JP Journal of Heat and Mass Transfer
© 2026 Pushpa Publishing House, Prayagraj, India
https://pphmjopenaccess.com
https://doi.org/10.17654/0973576326016
Volume 39, Number 2, 2026, Pages 299-320
P-ISSN: 0973-5763
E-ISSN: 3049-2556

ULTRASONIC VELOCITY AND ATTENUATION COEFFICIENT IN *ABELMOSCHUS SAGITTIFOLIUS* (KURZ) MERR ROOT AT TEMPERATURE FROM –30 TO 30°C

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Received: December 11, 2025; Accepted: February 11, 2026
Keywords and phrases: *Abelmoschus sagittifolius*, attenuation coefficient, ultrasound-assisted freezing, temperature dependence, ultrasonic velocity.
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How to cite this article: Hay Nguyen, The Bao Nguyen, Minh Hieu Ngo, Quang Huy Le, Thanh Dat Le and Xuan Dieu Mai, Ultrasonic velocity and attenuation coefficient in *Abelmoschus sagittifolius* (Kurz) Merr root at temperature from –30 to 30°C, JP Journal of Heat and Mass Transfer 39(2) (2026), 299-320. https://doi.org/10.17654/0973576326016
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Published Online: March 19, 2026

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Abstract

This study aims to characterize the acoustic properties of *Abelmoschus sagittifolius* (Kurz) Merr roots by employing contact ultrasonic measurements at a frequency of 21 kHz to determine the ultrasonic wave velocity and attenuation coefficient over a temperature range from –30°C to 30°C. These parameters are critical for the optimization of ultrasound-assisted freezing processes applied prior to freeze-drying. The results indicate a significant increase in ultrasonic velocity from 335.67 m/s at 30°C to 1764 m/s at –30°C, while the attenuation coefficient sharply decreased below 0°C from 2.687 dB/mm to 0.308 dB/mm at –30°C. These findings confirm that acoustic parameters are highly temperature-dependent, especially within the range where moisture in the material transitions from liquid to solid phase, thereby substantially altering the physical structure and mechanical properties of the material.

1. Introduction

Abelmoschus sagittifolius (Kurz) Merr, commonly referred to as "Bo Chinh ginseng", is a valuable medicinal plant cultivated in Vietnam. Its roots are rich in saponins, a pharmacologically active component commonly found in ginseng species. In the context of freeze-drying processes incorporating ultrasound-assisted freezing, accurate determination of the material's acoustic properties over the range of –30°C to 30°C is essential. While numerous studies have evaluated food quality through acoustic characterization, most are confined to temperatures above 0°C, and investigations involving sub-zero conditions remain limited (Liang et al. [1]).

Previous research has demonstrated the feasibility of ultrasonic methods in characterizing food structure and monitoring processing stages. For instance, Fariñas et al. [2] utilized ultrasound to evaluate the internal structure of post-harvest avocados. Guillermic et al. [3] tracked quality

variations in high-moisture meat analogs using changes in ultrasonic velocity correlated with moisture content. Vasighi-Shojae et al. [4] employed ultrasound to assess the mechanical properties of apples as indicators of product quality. Muramatsu et al. [5] applied non-destructive ultrasonic testing to quantify the firmness of fruits such as apricots, plums, and tomatoes. Mizrach [6] developed a non-destructive ultrasonic system for quantifying ripeness, firmness, and other quality indicators in mangoes and avocados. Wieja et al. [7] established correlations between ultrasonic velocity and compositional attributes such as protein, fat, sodium content, and density in poultry meat. Contreras et al. [8] investigated the ultrasonic characteristics of dry-cured ham during salting to monitor changes in salt content, moisture level, and microstructure. Mironovs et al. [9] employed ultrasonic velocity, attenuation, and waveform analysis to monitor dynamic changes in meat tissues during freezing. Similarly, Jha et al. [10] used ultrasonic velocity to track the thawing progression of frozen meat products.

Ultrasonic velocity is a fundamental parameter in non-destructive material characterization, as it is sensitive to compositional and structural variations within the material. Temperature exerts a significant influence on this parameter, primarily due to phase transitions in moisture content, which alter the mechanical and thermal properties of the matrix. The attenuation coefficient, meanwhile, quantifies the energy loss of an ultrasonic wave due to scattering and absorption phenomena as it propagates through the material. This property is frequency-dependent and influenced by the internal structure and physical state of the medium. Accordingly, processes such as freezing and drying, which induce phase changes and structural modifications, result in variable attenuation characteristics (Giacomozzi et al. [11]).

Both contact and non-contact ultrasonic measurement techniques have been utilized to quantify wave velocity and attenuation. Corona et al. [12] reported a velocity measurement deviation of approximately 1% between the two techniques, while Fariñas et al. [13] observed a deviation of 3%. However, non-contact approaches suffer from significant limitations,

particularly in accurately determining sample thickness and in measuring attenuation due to the reflection and energy loss encountered at the air-material interface. For these reasons, contact methods are predominantly employed in the determination of ultrasonic attenuation in solid or semi-solid materials (Giacomozzi et al. [11]).

The accurate determination of ultrasonic wave parameters - namely, propagation velocity and attenuation coefficient - plays a pivotal role in the investigation of ultrasound-assisted freeze-drying processes. This drying method typically comprises three sequential stages: freezing, primary drying (sublimation), and secondary drying under vacuum at low temperature (see Figure 1). Of these, the freezing stage is particularly critical, as it significantly impacts the microstructural and functional quality of the final product. The application of ultrasonic energy during this phase enhances heat transfer by promoting microchannel formation, disrupts dendritic ice crystal structures, and reduces crystal size. These effects collectively contribute to shorter drying durations and improved textural porosity of the dried material.

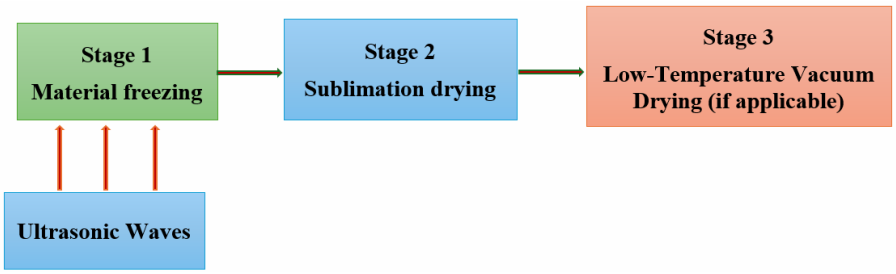


Figure 1. Ultrasonic wave assistance during the freezing stage of the freeze-drying process.

In this study, we aim to determine the temperature-dependent behavior of ultrasonic velocity and attenuation coefficient. Furthermore, a relationship between acoustic parameters and material temperature has been established. As a result, a contact ultrasonic measurement method was developed and implemented for the experiments conducted in this work.

2. Measurement Device Design Principles

The measurement system was designed based on the ultrasonic through-transmission technique, which utilizes two ultrasonic transducers aligned on opposite sides of the sample. One transducer functions as a transmitter (Tx) that emits ultrasonic pulses, while the other serves as a receiver (Rx) to capture the transmitted signal, as illustrated in Figure 2 (Kim et al. [14]).

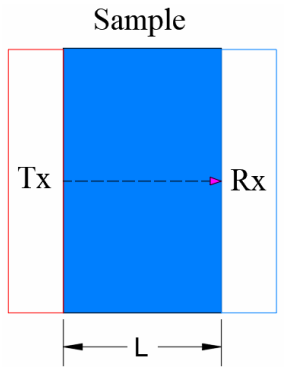


Figure 2. Through-transmission method.

As illustrated in Figure 3, in the through-transmission system, two ultrasonic transducers are positioned directly opposite each other, with the test sample of thickness *L* placed in the gap between them. A pulse generator produces a continuous wave signal at the resonant frequency of the transducers. This signal is transmitted to the transmitting transducer, which converts it into an ultrasonic wave of the same frequency. The generated ultrasonic wave propagates through the sample and is received by the second transducer, referred to as the receiving transducer. The receiving transducer converts the ultrasonic wave back into an electrical signal. An oscilloscope is used to record and monitor both the transmitted and received signals for comparison purposes.

Liang et al. [1] compiled various experimental studies on the measurement of ultrasonic wave parameters through materials at low temperatures. These studies emphasize that maintaining strict temperature control of the sample during measurement is crucial. The freezing methods

employed by the researchers include direct contact with a cooling surface or air-based cooling. Commonly used freezing equipment includes commercial freezers and refrigerators, with the air-cooling method inside freezers being the most widely adopted approach.

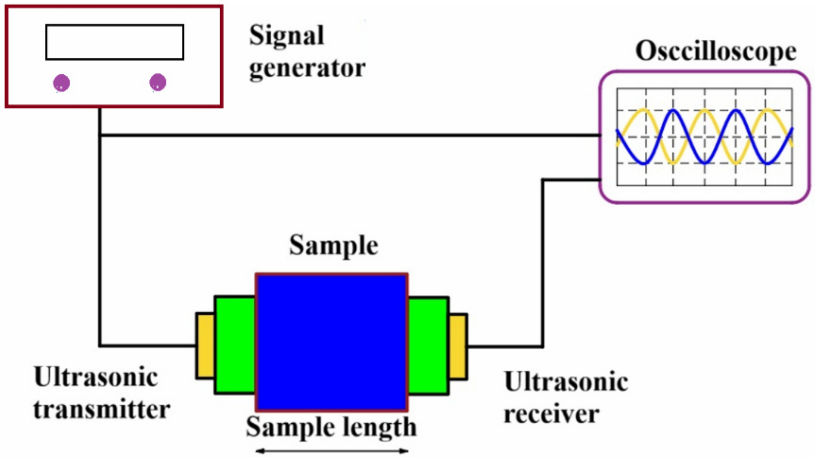


Figure 3. Schematic diagram of the measurement setup using the through-transmission technique (Firouz et al. [15]).

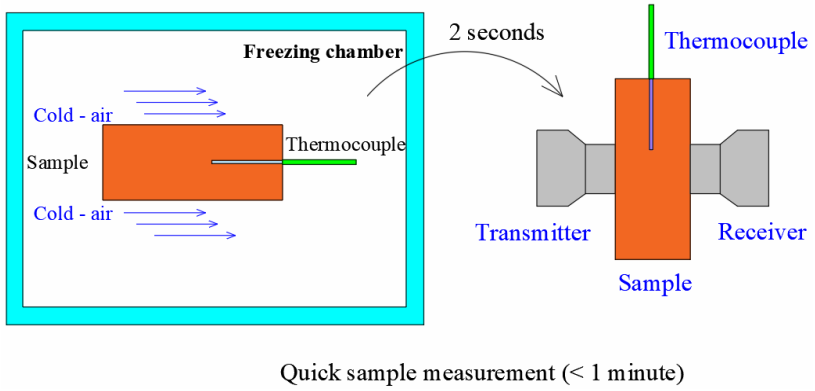


Figure 4. Sample freezing and measurement method (adapted from (Liang et al. [1])).

A temperature sensor is inserted into the sample prior to freezing to monitor the internal temperature of the material during both the freezing and measurement processes. In some studies, the sample was frozen in air, then

removed and quickly measured for ultrasonic parameters. In such cases, the sample retrieval time was limited to approximately 2 seconds, and the total measurement duration was kept under 1 minute to minimize any temperature rise during testing, as illustrated in Figure 4 (Liang et al. [1]).

Based on the above analysis, the research team selected the air-based freezing method using an Individual Quick Freezing (IQF) system. The material samples were placed on an IQF conveyor belt and cooled to the target temperature. During the freezing process, the conveyor belt remained stationary in order to maintain precise control over the material temperature - from its initial state to the desired setpoint.

The use of the conveyor belt system facilitates the rapid transfer of samples from the freezing chamber to the ultrasonic measurement device without requiring the chamber door to be opened, thereby minimizing thermal fluctuation in the material. An IQF freezing system was designed and installed for this purpose, as illustrated in Figure 5, with air temperatures adjustable in the range of –30°C to –40°C.

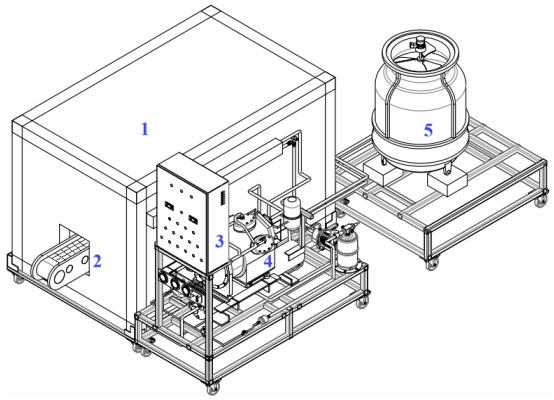


Figure 5. IQF freezing system.

1. Freezing chamber, 2. IQF conveyor belt, 3. Control electrical cabinet, 4. Compressor - refrigeration system, 5. Cooling tower.

Regarding the ultrasonic measurement system, which is designed to measure the ultrasonic velocity and attenuation coefficient at a transmission frequency of 21 kHz using the through transmission method, the setup

consists of the following components:

- Signal generator with a transmission frequency of 21 kHz.
- Ultrasonic transmitting transducer.
- Ultrasonic receiving transducer.
- Oscilloscope for signal acquisition and display.

The operation of the system is based on physical phenomena related to ultrasonic wave propagation. In this method, the ultrasonic wave is emitted from the transmitting transducer, passes through the test sample, and is detected by the receiving transducer. The oscilloscope records both the transmitted and received signals, enabling the calculation of wave travel time across the known sample thickness. As the wave propagates through the material, part of its energy is lost due to absorption within the material and scattering at internal interfaces. This results in attenuation of the wave amplitude, which is also captured by the oscilloscope. The measurement setup is illustrated in Figure 6.

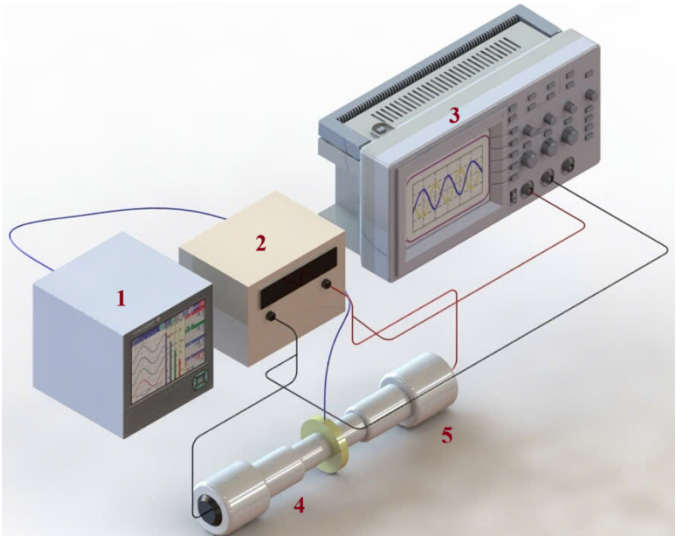


Figure 6. Ultrasonic measurement system diagram.

1. Temperature measuring device, 2. Ultrasonic wave signal generator, 3. Oscilloscope, 4. Transmitting transducer, 5. Receiving transducer.

Based on the aforementioned principle, the ultrasonic velocity through the material is determined using the sample thickness and the wave propagation time, as given by equation (1) (Kim et al. [14]):

$$v = \frac{L}{\tau} \text{ (m/s)}, \tag{1}$$

where

L (m) is the thickness of the material layer,

τ (s) is the ultrasonic wave propagation time,

v (m/s) is the ultrasonic velocity through the material.

The propagation time τ is determined by the time difference between the transmitted and received signals, as displayed on the oscilloscope, and is typically measured in microseconds (μs).

The ultrasonic attenuation coefficient through the material is determined using following equation (2) (Kim et al. [14]):

$$\alpha = \frac{20}{L} \log\left(\frac{A_0}{A}\right), \tag{2}$$

where

L (m) is the thickness of the material layer,

A_0 (V) is the amplitude of the input ultrasonic signal,

A (V) is the amplitude of the signal after transmission through the sample,

α (dB/mm) is the ultrasonic attenuation coefficient through the material.

3. Materials and Methods

Materials. One-year-old *Abelmoschus sagittifolius* (Kurz) Merr roots used in this experiment were cultivated in Quang Binh province and supplied by SBC Hoang Gia Co., Ltd. (Hue, Vietnam). The average root diameter was

approximately 25 mm, and the roots were stored at a temperature range of 6 to 8°C. For testing, the roots were sliced into discs with a thickness ranging from 6 to 10 mm.

Experimental equipment. The experimental apparatus was custom-fabricated by Sonigreen Technology Co., Ltd. (Vietnam) based on the through transmission technique as described in the previous section.

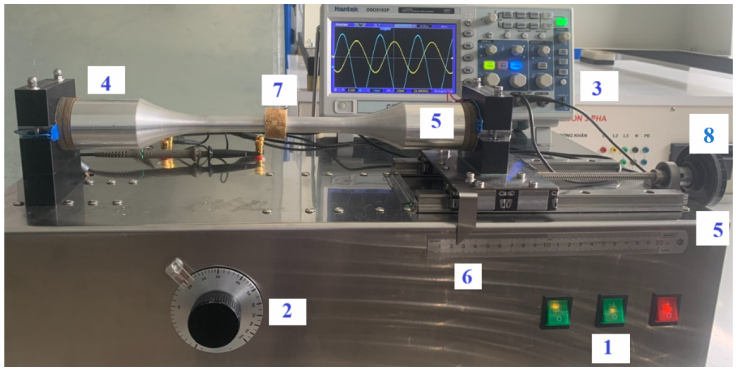


Figure 7. Ultrasonic measurement device.

1. Ultrasonic signal generator, 2. Frequency adjustment knob, 3. Oscilloscope, 4. Signal transmitting probe, 5. Signal receiving probe, 6. Material thickness gauge, 7. Sample material, 8. Gap adjustment knob between transmitter and receiver.

The measurement setup consists of two ultrasonic probes: one acting as the transmitter (4) and the other as the receiver (5). Both probes operate at a center frequency of 21 kHz. The transmitter and receiver are connected to an oscilloscope (3) via channels CH1 and CH2, respectively. The transmitted signal has an amplitude of 22.2 Vpp, while the received signal has an amplitude of 8.8 Vpp. The transmission frequency can be adjusted using knob (2), and the distance between the transmitter and receiver can be fine-tuned using knob (8). Material thickness is measured using a mechanical gauge (6).

- A Yokogawa FX1000 temperature recorder (Japan) was used to record temperature readings from a thermocouple sensor with a high measurement accuracy of ±0.15%.

- An IQF conveyor-type freezing system was employed, capable of reaching temperatures as low as –40°C.

Measurement method

Measurement procedure:

- System calibration: Set the frequency adjustment knob (2) to 21 kHz. Adjust the probe distance to zero to synchronize the transmitted and received waveforms on the oscilloscope.

- Freezing process: The root sample is placed on the IQF conveyor belt and cooled to the desired temperature.

- Measurement: After freezing, the sample is quickly transferred and clamped between the transmitting and receiving probes.

- Data recording:

+ The temperature change is logged using the temperature recorder.

+ The signal attenuation is recorded from the oscilloscope using a camera.

+ Each measurement cycle takes approximately 30 to 40 seconds.

- Observed temperature increases during the experiment:

+ For temperatures above 0°C: Temperature rise = 0.3 to 0.5°C.

+ For temperatures from 0°C to −15°C: Temperature rise = 1 to 1.5°C.

+ For temperatures from −20°C to −30°C: Temperature rise = 1.5 to 2.0°C.

These values were recorded through experimental measurements. In the temperature range above 0°C, the observed change in temperature was negligible. However, as the sample temperature decreased further, the rate of temperature increase became more significant. This phenomenon can be attributed to the larger temperature difference between the sample and the surrounding environment, despite the rapid sampling.

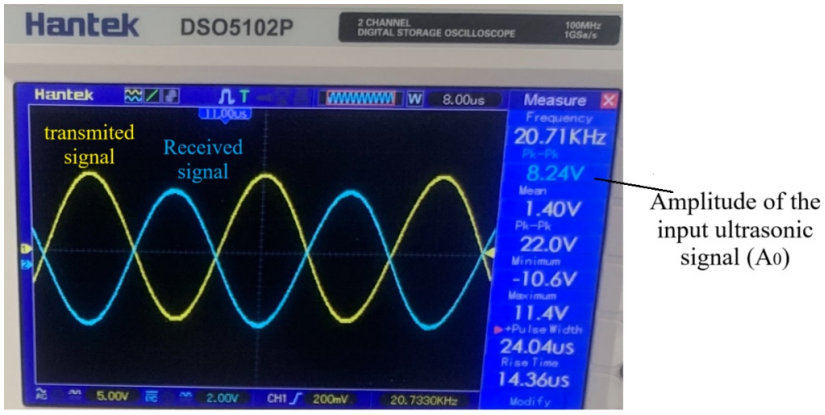


Figure 8A. Transmitted and received signals recorded on the oscilloscope without the presence of material.

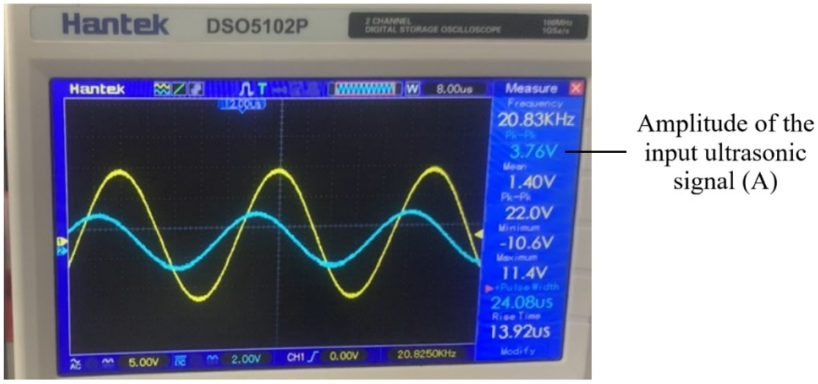


Figure 8B. Received signal recorded on the oscilloscope after transmission through the material.

Reliability verification of the measurement device. The ultrasonic measurement device was tested for reliability by measuring the propagation velocity of ultrasonic waves in air, and through carrot and potato samples at ambient temperature. The measurement results are summarized in the following table:

Transmission frequency: 21 kHz, Temperature : 30°C		
Materials	Ultrasonic velocity (m/s)	SD
Air	339.5	7.1
Carrot	347.8	13.7
Potato	535.8	13.5

The measured results are consistent with previously published data on ultrasonic velocity in various materials at ambient temperature, such as 509 m/s in potato (Sanchez-Jimenez et al. [16]), 341 m/s in carrot, and 333 m/s in air (Mizrach et al. [17]).

4. Results and Discussion

Ultrasonic velocity. Each material exhibits different ultrasonic propagation velocities due to its unique structure and physical properties. Additionally, variations in temperature lead to corresponding changes in the thermophysical properties of the material, which in turn affect the ultrasonic velocity.

This effect becomes particularly significant in frozen materials, where the internal moisture undergoes phase transition into ice. This crystallization alters the material's thermophysical characteristics, thereby significantly influencing its mechanical properties as well Firouz et al. [15]; Giacomozzi et al. [11].

Table 1. Ultrasonic velocity in ginseng samples at different temperatures

Temperature (°C)	Velocity (m/s)	SD	Temperature (°C)	Velocity (m/s)	SD
–30	1764	74.03	5	422.33	25.31
–25	1667	73.54	10	403.33	10.98
–20	1563	0	15	384.33	10.5
–15	1501.67	38.67	20	371.33	8.43
–10	1171.33	7.08	25	358.33	8.55
–5	958.67	25.31	30	335.67	2.27
0	454	10.98			

At temperatures equal to or above 0°C, the ultrasonic velocity through the material does not change significantly (from 335.67 m/s at 30°C to 454 m/s at 0°C), as the material's structure and thermophysical properties remain relatively stable. In this range, the internal moisture in the material is still in the liquid state.

However, at temperatures below 0°C, the moisture within the material begins to crystallize, leading to substantial changes in both the structure and thermophysical parameters. This is due to a phase transition of water from liquid to solid. As the degree of crystallization increases, the ultrasonic velocity increases accordingly. The lower the temperature, the greater the amount of crystallized water, and thus the higher the ultrasonic velocity. A sharp increase in ultrasonic velocity was observed, rising from 454 m/s at 0°C to 958.67 m/s at –5°C.

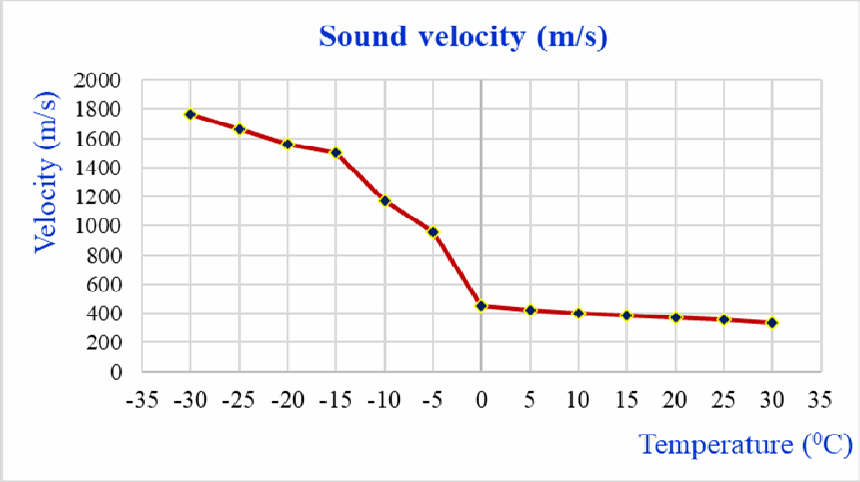


Figure 9. Variation of ultrasonic velocity in the material as a function of temperature.

These results are consistent with previous studies on ultrasonic velocity in both unfrozen and frozen materials. For example, Scholz and Span [18] investigated ultrasonic velocity in methanol solutions over a temperature range from –40°C to 80°C, and the results indicated that ultrasonic velocity

increases with decreasing temperature. Similarly, Miles and Cutting [19] studied ultrasonic wave propagation in unfrozen and frozen beef, reporting that the velocity in frozen beef increased by 70% compared to unfrozen samples. This phenomenon is attributed to the crystallization of internal moisture in frozen materials, which significantly increases the wave velocity compared to materials where water remains in the liquid phase. Liang et al. [1] synthesized findings from multiple studies and reported that ultrasonic velocity can increase by up to 189% when water undergoes a phase transition from liquid to solid. Likewise, Giacomozzi et al. [11] concluded that as the proportion of liquid-phase water decreases, the wave velocity increases, since the speed of sound in liquid water is slower than in solid materials.

Ultrasonic velocity is therefore a function of temperature.

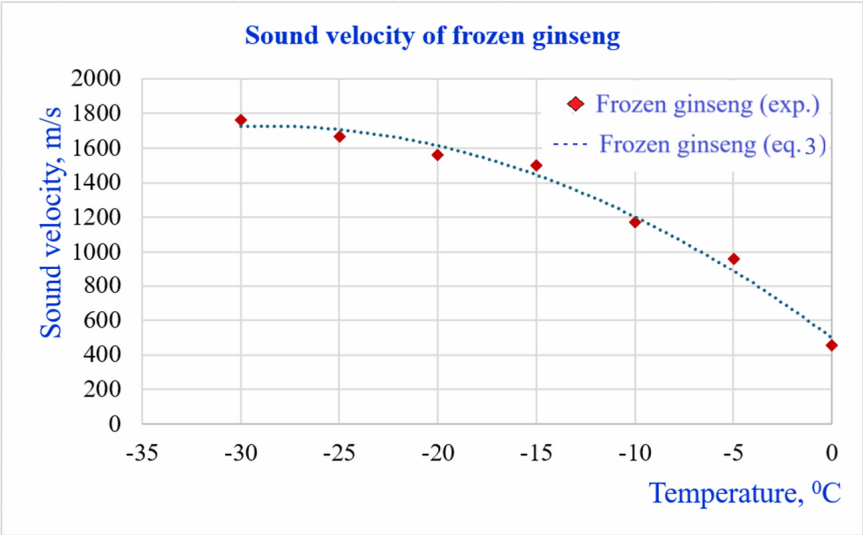


Figure 10. Ultrasonic velocity in frozen *Abelmoschus sagittifolius* root as a function of temperature.

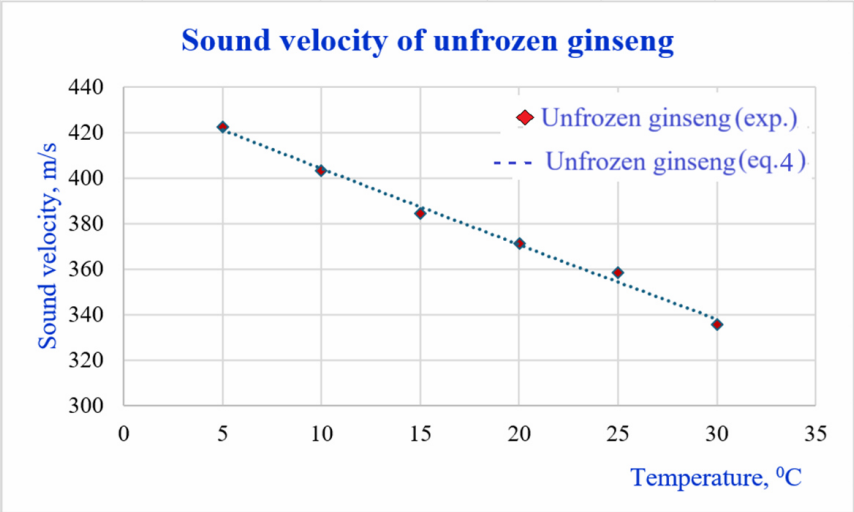


Figure 11. Ultrasonic velocity in unfrozen *Ginseng* root as a function of temperature.

Ultrasonic velocity is a function of temperature, as determined experimentally. Figure 10 and equation (3) stated below illustrate the relationship between ultrasonic velocity and temperature in the range from –30°C to 30°C, with a coefficient of determination $R^2 = 0.9873$. Figure 11 and equation (4) to follow represent the ultrasonic velocity as a function of temperature in the temperature range above 0°C, with a coefficient of determination $R^2 = 0.9931$:

$$v = -1.4856T^2 - 85.555T + 496.58, \quad T < 0^\circ\text{C} \quad (R^2 = 0.9873), \tag{3}$$

$$v = 0.0041T^2 - 3.4642T + 438.3, \quad T \geq 0^\circ\text{C} \quad (R^2 = 0.9931). \tag{4}$$

Attenuation coefficient. When ultrasonic waves propagate through a material, part of the wave energy is lost due to scattering and absorption mechanisms. This attenuation is influenced by several factors, including the ultrasonic wave frequency and the physical properties of the food material.

Table 2. Ultrasonic attenuation coefficient at different temperatures

Temperature (°C)	Attenuation coefficient (dB/mm)	SD	Temperature (°C)	Attenuation coefficient (dB/mm)	SD
–30	0.308	0.026	5	3.642	0.0107
–25	0.537	0.125	10	4.167	0.065
–20	0.782	0.041	15	4.444	0.006
–15	1.146	0.011	20	4.686	0.148
–10	1.835	0.109	25	4.787	0.096
–5	2.277	0.007	30	4.926	0.041
0	2.687	0.134			

In the temperature range from 5°C to 30°C, the attenuation coefficient shows minimal variation, increasing from 3.642 dB/mm at 5°C to 4.926 dB/mm at 30°C. However, at temperatures below 0°C, the attenuation coefficient decreases rapidly, with a reduction of approximately 88% as the material temperature drops from 0°C to −30°C. In this low-temperature range, the material properties change significantly due to the phase transition of liquid water into ice. As the temperature decreases further, the amount of crystalline ice increases, which contributes to the continued decrease in attenuation.

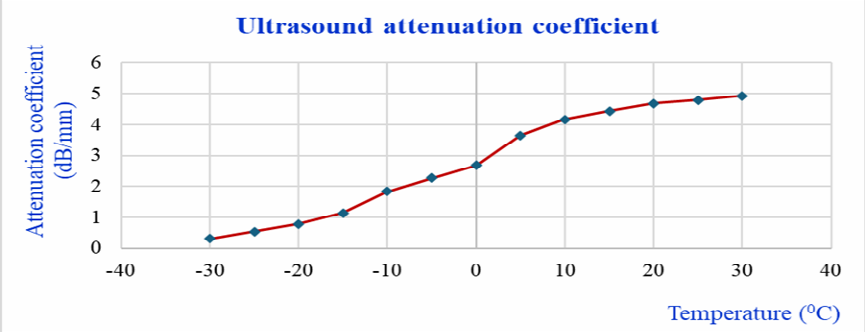


Figure 12. Ultrasonic attenuation coefficient in the material as a function of temperature.

A significant change in the attenuation coefficient in the phase transition region has also been reported by Liang et al. [1] in a comprehensive review of acoustic properties at subzero temperatures. Their findings indicated that the attenuation coefficient of bovine connective tissue exhibited a much

more pronounced change when water transitioned from the liquid phase to solid phase at −20°C, compared to the relatively minor changes observed between 0°C and 20°C.

The ultrasonic attenuation coefficient is temperature-dependent.

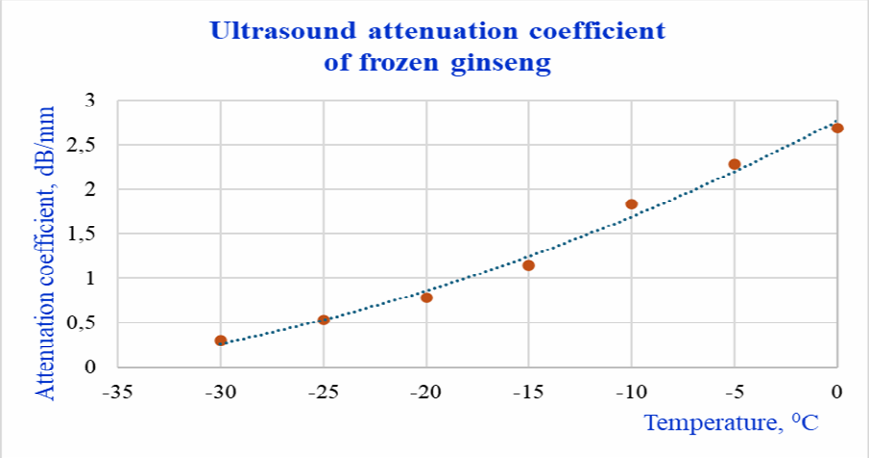


Figure 13. Ultrasonic attenuation coefficient in frozen *ginseng* as a function of temperature.

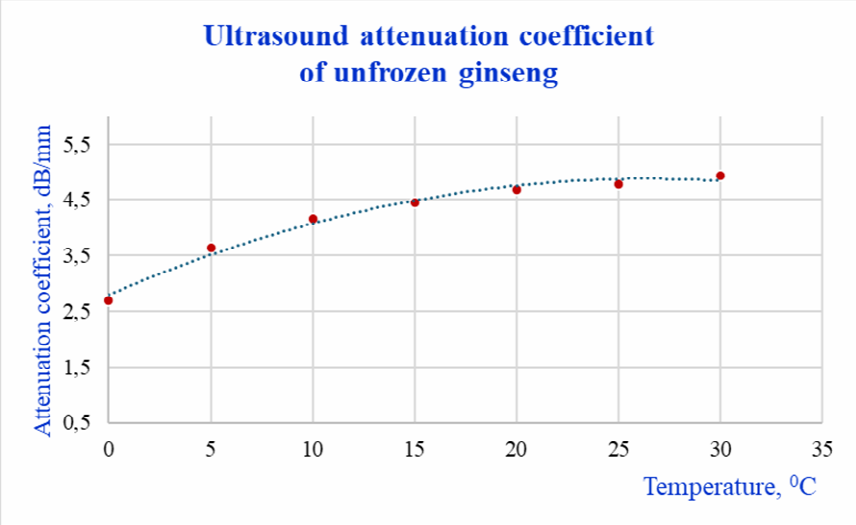


Figure 14. Ultrasonic attenuation coefficient in unfrozen *ginseng* as a function of temperature.

The ultrasonic attenuation coefficient is a function of temperature, as determined experimentally, and is described by equations (5) and (6) as follows:

$$\alpha = 0.0012T^2 + 0.1196T + 2.769, \quad T < 0^\circ\text{C} \quad (R^2 = 0.9899), \tag{5}$$

$$\alpha = -0.003T^2 + 0.1576T + 2.7974, \quad T \geq 0^\circ C \quad (R^2 = 0.9842). \tag{6}$$

Equations (5) and (6) represent the relationship between attenuation coefficient and temperature in the range of −30°C to 30°C, with a coefficient of determination $R^2 = 0.9899$ for equation (5) and $R^2 = 0.9842$ for equation (6). Both equations meet standard engineering accuracy requirements and are suitable for use in the simulation of the freezing process of ginseng root with ultrasound assistance.

5. Conclusion

This study applied the through transmission method to determine the ultrasonic wave velocity and attenuation coefficient in both unfrozen and frozen materials. The experimental results showed that in different temperature ranges, the acoustic properties of the material also vary.

Notably, in low-temperature regions, when the moisture content in the material crystallizes, both ultrasonic velocity and attenuation coefficient exhibit significant changes due to the transformation in material properties. The ultrasonic wave velocity increased by 288% as the material temperature decreased from 0°C to −30°C. Similarly, the attenuation coefficient decreased sharply as the proportion of frozen water increased with decreasing temperature.

The acoustic properties of the material are of great significance in research on the ultrasound-assisted freezing process. This dataset enabled the research team to both select an appropriate ultrasonic support method for the freezing stage of the material and to determine the amount of ultrasonic energy attenuation within the material throughout the freezing process.

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