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Experimental Assessment of the Elastic Properties of Exocarp–Mesocarp and Beans of *Coffea arabica* L. var. Castillo Using Indentation Tests

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Abstract: The development of selective coffee harvesting technologies requires detailed knowledge of the geometrical, physical, and mechanical properties of the subsystems of the coffee bush, including the elastic properties of the substructures of fruit and the coffee bean, which are directly related to the selectivity problem. The elastic properties of the mesocarp–exocarp and bean are not described in the literature due to the difficulty of characterizing these locally, since measuring each component of the coffee fruit structure (mesocarp–exocarp and bean) is not an easy task. However, determining the elastic properties (of the mesocarp–exocarp and bean) could help create realistic simulations as an initial estimation for selective coffee harvesting studies. The present work aims to bridge the gap in the mechanical characterization of the sub-structures of the coffee fruits by assessing the elastic properties of the mesocarp–exocarp and bean. Indentation tests were performed on eighty *Coffee arabica* L. var. Castillo fruits and beans, which were previously classified into four ripening stages using fruit color data in the CIELab color space. Young's modulus and indentation hardness of the mesocarp–exocarp structure and beans were calculated, applying the Oliver and Pharr indentation model and Hertz contact theory.

Keywords: *Coffe arabica* L. var. Castillo; indentation test; elastic properties; Young's modulus; hardness; selective harvesting

1. Introduction

Technology integration and innovation are increasing in developing countries, improving the agricultural sector's competitiveness. These challenges are currently being considered in the Colombian coffee industry. However, the small growers and peasant communities who support the coffee production systems are more vulnerable to economic losses. Multiple problems restrict the implementation of technological and technical solutions, putting sustainability and competitiveness at risk [1]. Furthermore, the volatility of international coffee prices and consumer preferences influences the Colombian coffee industry, affecting the sector directly [2]. Therefore, the knowledge of the production system and its properties is essential for successful development and innovation in the coffee industry. The most important design challenges include the heterogeneous characteristics of coffee fruits, plants architecture, crop distributions, topography, and production system configurations [3].

According to [4], the characterization of the physical properties of the coffee fruits will help researchers and designers optimize and design new harvesting technologies, reducing unwanted deformations, crop damage, and mechanical peeling improvement, among other factors [5]. For this reason, identifying the relationship between geometric attributes with physical, mechanical, and chemical fruit properties is vital for disruptive technology development. Furthermore, all these improvements will affect the current processing, transport, separation, sorting, and harvesting operations [6]. Therefore, for considering the above processes, agricultural machinery design requires planning, the applications of technical concepts, preliminary assessment, and a detailed design that considers all coffee requirements [3]. Additionally, in the particular case of harvesting, all tree properties and subsystems should be known to help better understand the dynamic nature of these substructures [7]. Therefore, studies aiming to evaluate the different critical mechanical properties required in coffee fruit harvesting are necessary. Therefore, the coffee fruit, peduncle, and branch elasticity moduli have been determined. Young's modulus for the coffee fruit peduncles was determined by applying a fixed load to the fruits and measuring the generated deformation [8].

Additionally, coffee fruit elasticity dissimilarity in its ripening stages was explained by the reduction in the mucilage stiffness due to the disintegration process as the fruit ripens [9,10]. It is essential to mention that coffee fruit elasticity fluctuates according to the coffee variety, plantation age, ripening stage, and harvest time [9]. The coffee fruit elasticity modulus decreases from the initial to the last stages of the ripening process. This reduction has been reported for the robusta [11] and arabica varieties [9,12,13]. Moreover, studies have reported ambiguous results where no significant differences have been found for the Poisson's ratio values of coffee fruit and pedicel among the initial and last ripening stages [9,11]. Additionally, a slightly higher Poisson's ratio was found for ripe coffee fruits and their pedicels than for unripe fruits [8].

The stiffness or firmness of fruits has been considered to be an indicator of food quality, texture measurement, shape, or susceptibility to damage [14]. This property changes during the fruit ripening stages in conjunction with the physicochemical and sensory characteristics [15]. Softening (stiffness decreasing) is a complex process in which the fundamental bases are still largely unknown [16]. Similarly, plant tissue softening occurs due to cell adhesion and wall integrity losses. Moreover, fruit texture is affected by rheological properties of the cell wall [17], water loss, and modifications in the pectic matrix [16]. Firmness has been used to establish the optimum harvesting time and measure resistance to mechanical damage during harvesting, handling, and transportation, even through nanoindentation and atomic force microscopy (AFM) [14]. Another crucial property is hardness, which is directly related to plasticity (Tabor, 1970) and can be measured through indentation tests, wherein the indentation test leaves an imprint on the material to measure its resistance to permanent deformations [18]. Indentation-based methods are beneficial to evaluate the mechanical characteristics of diverse synthetic materials [19] and natural source materials [20]. Different studies have used indentation to quantify important mechanical properties, such as toughness, elastic modulus, and hardness, in fruit and vegetables. Some mechanical properties of fallback foods (nuts, seeds, and root vegetables) were assessed using indentation as a technique [21]. In the case of fruits with structured endocarps, indentation or fracture methods are used to determine their mechanical properties [22]. More sophisticated indentations techniques, such as nanoindentation tests, were implemented to measure the hardness of the seed coats of tropical plants [23]. In addition, indentation techniques have been used to characterize the cellulose and lignin content differences in cuajilote fruits during their ripening stages [24].

Nevertheless, both experimentation and modeling are required to characterize the elastic properties of the coffee fruits and, therefore, to facilitate the development of technology and its integration for harvesting and post-harvesting [25]. Finite element analysis (FEA) is commonly used to determine the effect of mechanical impacts on fruit integrity [26,27]. This strategy requires essential parameters, such as Young's modulus, density, mass, and fruit geometry [28]. In addition, elastic properties are significantly affected by tip geometry and the force–indentation relationship, even at a cellular and subcellular scale [29]. Additionally, FEA has contributed to the elastic property evaluation of the structure of biological materials through a combination of nano-elasto-mechanical analysis with topographic imaging [30].

Studies on using simulation tests to visualize fruit stress–strain behavior as a function of time are pertinent to evaluating fruit responses under static and dynamic loads. FEA's main three fields in fruit mechanical modeling are predicting coffee fruit quality properties, predicting fruit bruise damage, and developing harvesting machines [31]. The elastic properties of coffee fruit have been studied through simulation approaches [7,32,33], and rigorous experimental tests should be considered to study coffee fruits' mechanical properties [13]. Coffee harvesting research has to focus on mechanical properties estimation because too few experimental studies have been carried out [34,35].

As described previously, different varieties of coffee have been studied in terms of their mechanical properties. However, there is a lack of experimental and simulation data related to other crucial varieties. The genetically modified coffee variety, named *Coffea arabica* L. var. Castillo, is resistant to coffee leaf rust (Hemileia vastatrix), and it is becoming the dominant crop in the Colombian coffee industry [36,37]. Another Colombian variety is the *Coffea arabica* L. var. Colombia, which has been studied in terms of its mechanical behavior. The elastic constants for the fruit–peduncle system of this variety were determined in some studies [7]; values of 22.61 MPa and 23.14 MPa were obtained for peduncles in their ripe and unripe stages, respectively [38]. However, not enough studies have been reported for *Coffea arabica* L. var. Castillo.

This work conducts indentation tests on *Coffea arabica* L. var. Castillo fruits and beans. Previously, fruits were classified into four ripening stages using a colorimetric approach. Eighty fruit samples were harvested to assess coffee fruits and beans. The obtained results represent an essential contribution to the future of *Coffea arabica* L. var. Castillo fruit harvesting. The findings of this work contribute to the lack of reliable experimental information about mechanical-elastic properties of the mesocarp-endosperm composite system. These results can be crucial for more realistic simulations that better characterize *Coffea arabica* L. var. Castillo's natural frequencies, leading to selective harvesting technology improvements. Section 2 will describe the experimental set-ups for color classification and the indentation tests. Force–displacement curves and *Coffea arabica* L. var. Castillo indentation hardness and Young's modulus values will be discussed in Section 3.

2. Materials and Methods

2.1. Sample Selection and Ripening Stage Classification

Coffea arabica L. var. Castillo fruits were used to represent the samples in this study. A farm located in Manizales-Caldas (Colombia) was designated as the chosen place for the coffee berry harvesting; Table 1 lists the parameters of its characterization. Each coffee bush was inspected to identify branches with damage, which allowed us to select the best bushes. A visual inspection was carried out to avoid fruits with evident imperfections. Coffee fruit defects, for example, partially formed fruits, could affect the elastic property measurements [39]. In addition, factors such as seasonal weather, relative humidity, terrain slope, and sunlight exposure are related to the health of the coffee plants; in the majority of the cases when plants are not in the best conditions, this can be seen in the coffee fruits themselves. Therefore, as a main qualitative parameter, a sample selection procedure was established in this work. The main objective was to visually determine and choose the best shaped coffee fruits, due to their relationship with the endosperm symmetry [40]. The fruit samples harvested for this study were classified into four ripening stages using a chromaticity-based approach proposed by [41]. The CIELab color space $a*$ (the gradient from green to red) and $b*$ (the gradient from blue to yellow) coordinates were measured with a colorimeter PCE-CSM 4 (PCE Instruments, Southampton, UK) for eighty *Coffea arabica* L. var. Castillo fruits. The covariances determined with the data determined the four ripening stages, conveniently named unripe, semi-ripe, ripe, and overripe. Each fruit is located in one of these previously established ripening categories. The details of the classification procedure are reported in [4,41].

Table 1. Farm characterization parameters.

Variable	Parameter Value
Environmental temperature	28.8 ± 0.5 °C
Atmospheric pressure	75.9 kPa
Relative humidity	$81 \pm 1.0\%$
Wind speed	3 km/h west-northwest direction
Altitude	1352 m
Coordinates	5°0′40″, 75°47′44″
Coffee tree age	2 years

2.2. Indentation Test Theory and Parameters

The indentation test is a technique used for characterizing several materials at different scales, which is widely used in the elasticity modulus (E) and indentation hardness (H) assessments. The test is based on the research conducted by [42], which has been the starting point for the current applications that include mechanical properties estimation for different composite materials [43], fibrous materials [44], and vegetable materials, for example coconut [22] and carrot [45]. This technique can be adapted to predict the mechanical behavior of biological materials, which is very practical for our study. The test involves applying a force over a surface that enters into contact with an indenter with different regular shapes. The applied force and the indenter displacement are measured during the test.

Further, two stages are carried out during the evaluation process: the loading and unloading stages. In this study, we propose using the indentation test to evaluate the elastic parameters of the exocarp–mesocarp and the bean of the coffee fruits. This allows us to characterize the sub-structures of fruit in different ripening stages. Figure 1 describes the proposed experiment without the details of the procedures, since the idea is to depict the theoretical concepts graphically, which means considering the most important parameters of the test. As the theory shows [46], elastic properties are closely related to the contact area, which can be inferred from the maximum indentation depth ($h_{\max}$), depth after elastic recovery (h_f), contact stiffness (S), and contact depth (h_c) [46]. Figure 1 shows the geometric variables involved in the test with a coffee fruit sample. According to [47], the indented material elasticity modulus (E) can be estimated from the contact stiffness, which is related to the unloading curve, specifically with the tangent line slope evaluated at its maximum point, as depicted in Figure 1. This parameter is defined as

$$S = \left(\frac{dP}{dh}\right)_{h=h_{\max}} = \frac{2}{\sqrt{\pi}} E_r \sqrt{A_c} \quad (1)$$

where dP is the variation in the pressure and dh is the depth variation. A_c is the contact area between the indenter and the indented material. As a result of the elastic contact between the indenter and the surface of interest, the reduced elastic modulus (E_r) is estimated in the following manner [46]. Considering the elastic contact between indenter and the surface of interest, a reduced elastic modulus is estimated to determine the relationship between the indenter and indented material [46], as follows:

$$E_r = \frac{1}{\beta} S \frac{\sqrt{\pi}}{2} \frac{1}{\sqrt{A_c}}. \quad (2)$$

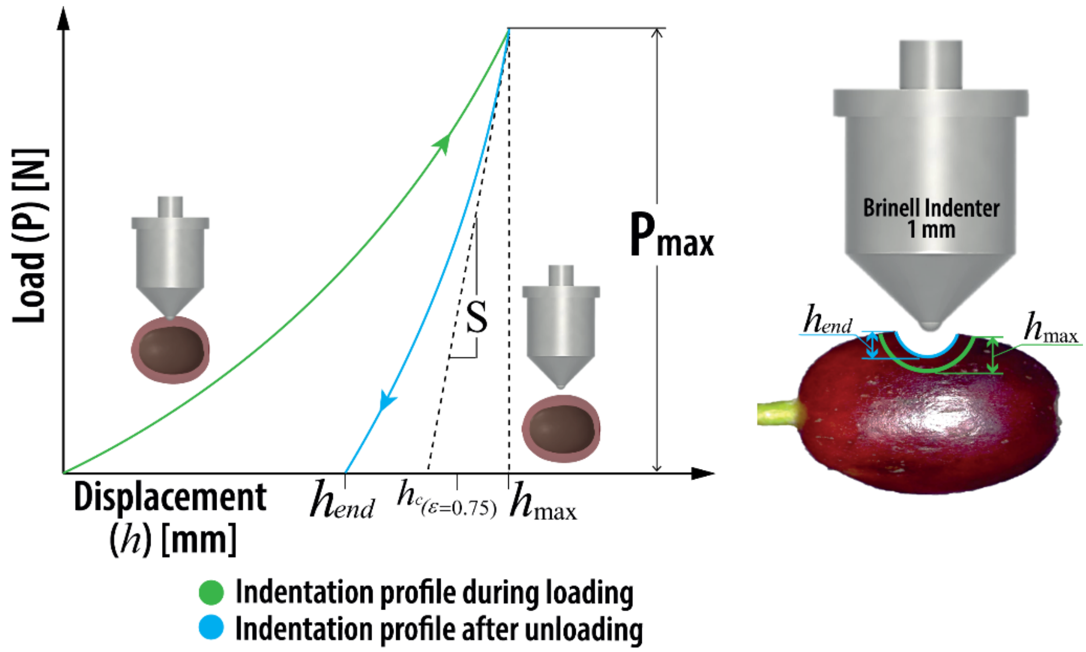

Figure 1. Loading and unloading process on the exocarp–mesocarp of coffee fruit.

This relation is obtained from Equation (1). However, this considers the effect of the indenter shape, represented by an empirical indenter shape correction factor parameter ($\beta = 1$ for a spherical indenter). Considering the projection dP/dh (see Figure 1) on the displacement axis, the value of h_c is defined as

$$h_c = h_{\max} - \varepsilon \frac{P_{\max}}{S}. \tag{3}$$

In Equation (3), $h_{\max}$ and $P_{\max}$ are the maximum values reached during the indentation process. The empirical geometrical parameter ε depends on the shape of the indenter that [46] describes. For tests with a spherical indenter ($\varepsilon = 0.75$), the projected area A_c can be determined by

$$A_c = a\pi^2 = \pi\left(2Rh_c - h_c{}^2\right), \tag{4}$$

where R is the indenter radius and a is the indenter track radius determined for the surface of interest, which is the exocarp–mesocarp and the coffee bean in our study. Given that, the indenter material suffers deformations during the load tests, and both materials' elastic moduli are related in the reduced modulus (E_r) as

$$\frac{1}{E_r} = \frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i}, \tag{5}$$

where E and ν are Young's modulus and Poisson's ratio of the studied material. The subscript i refers to the indenter material. Further, the hardness property can be established according to the general definition of stress, as [46] explains, whereby

$$H = \frac{P_{\max}}{A_c}, \tag{6}$$

Equation (6) describes the determination of hardness from the stress definitions, where A_c is a sensitivity parameter that depends on the contact area; therefore, this should be accurately determined.

2.3. Experimental Set-Up for the Indentation Tests on Coffee Fruits and Beans

The indentation tests were performed on 10 samples harvested at each ripening stage of *Coffea arabica* L. var. Castillo, with 40 samples gathered for the study. However, twenty tests were performed for each ripening stage, since beans and fruits were utilized. This experiment is similar to a standardized compression test; however, this uses an indenter that contacts the surface of the exocarp–mesocarp of the fruit or the endosperm of the bean. These tests were performed at room temperature of 25.4 °C on average, with 70% humidity. After the selection process, the coffee fruits were detached with the pedicel and humidified to prevent fruit water loss between transport time and the test; mass measurements controlled this parameter. The test was carried out in two batches, one with fruits to evaluate their surface (exocarp–mesocarp) and another with beans (endosperm evaluation). For the second test, the bean was released from the fruit, and its mucilage husk was removed through careful surface cleaning. Figure 2 details the experimental configuration of the tests, including the parts of the fruit, the bean, and the indentation markings. Indentation tests were carried out using a universal Mark-10 ESM 303 (Mark-10, Copiague, NY, USA) test machine coupled with a force gauge with an advance speed of 0.5 mm/min. Using a mechanical coupling, a Brinell indenter of 1 mm diameter was fixed to the force gauge. Additionally, an adjustable PLA holder was manufactured to sustain the fruit during the test, as depicted in Figure 2a. We established as input parameters the indentation depths for unripe and semi-ripe fruits of 1 mm and depths of 2 mm for ripe and overripe fruits; for the beans, 1 mm of depth was established. As a result of the test, we obtained load and displacement values to define the force–displacement relation. These control parameters were set based on elastic recovery differences between ripening stages. Before the final experimental design was established, previous tests were conducted. A PCE-WSM 100 microscope (PCE Instruments, Southampton, UK) was used to determine the track diameter made by the indenter in the tests.

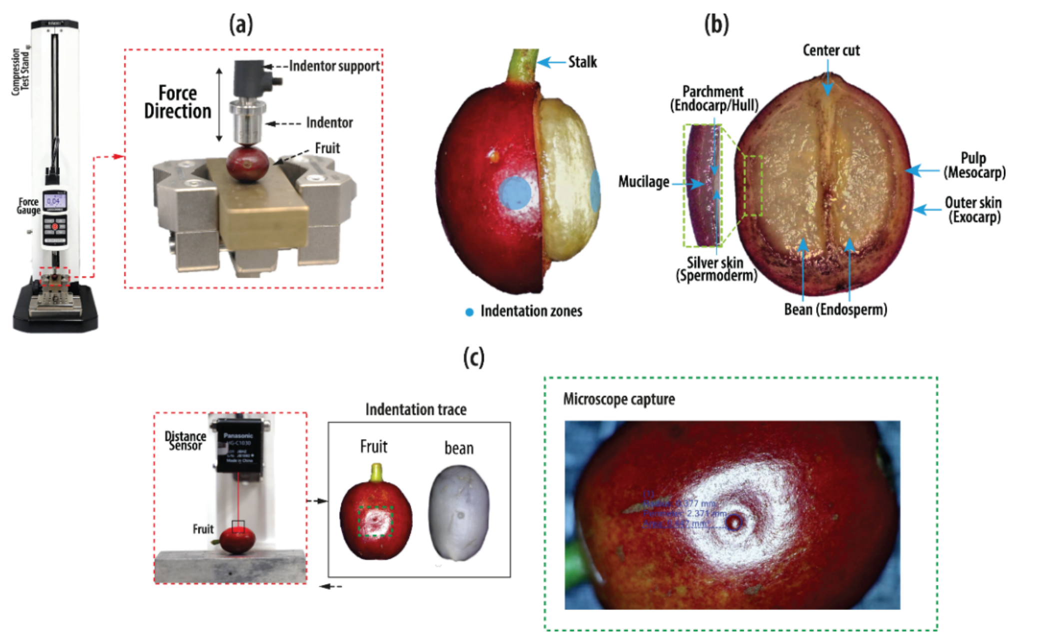

Figure 2. (**a**) Indentation test description. (**b**) Anatomy of the coffee fruit. (**c**) Indenter mark on the exocarp.

The indentation zones were selected on the outer fruit skin/pulp (exocarp–mesocarp) and bean (endosperm), as shown in Figure 2b. Coffee fruit consists of exterior skin (exocarp) that changes color depending on ripening. Internally, the skin covers a fleshy yellow-white pulp and mucilage (mesocarp); in this part, a plain yellow parchment (endocarp) and silver skin (integument) protect the seed (endosperm) [48].

Images taken for dimensional analysis are shown in Figure 2c, illustrating the indenter marks on the fruit and bean. The depth left by the indenter after elastic recovery in the material was measured by a sensor HG-C1030-P CMOS (Panasonic industrial devices SUNX co, Suzhou, China), which is a micro-laser distance sensor, as seen in Figure 2c. We made sure that all the fruits were marked at the same place in the tests, so the orientation of the fruit was standardized. Furthermore, the indentation mark was made on the face with the largest diameter (Table 2 shows the material properties of the indenter); according to the manufacturer, this is an indenter made from a carbide–cobalt alloy. This information is relevant since it is used to calculate the properties of the exocarp–mesocarp and the bean.

Table 2. Elastic properties of the indenter.

E_i (MPa)	ν_i	ν
550,000	0.22	0.3

3. Results

3.1. Force versus Displacement Curves

The experimental curves obtained from indentation measurements, with impressions made on the exocarp–mesocarp of the coffee fruits at depth $h_{\max} = 1$ mm (unripe and semi-ripe) and $h_{\max} = 2$ mm (ripe and overripe), are detailed in Figure 3. The higher orthogonal diameter defined the fruit orientation, which coincides with the indented face. Each curve represents the loading and unloading processes during the indentation tests. As seen in the labeled curve, it is illustrated that the load curve shows a nonlinear correlation governed by the elastoplastic behavior of the test, as detailed by [49], who likens this behavior to a linear combination of an elastoplastic process. The unloading curve represents the reversal process after the maximum depth was reached, which means that the elastic recovery after the load was removed. For the unripe curve, the measurements show a higher dispersion in the loading procedure than in the unloading part. The maximum values of the force are between 12.5 N and 15 N for 1 mm of depth. In the other ripening stages, it is seen that in semi-ripe fruits, the dispersion among data is very low, which is a good indicator of the reliability of the measurements.

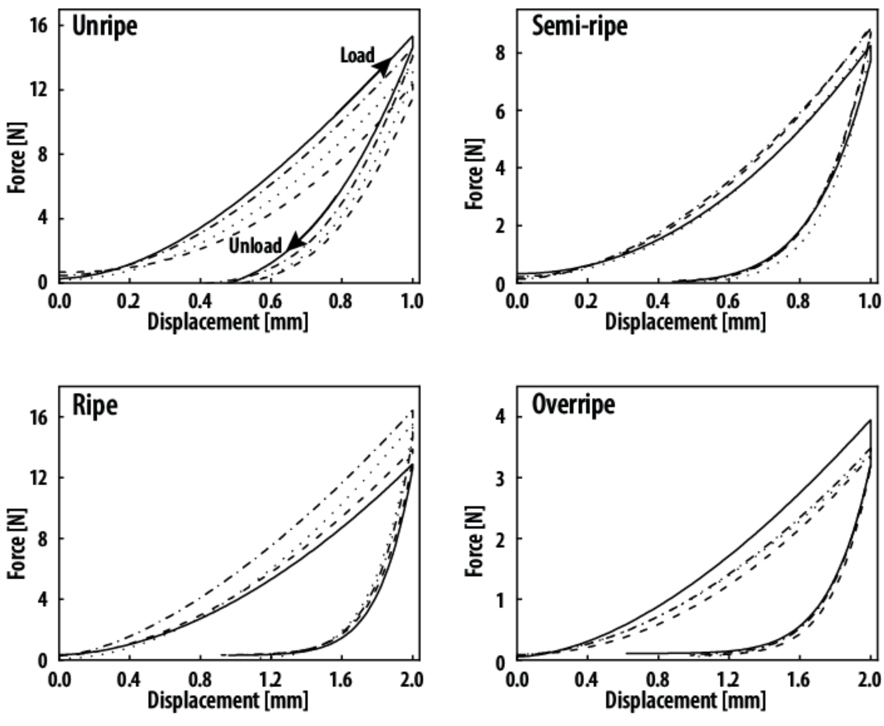

Figure 3. Loading and unloading curves for the exocarp–mesocarp. Dashed lines represent other samples.

The maximum force values oscillate between 8.0 N and 8.5 N for 1 mm of depth in the semi-ripe ripening stage. For ripe and overripe states, the indentation depths were a maximum of 2 mm, and the force values were between 12 N and 16 N for the ripe stage and between 3 N and 4 N for the overripe stage. It can be seen from the graph that the loading curve is scattered for both ripening stages. However, the unloading curve is more consistent in all experiments. This is reflected in the parameter represented by S, which characterizes the slope of the unloading curve; the calculations are described in Equation (1). It is observed that the unloading slope S decays by 70.26% from ripe until overripe, but this is constant from unripe to ripe, with an approximated value of 51.55 ± 3.48 N/mm, which means that there is a loss of stiffness caused by the biological changes that the fruits experience during ripening. This loss of firmness can be explained by the higher water content of the fruit at the later stages of ripening than in the earlier stages [50]. According to [33], ripening involves biological processes, such as transpiration from the fruit surface, and internal processes, such as cell division, differentiation, metabolism, and catabolism. The role of the exocarp is to provide external resistance in the fruit. Therefore, the layer should be more elastic when the fruit ripens; the exocarp is a monocellular structure protected by a waxy substance that changes with the ripening, affecting the mechanical properties [48]. The mesocarp is a fibrous and sweet pulp containing carbohydrates (glucose, fructose, and pectin), proteins, fat, lipid minerals, tannins, polyphenols, and caffeine [51]. In the mesocarp, the variations are more visible, since the fruit is soft to the touch when it is close to the ripe stage. This supports the hypothesis that ripening plays an influential role in fruit stiffness, as demonstrated in other studies [52]. On the basis of the data, we determined that the contact area A_c (see Section 2.2 and Table 3) increased at least six times in size due to the plastic deformation produced by the indenter in the exocarp–mesocarp, as shown in Figure 2. It was more challenging to produce a visible mark on ripe and overripe fruits that will help to describe the indenter's fingerprint; for this reason, the indentation depth was established at 2 mm for these two ripening stages.

Table 3. Parameters for calculation of elastic properties of *Coffea arabica* L. var. Castillo fruit and bean.

	Exocarp-Mesocarp						**Beans**					
	A_c (mm^2)	**Std.**	**h_c (mm)**	**Std.**	**S (N/mm)**	**Std.**	**A_c (mm^2)**	**Std.**	**h_c (mm)**	**Std.**	**S (N/mm)**	**Std.**
Unripe	6.435	0.091	0.244	0.056	48.57	13.30	6.646	0.006	0.505	0.038	23.49	5.630
Semi-ripe	6.573	0.038	0.348	0.039	55.38	15.69	6.440	0.140	0.253	0.080	78.83	21.49
Ripe	35.98	0.184	0.753	0.100	50.70	10.00	6.335	0.075	0.186	0.039	133.3	11.06
Overripe	36.06	0.090	0.621	0.208	15.08	7.035	6.269	0.076	0.153	0.036	124.5	10.58

Figure 4 describes the measurements carried out over the bean surface; the consolidation of the curves is very similar to that obtained for the exocarp–mesocarp. All experimental tests were performed to a depth of 1 mm; the maximum forces reached during the indentation process are 3.6 N (unripe), 19 N (semi-ripe), 39.8 N (ripe), and 40 N (overripe). Given the maximum forces achieved in the indentation, we note that the bean is stiffer during the ripening, unlike in the exocarp–mesocarp structure. This is because of the evolution of the bean's silver skin (perisperm), a hard shell that forms at the end of the ripening [48].

The low stiffness of beans extracted from unripe fruits is due to their early ripening stage; at this stage, they are soft. However, the bean is fully formed in the ripe stage, obtaining its maximum stiffness. As a final observation, there is no significant change between the loading and unloading curves determined for ripe and overripe beans (see Figure 4). From Equation (4), it is analyzed that the contact area of the track left by the indenter is similar in all the beans. We found that there are no soft zones around the indenter after applying indentation forces. This is because local stresses are concentrated on the indenter's contact surface. A plastic indentation leaves permanent traces of stress concentrations on the indentation surface, as in the case of the coffee bean; this is common in the indentation process, as reported by [46]. This aspect was very positive for characterizing the fruit's parameters, since the geometry of the mark left by the indenter revealed its 3D structure, which facilitated the determination of the properties. The exocarp–mesocarp and bean elastic properties showed a high level of dependence on the contact area of the indenter; this was corrected using the calculation of the contact area of the indenter. Several difficulties were addressed according to the pulp conditions (exocarp–mesocarp) of the ripe and overripe fruits, since the tests were affected by their soft pulp conditions (exocarp–mesocarp). For that reason, the indentation depths were increased for these ripening stages.

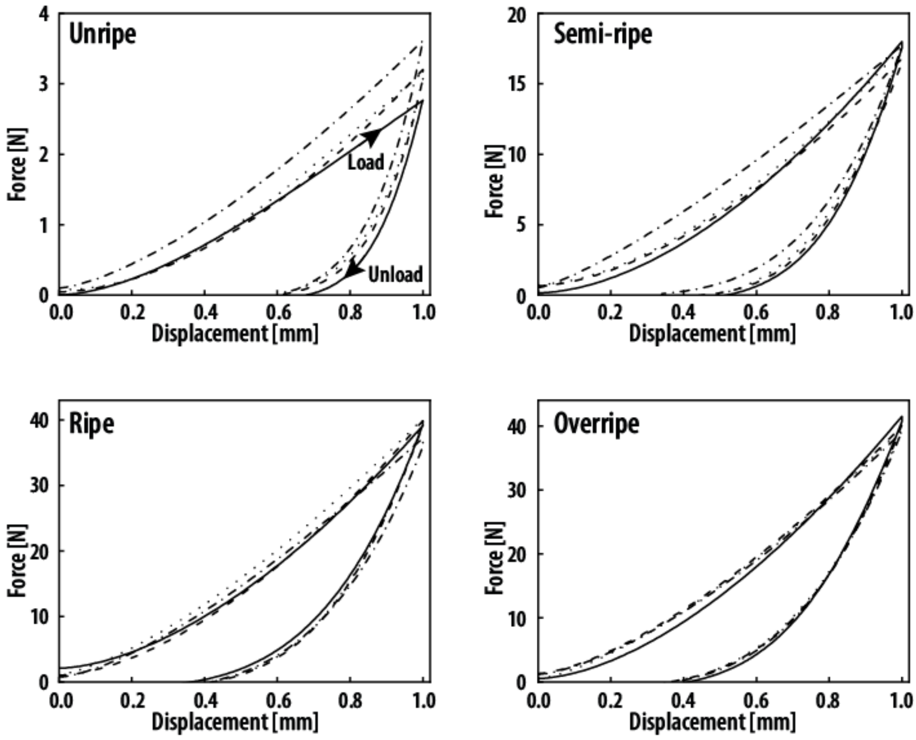

Figure 4. Loading and unloading curves for the bean. Dashed lines represent other samples.

3.2. Characterization of Young's Modulus and Indentation Hardness

The exocarp–mesocarp and bean elastic properties were determined from Equations (5) and (6), using the listed parameters in Table 2; some parameters, such as β and ε, were assumed according to other studies focused on seeds [53]. The calculation of Young's modulus and indentation hardness has a high level of dependence on the contact area of the indenter, so a parameter correction was performed according to the projected area left, given the specific conditions of the test. The main difficulty was addressed according to the pulp conditions (exocarp–mesocarp) of the ripe and overripe fruits, since these are very soft in those two stages. For this reason, the depth of indentation was increased, as explained in the above section. Young's modulus and indentation hardness calculations are shown in Figure 5. This corresponds with the properties of the exocarp-mesocarp and the bean. Figure 5a shows that Young's modulus decreases with the ripening, starting from 15.43 MPa for unripe, 17.43 MPa for semi-ripe, 6.8 MPa for ripe, to 2.02 MPa for overripe, and these results are contrasted with the properties obtained by [7] via finite element analysis. The results obtained are similar to those found in the study conducted by [7]; for example, the absolute error calculated between Young's modulus is 9.7% for unripe, 8.2% for semi-ripe, 6.84% ripe, and 53.4% for overripe. It is seen that the bean's elastic properties increased during ripening, from 7 MPa for unripe to 41.7 $\pm$ 1.42 MPa (ripe and overripe), which agrees with the discussion in the previous results section. Figure 5b illustrates the hardness properties; in general, the results of the hardness analysis are analogous to the effects of elasticity. These were correlated using the equations presented in Section 2. The theory describes hardness as a hybrid property that measures the strength as the reversible and irreversible loading conditions connected to the elastic modulus.

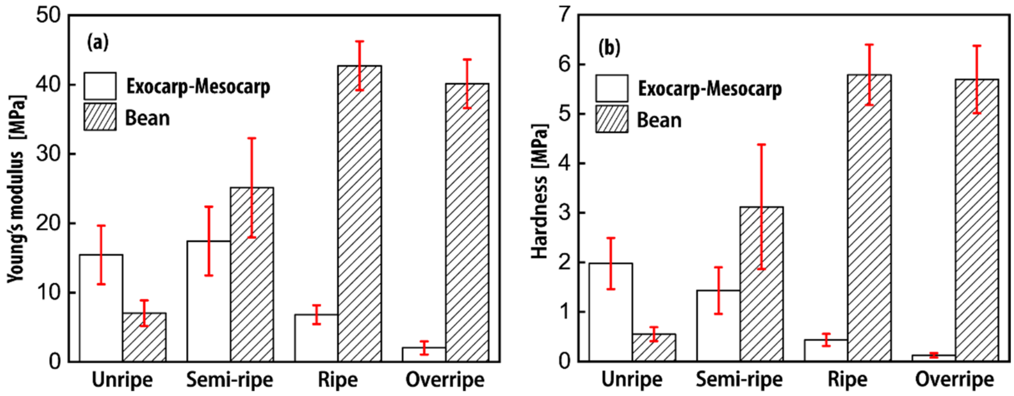

Figure 5. (**a**) Young's modulus. (**b**) Hardness.

4. Conclusions

In this study, a detailed experimental setup was proposed to characterize the elastic mechanical properties of the exocarp–mesocarp and beans of coffee fruits *Coffea arabica* L. var. Castillo. This setup is based on an indentation test, despite no standardized procedure for preparing biological structures existing due to their geometrical complexity and difficulty with manipulation. The indentation technique had never been applied to measure coffee fruits properties before. This work successfully measured important mechanical properties, such as Young's modulus and hardness, in coffee fruits using indentation tests. The ripening stages of coffee fruit have their own characteristics properties, though one can design separate experimental features to obtain feasible measurements. An indenter depth of 2 mm was set for the ripe and overripe fruit samples because 1 mm was not enough to avoid the elastic recovery that led to the indentation mark being erased. The loading and unloading curves obtained for the exocarp–mesocarp showed that the maximum forces reached during the indentation process were between 3.6 N and 40 N for the bean and for the fruit, between 3 N and 16 N. It can be concluded that the exocarp–mesocarp firmness decreases with ripening as beans become harder. This observation is probably caused by the evolution of the bean's silver skin (perisperm), which is a hard shell that forms at the end of ripening. With respect to the exocarp–mesocarp, the unloading slope evidenced a decay of 70.26% from ripe until overripe, but this kept a constant value from unripe until ripe, with an approximated value of 51.55 ± 3.48 N/mm. Additionally, it was found that the Young's modulus decreases with ripening, starting from 15.43 MPa for unripe, 17.43 MPa for semi-ripe, 6.8 MPa for ripe, to 2.02 MPa for overripe. A further observation is that the bean's elasticity increases with ripening, from 7 MPa for unripe beans to 41.7 ± 1.42 MPa on average for ripe and overripe beans. These results agree with other studies examining how ripening affects the mechanical behavior of coffee fruit. The correlation between pulp and bean can be seen in the Young's modulus values, showing how the pulp is softer during ripening, and then the bean becomes harder. Throughout the indentation equations, the results of the hardness calculations correlate directly with Young's modulus; therefore, the elastic analysis is analogous.

This work demonstrates the implementation feasibility of indentation tests that can be used to measure the elastic mechanical properties of the coffee fruit. The Young's modulus and hardness values for coffee fruit found in this work are going to supply crucial information to finite element simulations for improving or verifying modal frequencies and selective harvesting, among other applications.

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