

Article

A Mechanical–Acoustic Technique as a Novel Approach for Table Olive Texture Evaluation

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Abstract

This study investigates the texture of table olives by integrating mechanical, acoustic, and sensory approaches, with particular emphasis on the role of acoustic emission in the perception of crunchiness, a key quality attribute influencing consumer acceptance. Three Italian cultivars (Itrana Bianca, Nocellara del Belice, and Bella di Cerignola), processed using different debittering methods, were analyzed using needle and tip compression tests combined with simultaneous sound recording, as well as Texture Profile Analysis (TPA) and Kramer shear press, alongside sensory evaluation by a trained panel. Needle compression primarily characterized peel properties, identifying Itrana Bianca as having the firmest skin, while tip and Kramer tests, reflecting both peel and pulp, indicated that Bella di Cerignola was the hardest and most consistent sample. TPA revealed that Itrana Bianca exhibited higher elasticity and cohesiveness, whereas Bella di Cerignola showed greater firmness and chewiness. Nocellara del Belice consistently displayed the softest texture. Acoustic measurements suggested that sound emission was mainly associated with peel rupture rather than pulp characteristics and showed limited correlation with sensory crunchiness. Overall, the combined mechanical–acoustic approach provides a more comprehensive evaluation of olive texture and highlights the need for refined sensory descriptors, particularly for peel-related attributes, to better interpret acoustic responses.

Keywords: texture analysis; sensory analysis; acoustic emission; mechanical properties; table olives

1. Introduction

Table olives are widely consumed worldwide and represent an important component of the Mediterranean diet. They are commonly eaten both as a snack, accompanying alcoholic and non-alcoholic beverages, and as a food with recognized nutritional value. Their market is well established globally, with particularly strong demand in Europe and the United States.

Food quality is determined by several sensory and physicochemical attributes. Among them, texture, together with appearance, aroma/flavor and nutritional characteristics, plays a major role in consumer acceptance and overall quality perception [1]. Texture arises from multiple physical properties rather than a single parameter, reflecting the structural organization of the food matrix and its response to applied forces [2]. In table olives, texture plays a crucial role in defining product typology and strongly

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influences consumer acceptability. Sensory quality is a fundamental prerequisite for commercialization and is formally regulated by the official method for the sensory analysis of table olives established by the International Olive Council (IOC) (COI/OT/MO No. 1/Rev.3) [3]. Among the various textural attributes, crunchiness is recognized as a primary kinesthetic characteristic. Recent studies [4] have shown that loss of firmness negatively affects the overall sensory profile, while consumer surveys confirm that a firm and crunchy texture is one of the main drivers of purchasing behavior [5].

For these reasons, there is growing interest in developing objective methods to assess texture in a way that closely reflects human perception. Texture is a complex, multiparametric attribute that depends on structural organization at macroscopic, microscopic, and molecular levels. In plant tissues, it is largely influenced by the chemical and physical properties of cell walls, whose cohesion provides mechanical strength and resistance. In olives, mechanical properties are determined by cell wall thickness, middle lamella composition, and cellular turgor. Texture evaluation is, therefore, essential for comparing cultivars, assessing the effects of technological treatments (such as alkaline debittering, fermentation, and pasteurization), and monitoring structural changes during storage.

Each olive cultivar presents specific structural features, such as cell density, pectin composition, and flesh-to-stone ratio, that contribute to its final texture. Processing steps can significantly modify these characteristics. For example, alkaline debittering (e.g., Seville and Castelvetro processes) involves the use of sodium hydroxide, which promotes partial hydrolysis of pectic substances in the middle lamella. Similarly, during natural fermentation, lactic acid bacteria and yeasts may produce pectolytic and cellulolytic enzymes that degrade cell walls, reducing cell cohesion and causing progressive pulp softening. Texture evolution also occurs during shelf life due to osmotic processes and residual brine acidity, which induce slow acid hydrolysis of pectins, further decreasing firmness [6].

Instrumental methods are commonly used to quantify textural properties, although they capture only specific physical parameters that must be interpreted in relation to sensory perception. Texture perception involves multiple sensory modalities, with touch and pressure playing dominant roles [2]. Several mechanical tests have been developed for olives, most of which are based on compression. A widely used method consists of compressing the whole drupe using a cylindrical probe (1 cm diameter) and measuring deformation [7]. Deformation increases with ripening stage [8] and processing intensity [9], reflecting progressive softening.

Alternative approaches include compression with flat plates (e.g., 16 mm diameter at 0.125 mm/s), which allows measurement of the force required to reach a defined load without damaging the stone [10]. These studies have revealed structural heterogeneity within the fruit, with firmer tissues near the stone and softer outer layers due to brine interaction. Other authors have focused on the internal mesocarp by performing puncture tests on transversely cut olives [8]. In addition, Texture Profile Analysis (TPA) has been applied to olives to derive multiple parameters, such as hardness, elasticity, cohesiveness, adhesiveness, gumminess and chewiness, through double compression cycles [11].

Beyond mechanical properties, texture perception also involves auditory receptors. The relationship between sound and texture perception was first described by Drake [12], who identified a link between acoustic signals generated during chewing and sensory evaluation. Subsequently, Vickers and Bourne [13] developed a psychoacoustic theory of crispness.

The structural characteristics of plant tissues play a critical role in determining the acoustic emissions generated during mastication. High-moisture tissues are composed of turgid cells with elastic cell walls, where turgor pressure results from the force exerted by

intracellular fluids against the cell wall [13]. Upon mechanical rupture, these cells release their contents abruptly, generating transient pressure waves that contribute to the perception of crispness or crunchiness. Nevertheless, this sensory attribute is not solely governed by cellular moisture content, but also by the mechanical integrity and adhesion between adjacent cells. For example, the biting of a crisp apple produces a characteristic acoustic signature arising from the concurrent fracture of both the cell walls and the middle lamella that binds neighboring cells. In contrast, mealy apples exhibit a markedly weaker acoustic response, primarily associated with the separation of the middle lamella, as cells tend to dissociate and slide past one another rather than undergo fracture.

Quantitative assessment of these acoustic phenomena is typically conducted using destructive methodologies, which involve recording the sound emitted during instrumental compression tests or simulated mastication processes. Acoustic emission analysis has been proposed as a complementary approach for the objective assessment of apple crispness [14]. Vanoli et al. [15] showed that acoustic parameters, combined with mechanical and sensory measurements, allow effective discrimination among apple cultivars such as 'Braeburn', 'Gala', and 'Kanzi®', characterized by different flesh structures and textural properties. Moreover, both mechanical and acoustic parameters were found to decrease during the shelf life of 'Braeburn' apples, reflecting progressive softening and the development of mealiness [16].

The application of mechanical–acoustic testing is not limited to intact fruits but has also been extended to fresh-cut products and leafy vegetables. Cortellino et al. [17] successfully applied this approach to monitor texture changes in fresh-cut apples, whereas less consistent results were obtained in lamb's lettuce during storage [18], likely due to the different structural organization of leaf tissues. More recently, similar methods have been applied to rocket leaves [19], highlighting the growing interest in this rapid technique for postharvest quality evaluation.

Although texture in table olives is traditionally evaluated through mechanical tests and sensory panels, the integration of mechanical–acoustic techniques has only recently been investigated. Preliminary results obtained in table olives [20] suggest that acoustic parameters may complement conventional mechanical measurements, particularly for the assessment of crunchiness. However, information on the most suitable mechanical–acoustic testing procedures and on their relationship with sensory perception is still limited. Therefore, further studies are needed to evaluate the effectiveness of different mechanical–acoustic approaches for texture characterization in table olives.

The aim of this study was to evaluate different mechanical–acoustic methods in order to improve the assessment of table olive texture, with particular emphasis on crunchiness. The working hypothesis was that the integration of acoustic measurements with conventional mechanical measurements could provide a more accurate characterization of table olive texture, particularly of crunchiness, than mechanical measurements alone.

2. Materials and Methods

2.1. Table Olive Materials

A purposive sampling strategy was applied to select commercial table olives representing the main varieties on the Italian market in terms of cultivar, geographical origin, and processing technology. Commercial samples were collected in 2021 and used for the analysis (Figure 1). They were supplied by Romeo Ficacci S.r.l. (Castel Madama, RM, Italy) in sealed bags containing their original brine. The samples differed in cultivar, processing method, and storage conditions. For each cultivar, three independent batches were analyzed to guarantee statistical robustness. The detailed characteristics of the samples are reported in Table 1.



Figure 1. Commercial samples of table olives.

Table 1. Cultivars, processing methods, storage temperature and size of the commercial table olives analyzed.

Sample/Cultivar	Processing Method	Storage Temperature	Weight (g)	Longitudinal Diameter (mm)	Trasversal Diameter (mm)
Bella di Cerignola	Seville	Ambient	10.8 ± 0.1 c	36.7 ± 0.2 c	22.2 ± 0.1 c
Itrana Bianca	Natural	Ambient	3.9 ± 0.1 a	20.9 ± 0.1 a	16.7 ± 0.1 a
Nocellara del Belice	Castelvetro	Refrigerated	5.1 ± 0.1 b	21.5 ± 0.1 b	19.1 ± 0.1 b

Different letters correspond to a significant difference ($P < 0.05$).

The selected cultivars represent some of the most important Italian table olive varieties, each characterized by distinct morphological and geographical features: Itrana Bianca (Lazio region; medium-sized drupes with a roundish shape), Nocellara del Belice (Sicily region; large drupes with a spherical shape), and Bella di Cerignola (Puglia region; very large drupes with an elongated, ovoid shape).

The processing methods examined (natural, Seville, and Castelvetro) represent the main commercial debittering techniques currently adopted by the industry [21]. In the natural method, olives are directly immersed in brine without chemical treatment. Debittering occurs through diffusion phenomena and spontaneous lactic fermentation driven by indigenous microflora, resulting in a slow process (6–12 months). In contrast, both the Seville and Castelvetro methods involve treatment with an alkaline sodium hydroxide (NaOH) solution. In the Seville method, this step is followed by repeated washing and subsequent fermentation in brine for 3–4 months. In the Castelvetro method, olives are transferred directly into brine after alkaline treatment without washing, resulting in a product characterized by mild taste, firm texture, and bright green color. Unlike the other methods, the Castelvetro process does not include pasteurization; therefore, the final product requires refrigerated storage to maintain quality.

2.2. Texture Analysis

Texture analyses were performed using three compression tests (needle, tip, TPA) on 20 olives for each batch, for a total of 60 fruits per cultivar. Moreover, the compression/shear test (Kramer Shear Press) was performed on 50 g of pitted olives, with six replicates per lot for a total of 18 replicates per cultivar.

2.2.1. Compression Test with Needle and Tip

For the compression tests with a needle (Figure 2) and tip (Figure 3, the TA-XT Plus Texture Analyzer (Stable Micro Systems, Godalming, UK), equipped with a 50 N load cell and an acoustic detector (AED, Stable Micro Systems), was used. Two different probes were used: one with a diameter of 2 mm, with a pointed shape similar to a “needle”, and the other one with a diameter of 4 mm and a cylindrical shape similar to a “tip”. The probes were sent down at speeds of 6.67 and 3.33 mm s⁻¹, respectively, for the needle and tip tests, until they pierced the olive.



Figure 2. Needle test by TA.XT Plus Texture Analyzer.

The acoustic response was profiled by the AED device with a frequency cut-off set to 3.125 kHz, placing the microphone (Type 4188-A-021, Brüel & Kjær, Nærum, Denmark) approximately 1 cm away from the sample. The Brüel & Kjær Type 4231 sound calibrator was used to calibrate the system at sound pressure levels of 94 and 114 dB at 1000 Hz. Mechanical and acoustic characteristics were extracted from the data using Texture Exponent 32 software (Stable Micro Systems). All tests were performed in a laboratory without special soundproofing devices at room temperature. The force/displacement and sound/displacement curves were acquired simultaneously. The images (Figures 4 and 5) show a double graph, one force–distance and the other sound–distance, with vertical axes (y) showing the force (N) and sound (dB), while the horizontal axis (x) shows the distance (mm). The black curve represents the force versus distance, and the red trace reports the acoustic signal.

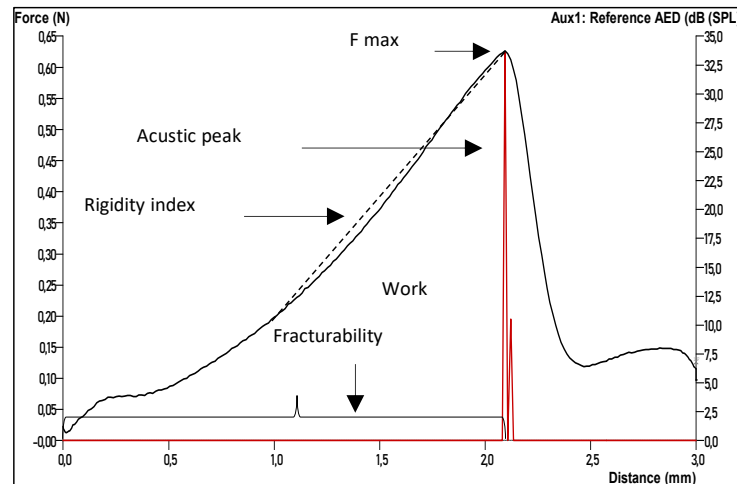


Figure 3. Tip test by TA.XT Plus Texture Analyzer.



Figure 4. Representative plot of mechanical–acoustic test by needle probe.

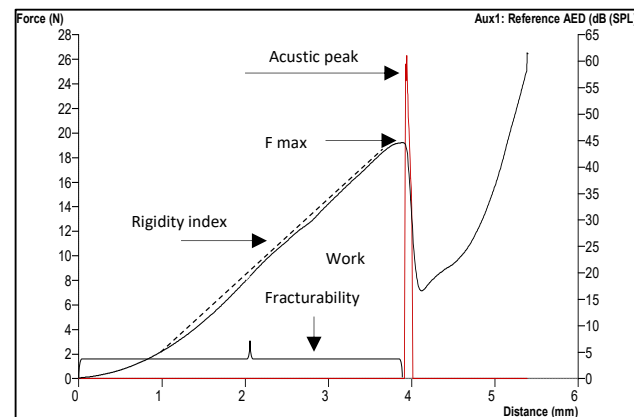


Figure 5. Representative plot of mechanical–acoustic test by tip probe.

In the initial phase, the force increased rapidly in an almost linear manner until reaching the peak, which was followed by a rapid decline. The peak of the curve identified the maximum penetration force (N), a parameter commonly used as an instrumental

index of the “hardness”. The initial slope of the curve (N/mm) is directly related to the apparent “rigidity index” of the system and the area under the curve up to the breaking point, calculated by the Texture Analyzer software, v. 6.2 indicating the mechanical “work” ($N \times mm$) of penetration. Furthermore, the distance (mm) at which the maximum peak occurred is a “fracturability index”. The number of peaks and their sound pressure level (expressed in dB) were extracted from the sound profile (red line).

2.2.2. Texture Profile Analysis (TPA)

Texture Profile Analysis (TPA) was performed on intact olives with the stone retained, according to previously reported procedures for table olives [11]. TPA was carried out by the TA-XT Plus Texture Analyzer. The olives were subjected to a double compression cycle, interspersed with a 2 s pause, using a plate with a diameter of 75 mm as a probe. The fruit was compressed by 15% of its initial size at a speed of 1 mm s^{-1} . The acoustic profile was not acquired with this test, since the slight compression did not produce acoustic peaks. Figure 6 is a representative plot of the TPA applied to a table olive sample. From the mechanical profile, the following parameters are obtained: *hardness* (N—maximum force recorded in the first compression cycle), *springiness* (ratio between distances $D2/D1$), *cohesiveness* (ratio between $A2/A1$ areas) and *chewiness* ($\text{hardness} \times \text{cohesiveness} \times \text{elasticity}$).

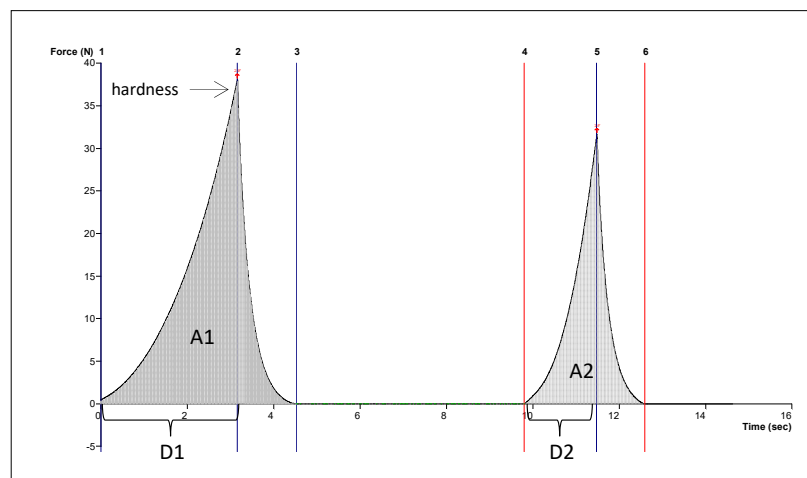


Figure 6. Representative plot of TPA.

2.2.3. Kramer Shear-Press Test

For compression/shear, a dynamometer (Instron, mod. 4301, High Wycombe, UK) was used, with a Shear Press system equipped with a lower compression-sliding cell containing the sample (about 50 g of pitted olives) and an upper multi-bladed part (Figure 7).

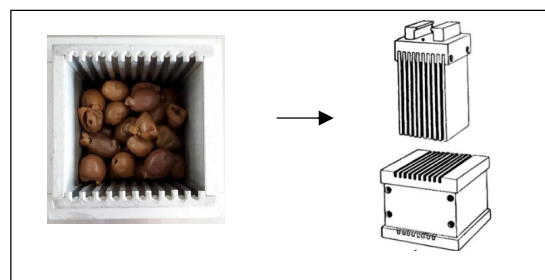


Figure 7. Kramer cell: top view of the measurement cell containing olives (left) and side-view schematic of the cell used to illustrate the operating principle (right).

The 10-blade cutting unit moved at a constant speed (100 mm min^{-1}) through the test material, compressing, cutting and extruding the sample through the perforated base plate. The acquired result was the force necessary to extrude the sample, and the result is expressed as N/g sample.

2.3. Sensory Analysis

The olives were also subjected to sensory analysis. Testing was organized into three separate sessions. For each session, three samples from a single product batch were analyzed (1 session/3 sample-cv/1 batch). Samples were presented in a randomized order and coded using a three-digit number. The tastings were carried out at room temperature using standard coded glasses [22], in which the samples were immersed in the conservation brine. The sensory characteristics of the table olives were evaluated by a panel of 10 tasters, in accordance with what is described by the standard “COI/OT/MO No. 1/Rev.3 Method for the sensory analysis of table olives” [3]. The method involved the evaluation of the texture characteristics (hardness, fibrousness, crunchiness), as well as negative attributes/defects (putrid/butyric fermentation, zapateria, etc.) and taste (salty, bitter, acidic) [23]. The evaluation sheet presented unstructured scales of 10 cm in length, whose extremes corresponded to 1 (no perception) and 11 (maximum perception), where the taster indicated the intensity of each descriptor.

Previously, the panel had been appropriately selected and trained according to the protocol described by Lanza & Amoruso [24]. The assessors belonged to an established sensory panel with longstanding experience in the evaluation of food products and were routinely involved in sensory analyses. The training protocol involved the use of reference standards, identified in two concentrations (taste attributes) or two products (texture attributes), whose values were, respectively, positioned in the low and high part of the scale. The coefficient of variation (CV%) calculated for the sensory attributes was always lower than 20%, indicating satisfactory repeatability and consistency of the panel assessments.

Results are expressed as the median intensity (Me) of attributes according to the method COI/OT/MO No. 1/Rev.3, Annex 3 [25].

2.4. Statistical Analysis

Statgraphics version 7 software (Manugistic Inc., Rockville, MD, USA) was used for statistical analysis. Data was analyzed by one-way analysis of variance (ANOVA) to determine statistically significant differences among means. Significance levels were set at * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$. When significant differences were detected, Tukey’s honestly significant difference (HSD) test was used as a post hoc procedure for multiple comparisons among means. Different letters within the same column indicate significant differences at $p < 0.05$. The results, except those relating to sensory analysis, are expressed as mean $\pm$ standard error. Relationships between sensory attributes and instrumental mechanical–acoustic parameters were evaluated using Pearson’s correlation coefficients.

3. Results and Discussion

The texture characteristics were determined by the combination of cultivar and debittering method to which the olives were subjected. Our data showed that all the mechanical parameters, acquired through all four instrumental tests, were strongly influenced by the cultivar/method combination.

3.1. Needle and Tip Compression Test

Regarding the needle compression test, the probe was characterized by a very small dimension and a pointed shape. Considering these features and the mechanical profile obtained (Figure 3), which showed a rapid increase followed by an equally rapid decrease in the force, it could reasonably be hypothesized that the acquired parameters were related to the characteristics of the peel rather than the pulp, as has already been observed by Bencresciuto et al. [26].

The results indicated (Table 2) that Itrana Bianca, when compared with the other cultivars, stood out for having the highest peel hardness and most work required for puncture, as well as the highest fracturability index. Meanwhile, Bella di Cerignola was characterized by the highest rigidity index. Bella di Cerignola and Nocellara del Belice, except for the rigidity index, had very similar characteristics.

Table 2. Mechanical parameters evaluated by needle compression test.

Sample	Hardness (N)	Fracturability (mm)	Work (N× mm)	Rigidity Index (N/mm)
Bella di Cerignola	0.53 ± 0.01 a	0.65 ± 0.01 a	0.13 ± 0.01 a	0.79 ± 0.02 b
Itrana Bianca	0.80 ± 0.02 b	1.27 ± 0.04 c	0.39 ± 0.01 b	0.66 ± 0.03 a
Nocellara del Belice	0.52 ± 0.01 a	0.74 ± 0.01 b	0.15 ± 0.01 a	0.68 ± 0.02 a
<i>Significance</i>	***	***	***	***

Different letters correspond to a significant difference ($P \leq 0.05$). Significance level: *** $p < 0.001$.

Regarding the tip compression test (Table 3), considering the dimension of the probe (diameter 4 mm) and the cylindrical shape, the results could be traced back to the sum of the characteristics of the peel and the pulp, even though the maximum peak presumably corresponded to the breaking point of the peel.

Table 3. Mechanical parameters evaluated by compression test with tip.

Sample	Hardness (N)	Fracturability (mm)	Work (N×mm)	Rigidity Index (N/mm)
Bella di Cerignola	18.72 ± 0.40 c	3.49 ± 0.08 b	31.98 ± 1.15 b	5.43 ± 0.13 b
Itrana Bianca	17.19 ± 0.45 b	4.02 ± 0.08 c	30.26 ± 0.74 b	4.44 ± 0.18 a
Nocellara del Belice	13.26 ± 0.41 a	2.80 ± 0.05 a	18.01 ± 0.75 a	4.72 ± 0.14 a
<i>Significance</i>	***	***	***	***

Different letters correspond to a significant difference ($P \leq 0.05$). Significance level: *** $p < 0.001$.

As expected, all values obtained with this test were much higher than the corresponding results acquired with the needle test. Unlike what was previously highlighted for the needle test, the Bella di Cerignola sample presented the highest values for both hardness and work. In particular, these olives were significantly harder than Itrana Bianca ones. This result is indicative of a more compact pulp structure of Bella di Cerignola olives. This confirms that Nocellara del Belice olives were the softest and required less work to be penetrated by the tip. Data regarding the rigidity index reflect the trend highlighted in the needle test, as the Bella di Cerignola sample was the most rigid and the other two samples were quite similar.

The data available in the literature are limited and not readily comparable with our results due to differences in the experimental conditions and the cultivars analyzed. In particular, no references are available for the needle test, although a few tests used a cylindrical probe of 2 mm. Cabrera-Banegil et al. [27] applied this compression test to olives of three different Spanish cultivars at different maturity degrees and throughout fermentation, reporting values of 40–80 N/cm² for fresh fruit and 20–35 N/cm² for fermented ones, which were lower than those obtained in our study using the tip (4 mm

diameter cylindrical probe) with a range of 105–149 N/cm² (data not reported in table, obtained considering the force and the area of probe). Moreover, Mafra et al. [8] measured the force required to insert a 2 mm diameter tip to a depth of 5 mm directly into the mesocarp of Negrinha do Douro olives, which were cut transversely and positioned vertically on the instrument plane, obtaining values ranging from 0.25 to 3.61 N, depending on the maturity stage. Other authors employed a 1 cm diameter probe to compress olives horizontally on the instrument plane with a set force (0.5–1 kg) for 15–30 s. Drupe deformation increased with ripening in cv. Negrinha do Douro from 1.09 to 7.52 mm [8] and with debittering in cv. Intosso d’Abruzzo, ranging from 0.80 to 1.49 mm [9], reflecting fruit softening. Catania et al. [10] compressed cv. Nocellara del Belice drupes with a 16 mm plate at 0.125 mm/s, recording forces up to 200 N to avoid stone breakage. They observed that the force required increased progressively toward the stone, indicating a firmer innermost layer (80–90 N) and a softer outer layer in contact with the brine (10–15 N).

As for the acoustic profile (Table 4), with needle compression, an extremely limited number of fruits produced an acoustic event, as only five Itrana Bianca olives made sounds, with a range of 25–50 dB, whereas a greater number of sounds was recorded using the tip compression test. The Itrana Bianca cultivar produced the highest number of sound events (30 fruits), far exceeding the other samples, with intensities ranging from 27 to 64 dB. In contrast, only a few Nocellara del Belice olives (six fruits) emitted sounds, with intensities between 42 and 59 dB. Notably, Bella di Cerignola olives did not produce any sound in either test. The analysis of both mechanical and acoustic profiles (Figure 3) shows that the acoustic peak coincides with the maximum force, suggesting that the sound may be caused by peel rupture. The absence of detectable acoustic events in some samples should not be interpreted as a failure of the acquisition system, since the microphone and acoustic detector successfully recorded sound emissions in other cultivars under identical experimental conditions. Rather, this result suggests that the rupture process in those samples did not generate acoustic emissions exceeding the detection threshold of the instrument.

Table 4. Fruits with acoustic events (n°/60 olives) and intensity range assessed by needle and tip compression testing. The symbol ‘-’ indicates that no acoustic events were detected in any of the tested fruits, rather than missing measurements.

Sample	Needle			Tip		
	n°	dB Min	dB Max	n°	dB Min	dB Max
Bella di Cerignola	-	-	-	-	-	-
Itrana Bianca	5	25	50	30	27	64
Nocellara del Belice	-	-	-	6	42	59

In relation to what is available in the literature, the only study concerning the application of mechanical–acoustic testing to evaluate the texture of table olives was conducted by Bacceli et al. [20]. Specifically, compression was applied until the cuticle broke and a 10 mm diameter probe penetrated the flesh while recording the sound. The authors examined 23 samples from four representative Italian cultivars (Bella di Cerignola, Itrana, Nocellara del Belice, Taggiasca). Despite the large sample size, sound intensity data were not reported. It is possible to extrapolate data from a compression/acoustic graph only for one sample of Bella di Cerignola, indicating an intensity of about 50–55 dB. This partially agrees with our results, as the sound intensity is similar to that observed for Nocellara del Belice and Itrana Bianca, while our Bella di Cerignola did not emit any sound when compressed. The authors [20] also reported that the sound measured by the microphone was generated by the breaking of the cuticle. Furthermore, in our tests, the

acoustic event coincided with the maximum force peak (peel rupture), whereas in Bacceli et al. [20], it occurred about 0.5 s later.

3.2. Texture Profile Analysis

The Texture Profile Analysis (TPA), not involving perforation or damage of the peel, evaluated the elastic, plastic and cohesive responses of the overall cellular mass of the pulp (mesocarp). The hardness obtained by TPA (Table 5) partially reflected that observed with the tip test, as Bella di Cerignola was confirmed as the hardest while Itrana Bianca was less hard than Nocellara del Belice, contrary to the tip test results (Table 3).

Table 5. Texture parameters evaluated by TPA.

Sample	Hardness (N)	Springiness	Cohesiveness	Chewiness (N)
Bella di Cerignola	57.52 ± 1.68 c	0.51 ± 0.01 a	0.48 ± 0.01 b	14.11 ± 0.52 c
Itrana Bianca	26.82 ± 1.29 a	0.79 ± 0.02 c	0.52 ± 0.01 c	10.27 ± 0.26 b
Nocellara del Belice	36.54 ± 1.06 b	0.55 ± 0.01 b	0.41 ± 0.01 a	8.29 ± 0.29 a
<i>Significance</i>	***	***	***	***

Different letters correspond to a significant difference ($P \leq 0.05$). Significance level: *** $p < 0.001$.

As the tip test evaluates the overall texture of the peel and pulp while the TPA evaluates only the pulp, this further supports the hypothesis that cv Itrana Bianca is characterized by a more consistent skin. The trend for hardness was not confirmed by the other parameters: Itrana Bianca showed the highest springiness and cohesiveness, indicating an elastic pulp that deforms without flaking or crumbling, whereas Bella di Cerignola was the firmest and chewiest, requiring the most force to chew.

TPA has been rarely used in olives. Only Lanza et al. [11] applied this test to evaluate three Italian cv (Peranzana, Taggiasca and Bella di Cerignola), reporting higher hardness values for Bella di Cerignola (84.20 N) than in our sample, likely due to differences in operating conditions.

3.3. Kramer Shear Press

The Kramer Shear Press combines compression and cutting and evaluates the olive texture as determined by both the pulp and the peel. This test is widely used in the food industry as it best simulates the chewing of a product [28]. Bella di Cerignola and Nocellara del Belice were, respectively, the most and the least consistent, while Itrana Bianca showed intermediate values (Table 6), confirming the trend observed by the hardness data obtained with the tip test.

Table 6. Hardness evaluated by Kramer Shear Press.

Sample	Hardness (N/g Sample)
Bella di Cerignola	42.94 ± 0.67 c
Itrana Bianca	38.24 ± 0.69 b
Nocellara del Belice	26.37 ± 0.32 a
<i>Significance</i>	***

Different letters correspond to a significant difference ($P \leq 0.05$). Significance level: *** $p < 0.001$.

Our results agree with Fernandez Diaz [29], who evaluated the texture of Manzanilla olives at different maturity stages (195–388 kg/100 g), showing a significant correlation between Kramer Shear press readings and 20 finger feel sensory tests. Moreover, Romero et al. [30] reported the shear force firmness (1300–3000 N/100 g) of Cacerena olives,

sterilized at different temperatures with the addition of different concentrations of Calcium. Garcia-Garcia et al. [31] found that the consistency of different Spanish cultivars during shelf life ranged from 2000 to 4000 N/100 g. Although there are no standard limits for marketing table olives, Sanchez et al. [32] estimated that olives with values lower than 1000 N/100 g are not suitable for sale.

3.4. Sensorial Analysis

Regarding the sensorial analysis, only the results relating to texture characteristics (hardness, fibrousness and crunchiness) were reported (Table 7).

Table 7. Sensory evaluation of the texture. Data are expressed as the average of the medians relating to the three lots.

Sample	Hardness	Fibrousness	Crunchiness
Bella di Cerignola	6.51 ± 0.38 b	4.73 ± 0.29 a	5.03 ± 0.14 a
Itrana Bianca	4.46 ± 0.65 a	4.86 ± 0.38 a	4.68 ± 0.35 a
Nocellara del Belice	4.49 ± 0.24 a	3.63 ± 0.39 a	5.92 ± 0.61 a
Significance	*	ns	ns

Different letters correspond to a significant difference ($P \leq 0.05$). Significance levels: ns (not significant), * $p < 0.05$.

Bella di Cerignola was rated by tasters as significantly harder, whereas the other two cultivars exhibited lower and comparable hardness. Regarding the other two sensory attributes, Nocellara del Belice showed the lowest fibrousness and the highest crunchiness, though differences were not statistically significant, while Bella di Cerignola and Itrana Bianca had similar values.

The following studies we refer to were carried out in accordance with the *Method for the sensory analysis of table olives* of the International Olive Council. Lanza et al. [23] reported higher scores for green Itrana Bianca samples (about seven) than those obtained for our Itrana Bianca olives for all the three texture attributes. Regarding the Bella di Cerignola sample, our sensory evaluations were quite consistent with Lanza et al. [11], who reported a score of 5.9 for hardness, 5.0 for fibrousness and 5.5 for crunchiness. Moreover, Catania et al. [10] reported a rather wide range of judgements for Nocellara del Belice olives for hardness (2.9–6.9), fibrousness (3.9–6.3) and crunchiness (3.1–7.6), depending on both the production year and the timing of packaging (either immediately after processing or after six months of storage in brine). The study also highlighted that the perceived kinesthetic sensations were consistent with compression force values. In addition, Garcia-Garcia et al. [31] found a good correlation between sensory hardness and Kramer Shear Press values for plain and pitted olives of three Spanish cultivars. Relationships between instrumental and sensory parameters are summarized in Table 8.

Table 8. Correlation analysis between instrumental (mechanical and acoustic) parameters and sensory texture characteristics of table olives.

Instrumental Parameter	Sensory Attribute	Pearson's r	p-Value	Significance
Tip hardness	Crunchiness	−0.7465	0.0209	*
TPA hardness	Hardness	0.7504	0.0199	*
Kramer Shear Press hardness	Fibrousness	0.6909	0.0393	*
Acoustic emission (needle test)	Crunchiness	−0.5831	0.0993	ns
Acoustic emission (tip test)	Crunchiness	−0.2029	0.6006	ns
Acoustic emission (needle test)	Hardness	−0.6485	0.0589	ns
Acoustic emission (tip test)	Hardness	−0.5307	0.1415	ns

Significance levels: ns (not significant), * $p < 0.05$.

Significant correlations were observed between hardness measured by the tip compression test and sensory crunchiness ($r = -0.7465$, $p = 0.0209$), between TPA hardness and sensory hardness ($r = 0.7504$, $p = 0.0199$), and between Kramer Shear Press hardness and sensory fibrousness ($r = 0.6909$, $p = 0.0393$). These results confirm that some instrumental measurements were able to reflect specific sensory perceptions of olive texture.

In contrast, no significant correlations were found between acoustic emission and the sensory attributes evaluated by the panel. The number of acoustic events detected during the needle and tip compression tests was not significantly correlated with sensory crunchiness (needle test: $r = -0.5831$, $p = 0.0993$; tip test: $r = -0.2029$, $p = 0.6006$). Similarly, no significant correlations were observed between acoustic emission and sensory hardness (needle test: $r = -0.6485$, $p = 0.0589$; tip test: $r = -0.5307$, $p = 0.1415$).

These findings are consistent with the cultivar responses observed in the present study. Itrana Bianca produced the highest number of acoustic events but was not perceived as the crunchiest sample. Conversely, Bella di Cerignola was rated as the hardest cultivar despite producing no detectable acoustic events. Taken together, these results suggest that acoustic emission is primarily associated with peel rupture rather than with the sensory perception of crunchiness or hardness. Since Itrana Bianca olives were characterized by the highest hardness values in the needle compression test, which mainly reflects peel properties, the acoustic response appears to be more closely related to peel texture than to pulp characteristics.

The official IOC sensory profile sheet evaluates the texture of the whole drupe and does not include descriptors specifically related to peel properties. Consequently, this limitation may have reduced the possibility of identifying direct relationships between acoustic measurements and sensory perception.

To overcome this problem, Bacceli et al. [20] modified the IOC official profile sheet [3] by distinguishing “skin hardness” from “flesh hardness” and introducing additional descriptors such as “skin persistence” and “flesh–stone detachment”. Although those authors reported that acoustic emission alone was not able to predict crunchiness or skin-related sensory attributes, acoustic information contributed to sample discrimination when combined with other instrumental variables through multivariate analyses.

Even though the potential of mechanical–acoustic testing for table olive texture evaluation was demonstrated, the approach shows some limitations, including the absence of detailed quantitative acoustic data and the use of a single compression configuration, which did not allow a clear distinction between peel and pulp contributions.

4. Conclusions

This study demonstrated that the textural properties of table olives are strongly influenced by the combined effect of cultivar and processing conditions, with each analytical method providing complementary information on peel and pulp behavior. The integration of multiple instrumental techniques, together with sensory evaluation, allowed a comprehensive characterization of olive texture.

The needle compression test proved to be particularly effective in describing peel properties, highlighting Itrana Bianca olives as the cultivar with the firmest and most resistant skin. In contrast, tests involving larger probes (tip compression and Kramer Shear Press) reflected the combined contribution of peel and pulp, identifying Bella di Cerignola as the hardest and most consistent cultivar, while Nocellara del Belice consistently showed the softest texture and lowest resistance to deformation.

Texture Profile Analysis further clarified differences at the pulp level, indicating that Itrana Bianca was characterized by a more elastic and cohesive mesocarp, whereas Bella di Cerignola showed higher firmness and chewiness. These findings confirm that

instrumental parameters vary depending on the specific tissue analyzed, reinforcing the need for a multi-method approach.

The acoustic measurements suggested that sound emission during compression is primarily associated with peel rupture rather than pulp characteristics. Indeed, Itrana Bianca produced the highest number of acoustic events, despite not being perceived as the crunchiest sample. This result, together with the lack of correlation between acoustic data and sensory crunchiness or hardness, highlights the limitation of current sensory protocols, which do not explicitly consider peel attributes.

Sensory analysis partially confirmed instrumental findings, particularly for hardness, which showed significant agreement with TPA and compression tests. However, other attributes such as fibrousness and crunchiness were less discriminating among cultivars. Significant correlations between instrumental and sensory parameters (e.g., TPA hardness and perceived hardness) support the reliability of instrumental techniques as predictors of sensory perception, although not all aspects of texture can be captured.

Overall, this work highlights the importance of combining mechanical, acoustic, and sensory approaches to fully understand olive texture. Furthermore, the results suggest that future studies should include more specific sensory descriptors related to peel characteristics and the application of a wider spectrum of varieties/processing, in order to better interpret acoustic responses and improve the correlation between instrumental and sensory data.

From a practical perspective, the integrated methodology proposed in this study may support quality control activities, cultivar characterization and optimization of processing conditions in the table olive industry.

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