a]	8.61 ± 0.71[a]	0.26 ± 0.01[a]
U50-6	987.3 ± 5.7[b]	0.64 ± 0.25[a]	0.12 ± 0.01[a]	5.1 ± 1.1[a]	9.52 ± 1.84[b]	4.03 ± 0.10[a]	8.42 ± 0.87[a]	0.30 ± 0.03[a]
U50-8	988.3 ± 0.6[b]	0.36 ± 0.08[b]	0.14 ± 0.01[b]	5.6 ± 0.6[a]	8.82 ± 0.52[b]	4.14 ± 0.08[a]	9.41 ± 0.63[b]	0.20 ± 0.02[a]
U70-4	990.9 ± 0.8[b]	0.52 ± 0.13[b]	0.18 ± 0.01[b]	7.2 ± 0.4[b]	6.72 ± 0.21[b]	3.99 ± 0.03[a]	8.61 ± 0.41[a]	0.36 ± 0.03[a]
U70-6	990.4 ± 1.2[b]	0.76 ± 0.16[a]	0.21 ± 0.02[b]	8.3 ± 0.1[b]	6.68 ± 0.08[a]	3.94 ± 0.04[a]	8.42 ± 0.32[a]	0.50 ± 0.01[b]
U70-8	990.3 ± 1.1[b]	0.35 ± 0.12[b]	0.19 ± 0.02[b]	6.6 ± 0.5[a]	6.95 ± 0.87[b]	4.01 ± 0.09[a]	7.92 ± 0.87[a]	0.31 ± 0.03[a]

Different letters within the same column indicate a statistically significant difference at the $p<0.05$ level.

Tablo 2. Color values of tea wines after fermentation

	L	a	b	ΔE
Control	81.76 ± 3.57[a]	5.65 ± 2.06[a]	35.78 ± 5.17[a]	8.02
U50-4	73.14 ± 1.25[b]	10.37 ± 0.64[b]	47.48 ± 0.51[b]	15.28
U50-6	78.79 ± 0.92[a]	7.96 ± 2.10[a]	42.59 ± 3.95[b]	7.85
U50-8	66.41 ± 1.14[b]	14.80 ± 1.72[b]	52.89 ± 1.57[b]	17.49
U70-4	76.09 ± 1.82[a]	7.13 ± 1.12[a]	43.03 ± 1.81[b]	9.14
U70-6	74.14 ± 1.82[b]	9.50 ± 1.06[a]	44.97 ± 2.04[b]	12.27
U70-8	80.03 ± 2.18[a]	6.36 ± 1.38[a]	41.53 ± 5.01[a]	7.51

Different letters within the same column indicate a statistically significant difference at the $p<0.05$ level.

Tablo 3. Color values of tea wines after two months aging

	L	a	b	ΔE
Control	72.32 ± 0.64[a]	4.31 ± 1.31[a]	38.22 ± 3.14[a]	9.87
U50-4	64.71 ± 1.09[b]	9.41 ± 0.04[b]	49.52 ± 0.08[b]	22.25
U50-6	69.36 ± 0.07[a]	6.53 ± 1.52[a]	45.31 ± 0.92[b]	15.69
U50-8	57.81 ± 0.80[b]	13.64 ± 1.19[b]	54.78 ± 1.01[b]	31.63
U70-4	63.67 ± 0.09[b]	6.12 ± 0.67[a]	44.54 ± 0.78[a]	20.62
U70-6	62.49 ± 1.02[b]	8.03 ± 0.81[b]	46.84 ± 0.84[b]	22.37
U70-8	71.63 ± 0.03[a]	5.73 ± 0.54[a]	43.37 ± 1.59[a]	12.69

Different letters within the same column indicate a statistically significant difference at the $p<0.05$ level.

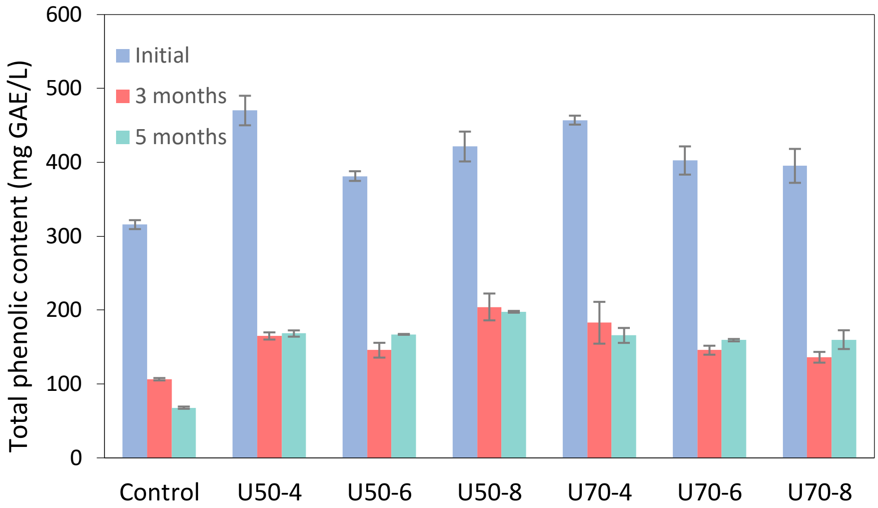

Figure 1. The effect of ultrasound amplitude and duration on the Total Phenolic Content of tea wines before and after fermentation and 2 months aging.

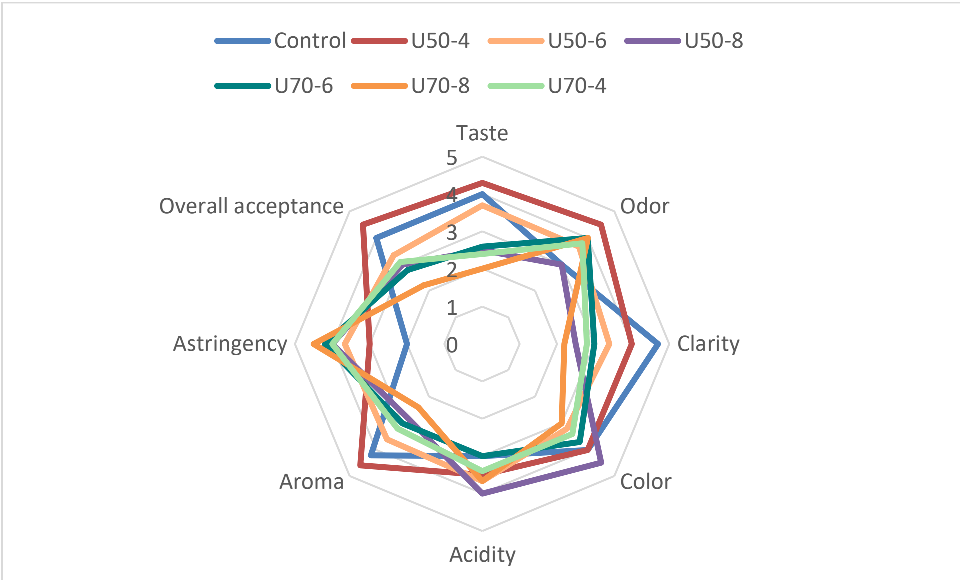

Figure 2. Radiation map of sensory profiles for tea wines. Taste, odor, clarity, color, acidity, aroma, astringency, and overall acceptance ranged from very unattractive (1) to very attractive (5).

Conclusion

This study successfully developed black tea wines through a 3-month fermentation process, incorporating ultrasound treatment at varying amplitudes and durations. The ultrasound application not only avoided any negative impact on the fermentation process but also enhanced the phenolic content of brewed black tea and influenced its color properties positively. The physicochemical analyses demonstrated significant variations in parameters such as total solids, ash, reducing sugar, alcohol, and total acidity. While a reduction in total phenolic content was observed during fermentation, ultrasound-treated samples consistently retained higher phenolic levels compared to the control. Notably, the highest phenolic content was achieved in samples treated with ultrasound at 50% amplitude for 4 minutes. Moreover, although the total phenolic content declined during fermentation, it remained stable during a 2-month storage period, underscoring the durability of these beverages. Sensory evaluations revealed changes in clarity, astringency, aroma, and color, influenced by the amplitude and duration of ultrasound treatment. Among all tested samples, the U50-4 beverage, characterized by its high phenolic content, emerged as the most preferred choice by the sensory panel. The findings of this research demonstrate the potential of tea—a widely consumed and culturally significant product—as a base for creating innovative beverages with high consumer acceptance. This work highlights the versatility of tea and opens new avenues for its application in diverse beverage categories, contributing to the development of value-added products with unique sensory and functional properties.

Compliance with Ethical Standards

Peer-review

Externally peer-reviewed.

Declaration of Interests

The authors have no conflict of interest to declare.

Author contribution

The contribution of the authors to the present study is equal. All the authors read and approved the final manuscript. All the authors verify that the Text, Figures, and Tables are original and that they have not been published before.

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