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Influence of the experimental environment on the ultrasonic characterization of organic and refined edible oils

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Abstract

The influence of the experimental environment on the ultrasonic characterization of edible oils was investigated using two different measurement configurations. The objective was to identify the most suitable experimental setup by comparing ultrasonic attenuation, velocity, acoustic impedance and reflection coefficient measurements. The selected configuration was then applied to distinguish between organic and refined soybean oils. Measurements were first performed in a cubic glass container using an immersed ultrasonic transducer, and then in a submerged multilayer container allowing ultrasonic wave propagation under normal incidence in water. In both configurations, ultrasonic signals were generated using the pulse echo method and processed with LabVIEW and OriginPro software. Ultrasonic velocity was determined using the envelope method, whereas attenuation, reflection coefficient and acoustic impedance were obtained from filtered signals using Fourier transform analysis. The results showed only slight differences in ultrasonic velocity and attenuation between the two experimental media, while the multilayer configuration provided faster acquisition and more versatile characterization conditions. This configuration was subsequently applied to the differentiation of organic and refined soybean oils through the analysis of ultrasonic velocity and reflection coefficient as a function of temperature. Statistical analysis based on linear regression revealed strong correlations between temperature and ultrasonic parameters, enabling discrimination between the two oils. The refined soybean oil exhibited greater temperature sensitivity than the organic oil, which may be associated with physicochemical modifications induced by the

refining process. These results demonstrate the potential of ultrasonic characterization as a rapid, non-destructive and reliable method for edible oil quality assessment and differentiation.

Keywords: ultrasonic, oils, characterization, propagation media, organic and refined edible oils

1 Introduction

The influence of the experimental environment on measurement accuracy and repeatability has been widely reported across various analytical techniques. In spectroscopic and optical methods, for instance, parameters such as temperature, path length, container geometry and light scattering conditions can strongly affect the acquired signal. Studies in near-infrared (NIR) spectroscopy have shown that even small variations in temperature or sample holder geometry can alter spectral calibration and prediction accuracy, leading to biases in quantitative models (Beurier et al. 2026; Ramadan et al. 2025; Xu et al. 2024). Similarly, investigations using portable NIR and Raman spectrometers reported that ambient light, sample thickness and contact pressure significantly modify the resulting spectra, highlighting the importance of environmental control in analytical measurements (Ong et al. 2020; Vandenabeele et al. 2014). These findings underline that the experimental configuration and the propagation medium must be carefully optimized to ensure reliable and reproducible data, regardless of the technique employed. In recent years, ultrasonic techniques have been increasingly employed as powerful, non-destructive tools for material and fluid characterization (Song et al. 2026). Their main advantages include high sensitivity to structural and compositional changes, fast data acquisition and the ability to operate without chemical reagents (Ma et al. 2026; Rehbein et al. 2025; Kumar 2026). The ultrasonic velocity, attenuation, acoustic impedance and reflection coefficient are particularly valuable parameters for describing the physical properties of liquids, such as density, compressibility and viscosity (Povey et al. 2025). These attributes have led to successful applications in the non-destructive testing of solids (Guo 2025; Zhang 2025) and in the evaluation of liquid systems including edible and essential oils (Hirnschrodt et al. 2000; Bamberger and Greenwood 2004). However, despite these developments, relatively few studies have addressed the influence of the experimental environment on the accuracy of ultrasonic measurements in liquids. The geometry of the measurement cell, the immersion medium and the boundary conditions can modify the propagation path, induce multiple reflections and alter attenuation or velocity. Such effects can limit the precision of ultrasonic characterization, especially when comparing oils with similar acoustic properties (Ettahiri et al. 2024a). Understanding and optimizing the measurement environment is therefore crucial to obtain reproducible and interpretable data.

In our earlier work, the quality assessment of argan oil was carried out through experimental ultrasonic characterization. Ultrasonic velocity and attenuation were analyzed as a function of temperature to evaluate their suitability for quality control

applications. The findings indicated that both ultrasonic velocity and acoustic attenuation decrease with increasing temperature, thereby enabling the establishment of a characteristic model for the quality control of the investigated argan oil (Ettahiri et al. 2024c). In this context, the present work aims to investigate the impact of the experimental environment on the ultrasonic characterization of edible oils. Argan oil was selected as a representative sample due to its stability during ultrasonic testing and its relevance in food and cosmetic industries (Ettahiri et al. 2024c). Measurements were performed using two different experimental configurations. The first consisted of a cubic glass container filled with oil, in which the ultrasonic waves propagated directly through the sample using an immersed ultrasonic transducer. The second employed a submerged multilayer container filled with oil and positioned on the same support as the transducer, allowing ultrasonic wave propagation under normal incidence through water and subsequently through the oil contained in the multilayer container. By comparing the ultrasonic parameters obtained in both setups, such as velocity, attenuation, acoustic impedance and reflection coefficient, this study seeks to identify the most suitable configuration for precise and reliable ultrasonic measurements.

In this experimental study, the selected multilayer ultrasonic configuration was further applied to the differentiation of organic and refined soybean oils through the analysis of ultrasonic velocity and reflection coefficient as a function of temperature. Particular attention was given to the reflection coefficient, an ultrasonic parameter that has received limited attention in previous studies on edible oils despite its potential relevance for oil characterization. To support the analysis and interpretation of the experimental data, a statistical approach based on linear regression was employed to evaluate the relationships between temperature and the investigated ultrasonic parameters. This methodology highlights the potential of ultrasonic characterization as a rapid, non-destructive, and reagent free approach for edible oil quality assessment, offering an alternative to conventional analytical techniques.

2 Materials and methodology

2.1 Sample preparation

During this experimental study, measurements of ultrasonic parameters (ultrasonic velocity, attenuation, reflection coefficient and acoustic impedance) used to characterize argan oil were carried out after processing the digital signal obtained from two different configurations of the electronic system shown in figure 1 and figure 3 . For the application of non-destructive characterization by ultrasonic technique of argan oil in two different media, the samples oil are obtained from a cold mechanical extraction (43°C) of argan seeds. This method helps preserve the biochemical and physical properties of the oil (Harhar et al. 2010). To ensure the reproducibility of the measurements taken, the obtained samples are stored away from light, thus protecting the oil from photochemical reactions and temperature variations.

2.2 Description of the first configuration

The device used consists of an ultrasonic transducer (Panametrics, Model V309, 13 mm, $f_0 = 5\ MHz$) and a container holding argan oil (140 x 80 x 25 mm^3), immersed in water maintained at a controlled temperature of 25°C. The system also includes a pulse generator (5052 Soufranel), a USB sampling oscilloscope (PicoScope 6402) and a computer equipped with LabVIEW and OriginPro software. The ultrasonic transducer is configured to operate as both a transmitter and receiver of ultrasonic waves in normal incidence. After the transducer is excited by the pulse generator, an ultrasonic wave propagates through the water, passes through the first plexiglas face of the tank, then through the oil in the container. The wave is reflected by the glass face of the container and returns along the same path to be transformed into an electrical signal. The obtained signal is finally processed and visualized on the computer screen using LabVIEW (figure 1).

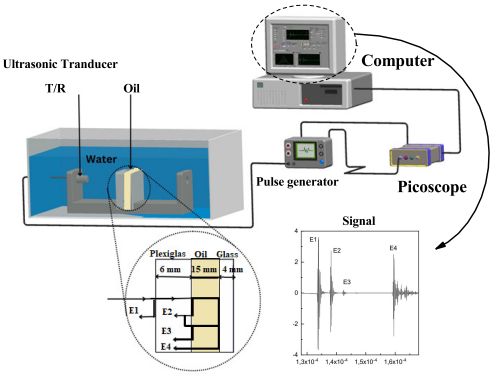


Fig. 1 The experimental device corresponding to the first configuration.

2.2.1 Ultrasonic measurement method

The obtained signal comprises four distinct echoes (E1, E2, E3 and E4) resulting from changes in the acoustic impedance of the propagation medium (figure 2).

The initial echo arises when a portion of the emitted ultrasound wave reflects back from the interface between the water and the first plexiglas slab of the container. Subsequently, the second echo occurs as the wave reflects from the interface between the plexiglas slab and the argan oil being characterized, providing insights into the oil's properties. Echo E3 occurs as the ultrasound wave traverses the plexiglas plate again, reflects off its rear surface, passes through the sample once more and returns. Lastly, the fourth echo corresponds to the reflection at the interface between the sample and the first face of the glass. In the subsequent analysis, the reflected signal containing these four echoes will be processed to determine the ultrasound parameters necessary for argan oil characterization.

2.2.2 Velocity analysis

The velocity of ultrasonic waves in mixtures was determined by measuring the flight time. In our study, we used the envelope method at a normal angle of incidence, corresponding to the peak of the backscattered signal. This method involves obtaining the reflected signal B(t) and its Hilbert transform T(t), then calculating the envelope E(t) (figure 2) of the signal B(t) using the following equation (Ettahiri et al. 2024b) :

$$E(t) = \sqrt{T^2(t) + B^2(t)} \tag{1}$$

The ultrasonic velocity was determined using the following formula (Mesbah et al. 2025; Banouni et al. 2022):

$$V_{c1} = \frac{2d}{\Delta t} \tag{2}$$

Where d represents the thickness of the mixture in meters and Δt is the flight time in seconds, corresponding to the time interval between echoes E2 and E4.

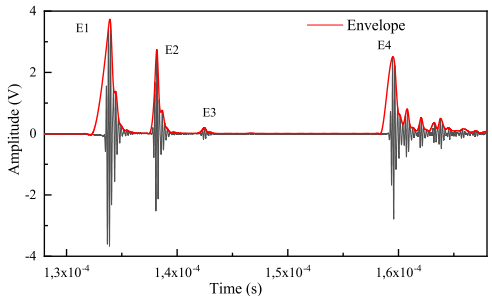


Fig. 2 The envelope of the reflected signal.

2.2.3 Reflection coefficient analysis

In the characterization of argan oil, the reflection coefficient was used to evaluate the amount of ultrasound waves reflected at interfaces, offering insights into the acoustic properties and quality of the oil. It was determined by measuring the echoes E2 and E1 of the signal. A straightforward calculation yields the following equation (Ettahiri et al. 2024b):

$$R_{\text{plexiglas/argan}} = \frac{Z^2_{\text{plexiglas}} - Z^2_{\text{water}}}{4 \cdot Z_{\text{plexiglas}} \cdot Z_{\text{water}}} \cdot \left| \frac{E_2}{E_1} \right| e^{2\alpha_p d_p} \tag{3}$$

Where $Z_{\text{plexiglas}}$ and Z_{water} respectively denote the impedance of the plexiglass plate and the impedance of the water. α_p represents the ultrasonic attenuation (Np/m) in the plexiglass plate, and d_p stands for the thickness of this plate in meters (figure 1).

2.2.4 Acoustic impedance analysis

The acoustic impedance ($Kg/S.m^2$) was calculated by exploiting the reflection coefficient $R_{\text{plexiglas/argan}}$ as shown in the following equation (Ettahiri et al. 2024b):

$$Z_{\text{argan}} = Z_{\text{plexiglas}} \cdot \frac{1 - R_{\text{plexiglas/argan}}}{1 + R_{\text{plexiglas/argan}}} \tag{4}$$

2.2.5 Attenuation analysis

The calculation of the acoustic attenuation α_{argan} (Np/m) is determined using the following equation (Ettahiri et al. 2024a):

$$\alpha_{\text{c1}} = -\frac{1}{2d} \ln\left(\xi_{\text{c1}} \cdot \frac{S_4}{S_2}\right) \tag{5}$$

Here, d represents the thickness of the mixture in meters, with S_2 denoting the spectral amplitude of the second echo and S_4 representing the spectral amplitude of the last echo and ξ_{c1} (equation 6) is an acoustic impedance coefficient of extreme media (Ettahiri et al. 2024b).

$$\xi_{\text{c1}} = \left| \frac{(Z_{\text{argan}} - Z_{\text{plexiglas}})(Z_{\text{argan}} + Z_{\text{plexiglas}})(Z_{\text{argan}} + Z_{\text{glass}})}{4Z_{\text{argan}}Z_{\text{plexiglas}}(Z_{\text{glass}} - Z_{\text{argan}})} \right| \tag{6}$$

2.3 Description of the second configuration

In this configuration, the transducer is placed on a graduated support in millimeters. The distance between the surface of the transducer and the bottom of the oil container can be measured using the controlled position of the transducer with a screw-nut system, allowing precise adjustment up to 40 mm. The temperature of the oil was maintained at 24°C. When recording a measurement, it is crucial to ensure that the face of the transducer is immersed vertically (in normal incidence) in the oil (figure 3).

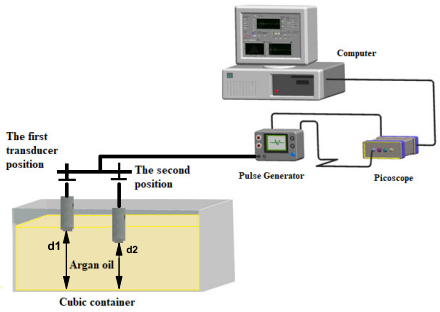


Fig. 3 The experimental device corresponding to the second configuration.

The same electrical acquisition and data processing device (hardware and software) used in the previous configuration is retained. The ultrasonic wave emitted by the transducer propagates through the argan oil until it reflects off the glass bottom of the container ($60 \times 60 \times 60$ mm^3). The same transducer receives the reflected wave and converts it into an electrical signal (signal 1). The acquisition of this signal was repeated by moving the transducer 7.5 mm downwards while maintaining the normal incidence of the wave (signal 2). The two acquisitions of the electrical signal (figure 4) are then processed to determine the ultrasonic properties of the argan oil.

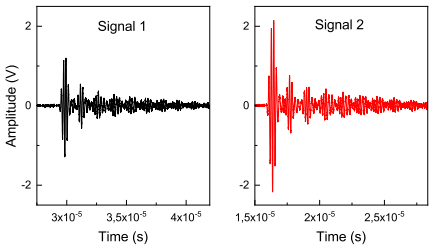


Fig. 4 The reflected signal corresponding to the second configuration.

2.3.1 Velocity analysis

The ultrasonic velocity V_{c2} (m/s) is calculated using equation 7 (Valoppi et al. 2021; Hamine et al. 2009), where d_1 is the distance (in meters) between the first position of the transducer and the bottom of the container, and t_1 is the instant (in seconds) of reception of the first echo of the reflected signal 1. d_2 is the distance between the second position of the transducer and the bottom of the container, and t_2 is the instant of reception of the first echo of the reflected signal 2, as shown in figure 5.

$$V_{c2} = \frac{2(d_1 - d_2)}{t_1 - t_2} \tag{7}$$

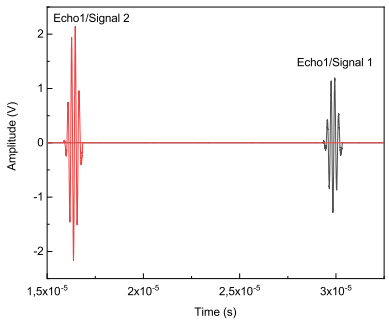


Fig. 5 The filtered echo 1 of signal 2 and the filtered echo 1 of signal 1.

2.3.2 Attenuation analysis

The calculation of acoustic attenuation α_{c2} (Np/m) is determined using the following equation (Ouacha et al. 2023; Tafkirte et al. 2023):

$$\alpha_{c2} = -\frac{1}{2(d_1 - d_2)} \ln\left(\frac{S_1}{S_2}\right) \tag{8}$$

Here, S_1 denotes the spectral amplitude of the first echo1 of signal 1 and S_2 represents the spectral amplitude of the first echo1 of signal 2.

3 Results and discussions

3.1 The impact of the measurement medium on determining the ultrasonic parameters of the sample oil

In Configuration 1 (medium 1), the time-domain signal consists of four distinct echoes (E1, E2, E3 and E4) resulting from changes in the acoustic impedance of the propagation medium (figure 6). These echoes allow for the measurement of several ultrasonic properties of argan oil, such as velocity, attenuation, reflection coefficient and acoustic impedance. The presence of multiple echoes helps to isolate the different effects of reflection and transmission, thus enabling a detailed analysis of the interactions of ultrasonic waves with the interfaces.

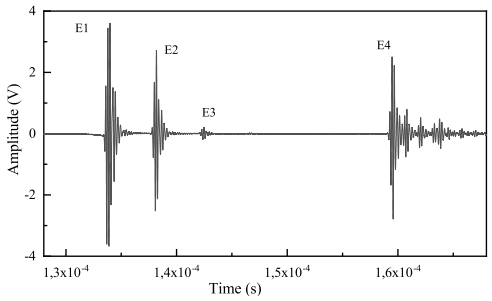


Fig. 6 The Reflected signal received by the ultrasonic transducer.

Conversely, in Configuration 2 (medium 2), the ultrasonic transducer is mounted on a support that allows for precise adjustment, and the signal is recorded at two different positions of the transducer (figure 5). The signal contains a primary echo resulting from the reflection on the glass bottom of the container. This configuration allows for the measurement of ultrasonic velocity and attenuation, but not the reflection coefficient or acoustic impedance due to the absence of multiple interfaces.

Moving from the time domain to the frequency domain, the spectra of medium 1 show interferences due to the multiple reflections of the echoes at the second interface of the multilayer tank (figure 7). The signal frequency presents variations related to the

multiple echoes, which can complicate the analysis but also provide rich information about the structure of the medium.

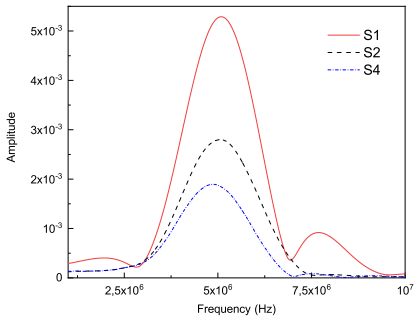


Fig. 7 The spectral amplitude of the echo1, echo2 and echo 4.

In contrast, the spectra of medium 2 show a reduction in echo interferences, offering a clearer and faster acquisition of ultrasonic properties (figure 8). This configuration makes it easier to distinguish the main echoes, thus reducing potential measurement errors, but it lacks the complexity needed to evaluate certain properties such as acoustic impedance.

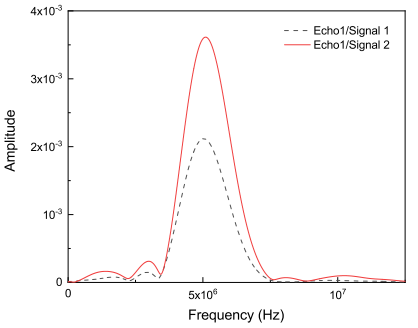


Fig. 8 The spectral amplitude of the first echo 1 of signal 1 and the spectral amplitude of the first echo 1 of signal 2.

Each medium has specific advantages and disadvantages. Medium 1 allows for a more detailed analysis due to the presence of multiple interfaces and echoes, despite the challenges posed by the interferences of the reflected echoes. The configuration associated with this medium allows for rapid and practical data acquisition, reducing the waiting time between measurements and facilitating a detailed analysis of the acoustic properties of argan oil. However, this configuration also has disadvantages,

notably the presence of a periodic component in the spectrum, which can affect the precision of the measurements and complicate the analysis of the results.

On the other hand, medium 2 simplifies data acquisition and reduces echo interferences, but its simplicity limits the ability to evaluate certain ultrasonic properties in detail. This medium allows for more precise measurements of certain properties such as the reflection coefficient and acoustic impedance. The configuration associated with this medium requires a distinct installation, which increases the preparation time and necessary adjustments. Moreover, it does not allow for direct measurement of the reflection coefficient and acoustic impedance with the same precision as Configuration 1.

Therefore, the choice of configuration depends on the specific properties that one wishes to measure and the practical requirements of the experiment.

3.2 Comparison of Measured Ultrasonic Properties

Table 1 indicates that Configuration 2 (medium 2) exhibits a slightly higher ultrasonic velocity (1500 m/s) compared to Configuration 1 (1404 m/s). This may indicate better transmission of the ultrasonic wave in the medium of Configuration 2. A higher velocity may also be due to different experimental conditions such as temperature, since it is difficult to maintain the same temperature in the multilayer medium of Configuration 1. In terms of acoustic attenuation, Configuration 2 presents a slightly higher value (35.19 Np/m) compared to Configuration 1 (25.67 Np/m). This difference could be due to the additional interferences observed in the multilayer medium of Configuration 1 and/or to the measurement conditions.

The reflection coefficient was measured only for the medium associated with Configuration 1 (36.66×10^{-2}) and is not available for medium 2. Measuring the reflection coefficient requires precise measurements of echoes at different interfaces, which is not possible with the simple configuration of Configuration 2. Similarly, the acoustic impedance was measured for medium 1 (1.49×10^{6} kg/s $\cdot$ m^2) but is not available for medium 2. Although it is theoretically possible to deduce the acoustic impedance from the ultrasonic velocity using the equation 9, where ρ is the density and V the ultrasonic velocity, this requires additional density measurements and different equipment.

$$Z = \rho \cdot V \tag{9}$$

Table 1 Ultrasonic properties of argan oil measured for both configurations.

Ultrasonic properties	Configuration 1 (medium 1)	Configuration 2 (medium 2)
Ultrasonic velocity (m/s)	1404	1500
Acoustic attenuation (Np/m)	25.67	35.19
Reflection coefficient	36.66×10^{-2}	Involves additional equipment
Acoustic impedance (kg/(s $\cdot$ m^2))	1.49×10^{6}	Involves additional equipment

Configuration 2 simplifies the measurement of velocity and acoustic attenuation through a medium with a single main interface, but it does not provide the necessary

conditions to measure the reflection coefficient and acoustic impedance. The echoes observed in Configuration 1 are essential for these measurements. The reduced complexity of the signal in Configuration 2 limits the information available for these specific parameters. Although it is theoretically possible to deduce the acoustic impedance from the ultrasonic velocity and density, this requires additional measurements and different equipment, which falls outside the scope of using ultrasonic waves alone. To measure the reflection coefficient and acoustic impedance, a configuration that exploits a multilayer medium, such as in Configuration 1, is necessary.

By comparing measurements obtained in two distinct media, each environment demonstrated specific advantages and limitations. Medium 1, using a submerged multilayer tank, allowed wave propagation in normal incidence in water, offering rapid measurements of velocity, attenuation, reflection coefficient, and acoustic impedance. In contrast, Medium 2, where the ultrasonic transducer is immersed in a cubic glass tank containing the oil, simplified data acquisition and reduced echo interferences, allowing more precise measurements of ultrasonic velocity and attenuation, but showed limitations for reflection coefficient and acoustic impedance due to the absence of multiple interfaces. The results indicate that the choice of experimental configuration depends on the specific ultrasonic properties to be measured and practical requirements. For comprehensive characterization, the submerged multilayer tank is more versatile, while the cubic glass tank is more practical for rapid measurements. These findings contribute to the optimization of ultrasonic characterization techniques for oils, potentially improving the precision and efficiency of oil quality evaluation methods in the food industry. Future research should explore the integration of these configurations into standardized protocols for the ultrasonic characterization of oils.

3.3 Application of the adopted configuration to distinguish organic from refined soybean oil

In the following, we extend the application of the adopted configuration to differentiate between refined soybean and organic oils based on their ultrasonic velocity and reflection coefficient as a function of temperature. The soybean oil samples were prepared and stored under optimal dark conditions. The first sample consists of commercial refined soybean oil purchased from a grocery retailer, while the second sample is organic soybean oil obtained using a screw extruder at 43°C under atmospheric pressure.

3.3.1 Ultrasonic velocity measurement

Figure 9 shows the variation of ultrasonic velocity as a function of temperature for organic and refined soybean oils between 25°C and 50°C.

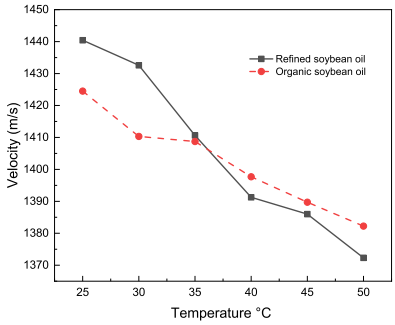


Fig. 9 Variation of ultrasonic velocity as a function of temperature.

For both oils, the ultrasonic velocity decreases as temperature increases. This behavior is explained by the relation:

$$v = \sqrt{\frac{B}{\rho}} \tag{10}$$

where B is the isentropic bulk modulus and ρ is the density (McClements 1991). With increasing temperature, intermolecular interactions become weaker and consequently decreases the ultrasonic velocity of edible oils (Tat and Van Gerpen 2003; Alouache et al. 2018).

At low temperatures (below 35°C), the refined soybean oil presents a higher ultrasonic velocity than the organic oil, indicating a greater resistance to compression. Around 35°C, the two curves become very close and intersect. Above this temperature, the organic oil shows slightly higher ultrasonic velocity values than the refined oil.

The refined oil also exhibits a stronger decrease in velocity with temperature, suggesting a higher sensitivity of its physicochemical properties to thermal variation (Alouache et al. 2018; Yildiz et al. 2024). Therefore, because the curves overlap and cross, a single ultrasonic velocity measurement is not sufficient to clearly distinguish the two oils. To overcome this limitation, the two media can be clearly differentiated by their ultrasonic velocity profiles as a function of temperature using a linear fit performed with OriginPro software (Figure 10).

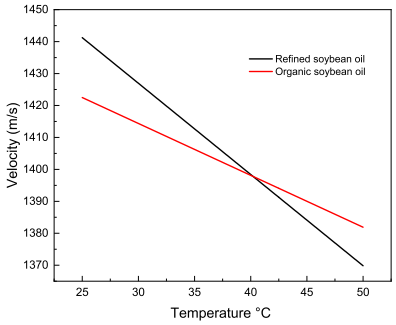


Fig. 10 Linear fit of ultrasonic velocity as a function of temperature.

Figure 10 indicates that the ultrasonic velocity of both refined soybean oil and organic soybean oil decreased linearly with increasing temperature in the range of 25 to 50 °C. This behavior is described by the linear regression equations obtained for each sample. For refined soybean oil, the relationship was expressed as:

$$V_{\mathrm{R}} = 1512.64 - 2.85T \tag{11}$$

while for organic soybean oil, the equation was:

$$V_{\mathrm{O}} = 1463.09 - 1.62T \tag{12}$$

where V_{R} and V_{O} are the ultrasonic velocities (m/s) of the refined and organic soybean oils, respectively, and T is the oil temperature in °C.

The negative slope values obtained in both equations indicate that ultrasonic velocity decreases as temperature increases. However, the decrease was more pronounced in refined soybean oil, which exhibited a larger absolute slope value (-2.856 m/s·°C^{-1}) than organic soybean oil (-1.624 m/s·°C^{-1}). This suggests that the ultrasonic properties of refined soybean oil are more sensitive to temperature variation.

Several statistical parameters were analyzed to evaluate the quality and reliability of these linear relationships. For refined soybean oil, the Pearson correlation coefficient was $r = -0.986$, indicating a very strong negative linear correlation between temperature and ultrasonic velocity. The coefficient of determination was $R^2 = 0.973$, meaning that approximately 97.35% of the variation in ultrasonic velocity could be explained by temperature changes. Similarly, organic soybean oil exhibited a Pearson coefficient of $r = -0.988$ and a determination coefficient of $R^2 = 0.977$, showing an even stronger linear fit, where about 97.7% of the velocity variation was attributed to temperature.

Overall, these findings demonstrate that temperature has a significant effect on the ultrasonic velocity of soybean oils. Refined soybean oil exhibited higher velocity values at lower temperatures but experienced a sharper decrease with increasing temperature, whereas organic soybean oil showed a more moderate decline. The intersection of the two curves around 40 °C indicates that both oils exhibit similar ultrasonic velocities

at this temperature. The steeper slope observed for refined soybean oil can be related to the refining process, which could alter the physicochemical composition of the oil and consequently increase its sensitivity to temperature variations.

3.3.2 Measurement of the reflection coefficient

Introducing the reflection coefficient as a characterization parameter is a key contribution of this study, as it proves to be more sensitive and discriminative than ultrasonic velocity alone. The reflection coefficient integrates changes in both velocity and density at the boundary surface (Biwa et al. 2005). Therefore, it can better detect the subtle structural differences resulting from the production methods, making it an excellent non-destructive tool for oil quality and authenticity control.

The temperature dependence of the ultrasonic reflection coefficient for refined and organic soybean oils (from 25 to 50 °C) is shown in figure 11. Throughout the entire temperature range, the reflection coefficient of the refined oil is significantly higher than that of the organic oil. This difference is mainly due to the industrial refining process which removes native components, free fatty acids and pigments (Čmolík and Pokorný 2000). The removal of these molecules changes the density and compressibility of the oil, altering its acoustic impedance and leading to a higher reflection coefficient at the interface (Mounts 1981).

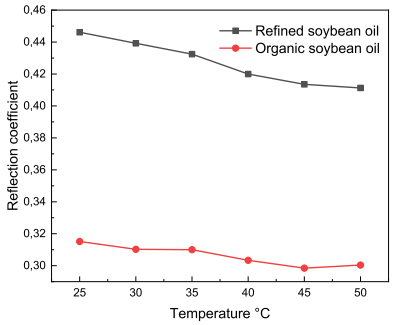


Fig. 11 Variation of the reflection coefficient as a function of temperature.

Regarding the temperature effect, both oils show a linear decrease in their reflection coefficients as temperature increases. To quantify this behavior, a statistical analysis was conducted using curve-fitting regression. This mathematical fitting allowed us to determine a predictive model that successfully correlates the reflection coefficient with temperature, providing a reliable tool to identify and classify unknown soybean oil samples (figure 12).

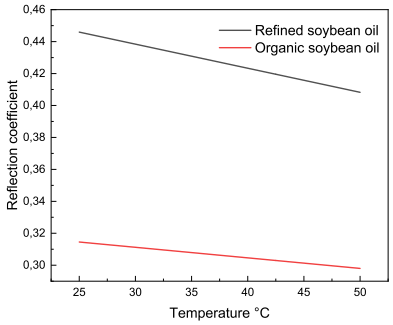


Fig. 12 Linear fit of reflection coefficient variation with temperature.

Figure 12 illustrates the variation of the reflection coefficient as a function of temperature for refined and organic soybean oils in the temperature range of 25–50 °C. A linear decrease in the reflection coefficient was observed for both oils. The obtained linear regression equations were, for refined soybean oil:

$$R_{\mathrm{R}} = 0.48364 - 0.00151T \tag{13}$$

and for organic soybean oil:

$$R_{\mathrm{O}} = 0.33106 - 6.61 \times 10^{-4}T \tag{14}$$

where R_{R} and R_{O} are the reflection coefficient of the refined and organic soybean oils, respectively.

The refined soybean oil exhibited a higher slope magnitude (0.00151 $^{\circ}\mathrm{C}^{-1}$) compared with organic soybean oil (6.61×10^{-4} $^{\circ}\mathrm{C}^{-1}$), indicating a stronger sensitivity of the reflection coefficient to temperature changes in the refined oil.

The statistical analysis confirmed the suitability of the linear regression models. Refined soybean oil presented a Pearson correlation coefficient of $r = -0.986$, indicating a very strong negative linear correlation between temperature and reflection coefficient. The coefficient of determination reached $R^2 = 0.972$, meaning that approximately 97.22% of the variation in the reflection coefficient was explained by temperature. In the case of organic soybean oil, the Pearson coefficient was $r = -0.948$, also showing a strong negative correlation, while the determination coefficient ($R^2 = 0.899$) indicated that about 89.97% of the variation in reflection coefficient was associated with temperature variation.

Overall, these results demonstrate that temperature significantly affects the reflection coefficient of soybean oils. Refined soybean oil showed higher reflection coefficient values and a stronger temperature dependence than organic soybean oil. This higher sensitivity may be related to physicochemical modifications induced by the refining process, which could influence intermolecular interactions and acoustic properties of the oil.

4 Conclusion

In this study, ultrasonic techniques were successfully applied to evaluate the influence of the experimental environment on the acoustic characterization of edible oils and to investigate the differentiation between organic and refined soybean oils. Two experimental configurations were compared, a submerged multilayer tank and a cubic glass tank with an immersed transducer. The obtained results demonstrated that each configuration presents specific advantages depending on the targeted ultrasonic parameters. The submerged multilayer configuration enabled the simultaneous determination of ultrasonic velocity, attenuation, reflection coefficient and acoustic impedance under normal incidence conditions, while the cubic glass tank provided simpler acquisition conditions and reduced echo interference, leading to more accurate measurements of ultrasonic velocity and attenuation.

The comparative analysis showed only slight differences in attenuation and ultrasonic velocity between the two experimental media, confirming the reliability of both approaches for oil characterization. However, the multilayer configuration proved more practical for comprehensive ultrasonic analysis, particularly for the determination of reflection coefficient and acoustic impedance. Consequently, this configuration was adopted for the characterization and differentiation of soybean oils.

The application of the adopted configuration to refined and organic soybean oils revealed that ultrasonic properties are strongly affected by temperature. Both oils exhibited a linear decrease in ultrasonic velocity and reflection coefficient with increasing temperature between 25°C and 50°C. Statistical analysis using linear regression confirmed the robustness and reliability of these relationships, with high Pearson correlation coefficients and coefficients of determination, indicating strong linear dependencies between temperature and the investigated ultrasonic parameters. The results also showed that ultrasonic velocity alone was not sufficient to clearly distinguish the two oils because the velocity curves approached and intersected at around 40°C. In contrast, the reflection coefficient provided a clearer differentiation between refined and organic soybean oils over the entire investigated temperature range. These findings confirm the relevance of combining ultrasonic parameters with statistical analysis to improve the discrimination of edible oils. Overall, this work demonstrates the significant influence of the experimental environment on the ultrasonic characterization of edible oils and confirms the potential of ultrasonic techniques as rapid, non-destructive and reliable tools for evaluating edible oils and distinguishing oils produced under different processing conditions.

Author Contributions

M.E.: conceptualization, investigation, writing—original draft, funding acquisition, methodology, visualization, validation, writing—review and editing, software, formal analysis, project administration, supervision, data curation; **H.M.**: investigation; **M.T.**: investigation, methodology; **A.H.**: investigation, methodology; **E.H.O.**: conceptualization, writing—review and editing, resources, supervision; **H.B.**: conceptualization, resources.

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Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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