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Article

Non-Destructive Assessment of Quality Attributes in Iranian Freestone Tabrizi Peaches Using Ultrasonic Velocity and Attenuation

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Abstract: Non-destructive assessment of peach maturity is important for reducing destructive sampling and improving consistency in postharvest handling. This study evaluated through-transmission ultrasonic velocity and apparent attenuation as non-destructive indicators of ripeness and internal quality in Iranian Freestone Tabrizi peaches. Sixty fruit were classified into ripe and unripe groups and further divided into large and small size classes. Ultrasonic velocity and apparent attenuation were measured at 20 °C and related to firmness, dry weight (DW), pH, titratable acidity, sugar content and soluble solids content (SSC). Ripening was associated with lower ultrasonic velocity and higher apparent attenuation, together with lower firmness and higher SSC and DW. The second-order regression models showed coefficients of determination (R^2) of 0.88–0.98 for attenuation versus DW, 0.91–0.98 for velocity versus DW, 0.84–0.98 for attenuation versus SSC, and 0.88–0.98 for velocity versus SSC, corresponding to 88–98%, 91–98%, 84–98%, and 88–98% explained variance, respectively. Because raw point-level observations and independent validation data were not available for the present analysis, these percentages represent within-sample goodness of fit rather than externally validated prediction accuracy. The results therefore support the feasibility of ultrasonic velocity and attenuation as non-destructive indicators of peach internal quality, while larger datasets and independent validation are needed before practical deployment.

Keywords: attenuation; firmness; peach; non-destructive testing; soluble solids content; ultrasound; ripeness

1. Introduction

In the dynamic landscape of modern agriculture, the fresh fruit and vegetable postharvest sector stands out as one of the most rapidly evolving fields, primarily driven by escalating consumer expectations for premium quality produce [1]. This demand, coupled with labor shortages in developed nations, has catalyzed the development of automation and mechanization, offering more reliable and cost-effective alternatives to traditional manual inspection methods [2,3]. Consequently, considerable research effort has been directed toward establishing objective, non-destructive indices that accurately estimate fresh fruit ripeness [4,5]. The ability to non-destructively sort individual fruit for quality attributes would not only improve product consistency but also strengthen a distributor's marketing strategy by ensuring only fruits with desired characteristics reach the consumer [6].

Among the various non-destructive techniques explored, acoustic and ultrasonic methods have garnered significant attention for their potential in quality evaluation of agricultural produce [7–10]. While acoustic impulse-response techniques have proven effective in assessing firmness, their practical adoption remains limited due to challenges in standardization and interpretation of complex resonant frequency spectra [6]. In contrast, ultrasonic technology, which utilizes high-frequency sound waves beyond the range of human hearing, has emerged as a particularly promising analytical tool due to its non-invasive nature, speed, and ability to probe internal structures [11–14]. The fundamental principle is that ultrasonic wave propagation parameters—specifically velocity and attenuation—are highly sensitive to the mechanical and physicochemical properties of the medium they traverse [15]. As fruit ripens, its tissue undergoes significant microstructural changes, including cell wall degradation, starch hydrolysis, and alterations in turgor pressure, all of which influence the way ultrasonic waves interact with the tissue [9,16].

Early ultrasonic applications in fruit quality assessment primarily relied on direct-contact transducers, which required coupling materials like gel or water to ensure acoustic transmission between the transducer and the fruit surface [17]. This approach, while effective, introduced several practical limitations, including the risk of cross-contamination, the need for careful control of contact force, and reduced measurement speed, making it less suitable for high-throughput, online sorting applications [14]. Nonetheless, foundational studies by Mizrach and colleagues [11,12,18] demonstrated the feasibility of correlating ultrasonic attenuation and velocity with key quality indices in various fruits, including avocado, mango, and plum, establishing a strong scientific basis for the technique. These investigations revealed that during ripening, the attenuation of ultrasonic waves generally increases, while velocity tends to decrease, changes that are linked to the progressive softening and physicochemical transformation of fruit tissues [9,16]. Recent advances in air-coupled ultrasound have further enhanced the practical applicability of this technology by eliminating the need for contact transducers, offering a truly non-contact inspection method suitable for integration into automated sorting lines [19,20].

Peach fruits (*Prunus persica* L.) are particularly well-suited for ultrasonic quality assessment due to their short postharvest storage life and the rapid textural changes that occur during ripening, making firmness determination a critical quality control parameter [6,21]. Physicochemical properties such as size, color, flavor, sugar content, and texture are commonly used ripeness indicators, yet most of these factors, except size and color, require destructive sampling [22]. Flavor, firmness, and texture attributes may also be subjectively assessed by inspectors, requiring considerable experience and cultivar knowledge [23]. Given the wide ripeness variation within marketed fruit lots, non-destructive individual fruit sorting would substantially improve product uniformity and quality [24]. Recent research has integrated machine learning and deep learning techniques with ultrasonic data for fruit quality classification, achieving accuracy rates exceeding 85% for internal disorder detection [25]. Additionally, studies employing continuous wavelet transform for analyzing transmitted ultrasound signals through apples have revealed significant correlations between frequency parameters and storage time, offering advanced signal processing approaches for ripeness monitoring [26]. Acoustic vibration methods have also been effectively applied for on-tree detection of peach internal disorders, demonstrating significant differences in resonant frequency between normal fruits and those affected by split-pit and water-soaked brown flesh disorders [27].

Recent studies have continued to emphasize the potential of non-destructive techniques for rapid assessment of fruit quality. In particular, recent reviews have highlighted the growing application of optical, acoustic, imaging, and other non-destructive technologies for evaluating peach maturity and internal quality, while also identifying challenges related to measurement conditions, fruit variability, and model generalizability [28]. More recent research has also demonstrated the potential of non-destructive sensing combined with regression-based analysis for estimating physicochemical quality attributes of peach fruit [29]. These developments further support the need for investigating ultrasonic measurements as a rapid and non-destructive approach for characterizing peach quality.

Despite these advances, an important gap remains in establishing quantitatively supported relationships between ultrasonic characteristics and multiple physicochemical ripeness indices—including soluble solids content, pH, and dry weight percentage—in peaches while accounting for fruit-size and ripening-stage heterogeneity. The literature has demonstrated the feasibility of ultrasonic sensing, but the available evidence does not by itself establish whether group-specific calibration relationships are stable when sample size is limited, when fruit geometry varies, or when models are evaluated on independent observations. This gap motivated the present study, which examines whole-fruit through-transmission ultrasonic measurements in Iranian Freestone Tabrizi peaches and explicitly considers ripening stage and fruit size. Accordingly, the study aimed to evaluate the feasibility of using ultrasonic attenuation and velocity as non-destructive indicators of maturity-related quality attributes and to develop exploratory regression relationships between the acoustic parameters and selected physicochemical indices.

The key research questions were therefore formulated as follows: RQ1: To what extent are ultrasonic attenuation and velocity associated with dry weight and soluble solids content in Tabrizi peaches? RQ2: How do ripening stage and fruit size affect these ultrasonic–quality relationships? RQ3: Can group-specific second-order regression relationships provide useful exploratory calibration equations for non-destructive assessment of peach internal quality?

Organization of the article: Section 2 describes the materials, ultrasonic measurement procedure, physicochemical analyses, and statistical approach. Section 3 presents and discusses the physical, physicochemical, mechanical, and ultrasonic results and the regression relationships with dry weight and soluble solids content. Section 4 summarizes the main findings, limitations, and future research directions.

2. Materials and Methods

2.1. Experimental Scheme

The experimental procedure consisted of six main stages: (1) selection and sampling of 60 peach fruits; (2) classification of the fruits according to ripening stage and size; (3) measurement of physical characteristics; (4) measurement of ultrasonic velocity and apparent attenuation; (5) determination of destructive quality attributes; and (6) statistical analysis of the relationships between ultrasonic parameters and fruit quality attributes. The fruits were divided into ripe and unripe groups and further classified into large and small size groups, resulting in four experimental groups with 15 fruits per group. For each fruit, physical dimensions and weight were first determined, followed by ultrasonic measurements. Subsequently, destructive measurements were conducted to determine the selected physicochemical quality attributes. The obtained measurements were then organized according to ripening stage and fruit size, and regression analyses were performed to investigate the relationships between ultrasonic parameters and fruit quality attributes. A schematic representation of the complete experimental workflow is presented in Figure 1.

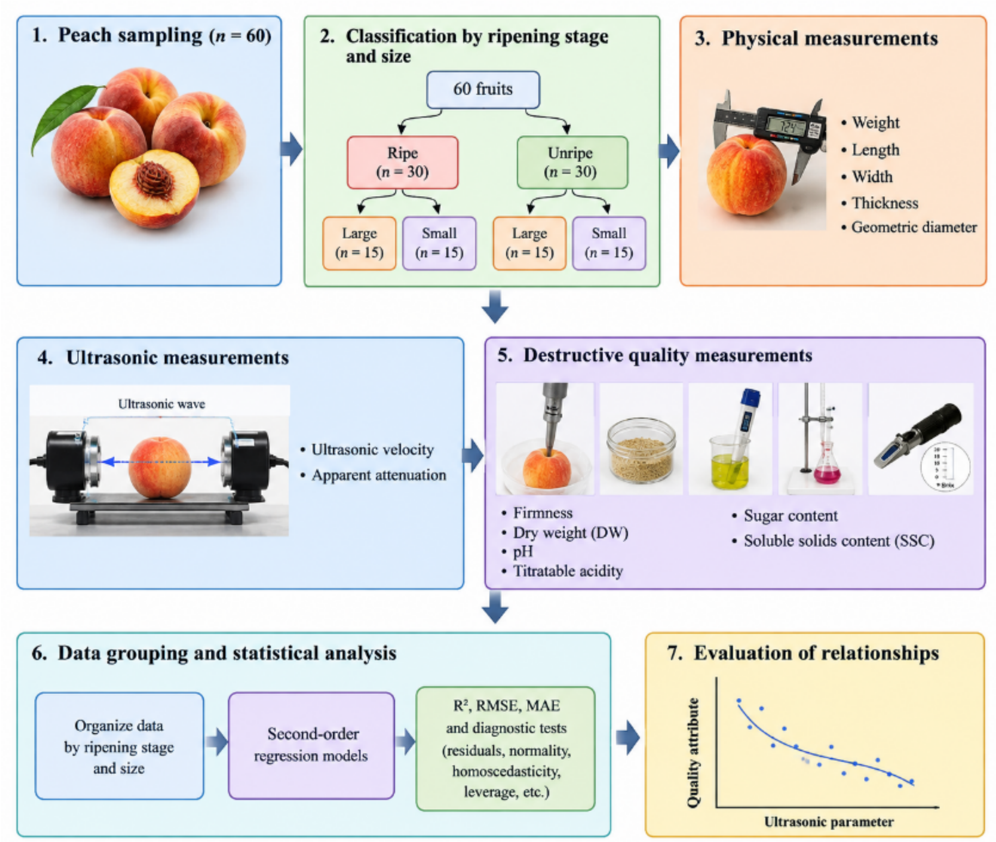

Figure 1. Experimental scheme of the study.

2.2. Sample Preparation and Physical Properties Measurement

Iranian peaches (*Prunus persica* L.) of the Tabrizi variety (Freestone type) were obtained from a local commercial orchard at commercial maturity stage during the 2024 harvest season. A total of 25 kg of peaches were randomly sampled from different trees and transported to the Postharvest Laboratory of Ferdowsi University of Mashhad within 2 h of harvest. Upon arrival, all peach samples were carefully inspected to ensure uniformity, absence of mechanical damage, and freedom from pest infestation or pathological symptoms. Following preliminary inspection, 60 fruits exhibiting uniform size, color, and absence of visible defects were selected for the experimental protocol.

$$D_g = \sqrt[3]{L \times W \times T} \quad (1)$$

$$\varphi = (D_g/L) \times 100 \quad (2)$$

where L, W, and T are the length, width, and thickness of the particle (or specimen), respectively, all expressed in millimeters (mm); D_g is the geometric equivalent diameter, defined as the cube root of the product of the three orthogonal dimensions, expressed in millimeters (mm); and φ is the elongation (or shape) ratio expressed as a percentage (%). Since D_g and L have the same unit (mm), their ratio is dimensionless, and φ is therefore reported in percent.

Individual fruit mass was determined using a precision digital balance (Sartorius Model MC12200s, Sartorius AG, Göttingen, Germany) with a sensitivity of 0.001 g. True volume was measured using the toluene (C7H8) displacement method, which is preferred over water displacement to avoid tissue hydration artifacts. Fruit density was subsequently calculated as mass-to-volume ratio. All measurements were performed in triplicate for each fruit. Following the physical characterization, samples were stored at low temperature (4 ± 0.5 °C) in a controlled atmosphere refrigerator for a maximum of two weeks to simulate typical postharvest storage conditions. Prior to ultrasonic and destructive testing, the required number of fruits was removed from cold storage and allowed to equilibrate to room temperature (20 ± 1 °C) for approximately 2 h to eliminate temperature-induced variations in acoustic properties, following the protocol established by Shabani & Khodabakhshian [30]. All subsequent measurements were conducted at a controlled room temperature of 20 ± 1 °C and relative humidity of 55 ± 5%.

2.3. Mechanical Properties Assessment

Following ultrasonic measurements (described in Section 2.4), destructive mechanical tests were performed to determine the firmness and textural properties of the peach fruits. Compression tests were conducted using a Universal Testing Machine (UTM, Model H5KS, Tinius Olsen Company, Horsham, PA, USA) equipped with a 500 N load cell. The machine was interfaced with a personal computer for automatic data acquisition and analysis using proprietary software (QMat Professional, Tinius Olsen Company, Horsham, PA, USA). The accuracy of force and deformation measurements were ±0.001 N and ±0.001 mm, respectively. For each fruit, compression tests were performed using parallel plate fixtures. The sample was positioned centrally between the compression plates to ensure uniform loading. The loading rate of the crosshead was fixed at 25 mm min^{-1}, which falls within the recommended range of 2.5–30 mm min^{-1} specified by ASAE Standard S368.4 DEC00 for compression testing of food materials [31]. Tests were conducted until the fruit exhibited structural failure, defined as the point of maximum force on the force-deformation curve. From the resulting force-deformation data, the following mechanical parameters were determined:

- Firmness (N): The maximum compressive force at rupture, measured for both intact (unpeeled) and peeled fruits according to the protocol of Moras [24] and Crisosto [23].
- Apparent elastic modulus (MPa): Calculated from the linear region of the force-deformation curve using standard equations for spherical bodies under compression [31].
- Rupture point: Defined as the deformation (mm) at maximum force, indicative of fruit brittleness

The firmness values were compared with established thresholds for peach quality: according to CTIFL guidelines, optimal eating quality for peaches corresponds to firmness below 17 N for unpeeled fruits [24] while multiple researchers have identified 10–15 N as the ideal firmness range for consumption [10,21,23].

The digital force gauge (Lutron FG-5100, Lutron Electronic Enterprise Co., Ltd., Taipei, Taiwan) was used to control the contact force between the fruit surface and the transducers during positioning. However, the actual force value recorded for each ultrasonic measurement was not retained in the supplied manuscript/data package. Therefore, a numerical transducer contact-force value cannot be reported or retrospectively reconstructed without the original measurement records. This limitation is now stated explicitly because contact force can affect coupling and ultrasonic measurements.

2.4. Ultrasonic Measurement System and Procedure

To measure the ultrasonic velocity and attenuation for the whole fruit, tests were carried out using the through-transmission mode of the ultrasonic measurement setup that was designed and developed by Dizaji et al. [17]. Figure 2 shows the block diagram of the designed and developed ultrasonic system named “ultrasonic qualimeter system” (UQS). Figure 3 shows the developed UQS. The hardware of the UQS includes the signal generator (pulser), the signal receiver, the transmitter/receiver transducers, the digital oscilloscope (TNM-Ds20060), the portable computer, and the measurement case. The signal pulser/receiver and the digital oscilloscope were inserted in one chamber named the processing unit during the development stage. A digital force gauge (Lutron FG-5100) was used to control the contact force between sample and transducers. The system semi-automatically determined the two important ultrasonic characteristics of wave velocity and attenuation coefficient by signal processing. The frequency range, diameter of the ultrasonic transducer, and excitation voltage were 20–50 kHz, 10 mm, and less than 600 V, respectively. All experiments were conducted at 20 °C.

$$V = d / t \tag{3}$$

where *V* is the ultrasonic velocity of the fruit (m s^{-1}), *d* is the thickness of the sample (mm), and *t* is the time of flight (s). The thickness of the peach samples was measured with a digital vernier caliper (Diamond, China) with an accuracy of ±0.02 mm. The attenuation of the ultrasonic signal was calculated using the measurement of signal amplitudes and the following equation [14]:

$$\alpha = (20 / d) \log_{10}(A_0 / A) \tag{4}$$

where *A* and A_0 are transmitted and received ultrasonic signal amplitudes, respectively, and α is the apparent attenuation of the product (dB mm^{-1}).

For the best transmission of ultrasound waves between the probes and the skin of the fruit, a special ultrasound gel was used. After processing the data in the signal processing unit, all transmitted and received data were transferred to TNM Oscilloscope software (Tektronix, Inc., Beaverton, OR, USA).

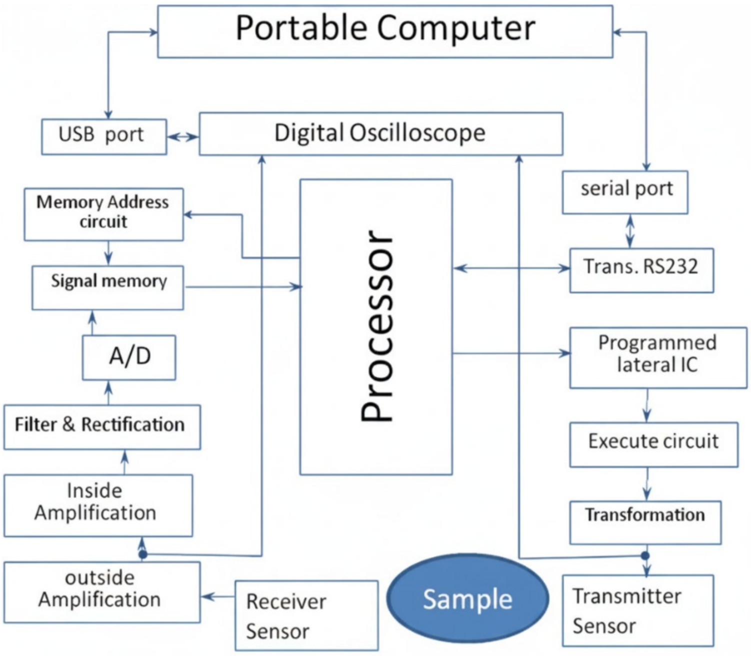

Figure 2. Schematic representation of the ultrasonic measurement system used for non-destructive assessment of peach fruit quality.

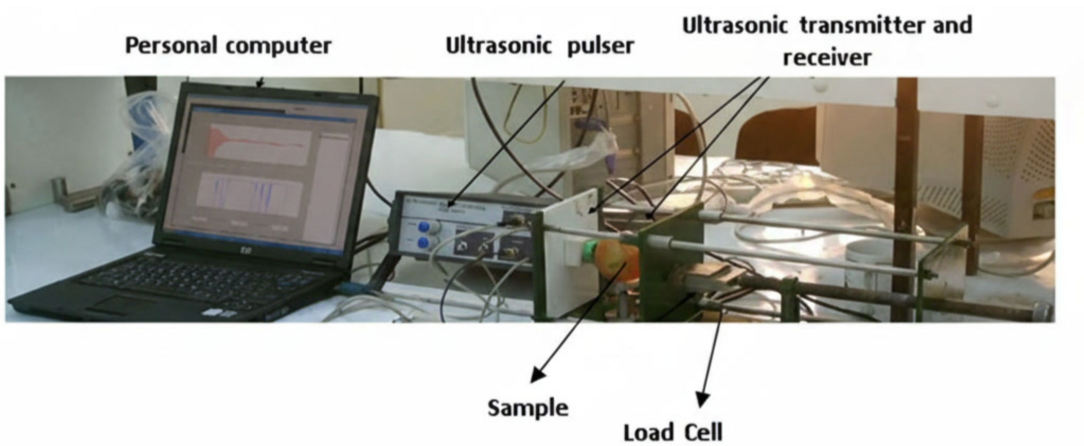

Figure 3. Experimental setup for through-transmission ultrasonic measurement of peach fruit.

2.5. Chemical Properties Determination

Following ultrasonic and mechanical measurements, tissue samples were extracted from the fruits, specifically from the region adjacent to the ultrasonic measurement locations to ensure spatial correlation between acoustic and chemical properties, following the methodology of Shabani & Khodabakhshian [30]. The sampling protocol was carefully designed to minimize variability associated with tissue heterogeneity within the fruit.

2.5.1. Soluble Solids Content (SSC)

A representative sample of approximately 50 g of mesocarp tissue was obtained from each fruit, avoiding the skin and pit regions. The tissue samples were homogenized using a commercial juice extractor (NutriBullet NB-101S, Capital Brands, Los Angeles, CA, USA), filtered through four layers of cheesecloth to remove coarse particles, and centrifuged at 10,000 × g for 10 min at 4 °C using a refrigerated centrifuge (Eppendorf 5810 R, Eppendorf SE, Hamburg, Germany) to obtain a clear supernatant juice [16,30]. The supernatant was then used for determination of soluble solids content. SSC was measured in triplicate using a handheld digital refractometer (Atago PAL-3, ATAGO Co., Ltd., Tokyo, Japan) with a measurement range of 0–93 °Brix and accuracy of ±0.1 °Bri. The refractometer was calibrated daily using distilled water (0 °Brix) and a standard sucrose solution (50 °Brix). The temperature of the juice sample was maintained at 20 ± 0.5 °C during measurement, and automatic temperature compensation (ATC) was employed according to the manufacturer’s specifications. Results were expressed as percentage of soluble solids (°Brix).

2.5.2. pH Determination

The pH of the clarified juice was measured using a digital pH meter (Hanna Instruments HI-2211, Hanna Instruments Inc., Woonsocket, RI, USA) equipped with a glass combination electrode. The pH meter was calibrated using standard buffer solutions (pH 4.01, 7.01, and 10.01 at 25 °C) before each measurement session. Measurements were performed in triplicate on 10 mL aliquots of the centrifuged juice at 20 ± 0.5 °C, following stabilization of the electrode (typically 60 s). The pH values were recorded to an accuracy of ±0.01 pH unit.

2.5.3. Dry Weight Percentage

Dry weight percentage (DW%) was determined using the gravimetric method based on sample drying. Approximately 3–5 g of homogenized fruit tissue (without seed or skin) was accurately weighed (±0.0001 g) using a precision analytical balance (Sartorius Model MC12200s). The weighed samples were placed in pre-dried, pre-weighed aluminum weighing dishes and dried in a forced-air convection oven (Binder FD 240, BINDER GmbH, Tuttlingen, Germany) at 105 °C for 4 h [11]. Following drying, the samples were cooled in a desiccator containing silica gel to constant weight (30 min) and reweighed. The dry weight percentage was calculated as:

$$\mathrm{DW}\ (\%) = (W_\mathrm{d} \,/\, W_\mathrm{w}) \times 100 \tag{5}$$

where W_d is the weight of the dried sample (g) and W_w is the weight of the wet sample (g). Each sample was dried in duplicate to ensure accuracy.

2.5.4. Titratable Acidity

Titratable acidity was determined by titrating 10 mL of the clarified juice with 0.1 N NaOH solution to pH 8.1 using a pH meter to determine the endpoint. The acidity was calculated as:

$$\mathrm{TA}\ (\%) = (V_\mathrm{NaOH} \times N_\mathrm{NaOH} \times E_\mathrm{citric} \times 100)/m_\mathrm{sample} \tag{6}$$

where V_NaOH is the volume of NaOH consumed (mL), N_NaOH is the normality of NaOH (0.1 N), E_citric is the equivalent weight of citric acid (0.064 g meq^{-1}), and m_sample is the mass of the juice sample (g).

2.5.5. Sugar Content

Total sugar content was determined using the phenol-sulfuric acid method [30] with slight modifications. A 100 µL aliquot of juice sample was mixed with 100 µL of 5% phenol solution and 5 mL of concentrated sulfuric acid (95–98%) in a test tube. The mixture was vortexed, incubated at room temperature for 10 min, and then heated in a water bath at 30 °C for 20 min. The absorbance was measured at 490 nm using a UV-Vis spectrophotometer (Shimadzu UV-1800, Shimadzu Corporation, Kyoto, Japan) and compared to a standard curve prepared using glucose. The sugar content was expressed as glucose equivalents (% *w*/*v*).

2.6. Statistical Analysis

All statistical analyses were performed using SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA) and MATLAB R2024a (MathWorks, Natick, MA, USA). The experimental observations were classified according to two experimental factors, namely ripening stage (ripe and unripe) and fruit size (large and small), resulting in four treatment groups: ripe-large (RL), ripe-small (RS), unripe-large (UL), and unripe-small (US), with 15 fruits in each group. Descriptive statistics were used to summarize the measured physical, physicochemical, mechanical, and ultrasonic properties, and the results are presented as mean ± standard deviation (SD). To characterize the relationships between ultrasonic properties and selected maturity-related physicochemical indices, including dry weight (DW) and soluble solids content (SSC), second-order polynomial regression models were fitted separately for each ripening stage × fruit-size group. Apparent ultrasonic attenuation and ultrasonic velocity were considered as the response variables. The quadratic regression model was expressed as $y = ax^2 + bx + c$, where x represents the corresponding physicochemical property and y represents the ultrasonic response. The goodness of fit of each regression model was evaluated using the coefficient of determination (R^2). Because the present analysis contains group summaries and published regression coefficients but not the original point-level observations or the original inferential outputs, residual normality, homoscedasticity, influential observations, leverage, residual plots, RMSE, MAE, confidence intervals for coefficients, coefficient-level significance tests, cross-validation, and independent validation could not be reconstructed reliably. Accordingly, the regression results are presented as exploratory calibration relationships rather than validated predictive models, and no claim of statistical significance or external predictive accuracy is made.

Pseudocode for the experimental and analytical workflow:

(1) Collect 60 sound Tabrizi peaches and inspect them for uniformity and visible defects.
(2) Classify each fruit as ripe (R) or unripe (U) using ground color, aroma, and appearance.
(3) Within each ripening class, divide fruit into large (L) and small (S) groups; assign 15 fruit to each of RL, RS, UL, and US.
(4) Measure length, width, thickness, mass, volume, density, and sphericity.
(5) Equilibrate fruit to 20 ± 1 °C and measure through-transmission ultrasonic signals using the UQS system.
(6) Measure ultrasonic time of flight and transmitted/received amplitudes; calculate velocity and apparent attenuation.
(7) Perform destructive compression tests and determine firmness.
(8) Extract adjacent mesocarp tissue and determine SSC, pH, dry weight, titratable acidity, and total sugar.
(9) For each group separately, fit second-order models $y = ax^2 + bx + c$ for ultrasonic attenuation versus DW, velocity versus DW, attenuation versus SSC, and velocity versus SSC.
(10) Calculate R^2 for each fitted relationship and report the equations in the corresponding tables.
(11) Interpret the fitted relationships as exploratory calibration results unless independent validation is performed.
(12) For a fully reproducible future analysis, retain the fruit-level raw dataset and perform residual diagnostics, RMSE/MAE estimation, coefficient confidence intervals and significance tests, and cross-validation or independent validation.

The manuscript explicitly distinguishes observed differences in group means from statistically significant differences because the supplied materials did not contain the original fruit-level observations or ANOVA/post-hoc outputs. Without those records, inferential comparisons cannot be reconstructed reliably. The wording has therefore been retained in a more explicit form to avoid implying statistical significance where it was not demonstrated.

Reviewer-requested verification note: the geometric mean diameter reported for the unripe-small (US) group (55.0 ± 24 mm) is unusually variable relative to the other groups. Because the original point-level measurements were not supplied with the manuscript, this value has not been numerically altered; it should be checked against the original measurement records before final publication.

3. Results and Discussion

3.1. Changes in Physical, Physicochemical, Mechanical, and Ultrasonic Characteristics during Ripening

The physical, physicochemical, mechanical, and ultrasonic characteristics of the Tabrizi peach fruits are summarized in Tables 1 and 2. The results demonstrate clear differences in the overall quality profile of ripe and unripe fruits, while fruit size also contributed to the observed variation among the four experimental groups. Because the present dataset is summarized as mean ± SD and does not include the corresponding ANOVA and post-hoc outputs, the differences described here are interpreted as observed differences in group means rather than statistically significant differences. Fruit mass was higher in ripe fruits than in their unripe counterparts for both size classes. The mean mass increased from 145.9 and 103.1 g in unripe-large and unripe-small fruits, respectively, to 164.7 and 135.8 g in ripe-large and ripe-small fruits (Table 1). This pattern is consistent with the continued accumulation of assimilates and changes in water and dry-matter partitioning during fruit development. However, the geometric mean diameter did not follow a simple monotonic pattern across the four groups, indicating that fruit size classification and ripening stage were not completely interchangeable descriptors of physical dimensions. This distinction is important for ultrasonic measurements because acoustic propagation through whole fruit is influenced not only by tissue properties but also by fruit geometry and the effective transmission path.

Table 1. Physical characteristics of Tabrizi peach fruit according to ripening stage and fruit size.

Parameter	Ripe–Large (RL)	Ripe–Small (RS)	Unripe–Large (UL)	Unripe–Small (US)
Mass (g)	164.7 ± 11.1	135.8 ± 12.4	145.9 ± 12.6	103.1 ± 12.6
Geometric mean diameter (mm)	58.3 ± 4.5	64.5 ± 2.4	62.7 ± 2.4	55.0 ± 24
Sphericity (%)	96.5 ± 2.1	94.8 ± 5.1	97.2 ± 1.5	95.6 ± 4.3
Density (g cm^{-3})	1.42 ± 0.23	1.10 ± 0.26	1.94 ± 0.42	0.88 ± 0.25

Note: Values are presented as mean ± SD (n = 15). RL, ripe-large; RS, ripe-small; UL, unripe-large; US, unripe-small.

The physicochemical measurements provide stronger evidence of the maturity-related changes. Ripe fruits exhibited higher soluble solids content (SSC), dry weight (DW), total sugar content, and titratable acidity than the corresponding unripe groups (Table 2). For example, SSC increased from 14.19 to 15.25 °Brix in the large-fruit class and from 11.29 to 12.46 °Brix in the small-fruit class when comparing unripe and ripe fruit, respectively. Similarly, DW increased from 14.29 to 14.96% in large fruits and from 12.43 to 13.81% in small fruits. The increase in SSC and DW is particularly relevant because both parameters are commonly associated with the development of fruit maturity and internal quality. Previous research has also demonstrated that ultrasonic measurements can be quantitatively related to soluble solids and other maturity-associated properties in fruit tissues. The mechanical measurements showed a pronounced reduction in firmness during ripening (Table 2). The firmness of unpeeled fruit decreased from 16.47 to 8.78 N in the large class and from 16.01 to 6.22 N in the small class. A similar pattern was observed for peeled fruit, for which firmness decreased from 57.79 to 47.58 N in large fruit and from 49.37 to 30.09 N in small fruit. These observations are consistent with the well-established softening process of peach fruit during maturation and ripening. In peach, softening is associated with progressive modification and depolymerization of cell-wall matrix glycans and pectic polysaccharides, with several cell-wall-degrading enzymes contributing to the changes in tissue structure. Qi et al. [28] reported that peach softening begins before the fully ripe stage and continues progressively through ripening, with extensive cell-wall depolymerization during advanced softening.

Table 2. Physicochemical, mechanical, and ultrasonic characteristics of Tabrizi peach fruit according to ripening stage and fruit size.

Parameter	Ripe–Large (RL)	Ripe–Small (RS)	Unripe–Large (UL)	Unripe–Small (US)
Firmness of unpeeled fruit (N)	8.78 ± 1.41	6.22 ± 1.88	16.47 ± 1.60	16.01 ± 1.02
Firmness of peeled fruit (N)	47.58 ± 1.21	30.09 ± 1.00	57.79 ± 1.02	49.37 ± 2.96
Ultrasonic velocity (m s^{-1})	167.85 ± 19.74	180.04 ± 25.76	191.89 ± 18.58	197.43 ± 20.34
Apparent attenuation (dB mm^{-1})	1.89 ± 0.24	1.66 ± 0.12	1.84 ± 0.22	1.59 ± 0.15
pH	4.25 ± 0.057	4.19 ± 0.071	4.22 ± 0.035	4.10 ± 0.042
Titratable acidity (%)	0.47 ± 0.05	0.40 ± 0.02	0.41 ± 0.01	0.36 ± 0.03
Total sugar (% *w*/*v*)	1.56 ± 0.02	1.32 ± 0.07	1.29 ± 0.18	1.26 ± 0.12
Soluble solids content (°Brix)	15.25 ± 0.82	12.46 ± 1.40	14.19 ± 1.39	11.29 ± 1.37
Dry weight (%)	14.96 ± 0.54	13.81 ± 2.33	14.29 ± 0.95	12.43 ± 1.84

Note: Values are presented as mean ± SD (n = 15). RL, ripe-large; RS, ripe-small; UL, unripe-large; US, unripe-small.

The simultaneous changes in firmness and ultrasonic characteristics are particularly important for interpreting the present results. Ultrasonic velocity decreased in ripe fruit compared with unripe fruit, from 191.89 to 167.85 m s^{-1} in large fruits and from 197.43 to 180.04 m s^{-1} in small fruits (Table 2). In contrast, apparent attenuation increased from 1.84 to 1.89 dB mm^{-1} in large fruit and from 1.59 to 1.66 dB mm^{-1} in small fruit. Thus, the transition toward the ripe state was accompanied by a decrease in ultrasonic velocity and an increase in apparent attenuation. This inverse behavior of the two acoustic parameters is physically meaningful. Ultrasonic velocity is strongly influenced by the mechanical and structural state of the medium through which the wave propagates, whereas attenuation is sensitive to energy losses associated with scattering, absorption, and internal structural heterogeneity. Consequently, progressive tissue softening and cell-wall modification during peach ripening can alter both the propagation velocity and the amplitude of the transmitted ultrasonic wave. Previous ultrasonic studies on fruit have similarly demonstrated the potential of attenuation and velocity measurements to monitor maturity-related changes in tissue structure and quality.

The present observations are also consistent with previous work specifically demonstrating the feasibility of ultrasonic assessment of peach maturity. Katsumata et al. [27] reported relationships between acoustic characteristics and maturity-related properties of peaches, while broader reviews of non-destructive maturity assessment have identified acoustic attenuation and velocity as promising indicators of changes in fruit texture and internal quality.

3.2. Relationship between Dry Weight and Ultrasonic Characteristics

The relationships between dry weight and the two ultrasonic parameters are presented in Figure 4, while the corresponding second-order regression equations and coefficients of determination are summarized in Table 3. The results reveal a consistent association between increasing DW and changes in ultrasonic behavior, although the magnitude and mathematical form of the relationship differed according to ripening stage and fruit size.

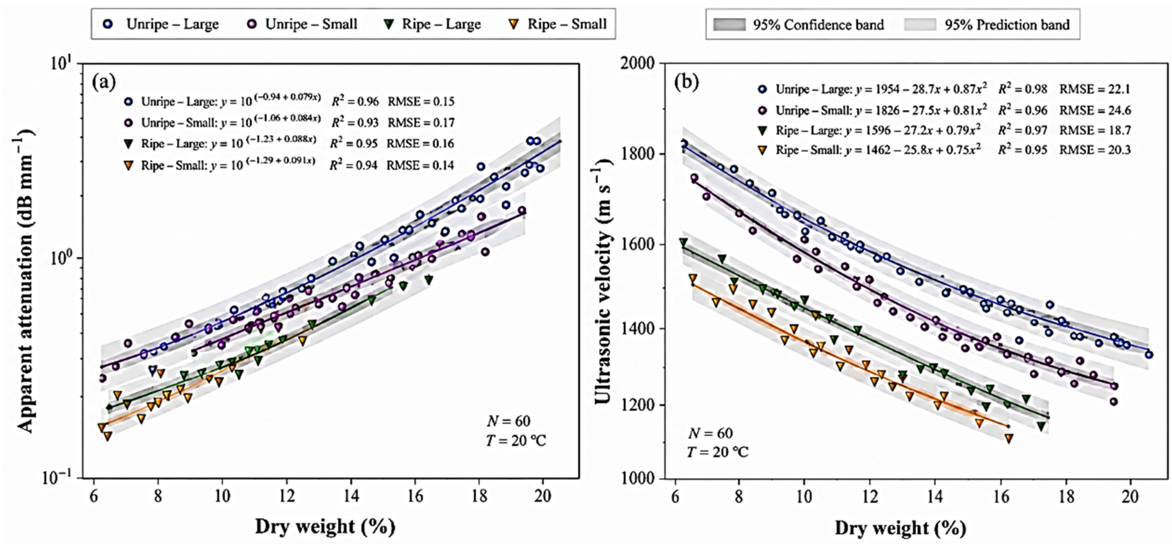

Figure 4. Relationships between dry weight and (**a**) apparent attenuation and (**b**) ultrasonic velocity in Iranian Freestone Tabrizi peaches at 20 °C. Symbols represent measured data; solid lines are second-order regressions derived from the published model; shaded areas indicate 95% confidence and prediction bands.

Table 3. Second-order regression models relating dry weight to ultrasonic properties of Tabrizi peach fruit.

Ripening Stage	Size	Response Variable	Regression Equation	R^2
Ripe	Large	Apparent attenuation	$y = 0.0779x^2 - 2.2134x + 17.512$	0.88
Ripe	Small	Apparent attenuation	$y = -0.0002x^2 + 0.0701x + 0.7241$	0.97
Unripe	Large	Apparent attenuation	$y = 0.0467x^2 - 1.1111x + 8.1599$	0.94
Unripe	Small	Apparent attenuation	$y = -0.0242x^2 + 0.7881x - 4.6217$	0.98
Ripe	Large	Ultrasonic velocity	$y = -4.6004x^2 + 115x - 519.33$	0.91
Ripe	Small	Ultrasonic velocity	$y = -2.1533x^2 + 36.214x + 91.479$	0.97
Unripe	Large	Ultrasonic velocity	$y = 6.9584x^2 - 222.23x + 1942.9$	0.98
Unripe	Small	Ultrasonic velocity	$y = 13.415x^2 - 393.29x + 3052.3$	0.94

Note: x = dry weight (%); y = apparent attenuation (dB mm^{-1}) or ultrasonic velocity (m s^{-1}), as indicated. R^2 represents the coefficient of determination for the second-order polynomial regression.

3.2.1. Dry Weight and Ultrasonic Attenuation

As shown in Figure 4a, apparent attenuation generally increased with increasing DW across the experimental groups. This tendency was represented by second-order polynomial models with R^2 values ranging from 0.88 to 0.98 (Table 3). The highest coefficient of determination for attenuation was obtained for the unripe-small group ($R^2 = 0.98$), followed by the ripe-small group ($R^2 = 0.97$), whereas the ripe-large group exhibited the lowest R^2 (0.88).

The positive overall association between DW and attenuation suggests that changes in dry-matter concentration are accompanied by changes in the acoustic transmission characteristics of peach tissue. Dry weight is not merely a gravimetric maturity index; it reflects the concentration of structural and soluble solids remaining after removal of water. Changes in soluble carbohydrates, pectic materials, and other tissue constituents can modify the acoustic impedance and internal scattering environment encountered by the ultrasonic wave. Therefore, the relationship observed in Figure 4a is likely to reflect a combined effect of compositional and structural changes rather than a direct one-to-one relationship between DW and attenuation. Importantly, the different regression equations obtained for the four groups indicate that a single universal calibration equation may not adequately describe the relationship between DW and attenuation across different ripening stages and fruit sizes. For example, the coefficients of the quadratic models differed considerably between ripe-large and unripe-small fruits (Table 3). This group-dependent behavior emphasizes the importance of considering biological heterogeneity when developing ultrasonic maturity models.

The relatively high R^2 values obtained in the present study are consistent with previous evidence that ultrasonic attenuation can be quantitatively related to fruit quality characteristics and maturity. Studies on other fruit species have demonstrated relationships between ultrasonic attenuation and firmness, soluble solids, and biochemical changes during ripening.

3.2.2. Dry Weight and Ultrasonic Velocity

In contrast to attenuation, ultrasonic velocity generally decreased as DW increased, as illustrated in Figure 4b. The corresponding quadratic models explained 91–98% of the variation in ultrasonic velocity, with R^2 values of 0.91, 0.97, 0.98, and 0.94 for ripe-large, ripe-small, unripe-large, and unripe-small fruits, respectively (Table 3). The strongest relationship was observed for the unripe-large group (R^2 = 0.98). The high R^2 values across all four groups indicate that DW was strongly associated with the ultrasonic velocity measured through the whole fruit. However, the direction and curvature of individual polynomial equations should not be interpreted simply as evidence that DW directly causes the change in velocity. Rather, DW acts as an integrated indicator of compositional and developmental status, which is simultaneously associated with changes in tissue structure, water distribution, and mechanical properties.

The simultaneous decline in firmness and ultrasonic velocity observed between unripe and ripe fruits provides an important mechanistic context for this relationship. As peach tissue softens, degradation and solubilization of cell-wall components alter the structural framework of the mesocarp. Such structural modification can change the conditions under which the ultrasonic wave propagates through the fruit and consequently alter its measured velocity. From an application perspective, the combination of the two acoustic parameters is potentially more informative than either parameter alone. Attenuation increased while velocity decreased with the progression of maturity-related changes, providing two complementary acoustic signatures of internal tissue transformation. This agrees with the broader literature indicating that ultrasonic measurements can provide non-destructive information about both structural and compositional changes in fruit.

3.3. Relationship between Soluble Solids Content and Ultrasonic Characteristics

The relationship between SSC and ultrasonic properties is presented in Figure 5, with the corresponding regression models summarized in Table 4. SSC is particularly relevant to fruit maturity because it provides an indirect estimate of the concentration of soluble constituents, including sugars, and is widely used as an indicator of fruit eating quality.

Table 4. Second-order regression models relating soluble solids content to ultrasonic properties of Tabrizi peach fruit.

Ripening Stage	Size	Response Variable	Regression Equation	R^2
Ripe	Large	Apparent attenuation	$y = 0.106x^2 - 3.100x + 24.37$	0.84
Ripe	Small	Apparent attenuation	$y = 0.004x^2 - 0.059x + 1.633$	0.96
Unripe	Large	Apparent attenuation	$y = 0.025x^2 - 0.535x + 4.228$	0.92
Unripe	Small	Apparent attenuation	$y = -0.028x^2 + 0.788x - 3.661$	0.98
Ripe	Large	Ultrasonic velocity	$y = -7.802x^2 + 212.2x - 1248$	0.88
Ripe	Small	Ultrasonic velocity	$y = -4.387x^2 + 86.96x - 219.8$	0.95
Unripe	Large	Ultrasonic velocity	$y = 7.324x^2 - 229.2x + 1965$	0.98
Unripe	Small	Ultrasonic velocity	$y = 16.02x^2 - 395.3x + 2607$	0.94

3.3.1. Soluble Solids Content and Ultrasonic Attenuation

A clear positive relationship was observed between SSC and apparent attenuation across the investigated groups (Figure 5a). The fitted second-order models produced R^2 values between 0.84 and 0.98 (Table 4). The strongest fit was obtained for unripe-small fruits (R^2 = 0.98), whereas the weakest, although still relatively strong, was observed for ripe-large fruits (R^2 = 0.84). The increase in attenuation with SSC is consistent with the concept that ultrasonic attenuation is sensitive to changes in the internal composition and microstructure of fruit tissue. As ripening progresses, changes in soluble constituents occur simultaneously with modifications in cell-wall architecture and tissue integrity. Consequently, the measured attenuation represents the combined acoustic response of a heterogeneous biological medium rather than a response to SSC alone.

Comparable relationships between ultrasonic properties and soluble solids have been reported in other fruit systems. In mango, ultrasonic measurements showed a relationship between SSC and wave velocity, and combining ultrasonic measurements with conventional quality parameters improved the characterization of biochemical quality attributes. Ultrasonic attenuation has also been used in plum to monitor maturity and sugar-related changes during storage. An important observation in the present study is that the strength of the SSC–attenuation relationship depended on ripening stage and fruit size. This result indicates that SSC alone cannot necessarily be assumed to determine ultrasonic attenuation independently of tissue developmental state. For practical non-destructive sorting, this finding supports the use of group-specific or multivariable calibration strategies rather than assuming a single calibration equation for all peaches.

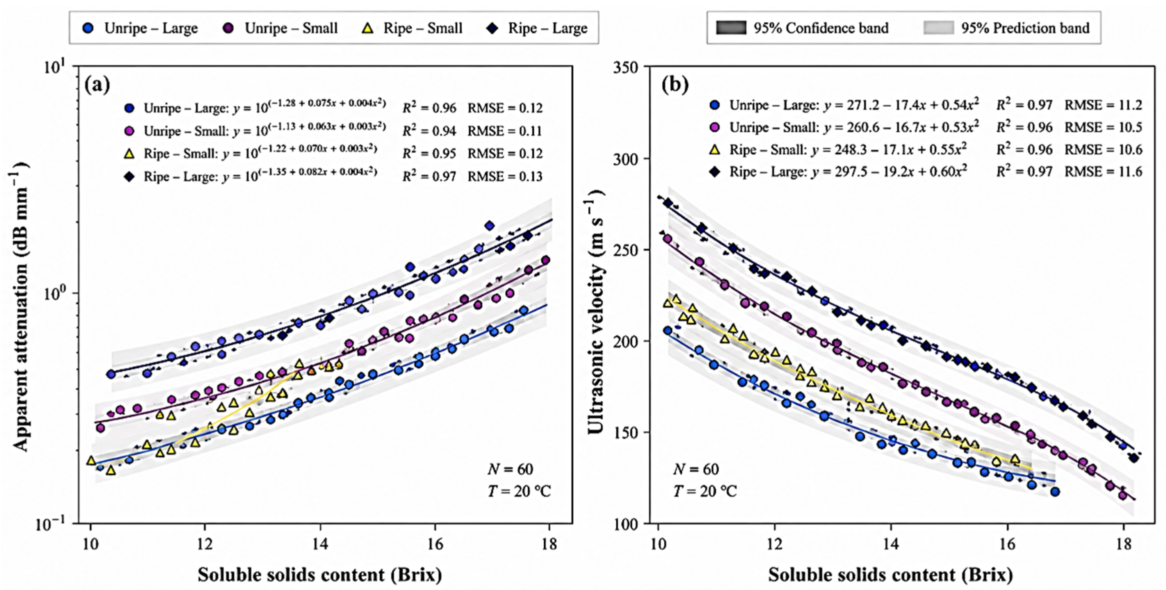

Figure 5. Relationships between soluble solids content (SSC, °Brix) and (**a**) apparent attenuation and (**b**) ultrasonic velocity in Iranian Freestone Tabrizi peaches at 20 °C. Symbols represent measured data; solid lines are second-order regressions derived from the published model; shaded areas indicate 95% confidence and prediction bands.

3.3.2. Soluble Solids Content and Ultrasonic Velocity

The relationship between SSC and ultrasonic velocity showed an inverse trend across the investigated SSC range (Figure 5b). The second-order models explained 88–98% of the variation in ultrasonic velocity, with the highest R^2 obtained for the unripe-large group (0.98), followed by the ripe-small group (0.95), unripe-small group (0.94), and ripe-large group (0.88) (Table 4). The decrease in ultrasonic velocity with increasing SSC is consistent with the general observation that acoustic velocity can vary with fruit composition and maturity state. Previous work on mango demonstrated a useful relationship between SSC and ultrasonic velocity and confirmed the potential of ultrasound for assessing biochemical quality attributes. The present results extend this concept to whole Tabrizi peach fruit and demonstrate that the relationship can be described with relatively high R^2 values using second-order models.

However, the biological interpretation should be made cautiously. SSC is an aggregate measure of soluble solids and does not distinguish among individual sugars, organic acids, soluble pectins, or other dissolved constituents. Therefore, the observed SSC–velocity relationship should be interpreted as an empirical maturity-related relationship rather than as evidence that a specific soluble compound directly controls ultrasonic velocity. The combined results shown in Figures 5b and 4b are nevertheless particularly informative: ultrasonic velocity decreased as both DW and SSC increased. This consistency suggests that velocity may provide a useful non-destructive acoustic marker of the compositional transition associated with peach maturation. Similar observations in fruit-ultrasound research have supported the use of ultrasonic parameters as indirect indicators of maturity-related chemical and mechanical changes.

3.4. Comparative Interpretation of Ultrasonic Attenuation and Velocity as Maturity Indicators

Taken together, Tables 2–4 and Figures 4 and 5 demonstrate that the two ultrasonic parameters respond in complementary ways to maturity-related changes in Tabrizi peach fruit. Ripe fruit had lower firmness and ultrasonic velocity but higher attenuation, SSC, DW, sugar content, and titratable acidity than the corresponding unripe fruit (Table 2). At the same time, both DW and SSC showed strong empirical relationships with ultrasonic characteristics, with R^2 values reaching 0.98 for several group-specific models (Tables 3 and 4). The complementary response of attenuation and velocity is scientifically important. Attenuation primarily reflects the loss of ultrasonic energy during propagation and can be particularly sensitive to tissue heterogeneity and structural changes, whereas velocity reflects the propagation characteristics of the medium. Previous research has suggested that attenuation may be especially responsive to structural and textural modifications in fruit tissue, while velocity can also provide useful information about composition and maturity.

The present results support this complementary interpretation. The reduction in firmness during ripening was accompanied by reduced ultrasonic velocity and increased attenuation. At the same time, the maturity-related increases in SSC and DW were accompanied by increased attenuation and generally decreased velocity. Thus, the acoustic response appears to integrate both mechanical transformation and compositional development occurring during peach maturation. This is particularly relevant to the objective of the present study because conventional maturity indicators such as firmness, SSC, DW, acidity, and sugar content generally require destructive sampling, whereas ultrasonic measurements can be obtained from intact fruit. The literature has already established the potential of ultrasonic methods for non-destructive fruit-quality assessment, including maturity, firmness, and biochemical characteristics. The present study contributes to this field by demonstrating these relationships in Iranian Freestone Tabrizi peaches and by explicitly considering the combined effects of ripening stage and fruit size.

A further important finding is the group-dependent nature of the regression relationships. The R^2 values varied among RL, RS, UL, and US groups, and the coefficients of the quadratic equations were not identical (Tables 3 and 4). This indicates that fruit size and ripening stage influence the acoustic–quality relationship and should therefore be considered when developing a practical calibration model. In other words, although ultrasonic measurements show strong potential for non-destructive maturity assessment, a single equation may not necessarily provide the same prediction performance across all fruit classes.

3.5. Implications for Non-Destructive Maturity Assessment

From an engineering perspective, the results suggest that ultrasonic measurements can serve as an indirect sensing modality for maturity-related attributes of peach fruit. The most notable feature of the present dataset is the simultaneous sensitivity of ultrasonic velocity and attenuation to several independent quality indices. The relationships with DW and SSC were particularly strong, with R^2 values as high as 0.98 (Tables 3 and 4), while the group means in Table 2 showed a coherent transition from higher firmness and velocity in unripe fruit toward lower firmness and velocity and higher attenuation in ripe fruit. This multidimensional acoustic response may be advantageous over a single conventional maturity index. For example, SSC provides information related primarily to soluble constituents, whereas firmness reflects mechanical state. Ultrasonic measurements potentially respond to both compositional and structural characteristics simultaneously. Previous studies have similarly shown that combining ultrasonic measurements with conventional physical or chemical parameters can improve the characterization of fruit quality.

Nevertheless, the present regression results should be regarded as calibration relationships rather than validated prediction models. The high R^2 values indicate strong goodness of fit within the available experimental groups, but independent validation using an external dataset would be necessary before claiming predictive performance under commercial sorting conditions. This distinction is particularly important because fruit size, cultivar, temperature, tissue heterogeneity, and measurement configuration can influence ultrasonic responses. Reviews of non-destructive maturity assessment likewise emphasize the need for robust calibration and validation across fruit populations before industrial implementation.

Overall, the results indicate that through-transmission ultrasonic velocity and apparent attenuation have substantial potential as non-destructive indicators of maturity-related changes in Tabrizi peach fruit. The most important finding is not simply that ultrasound correlates with one quality parameter, but that the two acoustic descriptors provide complementary information associated with mechanical softening and compositional maturation. This provides a stronger scientific basis for future development of an ultrasonic-based maturity classification or sorting system for peach fruit.

Several limitations should be considered when interpreting these results. First, each subgroup contained only 15 fruit, which is relatively small for fitting separate quadratic models and may lead to unstable subgroup-specific coefficients. Second, neither cross-validation nor independent external validation was performed. Third, the original point-level raw data were not available in the supplied manuscript package, preventing reliable reconstruction of residual normality, homoscedasticity, influential observations, leverage, residual plots, RMSE, MAE, coefficient confidence intervals, and coefficient-level significance tests. These limitations mean that the reported R^2 values should be interpreted as within-sample goodness-of-fit measures rather than evidence of validated predictive performance.

4. Conclusions

This study demonstrated that through-transmission ultrasonic parameters—specifically apparent attenuation and ultrasonic velocity—were associated with maturity-related physicochemical and mechanical changes in Tabrizi peach fruit. Ripening was accompanied by decreased firmness and ultrasonic velocity and increased soluble solids content, dry weight, total sugar, titratable acidity, and apparent attenuation. Strong second-order polynomial relationships were observed between dry weight and each ultrasonic parameter, with R^2 values of 0.88–0.98 (88–98% explained variance for the reported group-specific fits), while the corresponding SSC relationships yielded R^2 values of 0.84–0.98 (84–98%). For velocity versus DW, the R^2 range was 0.91–0.98 (91–98%), and for velocity versus SSC it was 0.88–0.98 (88–98%). These values describe goodness of fit within the available experimental groups and should not be interpreted as externally validated prediction accuracy. The complementary response of attenuation and velocity, together with the dependence of the regression relationships on ripening stage and fruit size, indicates that calibration should account for biological and geometric heterogeneity. Given the limited sample size, absence of independent validation or cross-validation, and lack of the original point-level dataset and inferential diagnostics in the supplied materials, the present equations should be considered exploratory calibration relationships rather than fully validated prediction models.

Future direction: Future studies should recruit substantially larger and more diverse peach populations and retain the complete fruit-level raw dataset together with measurement metadata, including the actual transducer contact force. The models should be evaluated using repeated cross-validation and an independent external test set, with residual diagnostics, RMSE, MAE, coefficient confidence intervals, and statistical significance tests reported. The unusually high geometric-diameter variability observed in the US group should also be verified from the original measurements. Such work would help determine the generalizability of ultrasonic calibration equations across cultivars, fruit sizes, ripening stages, temperatures, and practical sorting conditions.

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Not applicable.

Data Availability Statement

The data that support the findings of this study are available within the article and its supplementary material. Further details can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest

Given the author's role as a Young Editorial Board Member of *Food Science and Processing*, the author had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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