The influence of papaya shape on its mass model and mechanical properties

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Title: **The Influence of Papaya Shape on its Mass Model and Mechanical Properties**

Running title: **Papaya's Mass Model and Mechanical Properties**

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Abstract:

Post-harvest handling tasks include fruit grading and minimizing loss. Fruits are often packaged into grades based on size and mass for uniformity and proper handling. Losses caused by mechanical damage can be reduced by understanding the fruit's response to loads. Papaya's (cv. Exotica) irregular shape and short shelf-life are important factors for proper handling. This study aimed to develop a model for papaya mass based on geometric properties and to characterize its mechanical behavior when compressed along its major axis.

For mass prediction, single- and multiple-variable regression models using papaya's geometrical variables were developed. Despite its irregular shape, similar performance was observed in the best single- and multiple-variable mass models ($R^2 \approx 0.95$, RMSE ≈ 82 g). However, the single-variable model is likely more practical because only two axial lengths are needed and can be extracted from 2D images. For papaya's mechanical behavior, the results for elastic properties indicate some variations ($p>0.05$) in elastic modulus, and failure stress and strain along the major axis, while results for viscoelastic properties indicate significant variation ($p<0.05$) in the relaxation moduli. Overall, the bottom section is less resistant to deformation compared to the top. Therefore, reducing compression in the section could potentially reduce damage. Using the mechanical properties described here in computer simulation studies may provide more detailed load distribution. Mass modeling can aid the automation of papaya grading,

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while mechanical response characterization provides valuable information for designing post-harvest handling systems**.**

Keywords: Post-harvest loss; Mechanical injury; Mechanical behavior; Mass model; Irregular shape; Fruit grading

1. Introduction

Papaya (Carica papaya) is a tropical fruit that is widely cultivated and consumed worldwide. It is known for its sweet taste and numerous health benefits, including high levels of vitamin C, vitamin A, digestive properties, and anti-inflammatory properties (Koul et al., 2022). Proper post-harvest handling is crucial for maintaining fresh fruits' freshness, nutritional value, and sensory characteristics, while reducing the risk of spoilage and foodborne illnesses. Local environmental parameters such as temperature and humidity, as well as the fruits' material behavior such as their mechanical properties must be carefully considered during handling processes in the fruit supply chain to prevent post-harvest losses (Li & Thomas, 2014). The physical attributes and mechanical properties of fruits play a vital role in designing handling equipment, such as sorting and grading operations, and assessing fruit quality. The supply chain operations of fresh fruits, from harvest to table, involve a series of interconnected operations to ensure the fruit reaches consumers in a fresh and safe condition (Hussein et al., 2020).

1.1 Mass modeling of papaya for fruit grading

Fruit grading systems play a pivotal role in ensuring the quality, consistency, and efficiency of fruit production and distribution. The grading process involves the assessment of various attributes of fruits, including mass, size, color, texture, shape, and the presence of defects or diseases. Geometric properties like length, width, thickness, volume, projected area, and mass, are widely adopted parameters for fruit grading (Moustafa, 1971).

Grading facilitates the acquisition of uniformly characterized fruits, contributing to optimal packaging configuration, material selection, and transportation optimization.

For Carica papaya (cv. Exotica), fruits falling within a weight range of 250 - 850 g and having a color index of 2 are selected for export, fruits with color indices between 3 and 5 are typically sold in local markets, while those with a color index of 6 are considered overripe and rejected (*Tropical Fruit - Global Information System*, n.d.). The fruits can also be graded into large (601-800 g), medium (351-600 g), or small (250-350 g) (Riyadi et al., 2007). Traditionally, fruits are graded through manual inspection by human operators. However, these processing systems have evolved to incorporate computer vision and automation to achieve accurate grading and sorting (Desai et al., 2023; Seema et al., 2015). Therefore, a sizing mechanism must not be neglected in automating the grading and sorting process of papaya.

Conventionally, fruit sizes are often measured using a basic scale based on their mass. However, considering the fast pace of modern post-harvest processes, machine vision may provide more efficient options for grading fruit sizes based on their geometric properties. Alternative size classes could be established that likely align with consumer choices and the demand for consistently shaped fruits to fulfill packaging criteria (Schulze et al., 2015). The relationships between geometric properties and mass have been used by different researchers to develop models for predicting fruits' mass, ranging from single variable linear and non-linear regressions to more complex multi-variable machine learning models. For regular or uniform-shaped fruits such as pomegranate, mandarin, apples, and limes, single variable models are often optimal for modeling mass (Khoshnam et al., 2007; Mahawar et al., 2019; Mansuri et al., 2022). However, for non-uniform shaped fruits, the mass may be better predicted with multiple variables (Schulze et al., 2015; Spreer & Müller, 2011; Utai et al., 2019). Papaya's shape is not truly uniform; hence its mass may be optimally predicted either by a single or multiple geometrical variables.

Linear and non-linear regression models that have been used for mass prediction of fruits include linear, quadratic, curve, and power models, previously applied to fruits such as kiwi and citrus (Lorestani & Tabatabaeefar, 2006; Mahawar et al., 2019). More complex models such as advanced statistical models and machine learning models are also increasingly reported. For example, support vector machine and artificial neural network have been used to predict the mass of apples and cherry tomatoes (Mansuri et al., 2022; Nyalala et al., 2019). For mass prediction, one of the differences between the traditional and advanced models is in the number of variables used for prediction. Recent studies demonstrated that complex models outperformed traditional models when predicting fruits' mass using multiple geometric properties (Abdel-Sattar et al., 2021; Mansuri et al., 2022).

For this study, support vector regression (SVR), ordinary least squares (OLS), and linear least absolute shrinkage and selection operator (LASSO) regression are used for predicting or classifying fruit properties as each offers unique advantages and is designed to address specific challenges in fruit mass prediction. For instance, SVR leverages the concept of finding the optimal hyperplane to minimize error, making it particularly suitable for datasets with complex relationships. While OLS uses a straightforward approach of minimizing the sum of squared differences between observed and predicted values, offering intuitive interpretations and LASSO regression enhances model robustness by incorporating regularization to prevent overfitting through the penalization of large coefficients.

Therefore, this study aimed to determine the geometric variable(s) that will best predict the mass of papaya and compare the performance of traditional and complex regression models in predicting the mass of papaya.

1.2 The mechanical material behavior of papaya and damage minimization

During handling and transportation fruits are packed or arranged such that damage is minimized. Fruits' susceptibility to mechanical damage is dependent on its mechanical properties (Hussein et al., 2020). Fruits are complex biological systems, composed of various tissues, each with distinct mechanical properties. The composition, structure, water content, and distribution of pectin, cellulose, and hemicellulose at the cellular scale, as well as shape, size, and density at the macroscale, are all factors that influence the mechanical properties of fruits (Li et al., 2013). The mechanical properties of fruits are also influenced by factors such as cultivar, maturity stage, and environmental conditions (Arendse et al., 2014). For example, firmness, cohesiveness, springiness, gumminess, and chewiness have been reported to decrease as papaya fruit ripens (Sanchez et al., 2020). Fruits are perishable and many are highly sensitive to environmental conditions. Understanding their mechanical properties can provide valuable information on the structural and compositional changes that occur during growth, development, and ripening (J. Wang, 2004). As papaya's shape is oval-like, the mechanical properties may vary in the different areas of the fruit, particularly along the longest axis. Detailed information in this variation will assist proper storage arrangements, for example.

The rheological characterization of biological materials involves three key parameters: force, deformation, and time. Collectively, they determine the mechanical properties of biological materials (Mohsenin, 1970a). Common mechanical tests to determine the mechanical properties of fruits is recently reviewed (Li, Miao, et al., 2017). Important parameters such as failure stress, failure strain, failure energy, and Young's modulus are determined through a simple compression test which generates a force-deformation curve (Hussein et al., 2020; Jin et al., 2021; Liu et al., 2023), while characteristics such as the relaxation modulus, relaxation time, creep compliance and other viscoelastic properties are determined through stress relaxation or creep test (Kim et al., 2008; Mahiuddin et al., 2020; Sanchez et al., 2020). The determination of the mechanical characteristics of fruits enables the quantification of the loads that can lead to micro and macro mechanical damage to fruits. Mathematical models used to predict the mechanical response of fruit material generally include elastic, viscoelastic and elastic-plastic models. The elastic model obeys the Hooke's law, the plastic model describes permanent deformations, while the viscoelastic model describes the material behavior of fruit exhibiting viscous and elastic characteristics under deformation. The fluid and solid parts of a fruit are considered viscous and elastic, respectively.

For papaya, its puncture response has been described using the elastic-plastic material model for its skin-flesh tissues (Zulkifli et al., 2020, 2021). Additionally, the correlations between papaya's textural-mechanical attributes and physiochemical properties throughout its ripening stages were investigated and results indicated that the Maxwell model is appropriate to describe the mechanical changes throughout ripening (Sanchez et al., 2020). However, given the oval-like shape of papaya, the variation in its mechanical properties along its major axis should be investigated for a more accurate characterization of its mechanical properties.

Hence, this study aims to develop a mass model for papaya based on its geometrical properties and characterize its mechanical behavior by describing the elastic and viscoelastic material properties along its major axis. These properties include failure stress, failure strain, Young's Modulus, and viscoelastic parameters.

2. Materials and Methods

2.1 Materials

The fruits used in this study, *Carica papaya* (cv. Exotica) were purchased from the local market in Seri Kembangan, Selangor, Malaysia. In this study, we utilized fruits that were classified as having a ripeness index of 2. These fruits exhibited a predominantly green color, with trace of yellow, following the standard color chart (Kwok & Liang, 2019). The ripeness index 2 was used because papaya harvested at this stage are optimum for export and long-distance transportation (Barragán-Iglesias et al., 2018; Sekeli et al., 2018).

2.2 Mass Modeling

2.2.1 Determination of Geometric Properties

The mass and three axial lengths of whole papaya fruits (n=63) were measured. The orientation of the three axial lengths is shown in Figure 1(A). The fruit length *a* was measured along the major or *Y* axis, the largest diameter along the *X* axis was measured and recorded as *b*, and the largest diameter along the *Z* axis was measured and recorded as *c*. All measurements were taken at an accuracy of ±0.05 mm using a digital caliper.

Figure 1: (A) An illustration of the three axial lengths measured in each fruit. The fruit length, *a* was measured along the Y axis, and two largest diameters, *b* and *c* were measured along the X and Z axes. (B) The papaya was cut into three sections, top, middle and bottom (indicated by the dashed lines). Then each section was further sliced into 30 mm slices for the compression tests.

Next, the mean diameter, sphericity, and projected area were calculated based on the axial lengths. The geometric mean dimension, D_0, of the fruit was computed using equation (1) (Mohsenin, 1970b; Sahu, 2018), and its sphericity was computed using equation (2).

$$D_0 = \sqrt[3]{a * b * c} \qquad (1)$$

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$$Sphericity = \frac{\sqrt[3]{a*b*c}}{a} \quad (2)$$

The surface area *(S)* was calculated using equation (3) based on the geometric mean diameter, D_0 (Meisami-asl et al., 2009; Mirzabe et al., 2013).

$$S = \pi * D_0^2 \quad (3)$$

The projected area is an important parameter in modeling the mass of fruits (Mahawar et al., 2019; Mansuri et al., 2022). This parameter was computed using equation (4) (Mirzabe et al., 2013).

$$P_a = \left(\frac{\pi ab}{4}\right) \quad (4)$$

2.2.2 Model calibration and validation

Mass modeling was performed in Jupyter Notebook (Anaconda 4.10.1; Python version: 3.8.8) with NumPy, Pandas and Scikit-learn Python libraries. First, a descriptive statistical analysis was conducted on the geometric properties: mass, axial lengths *a, b,* and *c*, mean diameter, sphericity, surface area, and projected area. Then, the mass prediction models were developed based on the geometric variables. For this purpose, four single-variable regression models, namely linear, quadratic, S-curve, and power, and three multiple-variable regression models, namely ordinary least squares (OLS), linear least absolute shrinkage and selection operator (LASSO) and support vector regression (SVR) were used. The data was split into 70% and 30% for model calibration and validation, respectively.

Each single-variable model has between one to three coefficients requiring calibration (Table 1). The linear regression curve fitting method was used for the linear equation, and the non-linear regression curve fitting method was used for the three non-linear equations to determine the models' coefficients (Mahawar et al., 2019a; Mansuri et al., 2022a). The calibration of the multiple-variable models was performed using NumPy, Pandas and Scikit-learn libraries on Python platform.

Table 1: Single-variable regression equations for mass modeling.

Next, the predicted mass for each fruit in the validation dataset was determined for all models and compared to the measured mass. The coefficient of determination (R^2) and root mean square error (RMSE) were calculated for model validation. The model with the highest R^2 and lowest RMSE is likely the optimal mass model for the studied papaya species.

2.3 Mechanical Properties Characterization

2.3.1 Sample preparation

For mechanical properties characterization, 40 whole papayas were sectioned into three approximately equal sections along the major axis, namely the top (stem end), middle, and bottom (blossom end) (Figure 1(B)). Each section was further sliced into 30 mm thickness cylindrical samples. Then, 30 samples were randomly chosen from each section. Two sets of samples were prepared for the compression and compression-holding tests to determine the modulus of elasticity, failure stress, failure strain, and viscoelastic properties of papaya.

2.3.2 Determination of Elastic Properties

In the compression test, each cylindrical sample was laid horizontally and compressed with a 150 mm diameter compression plate until failure. The tests were performed using a Universal Testing Machine (10 kN INSTRON 5566, UK). The ASAE S368.4 DEC2000 standard (ASAE, 2008) was used as a guide for the compression speed, which was 10 mm/min. The yield stress and strain for all samples from the same section were averaged to obtain the stress and strain for each section. They are referred to herein as the failure stress and failure strain, respectively.

2.3.3 Determination of Viscoelastic Properties

In the compression-holding test, each cylindrical sample was also laid horizontally. The compression test speed was also 10 mm/min with a holding time of 300s. A hold time of 300s was chosen to allow the stress curve to reach equilibrium without a total rupture of the sample. The compression load, deformation, stress, and strain were recorded. The relaxation parameters: relaxation moduli *(E_0, E_1, E_2, E_3),* and relaxation time *(T_1, T_2, T_3)* were determined by fitting the stress relaxation data to the three element Maxwell model using non-linear regression (Sanchez et al., 2020).

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Figure 2: Three-element Maxwell model combination. E_1, E_2 and E_3 are the elastic moduli, η_1, η_2, and η_3 are the viscous coefficients, and E_e is the equilibrium modulus.

The stress relaxation curve resulting from the compression-holding test is typically modelled with a generalized Maxwell model comprising a spring and two parallel Maxwell units. Similarly, the creep curve resulting from the same test can be represented by a generalized Kelvin model featuring a spring, a dashpot, and a Kelvin unit that is connected in series. Figure 2 illustrates a three-element Maxwell model's springs and dashpot combination described by Equation (5):

$$E(t) = E_e + E_1 e^{-t/T_1} + E_2 e^{-t/T_2} + E_3 e^{-t/T_3} \; E_i = \frac{\eta_i}{T_i} \qquad (5)$$

where, relaxation function $E(t)$ is the stress history per unit strain imposed, E_1, E_2 and E_3 are the stiffness of the material, T_1, T_2 and T_3 are the relaxation time, η_i is the viscous coefficient of the i-th number of dashpots, t is the total time and E_e is the equilibrium stiffness (Flügge, 1975).

While the nominal stress ($\sigma(t)$) and strain ($E(t)$) can be expressed by equation (6):

$$\sigma(t) = \varepsilon_o E(t) \qquad (6)$$

2.3.4 Determination of the Variation in Mechanical Properties

ANOVA was used to determine the mean difference in the mechanical properties (elastic modulus, failure stress, failure strain, relaxation moduli, relaxation time) between the top, middle and bottom sections of the fruit,

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and the Tukey HSD post-hoc test was performed when appropriate. A significance level of $p < 0.05$ was used in all analyses.

3. Results and Discussion

3.1 Descriptive Analysis on the Geometrical Properties of Papaya

The geometrical parameters aid the design and development of post-harvest handling machines (Mahawar et al., 2019). The descriptive statistical analysis results for the physical and geometrical properties of the samples are shown in Table 2. The mass varied between 655.13 g and 2089.49 g with an average value of 1298.68 ± 319.46 g. The average papaya's axial lengths *a*, *b*, and *c* were 22.37 ± 1.97 cm, 10.50 ± 1.03 cm, and 8.93 ± 1.26 cm, respectively. The length of papaya, *a* was at least twice the diameters, *b* and *c*. In comparison to other variants, Exotica papaya variety has a larger major dimension (22.37 ± 1.97 cm) in comparison to golden papaya (13.83 ± 0.93 cm) (Santos Pereira et al., 2018). Other geometrical properties of papaya cv. Exotica are listed in Table 2.

Table 2: Physical and Geometrical Properties Parameters of Whole Papaya (n = 63)

Figure 3 presents the correlation coefficients between the geometrical variables. In terms of correlation with mass, sphericity exhibited the weakest correlation with mass (R = 0.39), while the surface area showed the strongest correlation with mass (R = 0.97). The mean diameter, projected area, and surface area generally showed strong correlations with mass (R > 0.9), while

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the individual axial length showed moderate correlation with mass. The strong correlations suggest that variations in mean diameter, surface area or projected area likely correspond to changes in papaya mass.

Figure 3: Correlation coefficient, R, matrix indicating the correlations between the geometrical properties and mass. The coefficients ranged between 0 (weakest correlation) to 1 (strongest correlation).

3.2 Mass Modeling

The model coefficients and performance of the single-variable mass models based on geometrical variables are listed in Table 3, while the performance of the multiple-variable mass models is listed in Table 4. The accuracy of the models was determined by comparing the predicted mass to the measured mass in the validation dataset and quantified using the R^2 and root mean squared error (RMSE).

For single-variable mass models, the results indicate that the projected area is the best mass predictor as it consistently produced the highest R^2 and the lowest RMSE for all four single-variable models (Table 3). When comparing across all four models, the power (R^2 = 0.947, RMSE = 82.284 g) and quadratic (R^2 = 0.947, RMSE = 82.793 g) models had comparable performance. Moreover, they outperformed the linear and S-curve models when using the mean diameter, surface area or projected area as mass predictor. The single-variable mass model results confirmed the correlation analysis, indicating that mean diameter, surface area and projected area correlate strongly with mass (Figure 3). This finding is similar with the mass model for mango, whereby the power model resulted in the best mass prediction using three axial lengths (Spreer & Müller, 2011).

Table 3: Model coefficients (α, β, and γ) and the performance measures (R^2 and RMSE) for the single-variable mass models for papaya fruits

For multiple-variable mass models, the OLS outperformed other models in predicting papaya's mass with R^2 and RMSE of 0.9479 and 81.723 g, respectively (Table 4). When considering multiple variables, (Mansuri et al., 2022a) reported that SVR had the best accuracy in predicting the mass of Berr apple using projected area ($R^2 = 0.968$). However, Berr apple can be considered as a uniform or regular-shaped fruit. For this study, the optimal single-variable and multiple-variable mass models resulted in comparable performance, namely R^2 ~0.95 and RMSE of ~82 g. This comparison indicates that less complex models can be used to predict papaya mass, as similarly reported for mango (Utai et al., 2019). For implementation purposes, the single-variable model would be more practical as only two axial dimensions have to be measured for determining the predictor variable, which is the projected area, which could be easily obtained from a 2D image.

Table 4: The performance of multiple-variable mass models for papaya fruits

3.3 Mechanical Behavior of Papaya

3.3.1 Elastic properties

In general, although variations were observed in the elastic modulus, failure load, failure stress and failure strain along papaya's major axis, the differences were not significant (p>0.05). Two trends could be seen among the four properties. First, the elastic modulus and failure stress showed the same trend, which reduced from top to bottom sections (Figures 4(A) and 4(D)). Second, the failure load and strain showed the same trend, whereby the mean was highest in the middle section, followed by the top and the bottom sections (Figures 4(B) and 4(C)).

The elastic moduli were 0.5063 ± 0.19 MPa (top), 0.4242 ± 0.20 MPa (middle) and 0.3916 ± 0.19 MPa (bottom). This change in elastic modulus indicate that the bottom end is likely more delicate and susceptible to mechanical damage compared to the top region (W. Wang et al., 2019, 2020; Zhang et al., 2021). The failure stress for the top, middle, and bottom regions was 0.0679 ± 0.02 MPa, 0.0619 ± 0.02 MPa, and 0.0454 ± 0.01 MPa respectively (Figure 4(D)). (Zulkifli et al., 2021) reported a yield stress limit of 0.05 MPa for the Exotica variety of papaya flesh tissue from unspecified section along the major axis, while (Arrázola et al., 2021) reported 0.0731 ± 0.0021 MPa and 0.0506 ± 0.0021 MPa for the stress yield limit of the *Tainung F1* papaya at ripeness levels 1 and 2 respectively.

The failure load for the top, middle, and bottom sections was 459.96 ± 146.39 N, 522.09 ± 160.43 N, and 352.85 ± 149.36 N, respectively. A possible explanation for the relatively higher failure load and strain for the middle section is due to its distance from both ends where load was applied. Furthermore, the diameter in the section is typically more uniform and larger compared to the other two sections. Therefore, the load may have dissipated along the axis, and the uniform and larger diameter may allow higher load and strain to be sustained.

Figure 4: The average and standard deviation for (A) elastic modulus, (B) failure load, (C) failure strain and (D) failure stress along papaya fruit's major axis. All observed variations between the three fruit sections were statistically insignificant (p>0.05).

3.3.2 Viscoelastic properties

Fruit structure is a multiscale continuity structure (Cáez-Ramirez et al., 2015; Ghysels et al., 2010; Ho et al., 2009). In the case of papaya tissue, its mechanical behavior can be described using Maxwell elements (Sanchez et al., 2020). The ANOVA test results indicate that the position along the major axis significantly (p<0.05) influenced the majority of the relaxation moduli ($Ee, E_1, E_2,$ *and* E_3) and one relaxation time (T_3) component (Table 5).

The instantaneous modulus (E_0) reduced along the major axis, with 0.1078 ± 0.023 MPa, 0.1019 ± 0.003 MPa, and 0.1010 ± 0.002 MPa in the top, bottom, and middle sections, respectively. The first spring (E_1) and dashpot (T_1) elements decreased along the major axis, which could represent the deformation of the primary cell wall and the middle lamella (Karaman et al., 2016; Sanchez et al., 2020). The components E_2, T_2, E_3, and T_3 which reduced along the major axis have been postulated to be related to structural features (Yildiz et al., 2013). From these results, it can be deduced that the cell walls in the top section is more resistant to deformation than the bottom since a lower elastic modulus indicates that lower stress is required to deform a material. The relaxation time (T_1) is the time during which the force applied to the viscoelastic material dissipates to approximately 36.8% of the initial value (Mohsenin, 1970a; Yildiz et al., 2013). In this study, the value of T_1 reduced along the major axis.

(Chen, 1994) described the components of the Maxwell model in relation to fruit tissue based on their time constants. T_1 represents the short time in which intercellular gases can only sustain load, T_2 represents the medium time for which the intercellular liquid flows, while T_3 represents the cells as a whole and has a very long relaxation time constant because fluids inside them move in and out slowly. Consequently, when the fruit is subjected to a constant load, the stress on each component of the tissue changes over time. Overall, the result of the viscoelastic parameters suggests that, under compression, the tissues located at the bottom section of papaya behaves differently from those at the top and middle sections due to differences in the cell structure compositions.

4. Conclusions

This study proposed a mass prediction model for papaya and described its mechanical behavior under compression that could be useful for post-harvest handlings. The correlations between the geometric properties of papaya were examined, and models were developed for mass prediction. Interestingly, the R^2 and RMSE values were comparable for both traditional and advanced regression models, indicating that simple models may perform as accurate as complex models. The power model has the highest R^2 (0.947) and lowest RMSE (87.72 g) among the single-variable regression models for mass prediction using projected area as a predictor, while the OLS model has the highest R^2 (0.947) and lowest RMSE (81.72 g) among the multiple-variable models.

Uniaxial compression and compression-holding tests were used to describe the elastic and viscoelastic properties of papaya along its major axis. While the variations were statistically insignificant, the highest elastic modulus and failure stress in the top section indicate that papaya fruit is more resistant to deformation at the top section (Figure 4). On the other hand, significant variations in some of the viscoelastic parameters indicate that papaya's cellular composition differs along its major axis. As results indicate that the bottom section is less resistant to deformation, reducing compression in this section is recommended to minimize mechanical damage.

There are two main limitations in this study, therefore the results should be interpreted within these limitations. First, the fruits were of a single ripeness level. While the mass models and mechanical behavior may not be applicable for other ripeness levels, the ripeness level selected for this study is reflective of the typical ripeness during harvesting and transport. Secondly, only static compression test was applied in this study, which is mainly encountered during storage in minimal movement environments. For papaya stored during transport, dynamic load should be considered, particularly for improperly packed fruits.

The findings of this study highlight the influence of papaya shape on its mass prediction and mechanical behavior. The mechanical behavior of the papaya could be made more comprehensive by investigating the relationship between geometrical variables and the mechanical properties. A comprehensive understanding of the variation in the mechanical behavior of papaya with its shape will enable more accurate computer simulation models for investigating papaya's response to other types of loading, as well as for designing technologies for sorting, storing, and transporting intact fruit while minimizing mechanical damage.

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Figures

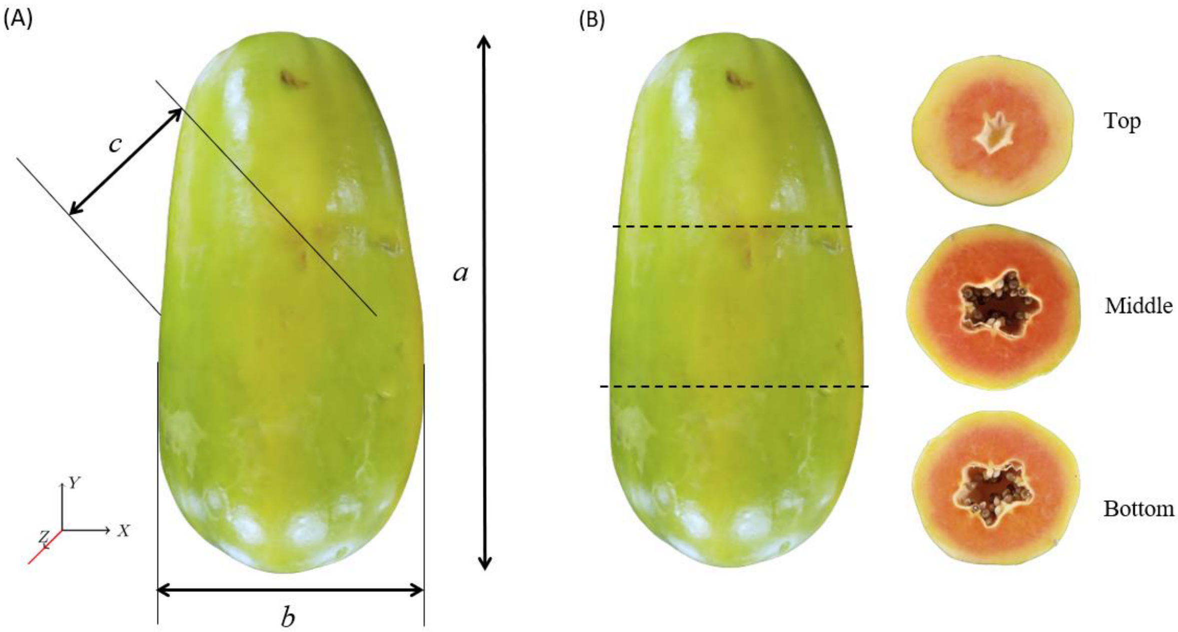

Figure 1: (A) An illustration of the three axial lengths measured in each fruit. The fruit length, *a* was measured along the Y axis, and two largest diameters, *b* and *c* were measured along the X and Z axes. (B) The papaya was cut into three sections, top, middle and bottom (indicated by the dashed lines). Then each section was further sliced into 30 mm slices for the compression tests.

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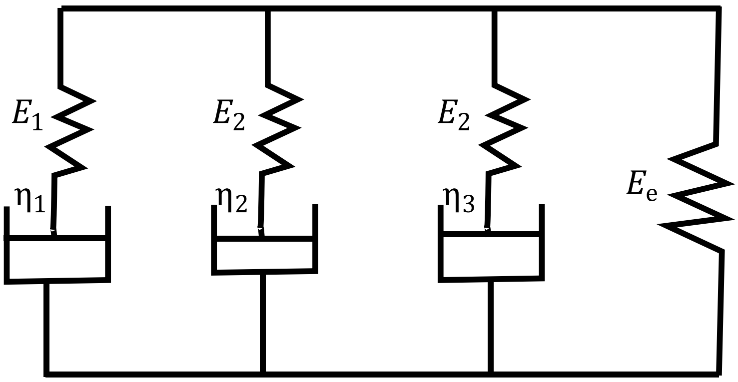

Figure 2: Three-element Maxwell model combination. E_1, E_2 and E_3 are the elastic moduli, η_1, η_2, and η_3 are the viscous coefficients, and E_e is the equilibrium modulus.

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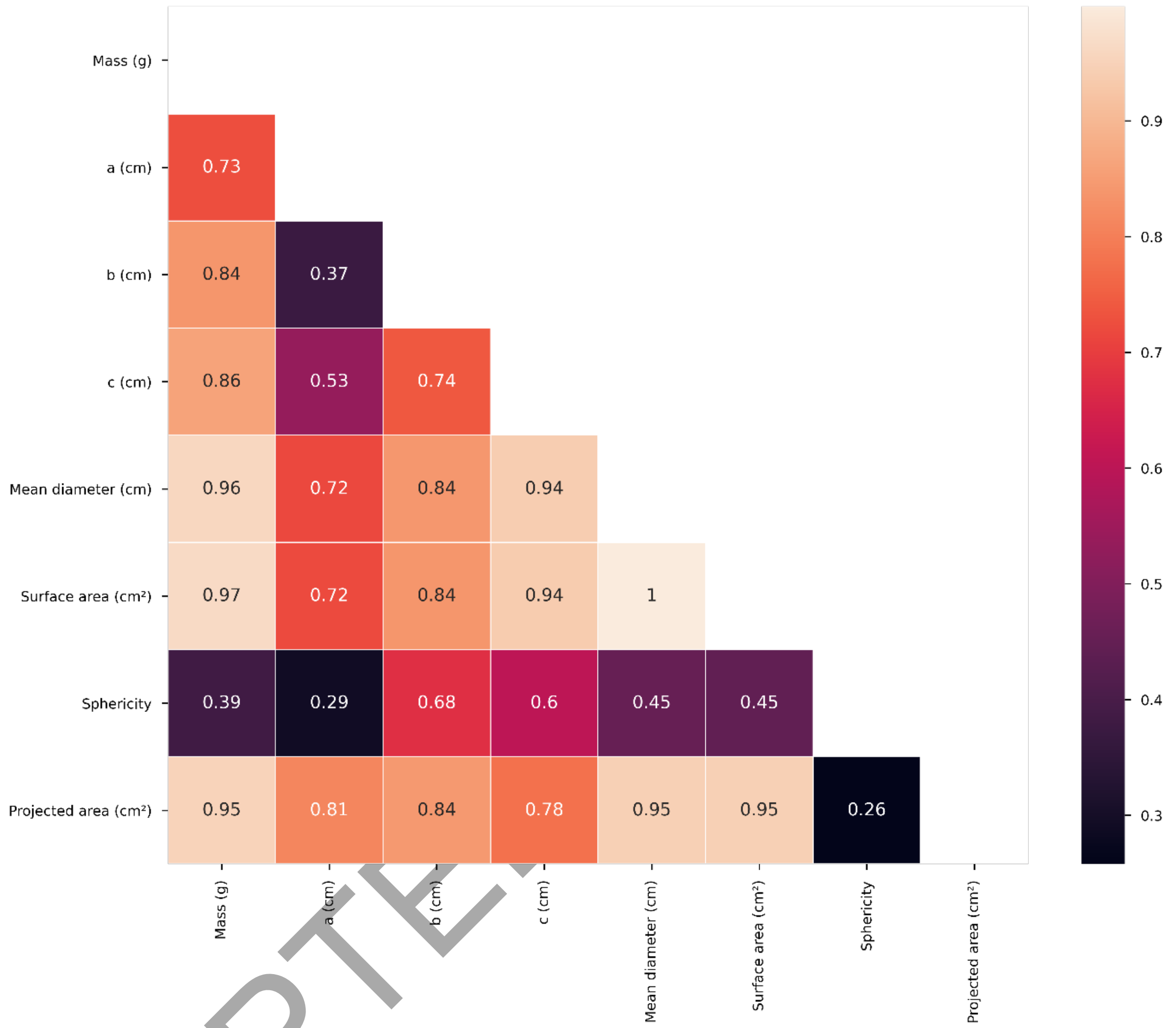

Figure 3: Correlation coefficient, R, matrix indicating the correlations between the geometrical properties and mass. The coefficients ranged between 0 (weakest correlation) to 1 (strongest correlation).

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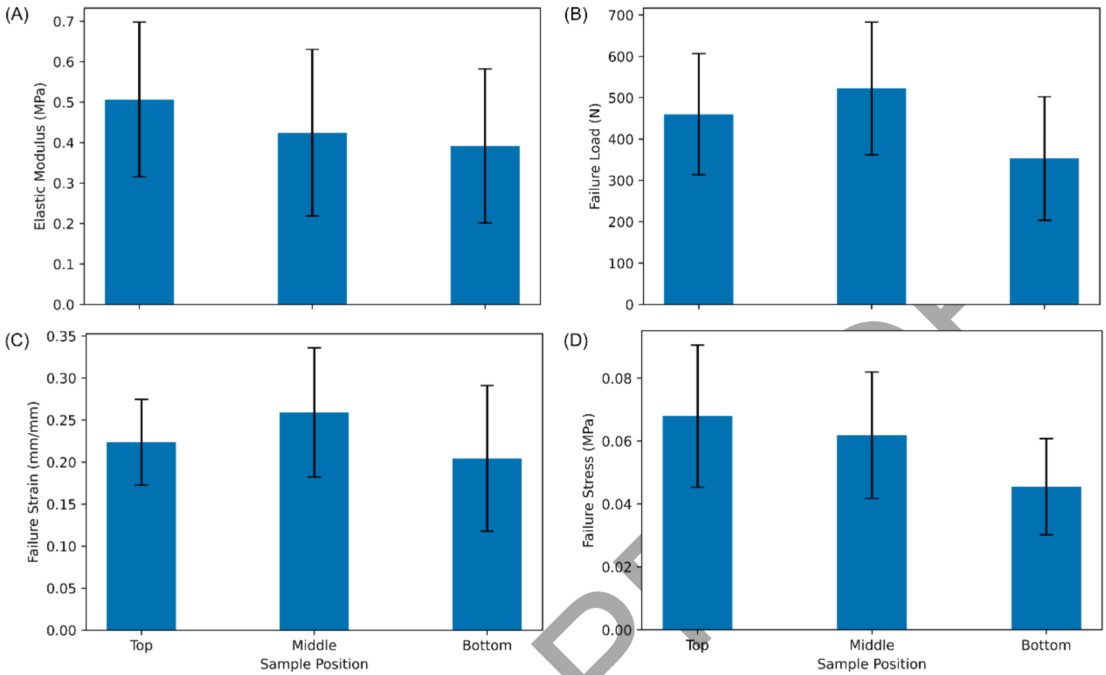

Figure 4: The average and standard deviation for (A) elastic modulus, (B) failure load, (C) failure strain and (D) failure stress along papaya fruit's major axis. All observed variations between the three fruit sections were statistically insignificant (p>0.05).