

Effect of ultrasound and pasteurisation on the structure and visual quality of black elderberry juice

*Anita Avena, Liene Ozola, Anete Ķeķe

Latvia University of Life Sciences and Technologies, Lielā iela 2, Jelgava, Latvia

Abstract. Black elderberry juice is rich in polyphenols but tends to form a visually unappealing, cloudy precipitate, which is unappealing to consumers. This study aimed to evaluate how high-intensity ultrasound combined with lower-temperature pasteurisation affects the particle size distribution, turbidity, centrifugal sedimentation rate, viscosity, and colour of black elderberry juice. Ultrasound alone reduced the particle mean diameter ($D_{4,3}$) values, indicating the deagglomeration of cell clusters and the formation of finer particles, while slightly decreasing centrifugal sedimentation. After ultrasound treatment (UT) and pasteurisation at 60–70 °C, particle size and the centrifugal sedimentation rate increased. Turbidity decreased to approximately 40 NTU, yielding clarified juice with large, dense aggregates that settled.

In contrast, prolonged UT combined with pasteurisation at 60–70 °C significantly reduced $D_{4,3}$ and increased turbidity to 425 NTU, indicating a fine, stable colloidal cloud. Colour analysis showed that UT followed by pasteurisation at 60 °C enhanced redness and chromatic hue. In contrast, prolonged UT and 70 °C temperature pasteurisation produced darker, less vivid red tones, consistent with partial pigment degradation and polymerisation. The results revealed two technological pathways within the same juice matrix: a clarification pathway (ultrasound + pasteurisation) and a cloud stabilisation pathway (extended ultrasound + pasteurisation), offering a tool for developing elderberry juices with the desired visual outcome.

Key words: *Sambucus nigra*; sonication; thermosonication; turbidity; sedimentation; colloidal stability.

Introduction

Black elderberry (*Sambucus nigra* L.) berries are a biologically valuable plant raw material with a high content of anthocyanins, phenolic acids, flavonols, vitamins, and fibre, which contribute to the pronounced antioxidant, anti-inflammatory, and antiviral effects of these berries (Avena, Ozola & Ķeķe, 2024; Deniz & Suna, 2025; Domínguez *et al.*, 2020; Haş *et al.*, 2023; Ren *et al.*, 2024; Terzi *et al.*, 2023).

Studies have shown that elderberry berry and flower extracts reduce cellular oxidative stress, inhibit inflammatory processes, and can reduce the duration and severity of symptoms of upper respiratory tract infections, including influenza (Boroduške *et al.*, 2022; Ferreira *et al.*, 2022; Osman *et al.*, 2023). The polyphenol complex present in elderberries, especially anthocyanins (such as cyanidin-3-glucoside) and phenolic acids, as well as lectins and other bioactive compounds, has been associated with antiviral, antibacterial, antidiabetic, cardioprotective,

neuroprotective, and anticancer activities, which makes these berries a promising raw material for the development of functional food products (Banach *et al.*, 2021; Deniz & Suna, 2025; Ferreira-Santos *et al.*, 2022; Przybylska-Balcerek *et al.*, 2021; Ren *et al.*, 2024).

However, the literature emphasises that elderberry products should be produced using appropriate processing technologies to minimise the presence of potentially toxic cyanogenic glycosides and lectins while maximising the retention of health-promoting compounds. This can be achieved through mild thermal processing regimes and modern processing solutions, such as ultrasound and fermentation (Appenteng *et al.*, 2021; Avena, Ozola & Ķeķe 2024; Rodríguez Madrera & Suárez Valles, 2021; Senica *et al.*, 2016).

Ultrasonic technology has emerged in recent years as a very promising non-thermal or mild thermal (thermosonication) approach for the processing of fruit

* Corresponding Author's email address:
 anita.avena@gmail.com

DOI: 10.2478/plua-2026-0006

© 2026 Anita Avena et. al. This is an open access article licensed under the Creative Commons Attribution-NonCommercial-NoDerivs License (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

and vegetable juices, as the mechanical and chemical effects induced by acoustic cavitation allow for the efficient inactivation of microorganisms and enzymes (polyphenol oxidase and pectin methylesterase), while reducing the processing time and energy consumption compared to conventional pasteurisation (Lepaus *et al.*, 2023; Li *et al.*, 2025; Yıkımsı *et al.*, 2025; Zhang *et al.*, 2024).

Unlike classical thermal processing, which often reduces the content of vitamin C, carotenoids, phenolic compounds and anthocyanins, ultrasound and thermosonication often maintain or even increase the measurable content of total phenolic compounds, flavonoids, carotenoids, and anthocyanins, as cavitation disrupts cell walls, promotes the release of intracellular compounds into the juice, and reduces particle size, thus improving the extraction and bioavailability of bioactive components in various juices, including citrus, berry, spinach, tomato, and broccoli juices (Demesa *et al.*, 2024; Lepaus *et al.*, 2023; Yıkımsı *et al.*, 2025; Zhang *et al.*, 2024).

Studies have shown that ultrasound and thermosonication can achieve antioxidant activity comparable to or even higher than that of thermal processing, while better preserving the colour, aroma, and cloud stability of the juice. They also improve rheological behaviour and particle stability, which are crucial for consumer perception and shelf life (Avena, Ozola & Ķeķe 2024; Lepaus *et al.*, 2023; Yıkımsı *et al.*, 2025).

Furthermore, combined strategies, such as ultrasound with moderate heating (thermosonication) or the integration of ultrasound with other novel non-thermal methods, enable processors to achieve pathogen reduction while maintaining “fresh-like” quality and aligning with clean-label and sustainable processing trends (Lepaus *et al.*, 2023; Yıkımsı *et al.*, 2025). Recently published studies on the thermosonication of vegetable and fruit juices have shown that carefully selected parameters of

frequency, amplitude, temperature, and time can simultaneously maximise the main phytochemical markers such as lycopene, β-carotene, ascorbic acid, and total phenolics, and ensure microbiological safety, confirming ultrasound and thermosonication as suitable new technologies in juice processing studies (Yıkımsı *et al.*, 2025; Zhang *et al.*, 2024).

This study, therefore, aims to investigate how high-intensity ultrasound, applied alone and in combination with lower-temperature pasteurisation, affects the particle size distribution, turbidity, sedimentation behaviour, viscosity, and colour properties of black elderberry juice, to identify technological approaches for either juice clarification or stable cloud formation that can be used to tailor visually appealing elderberry beverages for consumers.

Unlike previous studies that aim to maximise cloud stability or minimise sedimentation, this study demonstrates that black elderberry juice exhibits two distinct and controllable colloidal trajectories – clarification or stable cloud formulation – depending on ultrasound exposure before pasteurisation. This process-driven bifurcation has not been previously reported for anthocyanin-rich berry juices.

Materials and Methods

The frozen black elderberries used for the experiment were sourced from Ukraine. The berries were thawed at 18 ± 3 °C for 12 hours. After thawing, the berries were processed using a hydraulic juicer model 180P2 (Voran Maschinen GmbH, Austria) for 2 hours. Immediately following juice extraction, the juice was treated with ultrasound and then pasteurised. A total of seven samples were obtained and analysed for the experiment. The processing parameters of the obtained samples are presented in Table 1.

Ultrasound treatment

The obtained juice was processed using an ultrasonic processor UIP2000hdT (Hielscher

Table 1
Processing parameters of black elderberry juice samples

Sample abbreviation	Processing parameters
Untreated	No treatment
U50	Ultrasound treatment for 50 min.
U50+P60	Ultrasound treatment for 50 min. and pasteurised at 60 °C
U50+P70	Ultrasound treatment for 50 min. and pasteurised at 70 °C
U70	Ultrasound treatment for 70 min.
U70+P60	Ultrasound treatment for 70 min. and pasteurised at 60 °C
U70+P70	Ultrasound treatment for 70 min. and pasteurised at 70 °C

Ultrasonics GmbH, Germany), equipped with a CS4d40L3 probe with an active surface of 33 cm². 100 L of each juice sample was treated with ultrasound in a flow cell reactor equipped with a cooling jacket to maintain the juice temperature below 20 ± 2 °C. Ultrasound treatment (UT) was performed at a 100% amplitude level, corresponding to an amplitude of 49 µm for 50 or 70 min.

Pasteurisation

After UT, the juice was pasteurised in a flow-through system using a PA1500 pasteuriser (Voran Maschinen GmbH, Austria) for 15 seconds at 60 ± 3 °C or 70 ± 3 °C. It was then filled into 250 mL plastic bottles and sealed. All the obtained juice samples were stored in a dark, cool place (6 ± 2 °C) for one month before analysis.

Particle size measurements

Particle size measurements of elderberry juice were conducted using a laser diffraction particle size analyser, model PSA 1190L/D (Anton Paar GmbH, Austria). A 10 mL sample of the juice was placed in the sample chamber. For the analysis, the Mie scattering model was used with water as the solvent. Measurements were taken with obscuration limits set between 5% and 30%, at stirring and pump speeds of 150 and 45 rpm, respectively. Measurements were performed in three replicates.

For each sample, D_{10} , D_{50} , D_{90} , and the particle mean diameter ($D_{4,3}$) were calculated using the device's software. D_{10} , D_{50} , and D_{90} represent the particle diameters below which 10%, 50%, and 90% of the total particle volume, respectively, are contained.

Centrifugal sedimentation rate and turbidity measurements

The sample was centrifuged at 1,500 g for 30 min. (Centurion Scientific Ltd, UK). The absorbance of the supernatant was then transferred to a 30 mL transparent glass vessel, and turbidity was measured using a portable turbidity meter Turb 430 IR (WTW Xylem Analytics GmbH, Germany). Measurements were performed in three replicates. Results were expressed in NTU.

The elderberry juice sample was weighed (m_1 , g), after which the sediment obtained by centrifugation was collected and weighed (m_2 , g). The centrifugal sedimentation rate (CR) of elderberry juice was determined using Equation (1) (Jia *et al.*, 2022). Measurements were performed in three replicates.

$$CR(\%) = \left(\frac{m_2}{m_1} \right) * 100\% \quad (1)$$

Colour parameters

The colour of elderberry juice samples was analysed using L, a, and b coordinates measured with a ColorFlex EZ spectrophotometer/colourimeter

(HunterLab, USA). For each sample, colour was measured in five replicates.

The overall colour difference (ΔE) between the L, a, and b coordinates of the samples was calculated using Equation (2) (Jia *et al.*, 2022). L_0 , a_0 and b_0 represent an untreated elderberry juice sample. L, a, and b represent measurements after UT and pasteurisation (Zou *et al.*, 2024). Additionally, colour intensity, referred to as C (Chroma), was calculated using Equation (3) (Gomes *et al.*, 2022).

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

$$C = \sqrt{(a^2 + b^2)} \quad (3)$$

Viscosity

The viscosity of the juice samples was measured using a modular compact rheometer MCR 302 (Anton Paar, Austria) equipped with a double-gap measuring system (C-DG26.7, Anton Paar). Apparent viscosity was evaluated in the shear rate interval from 1 to 100 s⁻¹ at 20 °C. Measurement at 10 s⁻¹ was made, as this shear rate is representative of conditions related to oral perception and the mouthfeel of foods (Katsch *et al.*, 2025). The results were expressed in mPa·s.

To characterise the flow behaviour of the juices, the Power-Law (Ostwald–de Waele) model was applied to obtain the consistency index k and the flow behaviour index n, as given in Eq. (4). The shear stress σ (Pa) was plotted as a function of shear rate γ (s⁻¹). A value of n equal to one corresponds to Newtonian behaviour, whereas n < 1 indicates shear-thinning properties of the juice. The consistency index k was expressed in mPa·sⁿ (Katsch *et al.*, 2025; Kobus *et al.*, 2015).

$$\sigma = k\gamma^n \quad (4)$$

Statistical analysis

The mean and standard deviation were calculated for all measured elderberry juice samples. Statistical evaluation was performed using one-way analysis of variance (ANOVA), with a level of significance $p < 0.05$. Post hoc comparisons were performed using Tukey's Honest Significant Difference (HSD) test.

Principal component analysis (PCA) was used to characterise the effects of ultrasound and pasteurisation on the structural, rheological, and visual parameters of juice. The following variables were included in the analysis: particle mean diameter $D_{4,3}$, centrifugal sedimentation rate, turbidity, viscosity at 10 s⁻¹, consistency index k, and the flow behaviour index n, as well as the colour parameters L and a, and the total colour difference ΔE .

Data processing and statistical calculations were performed using RStudio (version 2024.12.0.467) and LibreOffice Calc (version 7.1.6.2).

Results and Discussion

Particle size measurements

The juice matrix consists of cell wall fragments, pulp, pectins, dietary fibres, proteins, and polyphenols (Zhu *et al.*, 2020) dispersed in the aqueous serum. Within this complex structure, suspended particles largely determine the juice’s stability, turbidity, and mouthfeel. When the juice matrix undergoes pasteurisation and ultrasound treatment, it can result in the breakdown into finer particles or the formation of larger aggregates (Li *et al.*, 2025; Muthukumarappan *et al.*, 2016).

Particle size measurement results (Table 2) showed that UT (samples U50 and U70) decreased the D_{10} , D_{50} , D_{90} and $D_{4,3}$ values, indicating that the particle size in the samples was significantly ($p < 0.05$) smaller than in the untreated sample. Furthermore, increasing the duration of UT led to an even greater reduction in D_{50} , D_{90} and $D_{4,3}$ values. The results show the progressive deagglomeration and fragmentation of cell clusters. This finding aligns with reports by other researchers on ultrasound-treated juices, including lily juice (Han *et al.*, 2024), tomato juice (Li *et al.*, 2025), and orange juice (Gomes *et al.*, 2022), which all report a significant reduction in average particle size after UT.

However, when a shorter time period UT (50 min.) was combined with pasteurisation at 70 °C, $D_{4,3}$ increased by 33% compared to the untreated juice. In contrast, longer UT (70 min.) combined with pasteurisation at 60 °C resulted in a decrease in the $D_{4,3}$ value by 67%. These results demonstrate that particle size is nonlinear with respect to ultrasound and heat treatments and may depend on the structural state of the elderberry juice matrix prior to pasteurisation.

UT primarily serves as a mechanical deagglomeration step, partially breaking cell clusters (Han *et al.*, 2024; Li *et al.*, 2025; Muthukumarappan *et al.*, 2016; Vuono *et al.*, 2026). It induces cavitation, reducing the length of the pectin chains and their molecular weight, thereby lowering the juice’s viscosity, delaying sedimentation, and altering particle size and particle-particle interactions. Under mild conditions, ultrasound mainly improves the extraction of water-soluble pectin. It reduces the particle size, ensuring cloud stability in the juice (Fatih Ertugay & Başlar, 2014; Zhou *et al.*, 2021). In contrast, stronger ultrasound (high power, long exposure time, elevated temperature) can shorten pectin side chains and reduce methylation levels, leading to further structural changes in pectin (Bachari *et al.*, 2024; Hernandez-Hernandez *et al.*, 2024; Larsen *et al.*, 2021) and altering the properties of the juice. In studies where ultrasound is combined with pasteurisation, this treatment regimen simultaneously disrupts cell structures, releasing more soluble pectin, and promotes partial degradation, forming either smaller, better-dispersed particles or reassociating into larger aggregates (Lepaus *et al.*, 2023; Li *et al.*, 2025; Wu *et al.*, 2008).

The pronounced decrease in D_{10} , D_{50} , D_{90} , and $D_{4,3}$ in the U70+P60 sample suggests that prolonged UT followed by pasteurisation at 60 °C could promote the fragmentation of pectin chains and thus the disaggregation of cell clusters, resulting in finer particles. These findings are consistent with those of Li *et al.* (2025) and Wu *et al.* (2008) on thermosonicated tomato juice, in which the combination of ultrasound and heat treatment significantly decreased the mean particle size of the juice compared to untreated juice.

Table 2
Particle size measurements for ultrasound-treated and pasteurised black elderberry juice samples

Sample	$D_{10} \mu\text{m}$	$D_{50} \mu\text{m}$	$D_{90} \mu\text{m}$	$D_{4,3} \mu\text{m}$
Untreated	7.95 ± 0.25^d	129.56 ± 9.21^b	355.82 ± 12.17^b	169.81 ± 8.64^b
U50	5.58 ± 0.55^e	99.46 ± 15.70^c	276.45 ± 29.48^c	129.19 ± 15.68^c
U50+P60	32.74 ± 0.29^b	131.76 ± 2.78^b	373.64 ± 2.42^b	185.17 ± 2.41^b
U50+P70	41.15 ± 0.63^a	186.41 ± 4.27^a	402.18 ± 2.53^a	226.10 ± 3.13^a
U70	4.82 ± 0.23^e	68.02 ± 5.22^d	191.95 ± 33.47^d	87.20 ± 13.77^d
U70+P60	5.51 ± 0.13^e	38.30 ± 2.09^e	128.12 ± 3.44^e	56.43 ± 1.83^e
U70+P70	14.62 ± 0.52^c	70.15 ± 1.82^d	220.13 ± 11.41^d	104.53 ± 3.61^d

Results are expressed as mean value $\pm$ standard deviation ($n = 3$); Significant differences in the column are marked with different letters ($p < 0.05$, Tukey HSD test); D_{10} – 10% of the particles below the specified diameter; D_{50} – 50% of the particles below the specified diameter; D_{90} – 90% of the particles below the specified diameter; $D_{4,3}$ – particle mean diameter. U50 – UT for 50 min.; U50+P60 – UT for 50 min. and pasteurised at 60 °C for 15 s; U50+P70 – UT for 50 min. and pasteurised at 70 °C for 15 s; U70 – UT for 70 min.; U70+P60 – UT for 70 min. and pasteurised at 60 °C for 15 s; U70+P70 – UT for 70 min. and pasteurised at 70 °C for 15 s.

Table 3

Viscosity, turbidity, and centrifugal sedimentation rate measurements for ultrasound-treated and pasteurised black elderberry juice samples

Sample	Viscosity at 10 s ⁻¹ , mPa·s	Flow behaviour index (n)	Consistency coefficient (k), mPa·s ⁿ	Turbidity, NTU	Centrifugal sedimentation rate, %
Untreated	1.460 ± 0.013 ^d	0.944 ± 0.001 ^a	1.664 ± 0.018 ^d	104.00 ± 0.10 ^e	1.209 ± 0.016 ^d
U50	1.570 ± 0.028 ^b	0.846 ± 0.009 ^c	2.237 ± 0.089 ^a	164.00 ± 2.00 ^c	0.851 ± 0.109 ^e
U50+P60	1.562 ± 0.018 ^b	0.849 ± 0.006 ^c	2.214 ± 0.056 ^a	40.27 ± 0.06 ^f	3.703 ± 0.147 ^a
U50+P70	1.540 ± 0.014 ^{bc}	0.857 ± 0.005 ^{bc}	2.141 ± 0.047 ^a	38.50 ± 0.17 ^g	2.221 ± 0.457 ^b
U70	1.455 ± 0.078 ^{cd}	0.900 ± 0.051 ^a	1.845 ± 0.215 ^{bc}	160.00 ± 1.73 ^d	0.939 ± 0.078 ^e
U70+P60	1.635 ± 0.015 ^a	0.942 ± 0.005 ^a	1.868 ± 0.038 ^c	351.67 ± 2.52 ^b	1.349 ± 0.135 ^d
U70+P70	1.568 ± 0.081 ^{ab}	0.882 ± 0.026 ^b	2.057 ± 0.015 ^b	425.33 ± 5.13 ^a	1.642 ± 0.012 ^c

Results are expressed as mean value ± standard deviation (n = 3); Significant differences in the column are marked with different letters (p < 0.05, Tukey HSD test). U50 – UT for 50 min.; U50+P60 – UT for 50 min. and pasteurised at 60 °C for 15 s; U50+P70 – UT for 50 min. and pasteurised at 70 °C for 15 s; U70 – UT for 70 min.; U70+P60 – UT for 70 min. and pasteurised at 60 °C for 15 s; U70+P70 – UT for 70 min. and pasteurised at 70 °C for 15 s.

In contrast, the increase in all percentiles and D_{4,3} in the U50+P70 samples could indicate a thermally induced restructuring of partially degraded pectin together with proteins and fibres, which promotes cross-linking into larger aggregates rather than further disaggregation. It is possible that the duration of UT was not sufficient to affect the pectin network and the subsequent pasteurisation led to the formation of a pectin-protein-fibre complex system and resulted in large aggregates, which is consistent with Li *et al.* (2025) reporting that heat treatment significantly increased the D₅₀ value of tomato juice compared to untreated tomato juice, while Wang *et al.*, (2026) reported a significant increase in D_{4,3} value after heat treatment compared to untreated juice.

Turbidity measurements

Turbidity results (Table 3) indicated that ultrasound and heat treatment of black elderberry juice led to two distinct trends. Shorter UT (U50) combined with pasteurisation at 60–70 °C significantly (p < 0.05) reduced turbidity, while prolonged UT (U70), especially when followed by heating, noticeably increased turbidity compared to the control.

Specifically, treatments U50+P60 and U50+P70 created a much clearer juice than the untreated sample, with turbidity decreases of 61% and 63%, respectively. In contrast, treatments U70+P60 and U70+P70 resulted in a much cloudier juice, with turbidity increases of 238% and 309%, respectively, compared to the control.

During UT (U50), cavitation dispersed cell fragments and colloidal particles, which increased light scattering and, consequently, turbidity relative

to the untreated control (Han *et al.*, 2024). When this pre-treated juice was heated to 60 or 70 °C, the combination of partial cell disruption and moderate heat likely promoted greater particle aggregation and sedimentation, leading to a significant (p < 0.05) reduction in turbidity to approximately 40 NTU. Similar results have been described for tomato juice after heat treatment, where an increase in D₅₀ and a decrease in cloud stability were found (Wu *et al.*, 2008).

Extended UT (U70) further disrupted the berry matrix, releasing additional polysaccharides and colloidal material. However, the change in turbidity compared to U50 is low. When this extensively disrupted matrix was heated (U70+P60 and U70+P70), the released pectins, proteins, and fine fragments could promote the formation of stable colloidal networks or fine flocs that remain suspended (Li *et al.*, 2025), significantly (p < 0.05) increasing turbidity to 351.7 – 425.3 NTU. The same trend is reported in the research of Wu *et al.* (2008) and Li *et al.* (2025) on the thermosonication of tomato juice, where, after thermosonication, a fine cloud with a uniformly distributed particle system forms in the juice, which remains in suspension and provides the juice with a stable colloidal cloud during storage.

From a technological point of view, this research reveals two distinct processing outcomes: juice clarification (moderate ultrasound combined with pasteurisation) and cloud stabilisation (extended ultrasound combined with pasteurisation). Both effects result from the same elderberry juice matrix. Similar trends have been observed for other fruit juices; for

example, in kiwi juice (Bhutkar *et al.*, 2024), all thermosonicated samples exhibited higher cloud values than both the untreated control and pasteurised juice, indicating that ultrasound-heat combinations can effectively enhance and stabilise juice cloudiness. Further studies are needed to investigate whether the specific processing regimes identified here would also induce comparable clarification effects in other berry juices with similar compositional characteristics.

Centrifugal sedimentation rate

Centrifugal sedimentation rate results (Table 3) indicated that UT alone reduced sediment formation compared to the control. However, when UT was combined with pasteurisation – particularly 50 minutes of UT following pasteurisation at 60 °C – there was a significant ($p < 0.05$) increase in the centrifugal sedimentation rate of black elderberry juice. Thus, UT alone (U50, U70) tended to decrease centrifugal sedimentation rate. At the same time, subsequent pasteurisation increases it, with the most pronounced effect observed in the U50+P60 sample.

Interestingly, the combination of UT and pasteurisation affected the centrifugal sedimentation rate and turbidity differently based on the UT conditions. For the U50 samples, UT followed by heat treatment reduced turbidity but significantly increased the centrifugal sedimentation rate. In contrast, for the U70 samples, the combination of UT and pasteurisation increased turbidity, while the centrifugal sedimentation rate remained similar to that of the untreated juice, or only slightly higher, as seen in the U70+P70 sample. For the U50 and U70 samples, cavitation likely breaks larger cell aggregates into smaller particles (Han *et al.*, 2024; Kidoń & Narasimhan, 2022; Li *et al.*, 2025) that remain suspended, thereby reducing the amount

of material that settles as sediment. This supports the observation of partial disintegration of the elderberry juice matrix, in which the disintegrated pectin, fibre, and cell wall structures form a more stable colloidal suspension rather than a compact sediment.

When UT was followed by pasteurisation (U50+P60, U50+P70, U70+P60, U70+P70), pasteurisation promoted the aggregation and compaction of the disintegrated biopolymers (pectins, proteins, fibres) into denser floc masses that settled more easily, thereby increasing the centrifugal sedimentation rate (Li *et al.*, 2025; Wu *et al.*, 2008; Yang *et al.*, 2025). The high centrifugal sedimentation rate in the U50+P60 sample suggests that the moderately disintegrated matrix (after 50 minutes of UT), combined with pasteurisation at 60 °C, was optimal for forming large, dense aggregates that can effectively settle. This explains the very low turbidity observed in the U50+P60 samples.

In contrast, for the more disintegrated matrix (U70), pasteurisation still increased the centrifugal sedimentation rate (U70+P60, U70+P70), but to a lesser extent, probably because a larger fraction of fine particles remained in the continuous phase, promoting persistent turbidity rather than the formation of compact sediments.

Colour parameters

Colour measurements (Table 4) indicate that ultrasound and heat have affected *a*, which is the red/green coordinate, *L* – lightness, ΔE – overall colour difference, while *b* – yellow/blue coordinate, was relatively stable across elderberry juice samples.

Under the influence of UT, the *L* value of the U50 sample increased significantly ($p < 0.05$), indicating that the colour became lighter. Conversely, a value

Table 4
Colour parameters of ultrasound-treated and pasteurised black elderberry juice samples

Sample	<i>L</i>	<i>a</i>	<i>b</i>	ΔE	Chroma value (<i>C</i>)
Untreated	2.628 ± 0.153 ^b	1.518 ± 0.288 ^b	0.212 ± 0.045 ^b	-	1.533 ± 0.291 ^b
U50	9.052 ± 0.984 ^a	1.170 ± 0.071 ^c	0.148 ± 0.049 ^b	6.434 ± 0.987 ^a	1.180 ± 0.076 ^c
U50+P60	0.424 ± 0.079 ^d	1.914 ± 0.178 ^a	0.558 ± 0.074 ^a	2.273 ± 0.067 ^b	1.995 ± 0.174 ^a
U50+P70	0.128 ± 0.022 ^d	0.602 ± 0.168 ^d	0.212 ± 0.027 ^b	2.666 ± 0.068 ^b	0.639 ± 0.165 ^d
U70	0.104 ± 0.015 ^d	0.628 ± 0.072 ^d	0.182 ± 0.028 ^b	2.677 ± 0.039 ^b	0.654 ± 0.077 ^d
U70+P60	0.194 ± 0.011 ^d	1.002 ± 0.036 ^c	0.174 ± 0.033 ^b	2.489 ± 0.019 ^b	1.102 ± 0.036 ^c
U70+P70	1.290 ± 0.198 ^c	1.472 ± 0.019 ^b	-0.088 ± 0.026 ^c	1.373 ± 0.193 ^c	1.475 ± 0.020 ^b

Results are expressed as mean value ± standard deviation ($n = 5$); significant differences in the column are marked with different letters ($p < 0.05$, Tukey HSD test); U50 – UT for 50 min.; U50+P60 – UT for 50 min. and pasteurised at 60 °C for 15 s; U50+P70 – UT for 50 min. and pasteurised at 70 °C for 15 s; U70 – UT for 70 min.; U70+P60 – UT for 70 min. and pasteurised at 60 °C for 15 s; U70+P70 – UT for 70 min. and pasteurised at 70 °C for 15 s.

significantly decreases ($p < 0.05$) compared to the untreated control sample. This particular sample also shows the highest ΔE value of 6.434 ± 0.987 , indicating the greatest ($p < 0.05$) difference from the untreated sample. An ΔE value greater than 3 indicates a clearly perceptible colour difference (Li *et al.*, 2022). Additionally, with prolonged UT, the L value of the U70 sample became significantly ($p < 0.05$) darker than that of the untreated juice sample. A value continued to decline and was significantly ($p < 0.05$) lower than both the untreated juice sample and the U50 sample.

Interestingly, after heat treatment at 60 °C, the C (brightness) and a (redness) of the U50 sample significantly increased ($p < 0.05$). In comparison, at 70 °C, a value was significantly ($p < 0.05$) lower than in the untreated, U50, and U50+P60 samples.

A study on the UT of pomegranate juice (Trishitman, 2025) reveals that as ultrasound intensity and duration increase, the kinetics of colour density, colour index, and browning index follow a first-order model. Initially, monomeric anthocyanin extraction predominates, but over time, browning occurs. This finding aligns with the results from elderberry juice samples treated with U70+P60 and U70+P70, which exhibited a very dark, but less bright, red colour (indicating low L and medium C), and a stable cloudiness. In contrast, the moderate ultrasound combined with a gentle pasteurisation regime (U50+P60) resulted in a very dark and highly saturated colour (low L and high C), highlighting the dominance of extraction over degradation.

Similar trends have been observed in other anthocyanin-rich liquids, such as red grape juices and anthocyanin extracts. In these cases, ultrasound initially increases the values of a and ΔE . However, at excessive energy levels, the degradation and polymerisation of the anthocyanin structure lead to stabilisation or a decrease in C, even as overall colour density increases (Amiri *et al.*, 2020; Li *et al.*, 2022; Tiwari *et al.*, 2010).

Viscosity

The rheological results (Table 3) of elderberry juice indicate that all samples exhibited shear-thinning behaviour, characterised by a flow behaviour index (n) ranging from 0.846 to 0.944. When subjected to a combination of ultrasound and pasteurisation, the juice matrix responded in two distinct ways. This is consistent with the study by Šimunek *et al.* (2014) on the UT of apple, cranberry, and blueberry juices and nectars, which indicates that the consistency coefficient (k) can increase or decrease depending on the product's UT parameters. The UT for 50 min with pasteurisation (U50, U50+P60, and U50+P70) significantly ($p < 0.05$) decreased the flow behaviour

index (n) and significantly ($p < 0.05$) increased the consistency index (k) to 2.141–2.237 mPa·sⁿ compared to untreated juice, indicating a more pronounced shear-thinning behaviour. Together with the increased centrifugal sedimentation rate, this suggests the formation of denser particle/pectin aggregates that settle more readily, which is in line with the observations on ultrasound and heat-induced flocculation in other juices (Šimunek *et al.*, 2014; Wang *et al.*, 2026).

Conversely, the treatment of U70+P60 and U70+70, which exhibited very high turbidity, produced a flow behaviour index (n) closer to 1 (0.882 - 0.942) and a significantly ($p < 0.05$) lower consistency index (k) compared to U50, U50+P60, and U50+P70 samples. This could correspond to a fine-particle, flowing solution that maintains a stable cloud. These findings align with studies on lily juice (Han *et al.*, 2024) and orange juice (Gomes *et al.*, 2022); with excessive ultrasound loading, a more homogeneous suspension is achieved, resulting in flow behaviour index (n) values closer to 1 and a lower consistency coefficient (k). This effect may be due to the breakdown of suspended solids in the juice, resulting in smaller particle sizes. The reduction in particle size, combined with smoother particle surfaces, creates a lubricating effect that decreases resistance to flow. Furthermore, rheological behaviour is significantly influenced by temperature, particle size, and soluble solids content. When pectin macromolecules are fragmented into shorter chains, the overall viscosity decreases, and the flow behaviour index tends to increase (Gomes *et al.*, 2022; Han *et al.*, 2024; Sogi *et al.*, 2010).

Furthermore, in all samples, the apparent viscosity at 10 s⁻¹ is in the range of 1.455–1.635 mPa·s – the changes between samples are statistically significant, yet small.

Effect of ultrasound treatment and pasteurisation on the analysed parameters of elderberry juice.

Principal component analysis (PCA) was applied to evaluate the effects of ultrasound and pasteurisation on particle mean diameter ($D_{4,3}$), centrifugal sedimentation rate, turbidity, apparent viscosity at 10 s⁻¹, consistency index k, the flow behaviour index n, and colour parameters (L, a, ΔE). PC1 and PC2 together explained 55.4% of the total variance, capturing the primary axes of variation in the dataset and clearly separating samples by physical stability and colour characteristics.

PC1 primarily represented a structural and physical stability axis. In Figure 1, the loading vectors for $D_{4,3}$ and centrifugal sedimentation rate were oriented in the opposite direction to the turbidity vector, with the vector for the consistency index k pointing in the same general direction as the turbidity vector. Negative PC1

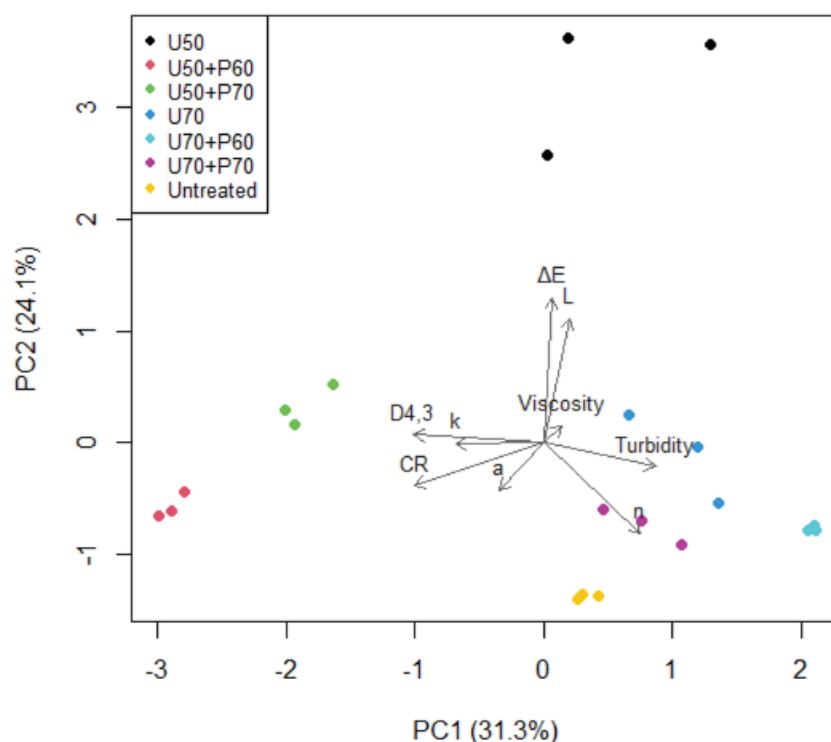


Figure 1. Principal component analysis of the effects of ultrasound and pasteurisation on the structural, rheological, and visual parameters of black elderberry juice.

$D_{4,3}$ – particle mean diameter ($D_{4,3}$); CR – centrifugal sedimentation rate; k – consistency index k; n – flow behaviour index n; Viscosity – viscosity at 10 s^{-1} .

scores were associated with a larger particle mean diameter ($D_{4,3}$), higher centrifugal sedimentation rate, and lower turbidity. In contrast, positive PC1 scores were associated with a smaller particle mean diameter ($D_{4,3}$), lower centrifugal sedimentation rates, and higher turbidity.

A secondary axis, PC2, was mainly influenced by colour-related variables, particularly L and ΔE , which showed positive loadings. The flow behaviour index n was negatively associated with PC2. Treatments that resulted in pronounced colour modifications and darker tones tended to be displaced along PC2. In contrast, samples with moderate colour differences and rheological properties similar to those of the untreated control remained near the origin of PC2.

The distribution of sample scores in the PC1–PC2 biplot showed that the untreated juice was positioned near the centre, reflecting its intermediate characteristics for $D_{4,3}$, turbidity, centrifugal sedimentation rate, viscosity, and colour. Samples treated only with ultrasound (U50, U70) shifted away from the control towards positive PC1 scores, in the direction of lower $D_{4,3}$ and centrifugal sedimentation rate and slightly higher turbidity. In contrast, the samples treated with 50 min. UT followed by pasteurisation at 60 or 70 °C (U50+P60, U50+P70)

were grouped on the negative side of PC1, in the same quadrant as the $D_{4,3}$ and centrifugal sedimentation rate vectors, and opposite to the turbidity vector.

The samples subjected to prolonged ultrasound followed by pasteurisation (U70+P60, U70+P70) clustered on the positive side of PC1, in the direction of the turbidity vector and away from $D_{4,3}$ and the centrifugal sedimentation rate. Their location in the biplot indicates that these treatments produced smaller, more finely dispersed particles ($D_{4,3}$), very high turbidity, and relatively lower increases in the centrifugal sedimentation rate, all characteristic of a stable colloidal cloud. In short, prolonged ultrasound, even when followed by pasteurisation, produced the most stable and finely dispersed juice cloud, whereas short ultrasound combined with pasteurisation promoted particle growth and sedimentation, reducing stability.

Conclusions

High-intensity UT applied to black elderberry juice significantly ($p < 0.05$) reduced particle size and the centrifugal sedimentation rate while increasing turbidity. This confirms its effectiveness in restructuring the colloidal matrix and delaying sediment formation compared to untreated juice.

When ultrasound was combined with pasteurisation, two distinct technological pathways emerged within the same juice matrix. The first method involved UT for 50 minutes, followed by pasteurisation at temperatures of 60–70 °C. This approach promoted floc formation, increased the centrifugal sedimentation rate, and reduced turbidity to 38.5 ± 0.17 NTU, resulting in clarified juice. The second method, which involved prolonged UT for 70 minutes combined with pasteurisation at the same temperatures, produced finer particles, higher turbidity (up to 425.33 ± 5.13 NTU), and a lower consistency index, indicative of a stable colloidal cloud.

Ultrasound-heat treatments also resulted in noticeable overall colour differences ($\Delta E > 3$) and altered redness and chroma levels. These changes reflect the complex balance between anthocyanin extraction and subsequent pigment degradation and polymerisation in black elderberry juice.

These findings suggest that by selecting appropriate durations of UT and pasteurisation temperatures, juice processors can intentionally develop black elderberry juices and beverages with specific characteristics of clarity, cloud stability, and colour to align with various market segments and “clean label” expectations.

Further research should focus on the long-term physical and microbiological stability, as well as the sensory perception, of UT black elderberry beverages.

References

- Amiri, A., Ramezani, A., Mortazavi, S. M. H., & Hosseini, S. M. H. (2020). Ultrasonic potential in maintaining the quality and reducing the microbial load of minimally processed pomegranate. *Ultrasonics Sonochemistry*, 70, 105302. <https://doi.org/10.1016/j.ultsonch.2020.105302>
- Appenteng, M. K., Krueger, R., Johnson, M. C., Ingold, H., Bell, R., Thomas, A. L., & Greenlief, C. M. (2021). Molecules Cyanogenic Glycoside Analysis in American Elderberry. *Molecules*, 26(5), 1384. <https://doi.org/10.3390/molecules26051384>
- Avena, A., Ozola, L., & Ķeķe, A. (2024). *Sambucus nigra* Fruits and Their Processing Solutions: A Review. *Annual 30th ISC Research for Rural Development 2024*, 39, (67-72). Jelgava, Latvia: Latvia University of Life Sciences and Technologies <https://doi.org/10.22616/RRD.30.2024.011>
- Bachari, S., Ghaderi-Ghahfarokhi, M., Gavlighi, H. A., & Zarei, M. (2024). Ultrasonic depolymerization of pomegranate peel pectin: Effect of sonication time on antioxidant, α -amylase inhibitory, and prebiotic properties. *Food Chemistry*, 24, 101901. <https://doi.org/10.1016/j.fochx.2024.101901>
- Banach, M., Khaidakov, B., Korewo, D., Węsierska, M., Cyplik, W., Kujawa, J., Ahrné, L. M., & Kujawski, W. (2021). The chemical and cytotoxic properties of *Sambucus nigra* extracts—A natural food colorant. *Sustainability (Switzerland)*, 13(22), 12702. <https://doi.org/10.3390/SU132212702>
- Bhutkar, S., Brandão, T. R. S., Silva, C. L. M., & Miller, F. A. (2024). Application of Ultrasound Treatments in the Processing and Production of High-Quality and Safe-to-Drink Kiwi Juice. *Foods*, 13(2), 328. <https://doi.org/10.3390/foods13020328>
- Boroduške, A., Balode, M., Nakurte, I., Berga, M., Jēkabsons, K., Muceniece, R., & Rischer, H. (2022). *Sambucus nigra* L. cell cultures produce main species-specific phytochemicals with anti-inflammatory properties and in vitro ACE2 binding inhibition to SARS-CoV2. *Industrial Crops and Products*, 186, 115236. <https://doi.org/10.1016/J.INDCROP.2022.115236>
- Demesa, A. G., Saavala, S., Pöysä, M., & Koironen, T. (2024). Overview and Toxicity Assessment of Ultrasound-Assisted Extraction of Natural Ingredients from Plants. *Foods*, 13(19), 3066. <https://doi.org/10.3390/FOODS13193066/S1>
- Deniz, Z., & Suna, S. (2025). Unlocking the potential of elderberry (*Sambucus nigra* L.) fruit leather: Optimization of production and evaluation of bioactive content and bioaccessibility using response surface methodology. *Food Chemistry*, 493, 146046. <https://doi.org/10.1016/j.foodchem.2025.146046>
- Domínguez, R., Zhang, L., Rocchetti, G., Lucini, L., Pateiro, M., Munekata, P. E. S., & Lorenzo, J. M. (2020). Elderberry (*Sambucus nigra* L.) as potential source of antioxidants. Characterization, optimization of extraction parameters and bioactive properties. *Food Chemistry*, 330, 127266. <https://doi.org/10.1016/j.foodchem.2020.127266>
- Fatih Ertugay, M., & Başlar, M. (2014). The effect of ultrasonic treatments on cloudy quality-related quality parameters in apple juice. *Innovative Food Science and Emerging Technologies*, 26, 226-231. <https://doi.org/10.1016/j.ifset.2014.06.013>
- Ferreira, S. S., Martins-Gomes, C., Nunes, F. M., & Silva, A. M. (2022). Elderberry (*Sambucus nigra* L.) extracts promote anti-inflammatory and cellular antioxidant activity. *Food Chemistry*, X, 15, 100437. <https://doi.org/10.1016/J.FOCHX.2022.100437>
- Ferreira-Santos, P., Nogueira, A., Rocha, C. M. R., Wilson, C. P., Teixeira, J. A., & Botelho, C. (2022). *Sambucus nigra* flower and berry extracts for food and therapeutic applications: Effect of gastrointestinal digestion on in vitro and in vivo

- bioactivity and toxicity. *Food & Function*, 13(12), 6762–6776. <https://doi.org/10.1039/D2FO00335J>
- Gomes, A., Costa, A. L. R., Rodrigues, P. D., Castro, R. J. S. de, & Silva, E. K. (2022). Sonoprocessing of freshly squeezed orange juice: Ascorbic acid content, pectin methylesterase activity, rheological properties and cloud stability. *Food Control*, 131, 108391. <https://doi.org/10.1016/j.foodcont.2021.108391>
- Han, S.-H., Zhu, J.-K., Shao, L., Yue, C.-H., Li, P.-Y., Bai, Z.-Y., & Luo, D.-L. (2024). Effects of Ultrasonic Treatment on Physical Stability of Lily Juice: Rheological Behavior, Particle Size, and Microstructure. *Foods*, 13(8), 1276. <https://doi.org/10.3390/foods13081276>
- Haş, I. M., Teleky, B. E., Szabo, K., Simon, E., Ranga, F., Diaconeasa, Z. M., Purza, A. L., Vodnar, D. C., Tit, D. M., & Nişescu, M. (2023). Bioactive Potential of Elderberry (*Sambucus nigra* L.): Antioxidant, Antimicrobial Activity, Bioaccessibility and Prebiotic Potential. *Molecules*, 28 (7), 3099. <https://doi.org/10.3390/MOLECULES28073099>
- Hernandez-Hernandez, O., Ferreira-Lazarte, A., Tiwari, B., & Villamiel, M. (2024). Update of high-intensity ultrasound applications for the extraction of pectin from agri-food by-products. *TrAC Trends in Analytical Chemistry*, 175, 117728. <https://doi.org/10.1016/j.trac.2024.117728>
- Jia, M., Zhang, C., Zhou, J., Cheng, C., & Ma, Y. (2022). Improving the quality of mandarin juice using a combination of filtration and standard homogenization. *Food Chemistry*, 383, 132522. <https://doi.org/10.1016/j.foodchem.2022.132522>
- Katsch, L., Sokolowsky, M., Gibson, B., & Schneider, J. (2025). Influence of different pasteurization conditions with equivalent pasteurization units on chemical, physical, and sensory properties of cloudy apple juice. *Applied Food Research*, 5(2), 101471. <https://doi.org/10.1016/j.afres.2025.101471>
- Kidoń, M., & Narasimhan, G. (2022). Effect of Ultrasound and Enzymatic Mash Treatment on Bioactive Compounds and Antioxidant Capacity of Black, Red and White Currant Juices. *Molecules*, 27(1), 318. <https://doi.org/10.3390/molecules27010318>
- Kobus, Z., Nadulski, R., Guz, T., Mazur, J., Panasiewicz, M., & Zawislak, K. (2015). Effect of Pasteurization on Rheological Properties of White Carrot Juice. *Agriculture and Agricultural Science Procedia*, 7, 99–102. <https://doi.org/10.1016/j.aaspro.2015.12.043>
- Larsen, L. R., van der Weem, J., Caspers-Weiffenbach, R., Schieber, A., & Weber, F. (2021). Effects of ultrasound on the enzymatic degradation of pectin. *Ultrasonics Sonochemistry*, 72, 105465. <https://doi.org/10.1016/j.ultsonch.2021.105465>
- Lepaus, B. M., Valiati, B. S., Machado, B. G., Domingos, M. M., Silva, M. N., Faria-Silva, L., Bernardes, P. C., Oliveira, D. da S., & de São José, J. F. B. (2023). Impact of ultrasound processing on the nutritional components of fruit and vegetable juices. *Trends in Food Science and Technology*, 138, 752–765. <https://doi.org/10.1016/j.tifs.2023.07.002>
- Li, L., Su, H., Ma, J., Wang, Z., Zhang, S., Chen, L., Qiao, L., & Song, J. (2025). Thermosonication achieves pasteurization-equivalent lethal effects on microorganisms while enhancing color, stability, bioactivity and flavor metabolites in tomato juice: Evidence from metabolomics. *Food Bioscience*, 73, 107718. <https://doi.org/10.1016/j.fbio.2025.107718>
- Li, L., Su, H., Pang, L., Pan, Y., Li, X., Xu, Q., Song, J., & Qiao, L. (2025). Thermosonication enhanced the bioactive, antioxidant, and flavor attributes of freshly squeezed tomato juice. *Ultrasonics Sonochemistry*, 115, 107299. <https://doi.org/10.1016/j.ultsonch.2025.107299>
- Li, W., Gong, P., Ma, H., Xie, R., Wei, J., & Xu, M. (2022). Ultrasound treatment degrades, changes the color, and improves the antioxidant activity of the anthocyanins in red radish. *LWT*, 165, 113761. <https://doi.org/10.1016/j.lwt.2022.113761>
- Muthukumarappan, K., Tiwari, B. K., O'donnell, C. P., & Cullen, P. J. (2016). 7 Ultrasound Processing: Rheological and Functional Properties of Food. In *Novel Food Processing: Effects on Rheological and Functional Properties* (85-102). Boca Raton, CRC Press.
- Osman, A. G., Avula, B., Katragunta, K., Ali, Z., Chittiboyina, A. G., & Khan, I. A. (2023). Elderberry Extracts: Characterization of the Polyphenolic Chemical Composition, Quality Consistency, Safety, Adulteration, and Attenuation of Oxidative Stress- and Inflammation-Induced Health Disorders. *Molecules*, 28(7), 3148. <https://doi.org/10.3390/molecules28073148>
- Przybylska-Balcerek, A., Szablewski, T., Szwajkowska-Michałek, L., Świerk, D., Cegielska-Radziejewska, R., Krejpcio, Z., Suchowilska, E., Tomczyk, Ł., & Stuper-Szablewska, K. (2021). *Sambucus Nigra* Extracts—Natural Antioxidants and Antimicrobial Compounds. *Molecules*, 26 (10), 2910. <https://doi.org/10.3390/MOLECULES26102910>
- Ren, Y., Meyer, G., Anderson, A. T., Lauber, K. M., Gallucci, J. C., Gao, G., & Kinghorn, A. D. (2024). Development of Potential Therapeutic Agents from Black Elderberries (the Fruits of *Sambucus nigra* L.). *Molecules*, 29(13), 2971. <https://doi.org/10.3390/molecules29132971>

- Rodríguez Madrera, R., & Suárez Valles, B. (2021). Analysis of Cyanogenic Compounds Derived from Mandelonitrile by Ultrasound-Assisted Extraction and High-Performance Liquid Chromatography in Rosaceae and Sambucus Families. *Molecules* 2021, 26(24), 7563. <https://doi.org/10.3390/MOLECULES26247563>
- Senica, M., Stampar, F., Veberic, R., & Mikulic-Petkovsek, M. (2016). Processed elderberry (*Sambucus nigra* L.) products: A beneficial or harmful food alternative? *LWT*, 72, 182–188. <https://doi.org/10.1016/j.lwt.2016.04.056>
- Šimuněk, M., Jambrak, A. R., Dobrović, S., Herceg, Z., & Vukušić, T. (2014). Rheological properties of ultrasound treated apple, cranberry and blueberry juice and nectar. *Journal of Food Science and Technology*, 51(12), 3577–3593. <https://doi.org/10.1007/s13197-013-0958-2>
- Sogi, D. S., Oberoi, D. P. S., & Malik, S. (2010). Effect of Particle Size, Temperature, and Total Soluble Solids on The Rheological Properties of Watermelon Juice: A Response Surface Approach. *International Journal of Food Properties*, 13(6), 1207–1214. <https://doi.org/10.1080/10942910903013373>
- Terzi, M., Majki, T., Zengin, G., Beara, I., Cespedes-Acuña, C. L., Cavi, D., & Radojkovi, M. (2023). Could elderberry fruits processed by modern and conventional drying and extraction technology be considered a valuable source of health-promoting compounds? *Food Chemistry*, 405, 134766. <https://doi.org/10.1016/j.foodchem.2022.134766>
- Tiwari, B. K., Patras, A., Brunton, N., Cullen, P. J., & O'Donnell, C. P. (2010). Effect of ultrasound processing on anthocyanins and color of red grape juice. *Ultrasonics Sonochemistry*, 17(3), 598–604. <https://doi.org/10.1016/j.ultsonch.2009.10.009>
- Trishitman, D. (2025). Ultrasonication as a tool for extraction of pomegranate juice and its colorant anthocyanins: Effects on quality parameters. *Food and Humanity*, 5, 100756. <https://doi.org/10.1016/j.foohum.2025.100756>
- Vuono, L. F., Pino, R., Sicari, V., Badalamenti, N., Tundis, R., Bruno, M., Schicchi, R., Geraci, A., Gattuso, A., & Loizzo, M. R. (2026). Impact of ultrasound, pasteurization, and their combination on quality parameters, bioactive compounds and health-promoting properties of juices from various *Citrus aurantium* cultivars. *Journal of Food Composition and Analysis*, 149, 108625. <https://doi.org/10.1016/j.jfca.2025.108625>
- Wang, D., Shen, R., Zhao, L., Wang, K., Hu, Z., & Liu, X. (2026). Stability and cell wall polysaccharide dynamics in industrial-scale litchi juice during high-pressure and thermal processing. *Food Hydrocolloids*, 172, 111880. <https://doi.org/10.1016/j.foodhyd.2025.111880>
- Wu, J., Gamage, T. V., Vilkhov, K. S., Simons, L. K., & Mawson, R. (2008). Effect of thermosonication on quality improvement of tomato juice. *Innovative Food Science & Emerging Technologies*, 9(2), 186–195. <https://doi.org/10.1016/j.ifset.2007.07.007>
- Yang, S., Xu, J., Liu, S., Cheng, Y., Cai, F., Zhang, Y., McClements, D. J., Shen, P., & Li, Q. (2025). Structural characterization of water-soluble pectin in NFC orange juice during cloud destabilization. *Food Chemistry*, 496, 146718. <https://doi.org/10.1016/j.foodchem.2025.146718>
- Yıkımlı, S., Türkol, M., Dülger Altın, D., Duman Altan, A., Sağlam, K., Abdi, G., Tokath, N., Çelik, G., & Aadil, R. M. (2025). Advancing sustainable food preservation: Ultrasound and thermosonication as novel approaches to enhance nutritional and bioactive properties of broccoli juice. *Food Chemistry*, 378, 102412. <https://doi.org/10.1016/j.foodchem.2025.102412>
- Zhang, M., Zhou, C., Ma, L., Su, W., Jiang, J., & Hu, X. (2024). Influence of ultrasound on the microbiological, physicochemical properties, and sensory quality of different varieties of pumpkin juice. *Heliyon*, 10(6), e27927. <https://doi.org/10.1016/j.heliyon.2024.e27927>
- Zhou, X., Wang, W., Ma, X., Xu, E., & Liu, D. (2021). Ultrasonication of Thawed Huyou Juice: Effects on Cloud Stability, Physicochemical Properties and Bioactive Compounds. *Foods*, 10(8), 1695. <https://doi.org/10.3390/foods10081695>
- Zhu, D., Shen, Y., Wei, L., Xu, L., Cao, X., Liu, H., & Li, J. (2020). Effect of particle size on the stability and flavor of cloudy apple juice. *Food Chemistry*, 328, 126967. <https://doi.org/10.1016/j.foodchem.2020.126967>
- Zou, W., Niu, H., Yi, J., & Zhou, L. (2024). Passion fruit juicing with or without seeds treated by high-pressure processing and thermal pasteurization: Effects on the storage stability of enzymes and quality properties. *Innovative Food Science & Emerging Technologies*, 91, 103554. <https://doi.org/10.1016/j.ifset.2023.103554>

Acknowledgement

The research was carried out under contract number 5.1.1.2.i.0/1/22/A/CFLA/003, established between ‘Latvian Food Competence Centre’ Ltd and the Central Finance and Contracting Agency. It was conducted by ‘Aneva J’ Ltd (Research project No. 28) with financial support from the European funds – Recovery and Resilience Facility.