Ultrasound as a Green Technology to Enhance the Bioactive Profile and Technological Parameters in a Functional Beverage Blend of Noni and Carambola Fruits

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Abstract

This study evaluated the effect of ultrasound (US) as a soft thermal processing or thermosonication technology to improve the properties of a functional beverage made from noni (*Morinda citrifolia*) and carambola (*Averrhoa carambola*). A 3^2 factorial design was applied with ultrasound temperatures (50-60^{o}C) and times (25-35 min). Physicochemical, bioactive, and colorimetric parameters were analyzed, modeling their responses using quadratic regression. The results showed that ultrasound significantly increased polyphenol content (up to 2200 mg FAGE/L) and antioxidant capacity (>100 μmol Trolox/g) under optimal conditions (60^{o}C/30 min), although it reduced vitamin C by 32% compared to the control. Viscosity decreased in the treated samples to 3.1 mPa s, improving product fluidity, while the pH remained stable (3.6-3.7). Predictive models showed a high fit (R^2 >95%) for antioxidants and color. It is concluded that ultrasound improves bioactive extraction and technological properties at 52.4 ^{o}C and 31.2 min at 40 kHz. This technology offers a sustainable alternative for functional beverages, although it highlights the need for a balance between maximizing bioactive compounds and preserving thermolabile components. Future studies should evaluate the sensory impact and shelf life of products optimized using this technology.

Keywords: Ultrasound; Functional Beverage; Noni; Carambola; Bioactive Compounds; Desirability function

1 Introduction

The increasing interest in functional and health-oriented foods has encouraged the food sector to explore natural ingredients with bioactive potential and to implement processing technologies capable of preserving or even improving such qualities. Within this context, tropical fruits are noteworthy due to their richness in biologically active compounds. For example, Noni (*Morinda citrifolia L.*) and carambola (*Averrhoa carambola L.*), which exhibit distinctive nutritional characteristics. Noni is particularly valued for its abundance of phytochemicals (iridoids, flavonoids, and phe-

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nolic acids) associated with antioxidant, anti-inflammatory, and immune-modulating effects (West et al., 2018). Meanwhile, carambola provides considerable amounts of vitamin C, dietary fiber, and phenolic compounds such as epicatechin and gallic acid, which contribute significantly to its antioxidant properties (Lakmal et al., 2021).

Despite their potential, the incorporation of these fruits into food matrices, specifically beverages, presents significant challenges. Noni juice has an intense, bitter flavor and aroma that can be unpleasant for many consumers, while carambola can present a pronounced astringency (Li et al., 2020). Blending both juices emerges as a viable strategy to balance their organoleptic profiles and create a synergistic beverage with a broad spectrum of bioactive compounds. However, conventional juice processing, which often involves heat treatments such as pasteurization, is effective in ensuring microbiological safety and enzymatic stability, but it entails a critical disadvantage: the degradation of thermolabile nutrients and bioactive compounds, which diminishes the nutritional and functional value of the final product (Wurlitzer et al., 2019).

This need has catalyzed the development and application of soft thermal, thermosonication or non-thermal processing technology, which are emerging as environmentally friendly and efficient alternatives for the food industry. Among these, power ultrasound (US) has gained considerable prominence. This technology is considered "green" due to its low energy consumption compared to thermal methods, the reduction in water and additive use, and its ability to operate at ambient or moderate temperatures (Bhargava et al., 2021). The mechanism of action of US is primarily based on the phenomenon of acoustic cavitation, where the formation, growth, and implosive collapse of vapor bubbles in the liquid generate microzones of high pressure and temperature, physical shear, and free radicals.

These physicochemical effects induce beneficial modifications in food matrices. At the microstructural level, ultrasound waves disrupt the cell walls of plant tissues, facilitating the release, extraction, and bioavailability of intracellular bioactive compounds (Yıkmış et al., 2020). Several investigations have reported that this approach enhances the levels of total polyphenols and flavonoids, as well as the antioxidant capacity, in different fruit juices including apple, grape, and pomegranate (Al-Dhabi et al., 2017; Bi et al., 2020; Buniowska et al., 2017; Fatima et al., 2023; Khandpur & Gogate, 2016; Pollini et al., 2020). Furthermore, US positively influences technological and product quality parameters: it can homogenize the mixture, reduce viscosity, inhibit pectinolytic enzymes that cause phase separation, and thus improve the colloidal stability and shelf-life of the beverage, without compromising its fresh sensory characteristics (Guerrouj et al., 2016).

While ultrasound has been investigated individually in noni and carambola fruit for compound extraction, there is a knowledge gap regarding its application as a direct processing treatment in a functional beverage blend of these two fruits. It is crucial to comprehensively evaluate how this eco-friendly technology not only modulates the bioactive profile (polyphenols, vitamin C, antioxidant capacity) but also its impact on key technological properties such as color, turbidity, suspension stability, and physicochemical parameters (pH, acidity, soluble solids) that define the acceptability and final quality of the product. Therefore, the objective of this study was to evaluate the effect of ultrasound treatment on the bioactive profile and technological parameters of a functional beverage based on a blend of noni and carambola fruit, positioning it as a sustainable and effective technology for the development of innovative and healthy foods.

2 Materials and Methods

2.1 Fruits material

Ripe fruits of noni (*Morinda citrifolia L.*) and carambola (*Averrhoa carambola L.*) were obtained from the Moshoqueque wholesale market in the José Leonardo Ortiz district, Chiclayo, Peru (20 m a.s.l., $6^o45'17.3"$S, $79^o50'32.3"$W). Samples were chosen based on consistent size and color, and only fruits free from visible defects or microbial contamination were included.

Figure 1: Fruits of noni (*Morinda citrifolia*) (a) (Martínez, 2019) and carambola (*Averrhoa carambola*) (b) (HerbaZest, 2023).

2.2 Juice preparation and beverage formulation

The fruits underwent washing and disinfection prior to extraction. Initially, they were washed manually with potable water to remove surface impurities. They were then immersed in a sodium hypochlorite solution (220 ppm) for 10 minutes, rinsed with potable water, and dried at room temperature (25 ± 2^{o}C).
To obtain noni juice, the exudate naturally released by ripe fruits was collected. To obtain carambola fruit juice, the disinfected fruits were mechanically processed. The juice was extracted by pressing and successively filtered through a sieve to remove seeds, coarse particles, and chaff, obtaining a clear extract. The functional beverage was formulated by blending noni and carambola juices at a constant ratio of 75:25 (v/v). Each juice was previously characterized, and the uniform mixtures were kept at -20 ^{o}C until further analysis.

2.3 Application of ultrasonic treatment

Ultrasound processing was carried out in an ultrasonic cleaner (Cole-Palmer 8892, Illinois, USA) operating at 40 kHz. A complete 3^2 factorial design was employed, considering two variables at three levels: temperature (50, 55 and 60 ^{o}C) and treatment time (25, 30 and 35 min), resulting in nine experimental conditions (T1-T9) (Table 1). For each condition, 100 mL of the juice blend was transferred into a beaker and sonicated under constant volume and immersion depth. Control samples [Noni juice (N), Carambola juice (C) and noni-carambola juice (N+C)], without ultrasound exposure, were held at the same temperature and time to exclude thermal influence. All experiments were performed in triplicate.

Table 1: 3^2 factorial experimental design.

Treatment	Coded variables		Decoded variables	
	Factor A	Factor B	Factor A	Factor B
T1	-1	-1	50	25
T2	-1	0	50	30
T3	-1	1	50	35
T4	0	-1	55	25
T5	0	0	55	30
T6	0	1	55	35
T7	1	-1	60	25
T8	1	0	60	30
T9	1	1	60	35

Factor A: Temperature (^{o}C) and Factor B: Time (min)

2.4 Physicochemical analysis

The pH was assessed by direct potentiometry following AOAC Method 981.12 (Latimer, 2016). Total soluble solids (°Brix) were determined using a digital refractometer according to AOAC Method 932.12 (Latimer, 2016). Titratable acidity was measured by titration with 0.1 N NaOH up to pH 8.1 following AOAC Method 945.15 (Latimer, 2016). The results were expressed as citric acid equivalents for carambola and the juice blend, and as tartaric acid equivalents for noni.

2.5 Viscosity determination

Apparent viscosity (η) was determined at 25.0 ± 0.1 °C with a vibrating viscometer (SV-10A, A&D Company, Tokyo, Japan). Each measurement used 45 mL of sample, and results were reported in mPa·s.

2.6 Color analysis

The color of the samples was quantified using a digital colorimeter (Model NS800, 3NH Technology, Guangzhou, China) in the CIE L*a*b color space. Luminosity (L), red/green coordinate (a), and yellow/blue coordinate (b) values were recorded for the pure juices, the control blend, and all ultrasonic treatments. Furthermore, the color variation was determined using the standard CIELAB equation: $\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]1/2$, taking the untreated mixture (N+C) as a reference.

2.7 Analysis of bioactive compounds and antioxidant activity

Total phenolic compounds

Quantification of these compounds was carried out following the Folin-Ciocalteu procedure described by Singleton et al. (1999). The diluted extract was reacted with Folin-Ciocalteu reagent and sodium carbonate solution, then incubated in the dark for 60 min. Absorbance was read at 765 nm, and results were expressed as mg gallic acid equivalents per liter of juice (mg GAE/L), based on a calibration curve (y = 0.0004x + 0.0077; R^2 = 0.9987).

Total flavonoids

Flavonoid concentration was evaluated through the aluminum chloride ($AlCl_3$) colorimetric assay. The sample aliquot was sequentially mixed with $NaNO_2$, $AlCl_3$, and NaOH, and absorbance was recorded at 415 nm after the reaction period. Quantification was based on a rutin standard curve (0-500 mg/L), and results were expressed as mg rutin equivalents per liter of juice (mg RE/L) (y = 0.0012x + 0.0059; R^2 = 0.9979).

Antioxidant capacity ($ABTS^+$)

Antioxidant capacity was determined using the $ABTS^+$ radical cation assay following the procedure of Re et al. (1999). The radical was produced by combining 7 mM ABTS with 2.45 mM potassium persulfate. After adding the sample or Trolox standard to the diluted radical solution, absorbance reduction at 734 nm was recorded after 6 min. Results were expressed as μmol Trolox equivalents per liter of juice (μmol TE/L) using a calibration curve (y = -0.0021x + 0.559; R^2 = 0.996).

Ascorbic acid (Vitamin C) content

Vitamin C content was determined using high-performance liquid chromatography with diode-array detection (HPLC-DAD, Nexera X2, Shimadzu, Santa Clara, USA). Separation was carried out on a Shim-pack GIST C18 column (150 × 4.6 mm, 5 μm) at 30 °C, employing a 50 μM orthophosphoric acid mobile phase at 1.0 mL/min. Detection was conducted at 254 nm, and quantification was achieved by comparison with a pure L-ascorbic acid standard (y = 3227.1x - 114647; R^2 = 0.9998).

2.8 Statistical analysis

The data obtained from the 3^2 factorial design were analyzed using analysis of variance (ANOVA), and the global desirability function was used to optimize process conditions (temperature and time) that simultaneously maximized the responses of interest (bioactive compounds and technological parameters). Data analysis was conducted using the trial version of STATISTICA 12.0 (StatSoft Inc., USA). All experiments were carried out in triplicate, and results are reported as mean ± standard deviation.

3 Results and Discussion

3.1 Characteristics of the untreated juices and juice blend

The bioactive compounds, physicochemical parameters, and color characteristics (Table 2) of the noni, carambola, and noni-carambola fruit blend (75:25) juices were analyzed before ultrasound treatment. Initial characterization revealed significant differences and synergistic effects among the blend components. Noni juice exhibited the highest concentration of total polyphenols (1737.42 mg AGE/L) and vitamin C (825.94 mg/L), consistent with its description as a source of antioxidants (West et al., 2018). The blend showed an even higher value of polyphenols (1907.42 mg AGE/L) than pure noni. This synergy phenomenon, where the blend value exceeds the weighted average of its components, suggests a possible interaction that increases the extraction or stabilization of these compounds, or a reduction of interferences in the Folin-Ciocalteu assay (Shahidi & Zhong, 2015). Despite having a lower polyphenolic content, carambola fruit juice showed a significantly higher antioxidant capacity (ABTS) (98.93 μM TE/L) than noni (79.90 μM TE/L). This indicates the presence of potent antioxidants not necessarily captured by the total polyphenol assay, such as vitamin C or carotenoids, which contribute significantly to neutralizing the $ABTS^{+}$ radical (Lakmal et al., 2021). The blend maintained a similar antioxidant activity to noni (81.77 μM TE/L).

The physicochemical profile presented the acidic character typical of both fruits, with carambola fruit being extremely acidic (pH 2.23). The blend resulted in a pH of 3.62, a more balanced and sensorially acceptable value. The viscosity of the blend (3.24 mPa s) was lower than that of the individual juices, possibly due to dilution and physicochemical interactions between the components. The color parameters (CIE L*a*b space) reflect the differences between the juices. Noni is characterized by low luminosity (L = 17.47) and negative b* values (a tendency toward negative blue/yellow), while carambola fruit has a positive a* value (a tendency toward red/magenta). The blend inherits properties from both, resulting in a darker, less intense color than pure carambola fruit, but with a more reddish/yellowish hue than pure noni.

3.2 Characteristics of the Ultrasound-Treated Juice Blends

Physicochemical Parameters

Ultrasonic treatment significantly influenced the physicochemical properties of the juice blends (Figure 2). Total soluble solids (^{o}Brix) increased significantly in the ultrasonic treatments compared to the controls, with the highest value observed at T8 (60 ^{o}C, 30 min) (Fig. 2a). The contour plot (Fig. 2b) indicated that optimal conditions were reached at 60 ^{o}C and 30 min, which can be attributed to the cavitation-induced release of intracellular compounds (Bhargava et al., 2021; Chemat et al., 2017). The pH remained stable (3.6-3.7) in all sonication treatments, showing no significant differences compared to the N+C control (pH 3.6) (Fig. 2c). Carambola fruit juice (C) had the lowest pH (2.2), while noni juice (N) had the highest (3.9). The contour plot (Figure 2d) shows that the pH remained constant across the range of temperatures (48-62 ^{o}C) and times (24-36 min), with a slight tendency towards higher values under intermediate conditions. Ultrasound did not alter the natural acidity of the system, as reported in various investigations (Abid et al., 2014; Gani et al., 2016). The titratable acidity showed moderate variations (0.61-0.72%), reaching a maximum at T5 (55 ^{o}C, 30 min) (Fig. 2e). The contour plot (Fig. 2f) shows that the maximum acidity is reached under intermediate conditions of time (30 min) and temperature (55-58 ^{o}C). This increase suggests an ultrasound-enhanced release of organic acids from the cell matrix under in-

Table 2: Bioactive compounds, physicochemical properties, and color characteristics of the noni-carambola fruit juices and blend.

Determination	Sample		
	Noni	Carambola	Noni-Carambola blend
Bioactive compounds			
Total polyphenols (mg AGE/L)	1737.42 ± 24.28	787.42 ± 3.82	1907.42 ± 10.41
Total flavonoids (mg RE/L)	702.56 ± 9.62	702.56 ± 5.09	555.89 ± 9.62
Antioxidant capacity by ABTS (uMol Trolox/g)	79.90± 2.43	98.93 ± 2.76	81.77 ± 10.54
Physicochemical			
Total soluble solids (°Brix)	6.78 ± 0.01	7.35 ± 0.11	6.77± 0.11
pH	3.95 ± 0.06	2.23 ± 0.01	3.62 ± 0.14
Titratable acidity (%)	0.64 ± 0.01	0.81 ± 0.03	0.64 ± 0.01
Vitamina C (mg Ac. Ascorbic/L juice)	825.94 ± 12.84	131.90 ± 1.81	597.96 ± 3.21
Viscosity (mPa.s)	4.05 ± 0.02	4.10 ± 0.01	3.24 ± 0.01
Color characteristic			
L	17.47 ± 2.16	11.26 ± 0.63	16.96 ± 4.06
a*	-1.00 ± 2.80	4.82 ± -0.63	3.41 ± 1.77
b*	-15.78 ± 1.61	-9.60 ± 4.89	-4.98 ± 5.12

Mean and standard deviation data

termediate temperature and time conditions (Tiwari et al., 2009; Zafra-Rojas et al., 2013). The viscosity decreased significantly in the treated samples, especially at T9 (60 °C, 35 min), which had the lowest value (3.1 mPa s) (Fig. 2g). This reduction is likely due to the depolymerization of polysaccharides and the alteration of colloidal structures under intense sonication, potentially improving colloidal stability and sensory acceptability (Hooshyar et al., 2020; Rawson et al., 2011). The contour plot (Figure 2h) confirms this trend, showing that the lowest viscosity is achieved at longer times (≥ 30 min) and higher temperatures (≥ 58 °C), while intermediate conditions allow for greater consistency.

Colorimetric Parameters

Ultrasonic treatment significantly influenced ($p < 0.05$) the colorimetric properties of the juice blends (Figure 3). Lightness (L*) was highest at T2 (50 °C, 30 min) (Fig. 3a), attributed to particle size reduction and improved pigment dispersion through acoustic cavitation (Chemat et al., 2011). In contrast, treatments at higher temperatures and longer durations (T7-T9) showed reduced L*, likely due to ultrasound-induced non-enzymatic browning. The contour plot (Fig. 3b) confirmed that the minimum L* occurred at >58 °C and >32 min, while intermediate conditions (55-57 °C; 28-30 min) preserved lightness. For the parameter a* (red-green coordinate), T1 and T3 presented the highest values (Fig. 3c), suggesting increased release of phenolic compounds or anthocyanins ((Chemat et al., 2017). Negative a* values at T5 and T9 indicated pigment degradation under intense processing conditions. The contour plot (Fig. 3d) showed maximum a* at low temperatures (48-50 °C) and short times (<26 min), with degradation at higher intensities. The parameter b* (yellow-blue coordinate) reached its maximum at T2 (50 °C, 30 min) (Fig.3e), indicating the preservation of yellow flavonoids or carotenoids (Chemat et al., 2011). Prolonged or high-temperature treatments (T6-T9) resulted in negative b* values, reflecting pigment degradation. The optimal b* value was observed at 48-52°C and 30 min (Fig. 3f). All ultrasound treatments (T1-T9) (Fig. 3g) induced significant color changes (ΔE* > 3) (Fig. 3h),

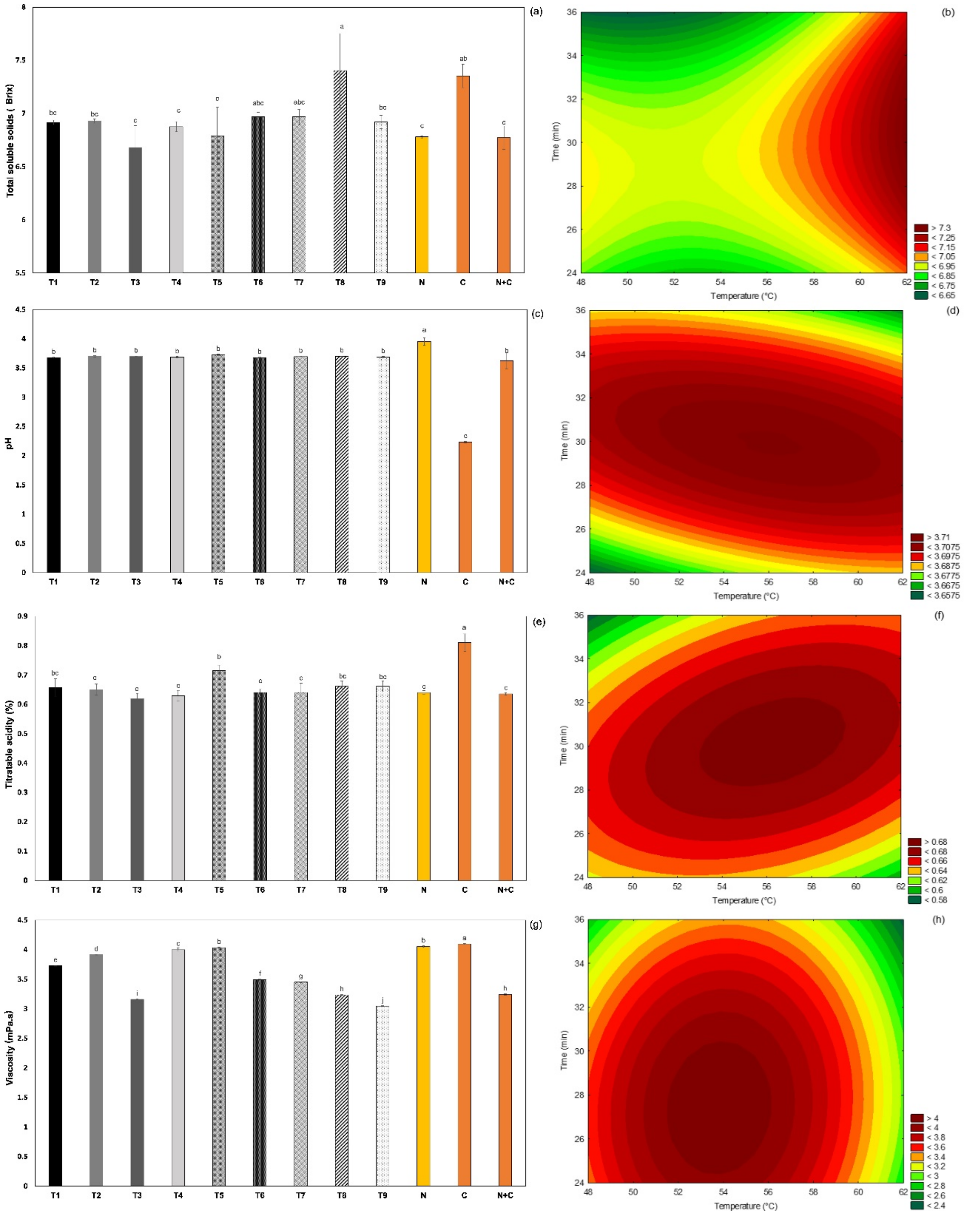

Figure 2: Effect of ultrasound-assisted treatment on noni and carambola fruit blends on: (a, b) total soluble solids, (c, d) pH, (e, f) titratable acidity, and (g, h) viscosity, of the different treatments (T1-T9) with their respective contour plots as a function of temperature and time, compared to untreated samples (N: noni beverage, C: carambola fruit beverage, N+C: noni and carambola fruit blend).

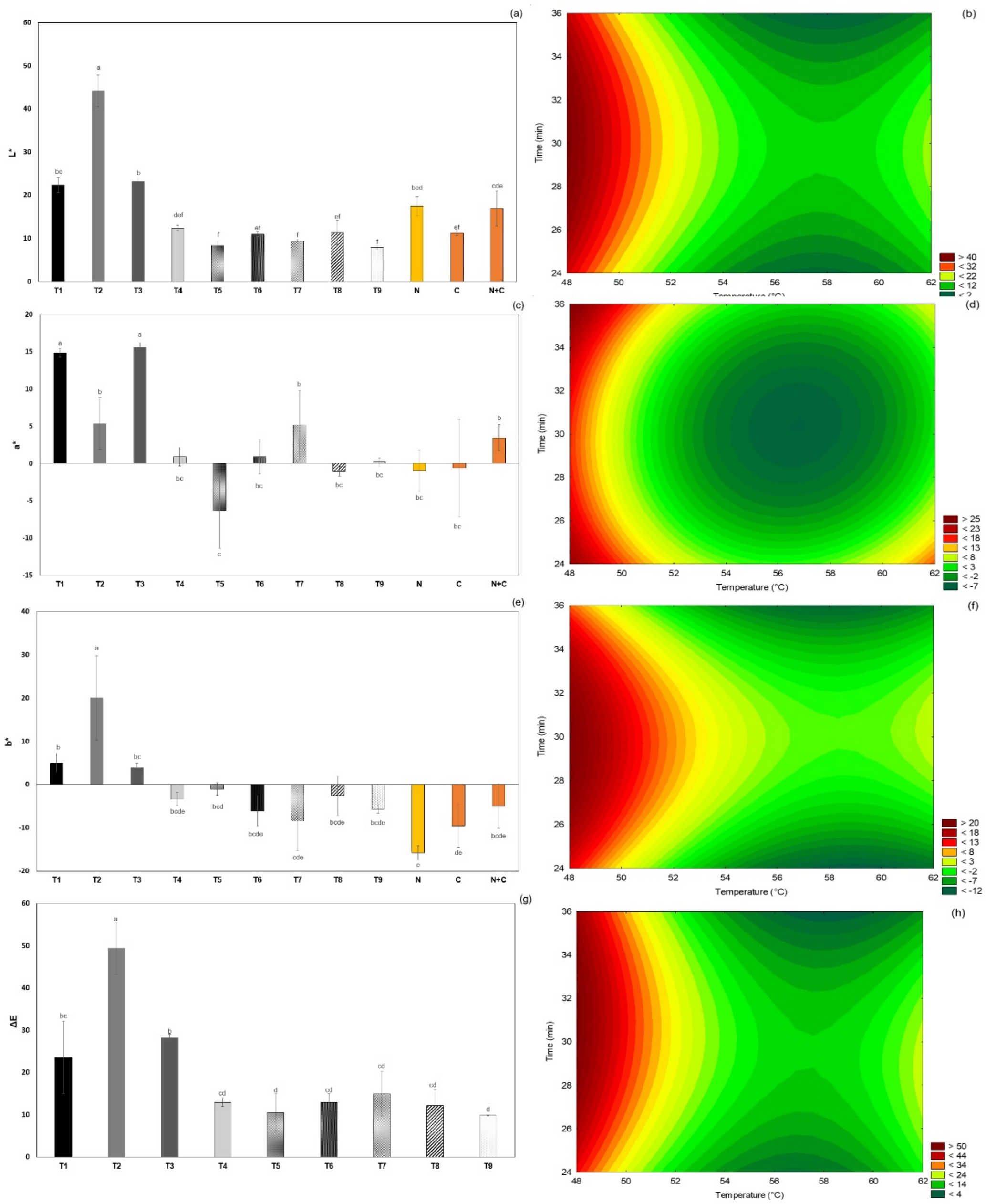

Figure 3: Effect of ultrasound-assisted treatment on noni and carambola fruit blends on: (a, b) Lightness - L*, (c, d) Redness - a*, (e, f) Yellowness - b*, and (g, h) ΔE, of the different treatments (T1-T9) with their respective contour plots as a function of temperature and time, compared to untreated samples (N: noni beverage, C: carambola fruit beverage, N+C: noni and carambola fruit blend).

with the most extreme conditions (T8 and T9: 60 ^{o}C/30-35 min) producing the greatest differences ($p < 0.05$). This notable increase in ΔE^* suggests the occurrence of non-enzymatic browning reactions and pigment degradation under intense thermosonication conditions. Treatments with moderate parameters (T1, T4-T6) showed minor alterations, demonstrating that optimizing temperature and time is crucial to minimizing unwanted sensory changes while maintaining the benefits of ultrasound processing. These results reveal the dual role of ultrasound in enhancing or degrading color attributes, emphasizing the need to optimize parameters to preserve visual quality in functional beverages (Jadhav et al., 2021; Tiwari et al., 2009).

Bioactive Compounds

Ultrasonic treatment significantly improved the extraction of bioactive compounds compared to untreated controls (N, C, N+C) (Figure 4). Total phenolic content peaked at T8 (60 ^{o}C, 30 min), exceeding 2200 mg EAG/L, while T6 and T7 showed lower values, indicating possible degradation under extreme conditions (Fig. 4a). The contour plot (Fig. 4b) identified an optimal zone at 55-60 ^{o}C and 30 min, consistent with efficient cell disruption by acoustic cavitation (Medina-Meza et al., 2016; Tiwari et al., 2010). Total flavonoids were highest in T3 (50 ^{o}C, 35 min) and T6 (55 ^{o}C, 35 min), exceeding 800 mg EAG/L (Fig. 4c). The contour plot (Fig. 4d) revealed optimal extraction at lower temperatures (≈50-52 ^{o}C) and longer times (≈34-36 min), emphasizing the need to avoid oxidative degradation (Chemat et al., 2017; Tiwari et al., 2009). Antioxidant activity (ABTS) was highest in T7-T9 (>100 μmolTrolox/g), significantly exceeding untreated samples (Fig. 4e). The contour plot (Fig. 4f) showed maximum activity at higher temperatures (60-62 ^{o}C) and longer times (≈34-36 min), likely due to enhanced release of bound phenolics (Rawson et al., 2011; Zhang et al., 2023). In contrast, vitamin C content decreased in all sonication treatments (530-560 mg/L) compared to untreated noni juice (>800 mg/L) (Fig. 4g). The contour plot (Fig. 4h) confirmed a downward trend with increasing temperature and time, reflecting thermal degradation. Nevertheless, ultrasound preserved a substantial fraction of ascorbic acid compared to conventional thermal processing (Bhat et al., 2011; Kentish & Feng, 2014).

3.3 Statistical Analysis and Predictive Model Fit

The analysis of variance (ANOVA) and regression coefficients for the fitted quadratic models are presented in Table 3. The models exhibited varying degrees of fit depending on the R^2 values, being particularly predictive for the color parameter a* ($R^2 = 96.65\%$), ascorbic acid ($R^2 = 96.83\%$), and antioxidant capacity ($R^2 = 95.05\%$), indicating a strong influence of ultrasound parameters on these properties. In contrast, total soluble solids ($R^2 = 56.42\%$) and total flavonoids ($R^2 = 66.09\%$) showed moderate predictability, suggesting greater complexity or the influence of external factors.
The p values revealed distinct patterns in the responses. For viscosity, significant quadratic and interaction effects ($p < 0.05$) indicated nonlinear behavior, associated with temperature- and time-induced structural changes. The a* color demonstrated high sensitivity to ultrasound conditions, with highly significant linear and quadratic terms ($p < 0.01$) reflecting the optimization of pigment stability under specific parameter combinations. The antioxidant capacity showed a predominance of significant linear terms ($p < 0.01$), confirming efficient antioxidant release by cavitation, although with possible degradation processes under extreme conditions. Ascorbic acid presented significant linear and quadratic terms ($p < 0.05$), confirming its sensitivity to thermal degradation during treatment. For total phenols and flavonoids, nonsignificant terms ($p > 0.05$) together with moderate R^2 values suggest that factors external to ultrasound, such as raw material variability, may affect these responses. However, the significant interaction for total phenols ($p < 0.05$) highlights the synergy between temperature and time in the extraction of these compounds. The models provide valuable information for process optimization, indicating that maximizing antioxidant capacity requires moderate ultrasound conditions,

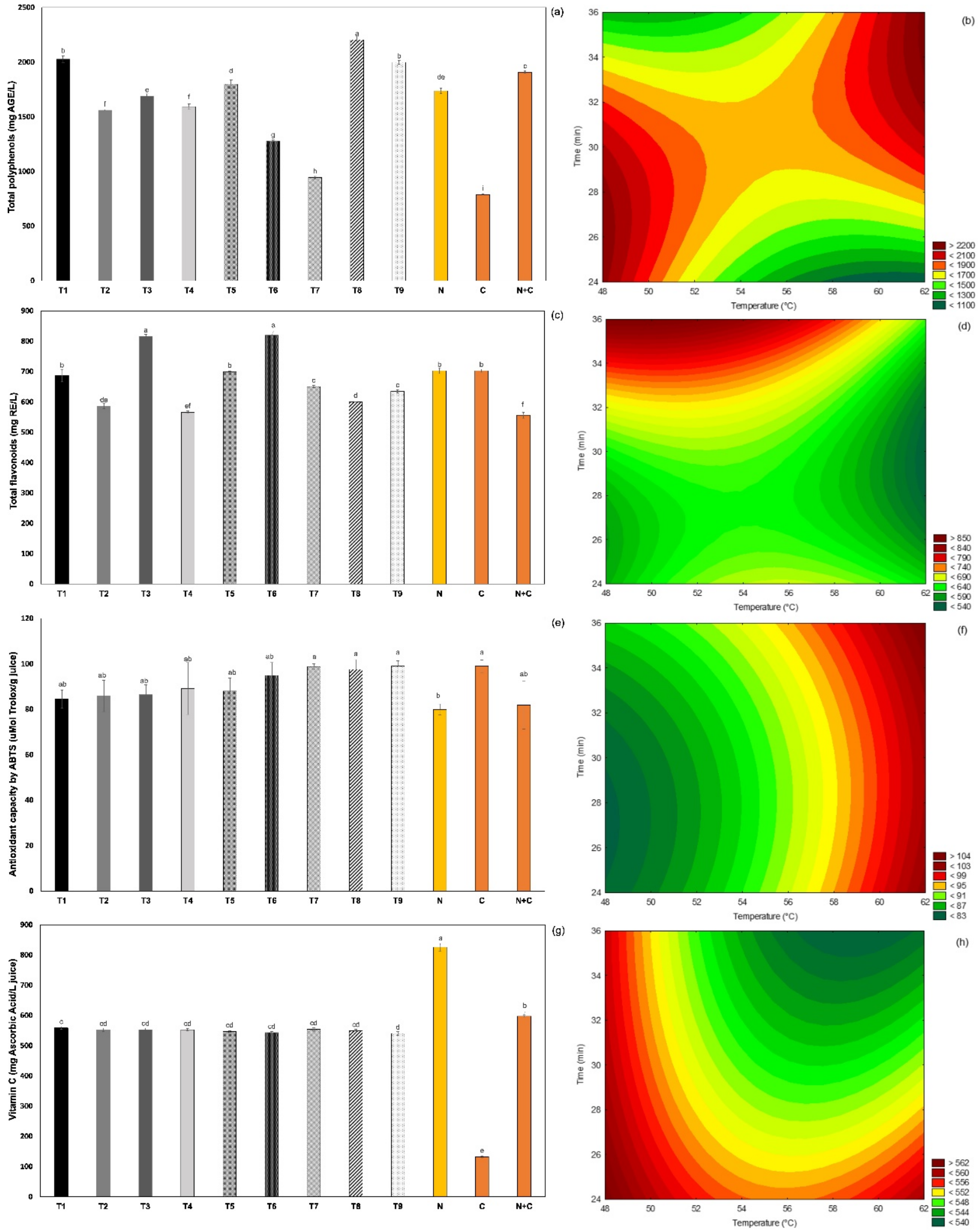

Figure 4: Effect of ultrasound-assisted treatment on noni and carambola fruit blends on: (a, b) total polyphenol content, (c, d) total flavonoid content, (e, f) antioxidant capacity by ABTS, and (g, h) vitamin C, of the different treatments (T1-T9) with their respective contour plots as a function of temperature and time, compared to the untreated samples (N: noni drink, C: carambola drink, N+C: noni and carambola fruit blend).

Table 3: Statistical parameters and predictive models obtained using 3^2 factorial design.

Model parameter	ANOVA					R^2
	Linear		Quadratic		Interaction	
	X1: Temperature	X2: Time	X1: Temperature	X2: Time	X1*X2	
Physicochemical						
Viscosity (V)	0.074	0.0338	0.0356	0.12	0.657	92.89
Total soluble solids (TSS) (°Brix)	0.237	0.735	0.587	0.386	0.691	56.42
pH	0.842	0.889	0.761	0.124	0.379	80.77
Titrable acidity (TA) (%)	0.622	0.929	0.541	0.169	0.351	63.42
Colorimeter						
L	0.0629	0.929	0.229	0.338	0.897	46.47
a*	0.0096	0.485	0.00127	0.0201	0.278	96.65
b*	0.0273	0.9255	0.188	0.093	0.706	89.37
Bioactive compounds						
Total polyphenols (TP)	0.908	0.717	0.582	0.431	0.192	58.33
Flavonoides Totales (TF)	0.417	0.189	0.64	0.362	0.473	66.09
Antioxidant capacity (AC)	0.0053	0.236	0.451	0.363	0.703	95.05
Ascorbic acid (AA)	0.014	0.0059	0.051	0.504	0.0986	96.83
Regression equations						
V = 3.56 - 0.35*X1 + 0.42*X12 - 0.49*X2 + 0.25*X22 + 0.08*X1*X2						
TSS = 6.93 + 0.25*X1 - 0.09*X12 - 0.06*X2 + 0.15*X22 + 0.09*X1*X2						
pH = 3.69 + 0.003*X1 + 0.003*X12 + 0.002*X2 + 0.021*X22 - 0.015*X1*X2						
TA = 0.65 + 0.012*X1 + 0.013*X12 - 0.002*X2 + 0.03*X22 + 0.029*X1*X2						
L = 16.67 - 20.34*X1 - 9.17*X12 - 0.67*X2 + 6.91*X22 - 1.21*X1*X2						
a* = 3.93 - 10.52*X1 - 8.22*X12 - 1.41*X2 -6.95*X22 - 2-87*X1*X2						
b* = 0.18 - 15.20*X1 - 5.54*X12 - 0.38*X2 + 7.93*X22 + 1.91*X1*X2						
TP = 1676.86 - 42.50*X1 - 180.42*X12 + 134.72*X2 + 266.25*X22 - 696.67*X1*X2						
TF = 673.17 - 67.78*X1 + 32.41*X12 + 122.22*X2 - 67.04*X22 - 72.22*X1*X2						
AC= 91.55 + 12.87*X1 - 1.32*X12 + 2.59*X2 - 1.63*X22 - 0.91*X1*X2						
AA = 549.84 - 7.05*X1 - 3.72*X12 - 9.59*X2 - 0.89*X22 - 3.96*X1*X2						

while minimizing ascorbic acid degradation requires shorter and less intense treatments.

3.4 Determination of ultrasonic temperature and time to improve bioactive compounds and technological parameters

The desirability function (Fig. 5) integrates the response variables to identify the experimental conditions that maximize the bioactive compounds and technological quality of the noni and carambola fruit functional beverage. The contour plot (Fig. 5a) shows that the highest desirability values (>0.4) are concentrated in an intermediate range of time (28-32 min) and temperature (50-58 ^oC), while under extreme processing conditions (short times <26 min or long times >34 min, and low temperatures <50 ^oC or high temperatures >60 ^oC) desirability decreases dramatically (<0.05). The surface plot (Fig. 5b) confirms this trend, showing a broad optimal point in the central zone, indicating a robust and reproducible operating window to simultaneously maintain adequate levels of these study variables. Finally, the appropriate experimental conditions were applied using ultrasound treatment at 52.4^oC for 31.2 min, with a desirability value of 0.59. This result highlights the usefulness of ultrasound as a process intensification tool, capable of improving multiple quality

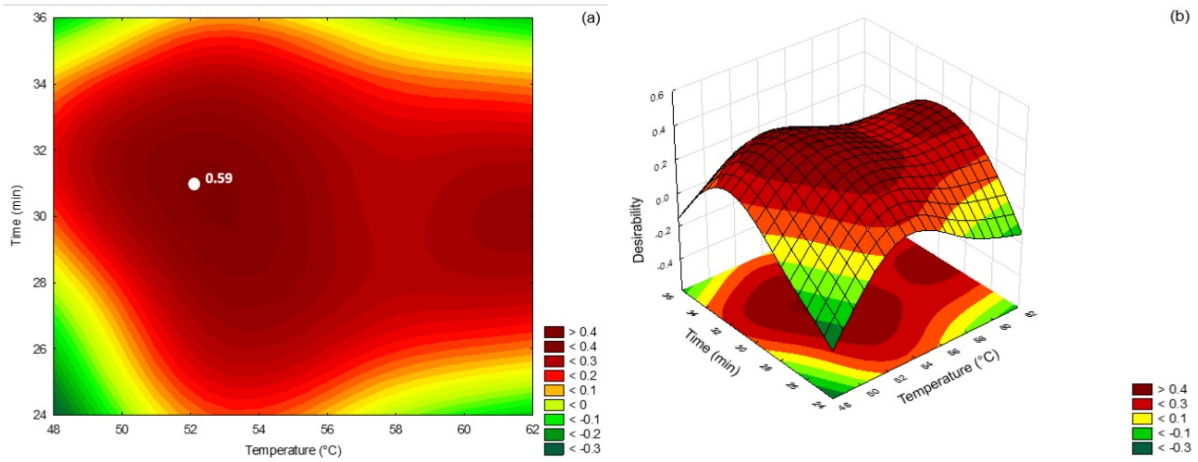

Figure 5: Desirability response maps for improving ultrasound-assisted treatment conditions in the noni and carambola fruit blend as a function of temperature and time.

attributes in a single processing step, in line with what has been reported in previous studies on the application of statistical design methodologies and desirability criteria in functional beverages and fruit juices (Baş & Boyacı, 2007; Bevilacqua et al., 2018). Furthermore, the existence of a broad optimum zone provides technological advantages for industrial scalability, reducing the process' sensitivity to small variations in time or temperature, which is key to a sustainable production approach.

4 Conclusion

The study demonstrates that ultrasound treatment is an effective technology for modulating the physicochemical, bioactive, and colorimetric properties of functional beverages based on a blend of noni and carambola fruit. Processing conditions (temperature and time) significantly impact each parameter evaluated. The stability of pH and titratable acidity confirm that ultrasound preserves the product's natural acidic characteristics, which is crucial for its microbiological stability. Furthermore, the controlled viscosity reduction improves the rheological properties of the final product. Color parameters (L, a, b*) showed high sensitivity to processing conditions, with optimal zones identified for preserving luminosity and color intensity. Regression models showed high predictive power ($R^2 > 95\%$) for key variables such as antioxidant activity, ascorbic acid, and the a* color coordinate, validating the robustness of the experimental approach. However, the variability in soluble solids and flavonoids suggests the influence of additional factors not considered in the model. The desirability function allowed to identify that temperatures between 50-55 ^oC and times of 30-35 minutes maximize the extraction of polyphenols and antioxidant capacity (recommending 52.4 ^oC and 31.2 min of ultrasound treatment), while values above 60 ^oC and prolonged times favor the degradation of thermolabile compounds such as vitamin C.

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