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# A sustainable approach to phalsa juice processing: ultrasonication for enhanced nutraceuticals and thermosonication for microbial safety

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Fruit juices are highly nutritious, and popular drinks but they are susceptible to quality degradation during pasteurization process. Research on non-thermal techniques of retaining fruit juice quality has grown rapidly in recent years. The aim of this study was to investigate how quality metrics of phalsa juice were affected by thermosonication (TS) and ultrasonication (US). Six samples were employed, in which T<sub>0</sub> (control), T<sub>1</sub> (thermal treatment) at 90 °C for 3 min, T<sub>2</sub>-T<sub>3</sub> samples were ultrasonically treated (US) at 37 kHz for 5–10 min (30 °C), and T<sub>4</sub>-T<sub>5</sub> samples were thermosonicated (TS) at 37 kHz for 5–10 min (50–60 °C) to determine their effect on physicochemical, phytochemical, and microbiological characteristics of phalsa juice. Physicochemical and microbial analyses were conducted at refrigerator temperature (4 °C) for 12 days. The results demonstrated that the T<sub>3</sub> sample (US treated) significantly had higher levels of vitamin C (414.57–462.09 mg/100 mL), total flavonoid (654.68–684.73 mg CE/100 mL), and total phenolic (134.83–152.43 mg GAE/100 mL) as well as their total antioxidant capacity (TAC) (589.69–648.44 µg/g) and DPPH (1204.5–1274.8 µg/g AAE) while TSS and TA are slightly affected in all treated samples. The T<sub>5</sub> Sample at 10 min (60 °C) had the highest inactivation of total plate count (2.76 CFU/mL), yeast and mold (2.21 CFU/mL) at 0 day, thus the microbial population was significantly inactivated by thermosonication. All treatments experienced a decrease in pH and TSS values, while titratable acidity increased significantly over a storage period. In comparison to the control group, total plate count, yeast, and mold significantly decreased in all treated group over a period of 12 days. The results of this study imply that US and TS treatments are a potential method for improving juice quality, economical and nutritional advantages of industrial processing for enhancing microbial safety and shelf life.

## KEYWORDS

Ultrasonication, phalsa juice, bioactive compounds, microbiological evaluation, safety

## Introduction

Phalsa (*Grewia asiatica* L.) is a subtropical fruit abundantly produced in South Asia, valued for its unique sweet–sour taste, vivid coloration, and substantial nutritional value. Phalsa is a significant source of phenolic compounds, anthocyanins, vitamin C, and other bioactive elements that enhance its substantial antioxidant capacity and related health advantages, which contribute to anti-inflammatory responses and cardiovascular protection (Mehmood et al., 2020; Kaur et al., 2024). However, phalsa fruit is highly perishable, demonstrating rapid deterioration in sensory and nutritional quality after harvest due to its high moisture content, active enzymatic processes, and susceptibility to microbial decay (Hassan et al., 2022).

Juice processing extends its availability beyond the short harvest season; nevertheless, typical thermal treatments usually have negative consequences, including nutritional degradation, color loss, and flavor change (Mehmood et al., 2020; Srivastava and Sit, 2025). The thermal processing of fruit juices is an efficient way to improve shelf life but nutritional and organoleptic properties of certain foods are adversely affected. Consumer demand for minimally processed, nutrient-dense fruit juices has increased recently, prompting explorations of green mild-processing methods. For instance, sonication alone or in combination with microwave or moderate-heat treatments has been shown to significantly improve retention of phenolics, flavonoids and antioxidant activity and reduce microbial load during storage of various juices (Siddique et al., 2023; Hussain et al., 2024b; Rehman et al., 2025).

Non-thermal and hybrid preservation technologies are increasingly promoted as sustainable food-processing strategies, because they can preserve nutritional value and sensory appeal while lowering thermal load and energy usage. Ultrasonication, a non-thermal process based on high-frequency sound waves, induces cavitation that can inactivate microorganisms and enzymes with minimal heating, protecting heat-sensitive nutrients (Barbhuiya et al., 2021; Pathania and Dubey, 2025). Thermo-sonication is the combined application of ultrasound and moderate heat utilizing the synergistic

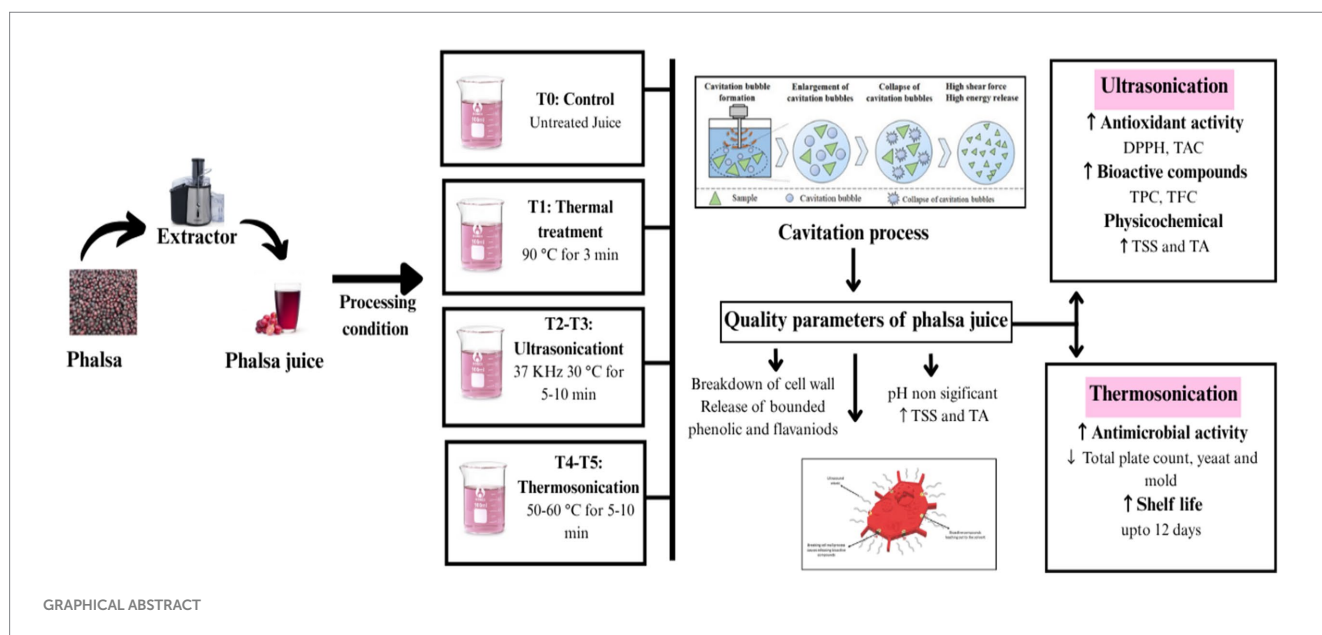
effects of cavitation and thermal to improve microbial inactivation and reduce enzymatic activity with a lower overall thermal load than conventional pasteurization (Oladunjoye and Awani-Aguma, 2023). These features give such techniques potential as eco-efficient alternatives for industrial juice processing.

Previous studies proved that ultrasonication and thermo-sonication may effectively preserve the physicochemical and bioactive properties of a variety of fruit juices, including jamun, beetroot, and watermelon during storage (Lino et al., 2022; Shahid et al., 2025; Mukhtar et al., 2024). Despite encouraging results in jamun, beetroot, and watermelon, the application of ultrasonication and thermo-sonication to phalsa juice remains unexplored. Existing studies rarely provide a systematic comparison across time, temperature and frequency combinations or consider both mechanistic explanations for bioactive release and the sustainability implications. Therefore, a comprehensive evaluation that links processing parameters to antioxidant retention, color stability and microbial safety in phalsa juice is needed. Thus, the purpose of this research is to investigate how ultrasonication and thermo-sonication at different temperature and time alter the antioxidant and microbiological properties of phalsa juice. This study also determined physicochemical and microbial analysis to evaluate the shelf life of phalsa juice during 12 days of storage at 4 °C.

## Materials and methods

### Raw material procurement and juice preparation

Fully ripe, high-quality phalsa fruits were procured from the model market in Faisalabad, Pakistan. Fruits were rinsed under running water, sorted to eliminate the infected or damaged, and air-dried. The cleaned fruits were pulped using a juice extractor (HR3752/ 00, Amsterdam, Netherlands), followed by filtration to remove seeds and small particles. The fresh juice was used immediately for processing treatments as shown in Table 1.



## Processing treatments

### Thermal processing

Freshly extracted phalsa juice (100 mL) was treated in clean sterile beaker for pasteurization in a thermostatically controlled water bath (Memmert, Germany) at 90 °C for 3 min for the T<sub>1</sub> sample (Santhirasegaram et al., 2013). By inserting a digital thermometer inside the sample's geometric center, the temperature was measured. After heating, samples were immediately cooled by keeping sample in an ice bath.

### Ultrasonication

An ultrasonic bath (Elma E 60 H, Germany) of frequency 37 kHz (600 W) was utilized at 30 °C, 5 min (T<sub>2</sub>) and 10 min (T<sub>3</sub>) (Mukhtar et al., 2024). The rectangular ultrasonic bath (281 mm × 132 mm × 149 mm) has a maximum tank capacity of 5.7 L. A 250 mL glass container with a 100 mL juice sample was placed in the center of the bath. In the ultrasonic bath, the juice level in the glass bottle was 35 mm below the water's surface. A thermometer was used to maintain the temperature at 25 ± 1 °C during US treatments.

### Thermosonication

Thermosonication performed at 37 kHz with mild heating at 50 °C and 60 °C. A time frame of 5 and 10 min was set for T<sub>4</sub> and T<sub>5</sub>, respectively. The treated samples were cooled to room temperature, then stored in a refrigerator at 4 ± 1 °C and used subsequently for different analyses. Three duplicates of each sample preparation and treatment were performed.

## Physicochemical analyses

### pH

A pH meter (Mettler FE20, Mettler Toledo, Shanghai, China) was used to determine the pH of Phalsa juice. After cleaning the probe with distilled water, buffer solutions were used for calibration. The measurements were carried out in triplicate, and the values were recorded (Barrón-García et al., 2021).

### Titrateable acidity (TA)

The acidity of the phalsa juice was determined with a slight modification in the method provided by Stadlmayr et al. (2020). Ten milliliters of phalsa juice was taken, and phenolphthalein was added as an indicator. Subsequently, 0.1 N NaOH was added drop by drop and was shaking continuously till the mixture turned pink. The volume of NaOH used was calculated by recording the burette

reading. The formula below was used to determine the acidity percentage:

$$\text{Titrateable acidity\%} = \frac{0.067 \times \text{Volume} \times 0.1N \text{ NaOH} \times 100}{\text{Weight of sample}}$$

### Total soluble solids (TSS)

Digital refractometer (Model 300,016, Super Scientific Ltd., Scottsdale, AZ) was used to calculate the TSS of phalsa juice by using the method specified by Rios et al. (2021).

### Color

Color is the appearance of the acceptance of the product. Color was measured according to CIE Lab system by using a high-quality colorimeter (Model: ST-CP60), the product's color was reported by calculating its L\* value (positive value indicates lightness, while negative values indicate darkness), a\* value (indicating the red and green color difference), and b\* value (specifying the yellow and blue color) (Orqueda et al., 2021).

## Bioactive compound and antioxidant analyses

### Total phenolic content (TPC)

The phenolic contents were measured spectrophotometrically using the (Hussain et al., 2024a) procedure, with minor modifications. To create the standard calibration curve, Folin-Ciocalteu reagent was mixed in a diluted juice sample of 0.5 mL, ended with mixing of gallic acid. Contents were represented in mg/GAE per 100 mL of juice.

### Total flavonoid content (TFC)

The flavonoid content was measured using the method described by Hussain et al. (2025). Catechin solubilized in ethanol served as the reference standard, and the contents were reported as mg/CE per 100 milliliters of juice.

### DPPH

The DPPH free radical scavenging activity of phalsa juice was examined by the prescribe method of Hussain et al. (2025) with some changes. To begin, combine 1 milliliter of diluted juice with 1 milliliter of 60 μM DPPH solution in ethanol. After that, the combined solution was incubated in a dark place for 30 min before being measured at 517 nm. The blank contained ethanol and lower absorbance was utilized to determine radical scavenging capabilities.

TABLE 1 Treatment plan for the processing of phalsa juice.

Treatments	Frequency (kHz)	Temperature (°C)	Time (min)	Power (W)
T <sub>0</sub> (control)	–	–	–	–
T <sub>1</sub> (thermal treatment)	–	90	3	–
T <sub>2</sub> (US)	37	30	5	600
T <sub>3</sub> (US)	37	30	10	600
T <sub>4</sub> (TS)	37	50	5	600
T <sub>5</sub> (TS)	37	60	10	600

## Total antioxidant capacity (TAC)

Total anti-oxidant capacity was determined by following the procedure of Zeng et al. (2015). At 695 nm absorbance, the juice's capability of proton donation was measured. Ascorbic acid 100–400 microgram/ milliliter was used as standard, and the results were represented as microgram ascorbic acid equivalent per gram of juice.

## Vitamin C

The vitamin C content of both treated and untreated phalsa juice has been investigated using the AOAC titrimetric procedure. Redox titration, which involves oxidation and reduction processes, was utilized to measure the vitamin C content of the treated juice samples. A standardized vitamin C solution and a standard dye solution were added together unless a pinkish color developed. The contents of vitamin C were calculated using mg/100 mL (Song et al., 2022).

## Anthocyanin content

Anthocyanins were calculated by following the procedure prescribed by Nadeem et al. (2021). Firstly, 5 milliliters of the juice was centrifuged at 5,000 revolution per min for 10 min. Then, 1 milliliter of the supernatant was mixed with 9 mL of potassium chloride buffer (0.025 M, pH 1.0). At the end, the absorbance was measured at 520 and 700 nm, respectively.

## Microbiological analysis

Microbial quality was assessed using the FDA's Manual (U.S. Food and Drug Administration, 2001), which included total plate count and yeast/mold enumeration. The plate count agar was used to calculate the colonies after 48 h of incubation at 37 °C (Zhang et al., 2024). For total plate count (TPC), 1 mL of juice sample was serially diluted in 9 mL of sterile 0.1% peptone water, and appropriate dilutions were spread-plated on Plate Count Agar (PCA; Oxoid, UK). Plates were incubated at 37 °C for 48 h. Yeast and mold counts (YMC) were determined on Potato Dextrose Agar (PDA) acidified with 10% tartaric acid and incubated at 28 °C for 72 h (Bhutkar et al., 2024). The results of all performed analyses were expressed as CFU/ml.

## Statistical analysis

Data was reported in the form of mean and standard deviation from triplicate analyses. One-way ANOVA was performed, and Tukey's HSD test was used to analyze data, at a 95% confidence level ( $p < 0.05$ ) by using software (Statistic 10).

## Results and discussion

### Impact of ultrasonication and thermosonication processing on pH and TSS

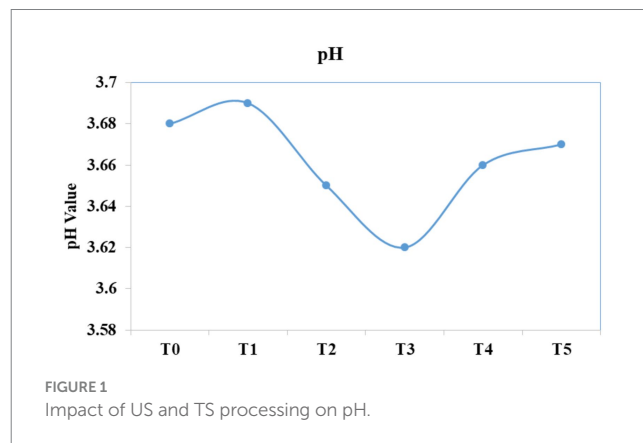
The pH of phalsa juice did not showed significant effect ( $p < 0.05$ ) from all treated samples (Figure 1). The pH value observed in T<sub>0</sub> and

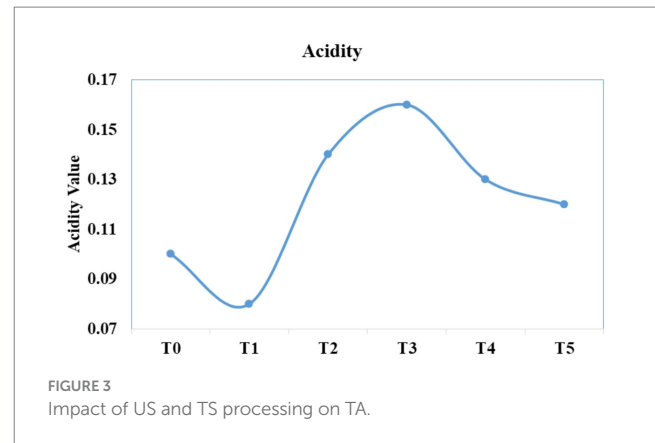
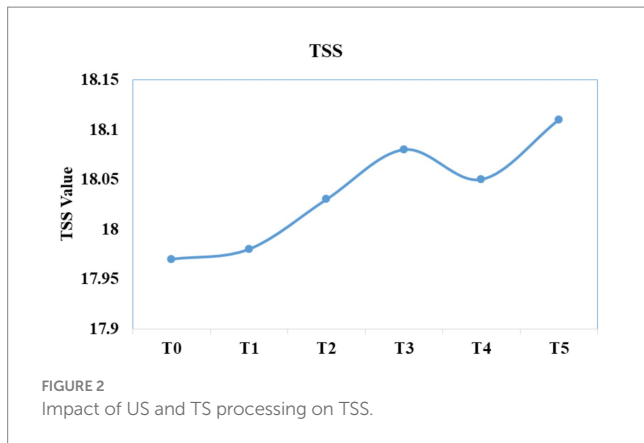
T<sub>1</sub> (control and thermal treated) were 3.68 and 3.69, while the pH value observed in ultrasonication (T<sub>2</sub> and T<sub>3</sub>) and thermosonicated samples (T<sub>4</sub> and T<sub>5</sub>) were 3.65, 3.62, 3.66, and 3.67, respectively. Compared to untreated and pasteurized phalsa juice, the thermosonicated juices pH levels did not differ significantly. However, it was found that when the time–temperature combinations increased, the pH values somewhat increased. Since fruit juice loses organic acids through evaporation, the higher pH value of pasteurized juice may be linked to their lower TA (Tian et al., 2018). Our results were similar to those of Alam et al. (2023), who found no discernible difference in the pH of litchi juice treated with microwaves and ultrasound at 0 days. Our results correlate with those of a previously published study that measured the pH of a watermelon-beetroot juice blend remained unaffected when exposed to ultrasonication and thermosonication treatments at 25 kHz for 40 to 50 °C (Mukhtar et al., 2024).

Total soluble solids showed a significant change in all treated samples (Figure 2). Samples treated with thermosonication and ultrasonication T<sub>4</sub> (18.05), T<sub>5</sub> (18.11), T<sub>2</sub> (18.03), and T<sub>3</sub> (18.08) had the highest TSS, whereas untreated samples T<sub>0</sub> (17.99) and thermally treated T<sub>1</sub> (17.98) had the lowest values. However, there were no differences in TSS between fresh and thermally treated juice. Cavitation process may potentially be the cause of the slight increase in TSS in TS and US. The ultrasonication process can damage or interfere with intracellular components, including sugars, acids, and other soluble substances in the juice, causing cell damage and creating microscopic channels that enhance TSS extraction (Gani et al., 2016; Zhang et al., 2024). Nguyen and Nguyen (2018) found that ultrasonic treatment had significantly affected the TSS in the mulberry juice. Moreover, ultra sonication can partially evaporate water, leading to the concentration of soluble particles and an increase in TSS value (Taha et al., 2024).

### Impact of ultrasonication and thermosonication processing on TA and color

Titrateable acidity samples showed a significant change in all treated samples. The ultrasonically treated sample T<sub>3</sub> had the highest acidity value (0.16%), whereas the thermally-treated sample T<sub>1</sub> had the lowest acidity value (0.08%) (Figure 3). Ultraonication can enhance the extraction rate of acidic chemicals from pulp and elevate the sample's acidity (Zhang et al., 2024). The disintegration of cell walls caused by



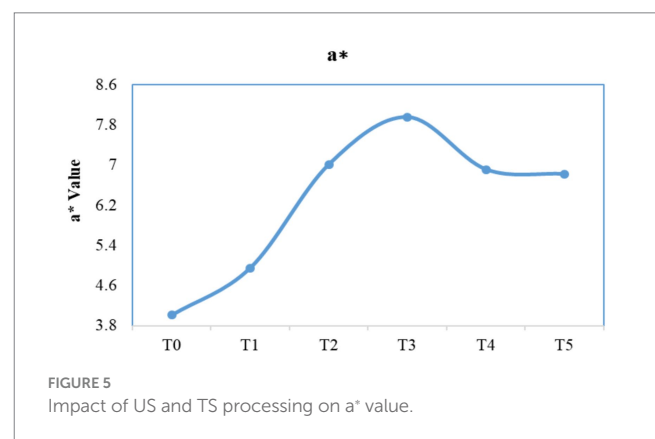
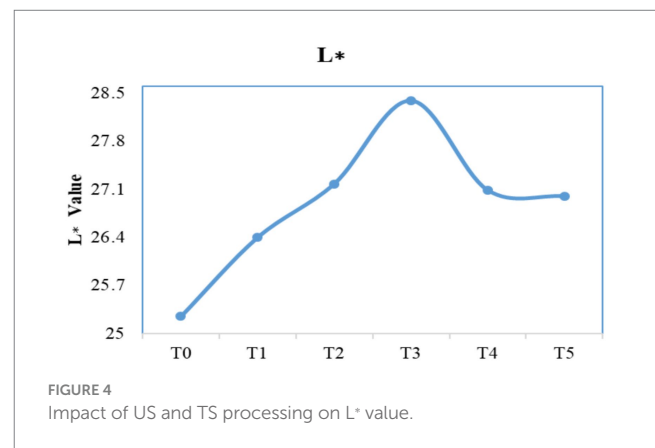


the ultrasonic process, which improved extraction performance, may be the cause of the increases in TA. As a result, more soluble substances may penetrate cell membranes and more water could enter the cells (Nguyen and Nguyen, 2018). Gómez-López et al. (2018) examined the influence of ultrasonication on titratable acidity and found that acidity increased following sonication, corroborating our findings.

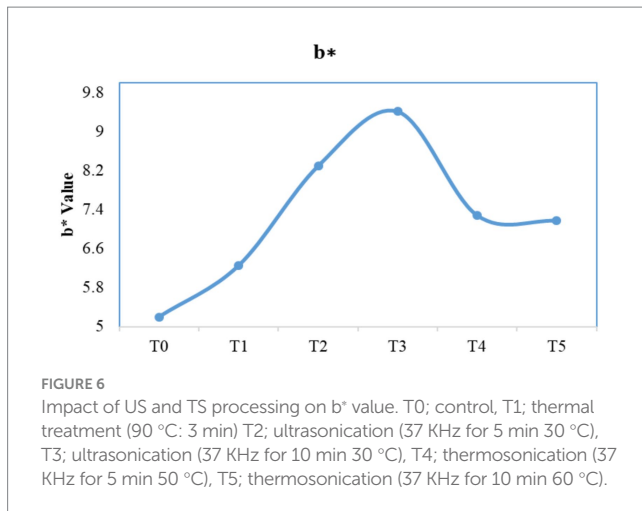
Ultrasonication, and thermosonication exhibited a significant affected on  $L^*$  (25.25–28.39),  $a^*$  (4.01–7.95), and  $b^*$  (5.20–9.41) values (Figures 4–6). Cavitation can cause color changes because it speeds up chemical reactions, increases the rate of diffusion, dispersion, forms aggregates, and breaks down particles (Tomadoni et al., 2017). It was determined that the US (10 min) treatment had the best color values with  $L^*$  (28.39),  $a^*$  (7.95), and  $b^*$  (9.41) which indicated high luminosity of juice, more reddish and yellow hues of phalsa juice. Our results are in accordant with prior research that found similar results from physicochemical parameters of a blend of apple and grape juice that was treated with TS and US (Saeeduddin et al., 2016). Cao et al. (2012) observed the increasing color of bayberry juice after ultrasonication. The partial precipitation of unstable suspended particles is responsible for a rise in the lightness value, which is subsequently followed by a drop because of oxidative darkening. When yellow watermelon juice was treated for 26 kHz, 4, 8, 12, and 16 min, the  $L^*$  parameter increased; however, when red watermelon was treated under the same parameters, no effect was noticed (Yikmiş, 2020).

## Impact of ultrasonication and thermosonication processing on total phenolic contents (TPC)

Table 2 displays the impact of heat, ultrasonic, and thermosonication treatments on the TPC in phalsa juice. The thermal treatment ( $T_1$ ) significantly reduced the TPC (98.43 mg GAE/100 mL) as compared to control ( $T_0$ : 111.33 mg GAE/100 mL). All ultrasonication treated samples were showed a significant increase in TPC ( $T_2$  and  $T_3$ ) in phalsa juice as compared to thermosonicated ( $T_4$  and  $T_5$ ) and thermal treated sample ( $T_1$ ). The maximum TPC was observed in  $T_4$  (152.43 mg GAE/100 mL) and  $T_3$  (134.83 mg GAE/100 mL). However, as the temperature rose above 40 °C, all of these bioactive compounds degraded more rapidly, indicating that temperature has notable effects on the bioactive chemicals. The US treatment exhibited the significantly increase in TPC because the



cavitation process generate bubbles in juice that produces shock and shear waves and decompose cellular structures and liberate phenolic chemicals that exist in bound form (Tomadoni et al., 2017). Although the phenolic content was decreased by 12 to 24% by thermosonication at high temperatures, which may be linked to the phenolic content being depleted by high temperatures (Dars et al., 2019). Abid et al. (2014a) and Abid et al. (2014b) examined the decrease of TPC in samples that were thermosonicated at 60 °C. Their findings showed that the temperature significantly affects the concentrations of all these bioactive compounds. Rehman et al. (2025) observed the highest total phenolic content in US treated sample (20 kHz for 10 min) in cantaloupe sugarcane blend juice.



## Impact of ultrasonication and thermosonication processing on total flavonoid contents (TFC)

Ultrasonication significantly increase the value of TFC in T<sub>3</sub> (684.73 mg CE/100 mL), T<sub>2</sub> (654.68 mg CE/100 mL) as compared to T<sub>4</sub> (631.1 mg CE/100 mL), T<sub>5</sub> (602.51 mg CE/100 mL), T<sub>1</sub> (471.9 mg CE/100 mL) and T<sub>0</sub> (520.11 mg CE/100 mL) (Table 2). Ultrasonication increases the TFC value from T<sub>2</sub> to T<sub>3</sub> (654.68 to 684.73 mg CE/100 mL) with increasing time (5 to 10 min). As time increases, US treatments dramatically increase the extraction of flavonoids. One possible explanation for this rise is that ultrasonic cavitation breaks down cell walls, releasing these cell wall-bound compounds. Similar outcome were reported by Choo et al. (2023), who found that US-treated noni juices can release phenolic compounds by ultrasound treatment. The breakdown of the plant cells' cell walls causes phenolic compounds to leak out, sonication may also be reason for the rise in TPC and TFC in noni juice. The collapse of cavitation-related gas bubbles raises the temperature and pressure, which causes water molecules in aqueous solutions to dissociate and create hydroxyl and hydrogen free radicals that ultimately increase the antioxidant capacity of flavonoids (Taha et al., 2024). The high temperature during thermal treatment resulted in greater phenolic losses. Chakraborty et al. (2015) who found that phenolic was thermally destroyed more rapidly at higher temperatures, resulting in a lowered concentration of biologically active substances in the pineapple puree. Strieder et al. (2022) observed similar results, stating that TS decreased the amount of flavonoids compared to fresh guava juice at a high temperature (80 °C), despite of processing duration. This could be because thermal degradation caused by high temperature thermosonication lowers these compounds concentration.

## Impact of ultrasonication and thermosonication processing on DPPH

The thermal treatment (T<sub>1</sub>) significantly reduced the DPPH (918.87 µg/g AAE) as compared to the control sample (T<sub>0</sub>: 1048.6 µg/g AAE) (Table 2). All ultrasonication treated samples showed a significantly increase in DPPH (T<sub>2</sub>: 1204.5 µg/g AAE and T<sub>3</sub>: 1274.8 µg/g AAE) in

phalsa juice as compared to thermosonicated (T<sub>4</sub>: 1192.57 µg/g AAE and T<sub>5</sub>: 1120.9 µg/g AAE) and thermal treated sample (T<sub>1</sub>: 918.87 µg/g AAE). In contrast to samples treated with the US, the DPPH value decreased with increasing duration and temperature during the thermosonication treatment. Various variables contribute to the increase in total antioxidant activity following sonication. Initially, sonication can activate enzymes that decompose cellular structures and liberate phenolic chemicals that exist in bound form. Second, ultrasonic waves can generate cavitation bubbles in juice that compromise the cell wall, releasing phenolic chemicals and thereby enhancing overall antioxidant activity (Zhang et al., 2024). The results of Wahia et al. (2020) showed that strawberry juice samples treated by ultrasonication had the highest DPPH values, which was comparable to our findings for DDPH values. Yildiz and Feng (2019) sought to examine the impact of US treatment on the physiological properties of cherry juice. The results demonstrated that ultrasonic treatment significantly affected antioxidant activity, showing that the antioxidant capacity notably increased with prolonged sonication duration in cherry juice samples across all methods. These results also attest to our research findings. Long-term exposure to high concentrations of these radicals has been shown to negatively affect antioxidant activity. At 60 °C, antioxidant levels may be declining due to this process (Oladunjoye et al., 2021).

## Impact of ultrasonication and thermosonication processing on TAC

The total antioxidant capacity of untreated juice (T<sub>0</sub>) was 504.78 µg/g AAE, while that of pasteurized juice (T<sub>1</sub>) was 451.74 µg/g AAE. US treatment increased TAC values of juice in samples (T<sub>2</sub>-T<sub>3</sub>) from 589.69 to 648.44 µg/g AAE at 30 °C, while thermosonication treated juice (T<sub>4</sub>-T<sub>5</sub>) significantly decreased from 544.98–530.83 µg/g AAE at temperature of 50–60 °C (Table 2). The bioavailability of phenolic chemicals during cavitation may be linked to an increase in antioxidant activity at lower temperatures. The release of bound phenolic compounds during US processing might be the primary cause of this rise in TAC levels. The high temperature and longer exposure period may have contributed to the lower rise in TAC value in TS in comparison to the US. Our results are comparable to Basumatary et al. (2020), who discovered a comparable rise in TAC values for grapefruit juice processed in the US treated samples and ascribed it to the release of phenolic compounds from the cell structure and the inactivation of enzymes. TAC levels in various juices have been reported to rise when US and TS are applied (Lepaus et al., 2023).

## Impact of ultrasonication and thermosonication processing on anthocyanin

All the treated samples showed a significant effect on phalsa juice (Table 3). Untreated juice (T<sub>0</sub>) had an anthocyanin value of 70.6 mg/100 mL, whereas pasteurized juice (T<sub>1</sub>) had an anthocyanin value of 67.91 mg/100 mL. Ultrasonication treatments significantly increased the anthocyanin value with an increasing time. US treatment increased anthocyanin value of juice treated samples (T<sub>2</sub>-T<sub>3</sub>) from 79.41 to 82.66 mg/100 mL, while juice treated at 50–60 °C (T<sub>4</sub>-T<sub>5</sub>) decreased from 75.77 to 73.93 mg/100 mL. Phenolic compound

TABLE 2 Impact of US and TS processing on TPC, TFC, DPPH and TAC.

Treatments	TPC (mg GAE/100 mL)	TFC (mg CE/100 mL)	DPPH ( $\mu\text{g/g}$ AAE)	TAC ( $\mu\text{g/g}$ AAE)
T <sub>0</sub>	111.33 $\pm$ 0.58 <sup>e</sup>	520.11 $\pm$ 0.95 <sup>e</sup>	1048.6 $\pm$ 0.79 <sup>e</sup>	504.78 $\pm$ 0.49 <sup>e</sup>
T <sub>1</sub>	98.43 $\pm$ 0.9 <sup>f</sup>	471.9 $\pm$ 0.64 <sup>f</sup>	918.87 $\pm$ 0.61 <sup>f</sup>	451.74 $\pm$ 0.62 <sup>f</sup>
T <sub>2</sub>	134.83 $\pm$ 0.29 <sup>b</sup>	654.68 $\pm$ 0.83 <sup>b</sup>	1204.5 $\pm$ 0.62 <sup>b</sup>	589.69 $\pm$ 0.64 <sup>b</sup>
T <sub>3</sub>	152.43 $\pm$ 0.75 <sup>a</sup>	684.73 $\pm$ 0.87 <sup>a</sup>	1274.8 $\pm$ 0.92 <sup>a</sup>	648.44 $\pm$ 0.7 <sup>a</sup>
T <sub>4</sub>	130.5 $\pm$ 0.45 <sup>c</sup>	631.1 $\pm$ 0.36 <sup>c</sup>	1192.57 $\pm$ 0.67 <sup>c</sup>	544.98 $\pm$ 0.32 <sup>c</sup>
T <sub>5</sub>	124.9 $\pm$ 0.66 <sup>d</sup>	602.51 $\pm$ 0.49 <sup>d</sup>	1120.9 $\pm$ 0.66 <sup>d</sup>	530.83 $\pm$ 0.32 <sup>d</sup>

Statistical differences between the samples were represented by different letters (a–f) ( $p < 0.05$ ). T<sub>0</sub>: control, T<sub>1</sub>: thermal treatment (90 °C: 3 min) T<sub>2</sub>: ultrasonication (37 KHz for 5 min 30 °C), T<sub>3</sub>: ultrasonication (37 KHz for 10 min 30 °C), T<sub>4</sub>: thermosonication (37 KHz for 5 min 50 °C), T<sub>5</sub>: thermosonication (37 KHz for 10 min 60 °C).

TABLE 3 Impact of US and TS processing on anthocyanin, Vitamin C, yeast and mold, and total plate count.

Treatments	Anthocyanin (mg/100 mL)	Vitamin C (mg/100 mL)	Yeast and mold (CFU/mL)	Total plate count (CFU/mL)
T <sub>0</sub>	70.6 $\pm$ 0.39 <sup>e</sup>	391.64 $\pm$ 0.39 <sup>e</sup>	3.93 $\pm$ 0.02 <sup>a</sup>	4.12 $\pm$ 0.12 <sup>a</sup>
T <sub>1</sub>	67.91 $\pm$ 0.43 <sup>f</sup>	304.85 $\pm$ 0.67 <sup>f</sup>	3.22 $\pm$ 0.03 <sup>b</sup>	3.61 $\pm$ 0.04 <sup>b</sup>
T <sub>2</sub>	79.41 $\pm$ 0.56 <sup>b</sup>	412.24 $\pm$ 0.84 <sup>b</sup>	3.05 $\pm$ 0.02 <sup>c</sup>	3.3 $\pm$ 0.01 <sup>c</sup>
T <sub>3</sub>	82.66 $\pm$ 0.68 <sup>a</sup>	420.42 $\pm$ 0.59 <sup>a</sup>	2.69 $\pm$ 0.04 <sup>d</sup>	3.11 $\pm$ 0.02 <sup>d</sup>
T <sub>4</sub>	75.77 $\pm$ 0.46 <sup>c</sup>	398.97 $\pm$ 0.12 <sup>c</sup>	2.64 $\pm$ 0.01 <sup>d</sup>	2.96 $\pm$ 0.04 <sup>d</sup>
T <sub>5</sub>	73.93 $\pm$ 0.72 <sup>d</sup>	394.18 $\pm$ 0.43 <sup>d</sup>	2.21 $\pm$ 0.03 <sup>e</sup>	2.76 $\pm$ 0.03 <sup>e</sup>

Statistical differences between the samples were represented by different letters (a–f) ( $p < 0.05$ ). T<sub>0</sub>: control, T<sub>1</sub>: thermal treatment (90 °C: 3 min) T<sub>2</sub>: ultrasonication (37 KHz for 5 min 30 °C), T<sub>3</sub>: ultrasonication (37 KHz for 10 min 30 °C), T<sub>4</sub>: thermosonication (37 KHz for 5 min 50 °C), T<sub>5</sub>: thermosonication (37 KHz for 10 min 60 °C).

bioavailability during cavitation may be linked to an increase in anthocyanin value at lower temperatures. The extraction of anthocyanins from tissue may be facilitated by the cavitation effects and faster disintegration of plant cells caused by ultrasonic treatment (Ramadan and Moersel, 2007). According to Chen et al. (2007), cyanidin-3-glucoside was extracted from raspberries with greater efficiency through ultrasonication process. Long-term exposure to greater power levels may cause anthocyanins to chemically decompose.

## Impact of ultrasonication and thermosonication processing on vitamin C

The vitamin C value of untreated juice (T<sub>0</sub>) was 391.64 mg/100 mL, whereas pasteurized juice (T<sub>1</sub>) was 304.85 mg/100 mL. US treatment increased vitamin C of treated juice (T<sub>2</sub>–T<sub>3</sub>) from 412.24 to 420.42 mg/100 mL, while juice treated at (T<sub>4</sub>–T<sub>5</sub>) at 50–60 °C decreased from 398.97 to 394.18 mg/100 mL (Table 3). The thermal treatment (T<sub>1</sub>) significantly reduced the vitamin C (T<sub>1</sub>: 304.85 mg/100 mL) as compared to the control (T<sub>0</sub>: 391.64 mg/100 mL). The decrease in temperature and the formation of cavitation due to sonication might be considered as the main factors contributing to this rise in vitamin C. Vitamin C levels in the juice rise as a result of the removal of dissolved oxygen and the dissolution of acid from the cell fluid by cavitation process caused by ultrasonic treatment. Ultrasonic waves can generate cavitation bubbles in juice that compromise the cell wall, releasing bounded phenolic chemicals (Nguyen and Nguyen, 2018). Yildiz and Feng (2019) reported similar findings in peach juice. The primary reasons of juice degradation are oxygen and heat. The removal of oxygen that was trapped by cavitation ultimately contributed to the increase in vitamin C levels. When compared to fresh phalsa juices, thermosonicated juices preserve more ascorbic acid. This could be because milder heating temperatures

were used during sonication rather than higher ones during pasteurization (Jabbar et al., 2015). Similarly, apple juice ultrasonically treated at 20 °C showed increases in ascorbic acid content (Abid et al., 2013). Similar results were reported by Arshad et al. (2025) in which vitamin C level increase with US processing time in pumpkin pulp at 15 and 20 min. Higher treatment temperatures may cause ascorbic acid degradation due to biological factors that cause bubbles to cavitate and collapse (Tiwari et al., 2008). The lowest Ascorbic acid levels in the thermal and TS treatments may be caused by temperature changes throughout the reaction and the generation of certain molecules that trigger the Vitamin C degradation mechanism in the presence of oxygen. A high temperature may have facilitated the electrochemical processes that degraded AA (Mukhtar et al., 2024).

## Impact of ultrasonication and thermosonication processing on total plate count

Thermal processing, thermosonication, and ultrasonication showed a significant decreasing trend in the total plate count (Table 3). The maximum decreasing trend was observed in the total plate count in T<sub>5</sub> (2.76 CFU/mL) samples, followed by T<sub>4</sub> (2.96 CFU/mL), T<sub>3</sub> (3.11 log CFU/ml), T<sub>2</sub> (3.3 CFU/mL), T<sub>1</sub> (3.61 CFU/mL) and T<sub>0</sub> (4.12 CFU/mL). Additionally, result demonstrated that ultrasonication and thermosonication can achieve the FDA-recommended 5-log decrease in microbiological population in phalsa juice. The intracellular cavitation process, which produces and continuously ruptures tiny bubbles due to pressure changes during ultrasound application, is responsible for the antibacterial properties of ultrasound. This process could be the cause of various kinds of harm to the structural elements of cells and their functions, which could result in cell lysis or death (Cassani et al., 2020).

Ultrasonication processing proved to be an efficient way of reducing the microbial population, possibly due to the cavitation effect. Free radical generation and rise in temperature and pressure are linked to the cavitation process, which leads to microbial mortality. The local microflora's growth rate is considerably reduced with longer ultrasonic exposure periods. Our results were comparable to those of the strawberry juices treated by ultrasonication, where cavitation is caused by the ultrasound treatment method (Tomadoni et al., 2017). Regardless of the type of sonication technique, microorganisms were completely inactivated at 60 °C. Several intricate physical processes that lead to microbial inactivation through thermosonication process. The primary cause of ultrasound's inhibitory effect on microbial cells is the mechanical destruction of microbial cells (Kalsi et al., 2023). Thermosonicated kutkura juice had the maximum microbial cell inactivation at 50 °C as compared to untreated juice (krishnan Kesavan et al., 2023). Further declines in the microbial population of the ultrasound-treated sample at higher temperatures suggested that heat and sonication might work in synergy (Wordon et al., 2012).

### Effect of ultrasonication and thermosonication processing on yeast and mold

The amount of mold and yeast in the phalsa juice was significantly decreased in all treated samples. The most noteworthy decreasing trend was observed in the T<sub>5</sub> (2.21 CFU/mL) sample followed by T<sub>4</sub>

(2.64 CFU/mL), T<sub>3</sub> (2.69 CFU/mL), T<sub>2</sub> (3.05 CFU/mL), and T<sub>1</sub> (3.22 CFU/mL) (Table 3). In comparison to the control, TS processing led to a significant drop in yeast and mold count activity. This decrease trend is in accordance with research by Nguyen and Nguyen (2018), who found a comparable decrease and linked it to electroporation in the cell membranes of microbes at high temperatures. The combination of heat and US is more effective, which may have a more lethal effect on microbial growth than ultrasonication. The physical action of cavitation and denaturation of proteins caused by a rise in temperature may inactivate microorganisms. The number of mold and yeast in the treated juice may decrease as a result of these combined actions (Abid et al., 2014a; Abid et al., 2014b). In their study, Nadeem et al. (2018) employed US treatment subjected to juice for longer period (60–90 min), and they found that the microbial activity of the juice blend clearly decreased as processing time increased. Yikmiş (2020) studied by comparing red and yellow watermelon juices at various processing times (4, 8, 12, and 16 min) to non-sonicated juice, and found that applying ultrasound (26 kHz) reduced the microbial load to a desirable level.

### Storage study of phalsa juice

#### Physicochemical analysis of phalsa juice

The pH of the phalsa juice samples was significantly affected by storage period. As storage time increases, the pH decreases significantly (Table 4). The untreated sample (T<sub>0</sub>) had the highest

TABLE 4 Impact of TS and US on pH of phalsa juice during storage.

Treatments	Day 0	Day 3	Day 6	Day 9	Day 12
pH					
T <sub>0</sub>	3.68 ± 0.01 <sup>ab</sup>	3.52 ± 0.02 <sup>def</sup>	3.51 ± 0.03 <sup>defg</sup>	3.49 ± 0.03 <sup>efghi</sup>	3.37 ± 0.02 <sup>l</sup>
T <sub>1</sub>	3.69 ± 0.01 <sup>a</sup>	3.58 ± 0.03 <sup>cd</sup>	3.51 ± 0.02 <sup>defg</sup>	3.51 ± 0.02 <sup>defg</sup>	3.45 ± 0.03 <sup>ghijk</sup>
T <sub>2</sub>	3.65 ± 0.02 <sup>ab</sup>	3.53 ± 0.02 <sup>de</sup>	3.51 ± 0.01 <sup>defg</sup>	3.47 ± 0.03 <sup>efghij</sup>	3.41 ± 0.02 <sup>ijkl</sup>
T <sub>3</sub>	3.61 ± 0.01 <sup>bc</sup>	3.49 ± 0.03 <sup>efgh</sup>	3.42 ± 0.03 <sup>ijkl</sup>	3.4 ± 0.02 <sup>ijkl</sup>	3.29 ± 0.03 <sup>m</sup>
T <sub>4</sub>	3.66 ± 0.02 <sup>ab</sup>	3.48 ± 0.03 <sup>efghi</sup>	3.45 ± 0.02 <sup>efghi</sup>	3.39 ± 0.03 <sup>kl</sup>	3.27 ± 0.02 <sup>m</sup>
T <sub>5</sub>	3.67 ± 0.01 <sup>ab</sup>	3.43 ± 0.02 <sup>hijkl</sup>	3.41 ± 0.03 <sup>ijkl</sup>	3.38 ± 0.03 <sup>l</sup>	3.23 ± 0.02 <sup>m</sup>
Total soluble solids (°Brix)					
T <sub>0</sub>	17.97 ± 0.02 <sup>def</sup>	17.81 ± 0.03 <sup>kl</sup>	17.71 ± 0.02 <sup>no</sup>	17.62 ± 0.01 <sup>o</sup>	17.49 ± 0.03 <sup>q</sup>
T <sub>1</sub>	17.98 ± 0.01 <sup>def</sup>	17.92 ± 0.01 <sup>ghi</sup>	17.82 ± 0.01 <sup>kl</sup>	17.74 ± 0.01 <sup>mno</sup>	17.62 ± 0.03 <sup>p</sup>
T <sub>2</sub>	18.03 ± 0.01 <sup>bcd</sup>	18.01 ± 0.02 <sup>cde</sup>	17.88 ± 0.01 <sup>hij</sup>	17.79 ± 0.03 <sup>lmn</sup>	17.73 ± 0.05 <sup>mno</sup>
T <sub>3</sub>	18.08 ± 0.02 <sup>ab</sup>	18.06 ± 0.02 <sup>abc</sup>	17.97 ± 0.02 <sup>def</sup>	17.9 ± 0.02 <sup>ghi</sup>	17.79 ± 0.02 <sup>klm</sup>
T <sub>4</sub>	18.05 ± 0.01 <sup>abc</sup>	18.01 ± 0.02 <sup>cde</sup>	17.96 ± 0.02 <sup>efg</sup>	17.85 ± 0.01 <sup>ijk</sup>	17.75 ± 0.03 <sup>lmn</sup>
T <sub>5</sub>	18.11 ± 0.02 <sup>a</sup>	18.06 ± 0.03 <sup>abc</sup>	18.01 ± 0.02 <sup>cde</sup>	17.94 ± 0.02 <sup>efg</sup>	17.84 ± 0.01 <sup>ijkl</sup>
Titratable acidity (%)					
T <sub>0</sub>	0.1 ± 0.01 <sup>no</sup>	0.13 ± 0.01 <sup>lm</sup>	0.19 ± 0.01 <sup>gh</sup>	0.23 ± 0.01 <sup>def</sup>	0.29 ± 0.01 <sup>ab</sup>
T <sub>1</sub>	0.08 ± 0.01 <sup>o</sup>	0.11 ± 0.01 <sup>mn</sup>	0.17 ± 0.01 <sup>hij</sup>	0.22 ± 0.01 <sup>ef</sup>	0.27 ± 0.01 <sup>bc</sup>
T <sub>2</sub>	0.14 ± 0.02 <sup>klm</sup>	0.17 ± 0.02 <sup>hij</sup>	0.21 ± 0.01 <sup>fg</sup>	0.26 ± 0.01 <sup>cd</sup>	0.28 ± 0.01 <sup>abc</sup>
T <sub>3</sub>	0.16 ± 0.01 <sup>ijk</sup>	0.19 ± 0.01 <sup>ghi</sup>	0.23 ± 0.01 <sup>ghi</sup>	0.27 ± 0.01 <sup>bc</sup>	0.3 ± 0.01 <sup>a</sup>
T <sub>4</sub>	0.13 ± 0.01 <sup>lm</sup>	0.15 ± 0.01 <sup>kl</sup>	0.19 ± 0.01 <sup>gh</sup>	0.23 ± 0.01 <sup>def</sup>	0.29 ± 0.01 <sup>ab</sup>
T <sub>5</sub>	0.12 ± 0.01 <sup>mn</sup>	0.14 ± 0.01 <sup>klm</sup>	0.17 ± 0.01 <sup>hij</sup>	0.24 ± 0.02 <sup>de</sup>	0.27 ± 0.01 <sup>bc</sup>

Means with similar letters in a row or column are statistically not significant, but those with different letters are (*p* < 0.05) significant. T<sub>0</sub>; control, T<sub>1</sub>; thermal treatment (90 °C: 3 min) T<sub>2</sub>; ultrasonication (37 KHz for 5 min 30 °C), T<sub>3</sub>; ultrasonication (37 KHz for 10 min 30 °C), T<sub>4</sub>; thermosonication (37 KHz for 5 min 50 °C), T<sub>5</sub>; thermosonication (37 KHz for 10 min 60 °C).

pH value at 0 days ( $3.68 \pm 0.01$ ), while  $T_3$  had the lowest value ( $3.61 \pm 0.01$ ). The pH was high declining rate after 9<sup>th</sup> days as compared to 3 and 6<sup>th</sup> days among all treatment. Change in pH was exhibited as the number of storage days increased, and  $T_3$ ,  $T_4$  and  $T_5$  showed a higher pH decreasing value ( $3.29 \pm 0.03$ ,  $3.27 \pm 0.02$  and  $3.23 \pm 0.02$ ) as compared to  $T_2$  ( $3.41 \pm 0.02$ ),  $T_1$  ( $3.45 \pm 0.03$ ) and  $T_0$  ( $3.37 \pm 0.02$ ) at 12 days. The pH of fruit juices decreases as a result of enzyme activity, which eventually breaks down cellular components and releases organic acid during storage. After 9<sup>th</sup> days pH is highly acidic due to release of organic acid and it create conducive environment to the growth of harmful microorganisms. The pH of the control and treated juices in the current research fell as the storage period increased. Our finding were comparable with Mahnoori et al. (2020), who noted comparable effects of blended juice of litchi and beetroot at varying ratios throughout a 90-day storage period. These findings were similar with Ibrahim (2016) investigation of pH variations in pineapple, papaya, and watermelon juices stored for 4 weeks at room temperature and 4 °C. According to their findings, all fruit juices' pH values seemed to drop with longer storage period. The results that Lagnika et al. (2017) found with pineapple juice were comparable to our findings.

TSS value of phalsa juice decrease significantly during storage study (Table 4). The lowest TSS value was found in  $T_0$  ( $17.49 \pm 0.01$ ) and the highest value in  $T_3$  and  $T_5$  samples ( $18.08 \pm 0.01$  and  $18.11 \pm 0.02$ ) (0 day).  $T_5$  and  $T_3$  results showed that TSS value decrease less significantly ( $17.84 \pm 0.01$ ) and ( $17.79 \pm 0.02$ ) as compared to control  $T_0$  ( $17.49 \pm 0.03$ ),  $T_1$  ( $17.62 \pm 0.03$ )  $T_2$  ( $17.73 \pm 0.05$ ) and  $T_4$  ( $17.75 \pm 0.03$ ) at 12 days. TSS values reduce during storage, as a result of microbial population that consuming the sugar of juices to produce energy and utilize for growth. However, Humayun et al. (2014) demonstrated that TSS of orange juice dropped after 4 weeks at 7 °C. They linked their findings to microbial development. Passion fruit showed a similar decreasing trend of TSS values

during 10 days of storage (Gómez-López et al., 2018). Similar result were reported in litchi juice in which TSS value decrease ( $15.33$ – $14.43$  °Brix) over a 21 days of storage (Alam et al., 2023).

TA results were significant and acidity value increase with respect to storage time. The lowest TA value was found in  $T_1$  ( $0.08 \pm 0.01$ ) and the highest value in  $T_2$  and  $T_3$  samples ( $0.14 \pm 0.02$  and  $0.16 \pm 0.01$ ) (0 day).  $T_5$  results showed that TA value increase less significantly ( $0.27 \pm 0.01$ ) as compared to control  $T_0$  ( $0.29$ ),  $T_2$  ( $0.28 \pm 0.01$ )  $T_3$  ( $0.30 \pm 0.01$ ) and  $T_4$  ( $0.29 \pm 0.01$ ) at 12 days (Table 4). At the end of storage, the high microbial load in treated and untreated samples may have contributed to the production of metabolic byproducts like acetic acids. Our finding was similar with the result of TA in carrot juice in which TA increase significantly during storage period as explained by Jabbar et al. (2014) and reason of increasing trends due to addition of acid and hydrolysis of polysaccharides. Similar increasing trend of TA was observed when probiotic rich strawberry juice was subjected to ultrasonication at 40 kHz for 15 to 30 min (Cassani et al., 2020).

### Microbial analysis of phalsa juice

The total plate count of phalsa juice was significantly impacted by storage time ( $p < 0.05$ ). The control sample juice had total plate count  $4.12 \pm 0.012$  CFU/mL while thermal treated sample had count  $3.61 \pm 0.04$  CFU/mL at 0 day (Table 5). There was a significant drop in microbial population of phalsa juice in  $T_4$  and  $T_5$  after 3 and 6 days of storage in comparison to controls  $T_0$ , untreated sample  $T_1$ , and US-treated samples. Furthermore, TS had a stronger antibacterial impact after 10 min of application, indicating that the longer the TS processing period, the more microbial counts were reduced. The microbiological counts of untreated samples were actually higher than 7 CFU/mL until day 12 of storage, which is the upper limit set by the Spanish rule of

TABLE 5 Impact of TS and US on total plate count, yeast and mold of phalsa juice during storage.

Treatments	Day 0	Day 3	Day 6	Day 9	Day 12
Total plate count (CFU/ml)					
$T_0$	$4.12 \pm 0.12^h$	$4.68 \pm 0.04^{ef}$	$5.46 \pm 0.05^c$	$6.15 \pm 0.03^b$	$7.88 \pm 0.04^a$
$T_1$	$3.61 \pm 0.04^j$	$3.88 \pm 0.03^{hi}$	$4.23 \pm 0.04^{gh}$	$5.12 \pm 0.03^{cd}$	$6.38 \pm 0.03^b$
$T_2$	$3.3 \pm 0.01^{klm}$	$3.53 \pm 0.04^{jk}$	$4.09 \pm 0.04^h$	$5.04 \pm 0.03^{de}$	$6.14 \pm 0.03^b$
$T_3$	$3.11 \pm 0.04^{lmn}$	$3.32 \pm 0.04^{kl}$	$4.49 \pm 0.58^{fg}$	$4.97 \pm 0.02^{de}$	$5.12 \pm 0.03^{cd}$
$T_4$	$2.81 \pm 0.03^{no}$	$3.14 \pm 0.03^{lmn}$	$3.38 \pm 0.03^{kl}$	$4.82 \pm 0.03^{def}$	$4.98 \pm 0.03^{de}$
$T_5$	$2.58 \pm 0.04^o$	$2.96 \pm 0.04^{mn}$	$3.18 \pm 0.03^{klm}$	$3.59 \pm 0.04^j$	$4.12 \pm 0.03^b$
Yeast and mold (CFU/ml)					
$T_0$	$3.93 \pm 0.02^{lm}$	$4.62 \pm 0.04^h$	$5.55 \pm 0.03^d$	$6.35 \pm 0.04^b$	$7.13 \pm 0.04^a$
$T_1$	$3.22 \pm 0.03^q$	$3.64 \pm 0.04^o$	$4.29 \pm 0.04^i$	$5.04 \pm 0.03^c$	$6.17 \pm 0.03^c$
$T_2$	$3.05 \pm 0.02^{rs}$	$3.86 \pm 0.05^{mn}$	$4.11 \pm 0.04^{jk}$	$4.83 \pm 0.02^f$	$5.48 \pm 0.03^d$
$T_3$	$2.71 \pm 0.06^t$	$3.81 \pm 0.03^{no}$	$4.03 \pm 0.02^{kl}$	$4.74 \pm 0.03^{fg}$	$5.05 \pm 0.04^c$
$T_4$	$2.44 \pm 0.04^u$	$3.15 \pm 0.04^{qr}$	$3.98 \pm 0.06^{lm}$	$4.33 \pm 0.02^i$	$4.99 \pm 0.05^c$
$T_5$	$2.18 \pm 0.06^v$	$2.98 \pm 0.04^s$	$3.74 \pm 0.04^{op}$	$4.15 \pm 0.03^j$	$4.65 \pm 0.04^{gh}$

Means with similar letters in a row or column are statistically not significant, but those with different letters are ( $p < 0.05$ ) significant.  $T_0$ ; control,  $T_1$ ; thermal treatment (90 °C; 3 min)  $T_2$ ; ultrasonication (37 KHz for 5 min 30 °C),  $T_3$ ; ultrasonication (37 KHz for 10 min 30 °C),  $T_4$ ; thermosonication (37 KHz for 5 min 50 °C),  $T_5$ ; thermosonication (37 KHz for 10 min 60 °C).

permitted mesophilic total counts of minimally processed product at expiry. Hashemi et al. (2024) subjected the celery juice to thermosonicated at 37 KHz, and 50, 60, and 70 °C for 6 min in order to see if *Salmonella* and *E. coli* were inactivated. Nearly all infections were successfully eradicated by thermosonication. The *E. coli* count decreased by 27%, and the *Salmonella* count decreased by 15% when the temperature was raised from 50 to 70 °C. Their results indicated that the physical breakdown of cell walls and the maximum elimination of microbes would be caused by varying sonication frequencies and intensities. According to Lepaus et al. (2023), thermosonication also reduced the microbial load of orange-carrot juice.

The yeast and mold count of phalsa juice was significantly impacted by storage time ( $p < 0.05$ ). The control sample juice had yeast and mold count  $3.93 \pm 0.02$  CFU/mL while thermal treated sample had count  $3.22 \pm 0.03$  CFU/mL at 0 day (Table 5). During 3 and 6 days of storage, substantial decrease in every microbial population count of Phalsa juice in  $T_4$  ( $3.81 \pm 0.03$ ,  $4.03 \pm 0.02$ ) and  $T_5$  ( $2.98 \pm 0.04$ ,  $3.74 \pm 0.04$ ) as compared to controls  $T_0$ , and thermal treated sample  $T_1$ . Increases in the thermosonication temperature were shown to be linked to a decrease in the microbial counts, with 60 °C producing the greatest reduction in microorganisms. Thermosonication may have altered the bacteria' cell membranes, which could explain the decline in microbial numbers in phalsa juices. By weakening and rupturing the cell membrane through the cavitation effect, TS causes the intracellular matrix to flow out, killing the microbes (Roobab et al., 2018). Our results were comparable to those of Kesavan et al. (2023), who investigated the effects of thermosonication on Kutkur juice and discovered that the TS decreased the proliferation of mold. According to another study, applying thermosonication reduced the amount of yeast and mold in bor-thequera juice (Gogoi et al., 2024).

## Conclusion

In this study, phalsa juice was treated to both ultrasonication and thermosonication in order to improve its quality in comparison to traditional pasteurization treatment. A notable increase in bioactive and antioxidant properties like TPC, TFC, TAC, and DDPH, vitamin C and anthocyanin contents was observed in ultrasonication treated samples at 5 and 10 min as compared to control and thermosonication samples, while TSS and acidity increase in ultrasonication treated samples. US may be the best option among the treatments because it improves the phalsa juice nutritional value, whereas thermosonication has certain limitation in terms of losses of bioactive compounds. A significant level of microbial inactivation was achieved in thermosonication samples during 12 days of storage as compared to other treated samples. However, most of these quality features were not favored by the higher temperature (60 °C), which may require additional treatment parameter modification for maximum quality preservation. Non-thermal processing can be regarded as a sustainable substitute for making fruit juice without additives or preservatives. Future research could be conducted for certain fruit and vegetable blends and examining the effect of

ultrasonication, and thermosonication on the sensory, microbiological safety and shelf life of these beverages.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

ZA: Methodology, Writing – review & editing. NA: Methodology, Writing – review & editing. FJ: Writing – original draft, Methodology. SHA: Methodology, Supervision, Writing – original draft. RS: Writing – original draft, Methodology. SSA: Investigation, Writing – original draft, Methodology. AAA: Data curation, Writing – review & editing, Methodology. ASA: Project administration, Methodology, Writing – original draft. RJ: Formal analysis, Methodology, Writing – review & editing. RK: Methodology, Writing – original draft, Resources. AK: Software, Methodology, Writing – original draft. FA: Writing – original draft, Methodology, Conceptualization. SQ: Writing – review & editing, Methodology, Validation.

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## Conflict of interest

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