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Modeling of Coffee Fruit: An Approach to Simulate the Effects of Compression

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Abstract: The flavor, aroma, and color of coffee can be changed due to mechanical damage, reducing its quality. To measure the mechanical behavior of the fruit, compression tests can be performed at different stages of ripeness. In this study, we analyzed the deformation, strain energy, and von Mises stress of coffee fruits at mature, semi-mature, and immature stages under compression forces. Compression in three directions (x, y, and z) was simulated on coffee fruit models using the finite element method. A compression support was applied in the opposite direction to the force application axis. Numerical simulations of the compression process allowed us to verify that the more mature the fruit, greater the associated mean deformation (2.20 mm mm^{-1}, 0.78 mm mm^{-1}, and 0.88 mm mm^{-1}), the lower the mean strain energy (0.07 mJ, 0.21 mJ, and 0.34 mJ), and the lower the mean equivalent von Mises stress (0.25 MPa, 1.03 MPa, and 1.25 MPa), corresponding to ripe, semi-ripe, and immature fruits, respectively. These analyses not only save time and professional resources but also offer insights into how strain energy and von Mises stress affect fruits at different maturation stages. This information can guide machine adjustments to reduce coffee harvesting damages.

Keywords: deformation; finite element method; mechanical damage; mechanical properties; numerical simulation

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1. Introduction

In the production process of agricultural products, the loss rates accumulate throughout the entire production chain, from the harvest to the consumer's table. This scenario makes it essential to use techniques and technologies that promote a reduction in such losses [1]. Additionally, to provide conditions that favor the maintenance of product quality, one must know the physical and mechanical properties of the material being worked on for proper use of processing techniques and equipment [2,3].

Coffee is one of the products that has an increase in value and export volume due to better quality. However, its flavor, aroma, and color can be changed due to the occurrence of mechanical damage, which affects the desired attributes [4]. In this context, there has been a strengthening of the industry standards for the production of high-quality coffee, as well as of the institutions that evaluate its excellence and qualify specialty coffees. This influences the sales price of the lots and can favor the reputation of the countries and regions that produce this coffee [5,6].

Arabica coffee (*Coffea arabica* L.) belongs to the order Gentianales, family Rubiaceae, and genus *Coffea*. It is a shrub native to the region of southwestern Ethiopia, southeastern Sudan, and northern Kenya. It has also been cultivated in other locations, such as in Brazil, where there are approximately 132 cultivars registered with the responsible agencies [7,8].

The coffee plant, a shrub of continuous growth that reaches between 2 and 4 m in height, has a cylindrical, yellowish-white stem, with hardwood, dark green leaves, that are oval, opposite, and paired, as well as white aromatic flowers [7]. Its phenological cycle takes two years to complete. The formation of vegetative branches (plagiotropic or transverse), from the orthotropic branches (orthogonal or perpendicular to the soil), containing nodes with auxiliary buds, occurs in the first year. In the second year, flowering begins, followed by the formation of pellets, grain expansion, fruit germination, and maturation [9].

Among the coffee producing countries, Brazil produces the largest amount, (approximately 50 million bags in 2022), which contributes to the gross domestic product (GDP) of the country. The Brazilian coffee production accounts for 30% of global production [10–12].

The species *Coffea arabica* was first introduced in Brazilian soil in the state of Pará, in approximately 1727. It spread throughout the states of Maranhão, Bahia, Rio de Janeiro, São Paulo, Minas Gerais, Paraná, and Espírito Santo, occupying a relevant position in the worldwide supply in the twentieth century [13].

The country is also a significant consumer, emphasizing the product's importance for both export and domestic consumption [14]. Mechanical harvesting, while efficient, can cause branch breakage and fruit damage, necessitating the selection of appropriate harvesting technology [15]. This choice should consider various factors, including the tree's properties and the fruit's characteristics [15].

During the fruit ripening process, there is a reduction in chlorophyll and an increase in anthocyanins and carotenoids. This, combined with the action of ethylene and the increase in the activity of the enzymes responsible for the softening of the cell wall, transforms the hard, green, and rigid fruit into soft fruit [9]. The degree of maturation, together with the size of the beans, which are thinner than Robusta coffee, can reduce harvest efficiency and change the quality of the Arabica coffee beverage products, which tend to have a low caffeine content and favorable aroma and flavor [16,17].

However, if coffee is to continue to contribute effectively to Brazil's economic development, attention must be paid to the damage caused to this fruit by the mechanical, semi-mechanized and mechanized processes to which it is subjected from harvest to final destination [18]. Ref. [4] points out that during the harvesting process, mechanical damage can occur to the fruit, affecting the quality of the product (coffee) and, thus, jeopardizing the value and volume of commercialization. Therefore, there is a need to look for effective methods to optimize mechanical processing design and minimize these injuries, such as computer modeling and simulation [19].

Ref. [19] found that one of the ways to change the mechanical processes of coffee processing that can induce injuries to the fruits is the study and evaluation of scenarios. These scenarios involve damage prediction of the fruits via computer simulation, mechanical behavior during the storage, and harvesting processes for different stages of maturation. In this case, the use of known mechanical properties, such as elastic modulus, Poisson coefficient, and density is essential to predict the deformation, energy distribution, and equivalent stress of the material after the application of compression loads [20].

Ref. [21] highlighted that one of the ways to measure the mechanical response of materials is through compression testing and that parameters, such as moisture content and force application region, can affect the mechanical behavior of the fruit.

The Hertz theory is essential for understanding interactions between solids in contact. It establishes that, when compression occurs between two solid bodies, they initially touch at a single point in the contact region, resulting in elastic deformation in the vicinity of this primary contact point, particularly under light loads. The elastic properties and material geometries play a critical role in determining the pressure distribution in this contact region. This detailed understanding of pressure distribution is of utmost importance, particularly in applications, such as load measurement, where optimizing measurement precision and reliability is essential [22].

Ref. [19] highlighted that fruit cells in such a contact area are compressed, while the adjacent cells are subjected to stress, shearing, or bending loads. Mechanical response may be related to the internal structure of the fruit and the solid biomaterials of tissues and cellular components. Thus, it is important to analyze these responses in fruits with different maturation stages.

In modern industrial production, empirical design solutions, traditionally based on trial and error and heavily reliant on a designer's experience, have been both time-consuming and expensive. However, the recent surge in technological advancements has shifted the industry towards computational modeling as a more efficient approach to address these challenges [23].

The origins of modeling and simulation can be traced back to the 1950s in the United States; they were initially developed for military applications. Over time, its utility expanded, serving as a robust tool for decision making by facilitating the evaluation and analysis of real systems via computational models [23].

As suggested by Refs. [24,25], models can be conceptualized as a set of equations formulated to predict a process's behavior through an approximate representation. The complexity of these models often varies based on their intended application. Emphasizing the multidisciplinary nature of computational modeling, Ref. [26] described it as a technique that offers simplified representations of the system under study, employing tools to craft microsystems. Furthermore, Ref. [27] elaborated on the application of computational techniques and mathematical models, emphasizing their role in deciphering complex phenomena and simulating problem solutions.

One of the primary advantages of simulation, when paired with modeling, is its ability to emulate real-world scenarios without incurring the high costs associated with physical experiments. This method is versatile, facilitating system improvements, concept testing before actual implementation, and the optimization of processes and resources [23,25]. As Ref. [24] underscored, a model's intrinsic value lies in its capacity to probe a system's responses under diverse conditions without any physical alterations.

The modeling process entails problem definition, solution determination, model construction, and result analysis. Computer-aided design (CAD) tools, during model creation, offer a precise and reliable means to simulate the envisaged model numerically [26,28]. CAD employs the finite element method (FEM), a numerical technique rooted in mathematical formulas. Originally introduced in the 1960s for aeronautical applications, FEM has since found widespread use across various engineering disciplines [28].

FEM, or finite element analysis (FEA), is a computational strategy that approximates problem solutions by dissecting both partial and ordinary differential equations [29]. With the evolution of computational power, FEM has become indispensable, enabling predictions of the mechanical behavior of a diverse range of materials, encompassing organic, nonmetallic, and metallic entities, like vegetables, fruits, and agricultural machinery [30]. According to Ref. [31], FEM has been instrumental in simulating the ripening process of *Coffea arabica* L. var. Colombia, providing insights into its mechanical and geometrical characteristics.

When analytical methods become overly intricate, consuming significant time and professional resources, FEM-based analysis emerges as the preferred choice [28]. FEM is considered a system discretization, which involves segmenting the problem domain into small, geometrical, and simple regions [29]. This discretization results in a mesh, characterized by nodes that interconnect basic elements, whether linear, triangular, or rectangular. These foundational elements facilitate FEM analyses, supported by commercial software like Ansys, Nastran, Procal3D, Rocky DEM, and SolidWorks, which predict system behavior [28,29].

In this context, this study aimed to analyze deformation, strain energy, and von Mises stress of coffee fruit using a computer simulation. Mature, semi-ripe, and immature maturation stages of coffee fruits are analyzed after being compressed by collapse forces. The relevance of modeling in obtaining data can help producers to reduce the compression damage caused during harvesting and storage processes of coffee fruits at different stages of maturation.

2. Materials and Methods

In SolidWorks®, geometric models of coffee fruits at the mature, semi-mature, and immature maturation stages were developed (Figure 1) for subsequent simulation in Ansys®

version 14.5. The model was based on images of *Coffea arabica* L. variety Colombia fruits, with dimensions reflecting the average provided by Ref. [32]. Coffee fruits were modeled with a circumference of approximately 0.013 m at its smallest (x) and 0.017 m at its largest (z). The peduncle was created by moving a scan of a 2D profile along a 3D sketch path.

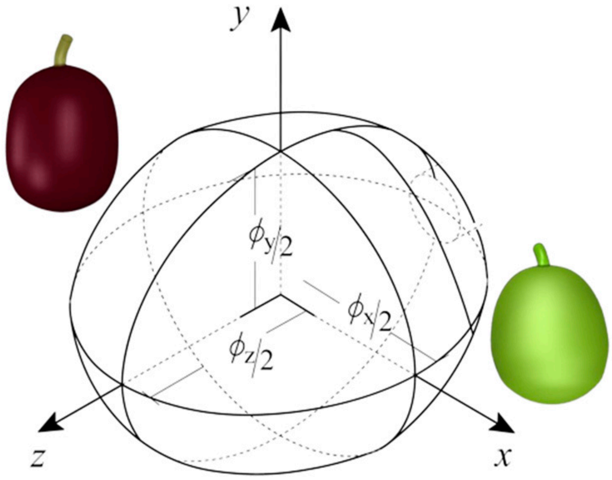

Figure 1. 3D model of coffee fruits with dimensions on axes x (φx), y (φy), and z (φz).

To check the reliability of the numerical analysis, a standard mesh convergence study was performed using the standard mode of the Ansys® software itself, with the use of meshes with different levels of refinement until the best one was found to represent the geometry of the coffee fruit with a greater number of elements and an element quality metric close to 1, a value that, according to Ref. [33], represents a perfect cube for a 3D element. For this purpose, a mesh with 3 mm elements was obtained initially (Figure 2a), and the final size was 0.7 mm (Figure 2b). The load intensity and its location (x, y, and z) were determined, in addition to the compression points, which were at the side of the model opposite to the applied forces. Thus, finite element models were generated with the tetrahedral mesh that best represented the fruit geometry, containing 6725, 13,393, and 9516 second-order elements for the mature, semi-mature, and immature maturation stages, respectively.

In the search to determine the response of the evaluated structure, numerical simulations were performed in Ansys®, by static structural analysis, compressing the fruit along three directions (x-, y-, and z-axes) to establish its deformation (ε), strain energy (μ), and equivalent von Mises stress (σ_{vonMises}), according to Equations (1)–(3), respectively. Equation (1) is as follows:

$$\{\varepsilon\} = \{\varepsilon xx\ \varepsilon yy\ \varepsilon zz\ \varepsilon xy\ \varepsilon xz\ \varepsilon yz\} \quad (1)$$

where εxx = ∂u/∂x, εyy = ∂s/∂y, εzz = ∂w/∂z, εxy = ∂u/∂y + ∂s/∂x, εxz = ∂u/∂z + ∂w/∂x, and εyz = ∂s/∂z + ∂w/∂y. Equation (2) is as follows:

$$\mu = \int_0^{\varepsilon} \sigma \cdot d\varepsilon \quad (2)$$

where $\sigma = \frac{F}{A}$ and $d\varepsilon = \frac{\partial x}{l}$. Equation (3) is as follows:

$$\sigma_{\text{vonMises}} = \sqrt{\frac{[(\sigma 1 - \sigma 2)^2 + (\sigma 2 - \sigma 3)^2 + (\sigma 1 - \sigma 3)^2]}{2}} \quad (3)$$

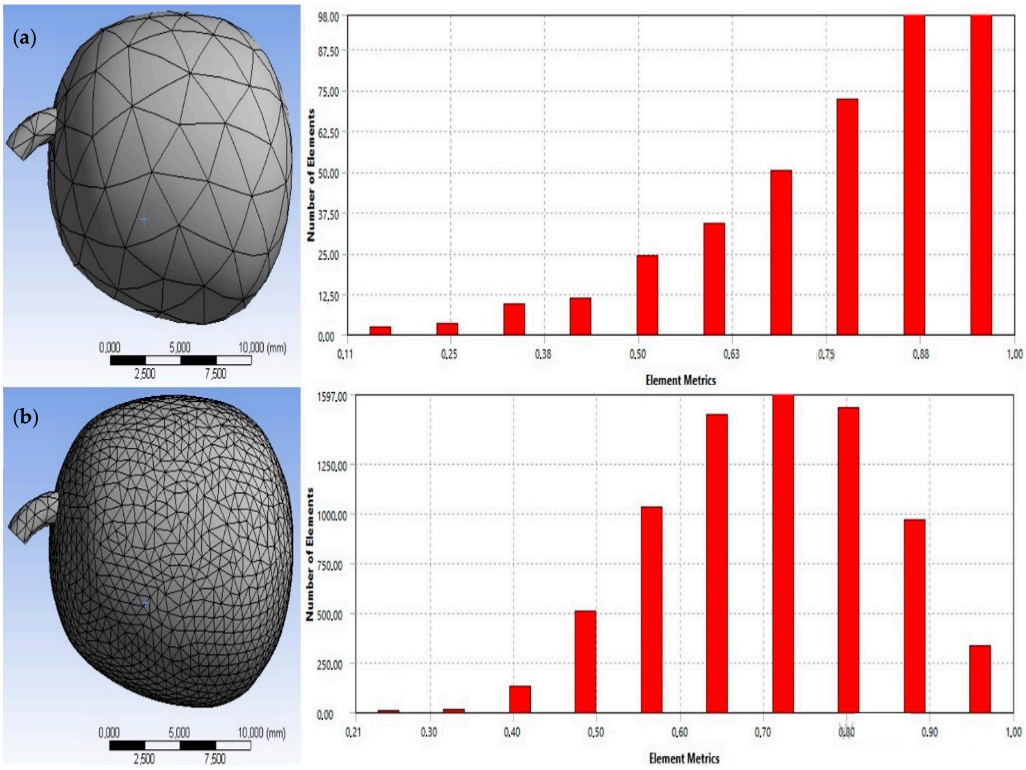

Figure 2. Second-order tetrahedral mesh refinement applied to coffee fruits with element sizes of 3 mm (**a**) and 0.7 mm (**b**).

In the proposed simulations, it was decided to position a compression support in the opposite direction to the applied force, which is distributed throughout the body, as shown in Figure 3.

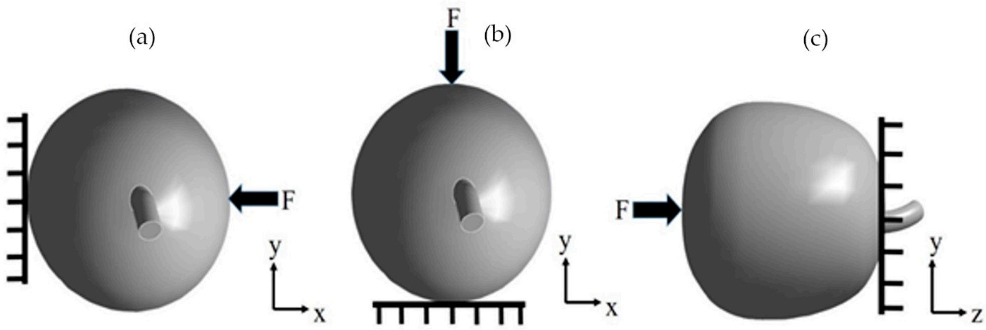

Figure 3. Loads applied to coffee fruit planes in the x-axis (**a**), y-axis (**b**), and z-axis (**c**).

To perform the simulations, known values of properties, including the collapse force (F), elastic or Young's modulus (E), Poisson coefficient (μ), and density determined in other studies (Table 1), were adopted, and the material was considered to be an elastic, homogeneous, and isotropic material for simplifications, as stated by Ref. [18].

Collapsing force represents the load acting during the compression of the material that reaches a maximum value upon reaching the greatest resistance of the fruit peel; then, its intensity is reduced upon reaching the pulp, which is milder and is reduced to a minimum after the breakage of the fruit. Young's modulus, which expresses the rigidity of the material, consists of the ratio between the applied stress and the strain felt by the material, while the Poisson coefficient measures the transverse strain related to the longitudinal direction of the force application [34,35].

Table 1. Mechanical properties of coffee fruit in the mature, semi-ripe, and immature stages of maturation.

Property	Fruit			Source
	Mature	**Semi-Mature**	**Immature**	
Collapse force (N)	50	195.00	231.80	[34]
Density (kg m^{-3})	1020	1087	1130	[18]
Young's modulus (Pa)	2,930,000	19,570,000	15,820,000	
Poisson coefficient (dimensionless)	0.27	0.25	0.24	

From the input data and the configuration of the scenarios to be studied, which related the applied compression and the maturation stages of the fruits, it was possible to perform computer simulations to determine the following parameters: total deformation, strain energy distribution, and equivalent von Mises stress. In this context, from the results of the simulations, the distributions of the fruit strain, the stress concentration points, and the strain energy involved in the process were analyzed.

3. Results and Discussion

Numerical simulations of the ripe coffee fruit, applying forces in three directions (x, y, and z) were performed. Clamping support was used in the opposite direction to the load, and deformation results were obtained (Figure 4).

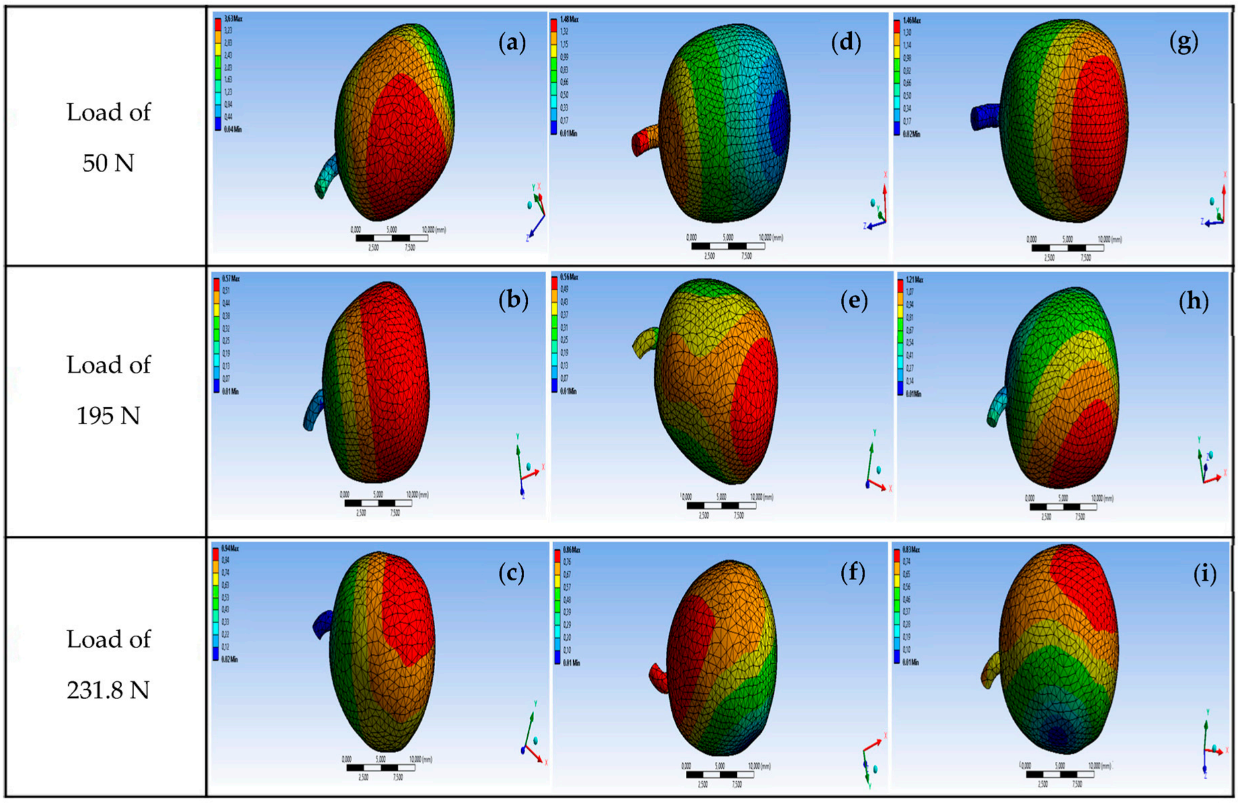

Figure 4. Total deformation (mm mm^{-1}) of ripe, semi-ripe, and immature coffee fruits when subjected to loads of 50 N, 195 N, and 231.8 N in x (**a**–**c**), y (**d**–**f**), and z (**g**–**i**), directions, respectively.

It was observed that the maximum deformation values of the ripe fruit were 3.63 mm mm^{-1}, 1.49 mm mm^{-1}, and 1.47 mm mm^{-1}, while those of the semi-ripe fruit were approximately 0.57 mm mm^{-1}, 0.55 mm mm^{-1}, and 1.21 mm mm^{-1}, and those of the immature fruit were 0.94 mm mm^{-1}, 0.86 mm mm^{-1}, and 0.84 mm mm^{-1}, corresponding to the application of loading in the x, y and z directions, respectively.

These values were applied opposite to the direction of the applied loading, to simulate crushing of the fruit, which can generate perceptible deformation in the sides of the fruit, corroborating the study by Ref. [36], who affirm the occurrence of transverse expansion in elastic material after compression, coinciding with Hertz theory, which states that deformation remains in the vicinity of the body after compression.

The results obtained suggest that, except for the semi-ripe fruit, the smallest deformations were obtained by compressing the fruit in the direction of the z-axis, corroborating the study by Ref. [37], who found lower firmness in the fruit peel when compressed in the direction of this same axis. Thus, there is a need to seek mechanisms that allow the storage of fruits with compression occurring in the direction of the z-axis, as this will be the best way to avoid deformation damage.

Notably, the largest deformation was found in the ripe fruit, with a tendency for less mature fruit to present smaller deformations (64% and 59%, respectively) more than in semi-ripe and immature fruit. This behavior was predictable because, according to Ref. [32], the more mature the outer layer of the fruit, the less the resistance; according to Ref. [38], during maturation, the cells grow and the cell wall thickness decreases, reducing this mechanical property; according to [39], a higher water content is present in ripe fruit, compared to the semi-ripe and immature maturation stages, making the fruit more flexible and resulting in a lower force required for collapse. Thus, the deformation of more mature fruit will be greater. This lower collapse force and greater deformation in wetter fruit is similar to the findings of Ref. [40].

When analyzing the strain energy distribution, it was observed that in the ripe fruit, the maximum values were 0.06 mJ, 0.05 mJ, and 0.11 mJ, corresponding to the application of force in the x, y, and z directions, respectively, while in the semi-ripe fruit, they were 0.31 mJ, 0.20 mJ, and 0.12 mJ, corresponding to the application of force in the x, y, and z directions, respectively; in the immature fruit, the maximum results were 0.47 mJ, 0.25 mJ, and 0.31 mJ, corresponding to the application of force in the x, y, and z directions (Figure 5), where the compression support was fixed.

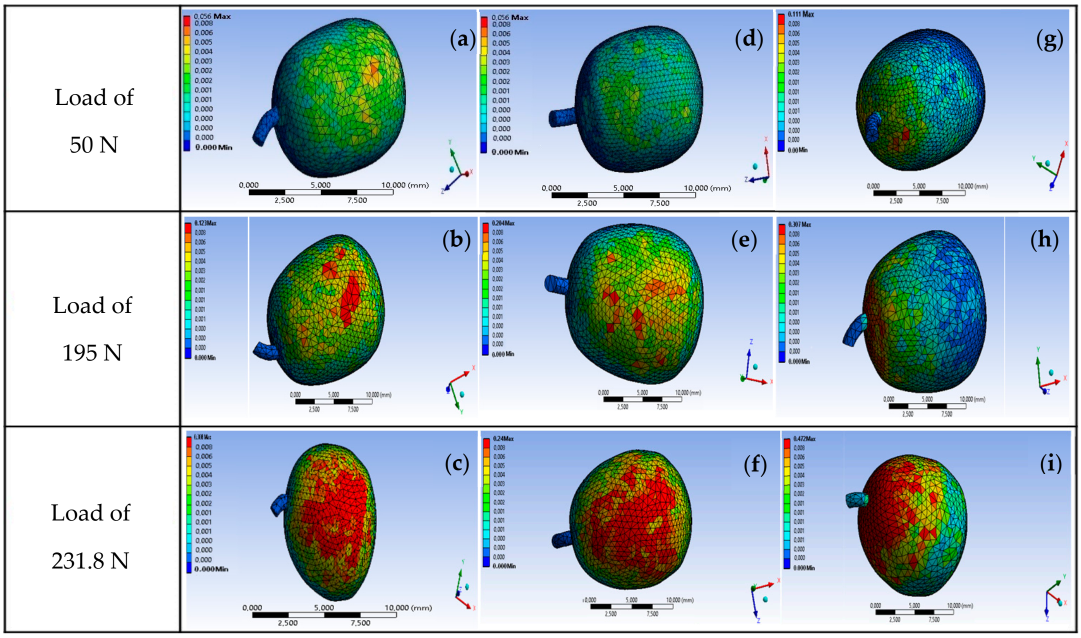

Figure 5. Strain energy distribution (mJ) in the ripe coffee fruit when subjected to loads of 50 N, 195 N, and 231.80 N in x (**a**–**c**), y (**d**–**f**). and z (**g**–**i**), directions, respectively, and compressed in the opposite load direction.

For the immature fruit, the values of the strain energy distribution exceeded those found in the ripe and semi-ripe fruit, being around 78.6% and 38.8% higher, respectively, which occurred due to the greater resistance to deformation found in this stage of maturation.

These conditions highlight the need for caution during the unloading process of the fruits from harvesters to the trucks transporting the coffee fruits, especially when their maturation stage is more advanced and their mechanical resistance is lower. This care is essential because unloading at a higher acceleration could result in greater damage to the coffee, as there will be more force applied to the fruits, given that force is the product of mass and acceleration.

It was also possible to observe that for the mature stage, when compressing the coffee fruit in the direction of the peduncle (z-axis), the higher the strain energy applied, the greater the distance was between the points of force application and the compression support in this direction of application.

This result corroborates with the study performed by Ref. [41] which used strawberries, in which the longitudinal compression of the fruit required a greater force and consequently higher strain energy, compared to the transverse compression.

Regarding the von Mises stress results, the maximum values in the ripe fruit for the application of force in the x, y, and z directions were 0.18 MPa, 0.18 MPa. and 0.39 MPa, respectively (Figure 6). These results also show that the highest von Mises stress value was located at the end of the fruit (close to the peduncle), representing a value more than 116% greater than the deformation on the x- and y-axes. This means that there was a greater concentration of stresses in this area and, consequently, a greater likelihood of collapse. Therefore, direct contact of the fruit detachment mechanism with this area during harvesting should be avoided.

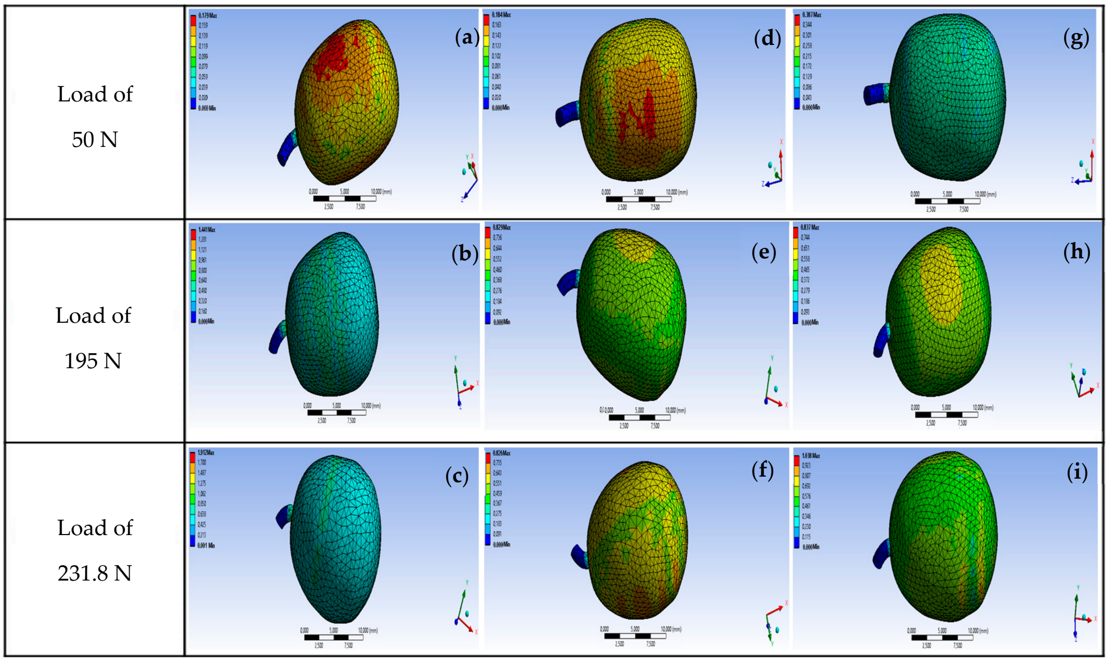

Figure 6. Von Mises equivalent stress distribution (MPa) in the ripe coffee fruit when subjected to loads of 50 N, 195 N, and 231.80 N in x (**a**–**c**), y (**d**–**f**), and z (**g**–**i**) directions, respectively, and compressed in the opposite load direction.

When analyzing the von Mises stress for the semi-ripe fruit, it was observed that the maximum values obtained when applying force along the x-, y-, and z-axes were approximately 1.44 MPa, 0.83 MPa, and 0.83 MPa, respectively. These values were 75.7% higher than those of ripe fruits due to the greater internal resistance to the application of external force (compression) inherent to this maturation stage; it can be inferred that during harvest by harvester stems, these find less resistance in mature fruits, making such fruits more susceptible to damage.

By analyzing von Mises stress for the immature fruit, it was observed that, concomitant with the ripe and semi-ripe fruit, the maximum values for the application of force in the x, y, and z directions were 1.91 MPa, 0.83 MPa, and 1.04 MPa, respectively. These values were higher where the compression support was fixed, indicating a higher concentration of this property in these locations. This makes them points with a higher probability of collapse. It was also evident that the highest stresses occurred at this stage of maturation. On average, these stresses were 80.1% and 18.2% higher than in ripe and semi-ripe fruit, respectively. These findings corroborate the results of Ref. [42], who also found maximum values for immature fruit.

Based on the two studies, it is possible to observe that compressive stress was higher in the green maturation condition compared to the mature maturation condition. These results are in line with the literature and support the conclusion of Ref. [42], which suggests that selective harvesting using mechanical vibrations and the brake force on the vibration rollers is feasible, as long as an appropriate excitation frequency is chosen, related to the modal parameters of the system to prevent damage to coffee fruits due to compression.

4. Conclusions

The numerical simulation of the coffee fruit compression process made it possible to verify that the more mature the fruit is, the greater the mean deformation (2.20 mm mm^{-1}, 0.78 mm mm^{-1}, and 0.88 mm mm^{-1}, corresponding to ripe, semi-ripe, and immature fruit, respectively), the lower the mean strain energy (0.07 mJ, 0.21, mJ and 0.34 mJ, corresponding to mature, semi-ripe, and immature fruit, respectively) and the lower the mean equivalent von Mises stress (0.25 MPa, 1.03 MPa, and 1.25 MPa, corresponding to ripe, semi-ripe, and immature fruit, respectively). These properties can guide adjustments in the harvest and storage systems to minimize losses due to mechanical damage by compression.

The computer simulation model proposed for the coffee fruit compression process proved to be efficient in predicting deformation, von Mises equivalent stress, and deformation energy, obtaining results that corroborate previous studies.

The performance of this type of analysis, besides reducing the time and professional resources used to solve problems, shows itself as an alternative to help improve the mechanized harvesting techniques, by indicating how the strain energy and the von Mises stress impact the fruit in the various stages of maturity. These data can provide more adequate indicators for machine regulation, which would minimize the injuries caused during harvesting.

For future works, it is proposed to analyze damages during the processing of the fruit in the drying and roasting stages, etc. and how it can be related with other variables, such as moisture, the temperature to which it is subjected during toasting. This can help to improve the technological processes and the quality control of the fruit that is processed in each of the stages of maturation.

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