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Effect of the probe diameter, cultivar and post-harvest storage on the cocoa pod firmness and deformation energy

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Abstract: The mechanical characterisation of cocoa pods is essential for improving the post-harvest handling, mechanised processing, and objective quality assessment. This study investigated the effects of the probe diameter, cultivar, and post-harvest storage duration on the cocoa pod firmness, deformation energy, and yield stress using penetration testing. Three cultivars (Amazonia, Forastero and Amelonado) were evaluated under controlled conditions (27 ± 2 °C; 70 ± 5% RH) over 8 days using probe diameters of 3.5, 8 and 11 mm. The results showed that the probe diameter significantly influenced the measured firmness, with smaller probes producing higher values due to stress concentration effects. The firmness and deformation energy decreased significantly during storage, particularly within the first 2–4 days, indicating rapid structural degradation. Cultivar-specific responses were observed, with Forastero exhibiting the highest mechanical strength and slowest softening, while Amazonia showed the fastest degradation, losing approximately 60% of firmness by Day 6. A strong positive correlation between the firmness and deformation energy (r = 0.9478–0.9999; P < 0.05) confirms the deformation energy as a reliable substitute for the mechanical integrity. The Partial Least Squares Regression models improved with the increasing probe diameter, with optimal performance observed in Forastero (R^2 = 0.8118; RMSE = 1.4036 MPa).

Keywords: mechanical modelling; penetration resistance; pod mechanics; texture analysis; yield stress

The global cocoa demand necessitates understanding cocoa pod characteristics and mechanical properties affecting the post-harvest handling, processing efficiency, and bean quality. Cocoa pod quality assessments use traditional methods like visual checks and cut tests, alongside modern techniques such as mechanical tests, moisture measurements, and an internal bean evaluation. Traditional methods for quality assessment, such as the cut test, are often destructive and subjective, necessitating the development of rapid and non-destructive evaluation techniques (Alvarado et al. 2023). The cocoa pod husk, which is 76% of its mass, is researched for applications affecting its mechanical properties (Murray et al. 2021). The research over the years has shown that the maturity signifi-

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cantly influences the mechanical properties of the pod husk, which is a crucial consideration for its mechanisation (Murray et al. 2021). The mechanical properties of the pod, including its firmness and resistance to deformation, directly impact the ease and efficiency of the bean extraction, which is a critical step in cocoa processing and mechanisation (Ghonimy et al. 2025). These mechanical properties are intrinsically linked to the cocoa pod's resilience against physical damage during transport and storage, thereby influencing the overall post-harvest losses and the quality of the harvested beans (Nwakuba et al. 2022). Thus, understanding the mechanical properties, such as the firmness and energy absorption of cocoa pods, is essential for designing efficient post-harvest machinery and optimising processing techniques. Such insights are crucial for developing rapid and non-destructive methods for quality assessment, which can overcome the limitations of subjective human inspection and destructive conventional analytical techniques (Alvarado et al. 2023). Researchers have focused on studying the mechanical properties and characteristics of cocoa pods and have reported strong correlations among some cultivars. For example, Fonsso et al. (2019), compared three cocoa cultivars by measuring their rapture forces, deformation, stiffness and energy absorbed at failure and reported strong correlation between pod rigidity and peak rupture force. Similarly, Maduako and Faborode (1994) researched on the breaking behaviour of the whole cocoa pods by measuring the force-deformation behaviour, firmness, and fracture characteristics and reported that cocoa pods are significantly weaker laterally than longitudinally and also the energy required to break the pods depended strongly on the direction of loading. In another study Arulmari et al. (2024), conducted compression loading test on cocoa pods using a UTM and measured rupture forces, deformation at breaking points and cutting force, and reported that cocoa pod geometry influences firmness and rupture resistance.

Cocoa pod softening is not only mechanical, but is also driven by biochemical and microstructural changes, such as the enzymatic breakdown of cell wall components (e.g. pectin and cellulose). Differences in the cell structure, fibre content, and lignification among cultivars influence their firmness and rate of softening. Therefore, understanding these biological factors helps explain the observed mechanical behaviour of cocoa pods during storage. This research aims to provide quantitative insights on how the probe diameter, post-harvest storage duration, and cocoa variety affect the cocoa pod firmness and deformation energy under penetration loading. Unlike previous studies focused primarily on the rupture force and compression behaviour, this study integrates the probe geometry, cultivar variability, and post-harvest storage effects into a unified penetration mechanics framework. Furthermore, the deformation energy is introduced and validated as a robust non-destructive proxy for firmness across varying conditions, combined with predictive Partial Least Squares Regression (PLSR) modelling for cultivar-specific quality assessments. This approach provides a novel basis for sensor-based automation in cocoa post-harvest systems.

MATERIAL AND METHODS

Cocoa pod procurement and preparation. Freshly harvested cocoa pods (*Amazonia, Forastero*, and *Amelonado*) were sourced from farms in the Eastern Region of Ghana. These cocoa cultivars were chosen for their commercial significance and varied physical traits, with pod samples taken from the region to maintain genetic authenticity and reduce handling variations. Pods were selected based on their uniform maturity and absence of visible defects. Samples were stored under controlled conditions (27 ± 2 °C; 70 ± 5% RH) for 8 days.

Determination of cocoa pod penetration resistance and firmness. Penetration tests were conducted using a digital fruit sclerometer (Model GY-4 430621291, accuracy ±1) equipped with interchangeable probe tips of diameters 3.5 mm, 8 mm, and 11 mm. The instrument measures the maximum force required to penetrate the cocoa pod husk, which reflects the resistance to deformation. Each cocoa pod was tested at three positions (top, middle, and bottom), and the probe was driven perpendicularly into the pod surface under quasi-static loading conditions. The test was conducted at a speed of 1 $mm.s^{-1}$. The maximum penetration force derived from the force-deformation curve was noted as the penetration resistance. Firmness was expressed as the maximum penetration stress calculated from the force-deformation curve, using the maximum penetration force (F) and the contact area (A) of the probe:

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$$\sigma = \frac{F}{A} \quad (1)$$

where: σ – maximum penetration stress (firmness) (MPa); F – maximum penetration force (N); A – probe contact area (mm^2). Given the probes' circular shape, the area was determined as:

$$A = \frac{\pi d^2}{4} \quad (2)$$

where: d – probe diameter (mm).

The firmness reflects the resistance of the cocoa pod tissue to mechanical intrusion, allowing for comparisons among probe sizes and cultivars, using averages from three positions of the pods across three biological replicates. Figure 1 illustrates the experimental arrangement used to measure the penetration resistance of the cocoa pods.

Assessment of cocoa pod deformation energy. The deformation energy quantifies the total mechanical work on the cocoa pod tissue during penetration until maximum deformation, represented by the area under the force-deformation curve. This metric indicates the pod tissue's energy absorption capacity before structural failure, reflecting its integrity and susceptibility to mechanical damage. The compressive penetration resistance force-deformation curves were analysed, with OriginLab 2019b software (OriginLab Corporation, United States). The area under the force-deformation curve was numerically integrated using the trapezoidal method between consecutive data points. The resulting deformation work was normalized by the cross-sectional area of the probe to obtain deformation energy per unit area.The deformation energy was calculated using Equation (3):

$$E = \sum_{i=1}^{N-1} \frac{(F_i + F_{i+1})}{2} \times (x_{i+1} - x_i) \quad (3)$$

where: E – deformation energy per unit area (J.m^{-2}); F_i and F_{i+1} – force values at consecutive data points (N); x_i and x_{i+1} – corresponding penetration depth values in m); N – the number of recorded data points. A was calculated as $A = \frac{\pi d^2}{4}$, where d is the probe diameter (m).

Statistical data analyses. The study employed a 3 × 3 × 5 factorial strategy featuring three cocoa varieties, three probe sizes, and five storage times, using three independent cocoa pods for each treatment as the biological replicates. The penetration measurements were averaged before the statistical analysis. The three-way analysis of variance (ANOVA) assessed the effects of the cultivar, probe diameter, and storage duration, alongside their interactions on the mechanical properties. The descriptive statistics provided summaries of these properties. The Partial Least Squares Regression (PLSR) analysed the predictive relationships between the penetration measurements and firmness, with the model based on the averaged penetration force data across different conditions. PLSR is commonly applied in agricultural predictive modelling.

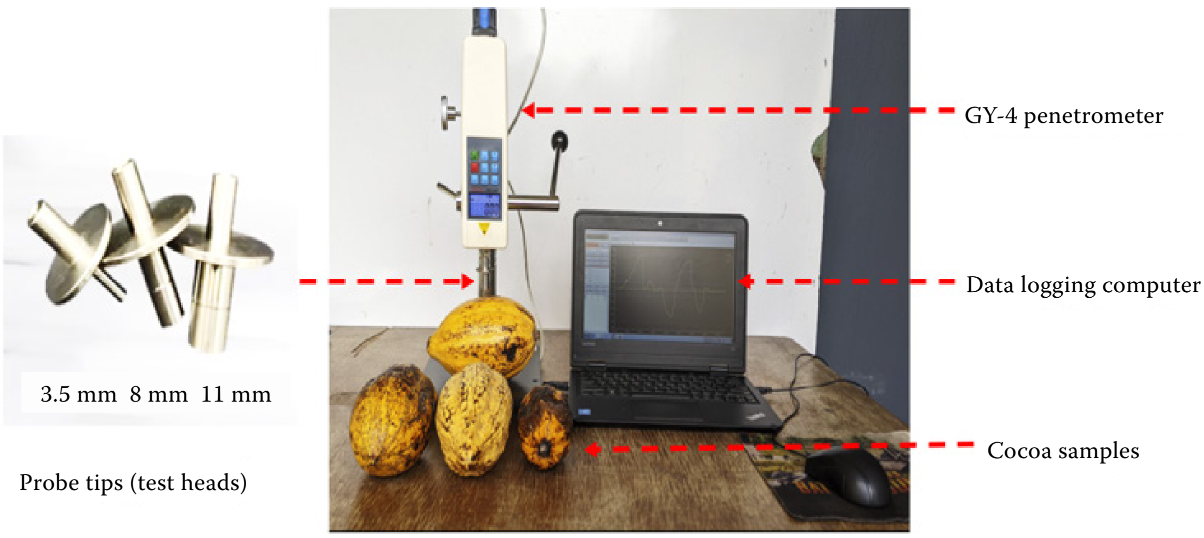

Figure 1. Assessing cocoa pod penetration resistance

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The predictive performance of PLSR models was evaluated through the coefficient of determination (R^2) and the Root Mean Square Error of prediction (RMSEP); higher R^2 values indicate better agreement between measured and predicted values. The R-value was calculated using Equation (4) (Asuero et al. 2006); R^2 was determined by squaring the R-values.

$$R = \frac{\sum_{i=1}^{N}(T_{im} - \overline{T_{im}})(S_{ip} - \overline{S_{ip}})}{\sqrt{\sum_{i=1}^{N}(T_{im} - \overline{T_{im}})^2 \times \sum_{i=1}^{N}(S_{ip} - \overline{S_{ip}})^2}} \quad (4)$$

where: T_{im} and $\overline{T}_{im}$ – the reference values of the i^{th} sample and the average values of the reference values, respectively. S_{ip} and $\overline{S}_{ip}$ – estimated by the i^{th} and the average values of the predicted values, respectively; N – the number of samples.

The Root Mean Square Error (RMSE) served to measure the prediction error of the regression models. RMSE denotes the square root of the average squared deviation between the observed and forecasted values (Chicco et al. 2021), and it is expressed as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(S_{ip} - T_{im})^2}{N}} \quad (5)$$

Lower RMSE values indicate better model performance and improved prediction accuracy. To examine the relationship between the firmness and deformation energy, Pearson's correlation analysis was calculated using Equation (6) (Sedgwick 2012):

$$r = \frac{[n(\sum xy) - \sum x \sum y]}{\sqrt{[n(\sum x^2) - (\sum x)^2][n(\sum y^2) - (\sum y)^2]}} \quad (6)$$

where: n – the number of observations; x – the independent variable; y – the dependent variable; $\sum xy$ – the sum of the product of the independent and dependent variables; $\sum x$ and $\sum y$ – the sums of the independent and dependent variables; $\sum x^2$ and $\sum y^2$ – the sums of squares of the dependent and independent variables.

The cross-validation calibrated Partial Least Squares Regression (PLSR) models, evaluating the robustness by dividing the dataset into calibration and validation subsets to reduce overfitting. Optimal latent variables minimised the prediction error, ensuring unbiased distribution for estimating the cocoa pod firmness across storage conditions.

RESULTS AND DISCUSSION

Descriptive statistical analysis. Descriptive statistics were used to summarise the firmness and deformation energy across the cultivars, probe diameters, and storage durations. Table 1, showed variability among the samples, reflecting the inherent heterogeneity in the cocoa pod structure and composition. The mechanical strength of the cocoa pod tissue declines with storage, indicating structural degradation. The firmness decreases from Day 0 to Day 8, with *Forastero* being the highest, followed by *Amelonado*, and *Amazonia* being the lowest. The more pronounced reduction observed with the 3.5 mm probe reflects its higher sensitivity to macro-scale surface degradation. Due to its smaller contact area, the probe concentrates stress within the superficial tissue layers, making it more responsive to early-stage softening compared to larger probes that integrate bulk properties. By Day 8, all the cultivars exhibited significant ($P < 0.05$) reductions in the firmness. The deformation energy followed a trend similar to the firmness, decreasing progressively over the storage time. Initially, *Forastero* exhibited the highest values (e.g. 112 $J.m^{-2}$ at 3.5 mm), reflecting stronger tissue structure at harvest, but all the cultivars showed substantial reductions by Day 8. The relatively large standard deviations indicate inherent variability in the pod structure and ripening stages, which may explain minor fluctuations across the sampling points. The results generally demonstrate that prolonged storage markedly reduces the mechanical strength, with Forastero consistently exhibiting superior properties compared to *Amazonia* and *Amelonado*. Additionally, the probe diameter influenced the measurements, as smaller probes were more sensitive to tissue softening, highlighting differences in the post-harvest mechanical stability among the cultivars. From an engineering perspective, this decline underscores the need to optimise the post-harvest handling, packaging, and processing systems to minimise the mechanical damage and preserve the pod integrity throughout storage.

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Table 1. Descriptive analysis of the cocoa pod mechanical properties

Cultivar	Probe diameter (mm)	Day 0	Day 2	Day 4	Day 6	Day 8
Firmness (MPa)						
	3.5	5.74 ± 2.45	4.34 ± 2.52	3.51 ± 2.11	2.45 ± 2.07	1.67 ± 1.56
Amazonia	8	2.35 ± 0.82	1.12 ± 0.56	0.81 ± 0.43	0.61 ± 0.36	0.47 ± 0.32
	11	1.32 ± 0.52	0.87 ± 0.49	0.54 ± 0.41	0.35 ± 0.29	0.21 ± 0.22
	3.5	16.73 ± 5.12	10.05 ± 3.59	5.06 ± 2.51	3.10 ± 2.04	2.74 ± 1.75
Forastero	8	3.99 ± 2.00	3.10 ± 1.33	2.25 ± 1.49	1.20 ± 0.71	0.62 ± 0.44
	11	2.70 ± 1.11	1.80 ± 0.73	1.30 ± 0.65	0.79 ± 0.46	0.50 ± 0.39
	3.5	10.23 ± 6.28	8.25 ±5.05	3.54 ± 2.38	2.64 ± 1.76	1.99 ± 1.48
Amelonado	8	2.46 ± 1.07	2.16 ± 1.04	1.76 ± 0.94	1.24 ± 0.81	0.54 ± 0.35
	11	2.04 ± 0.90	1.36 ± 0.70	0.93 ± 0.63	0.64 ± 0.54	0.28 ± 0.18
Deformation energy ($J.m^{-2}$)						
	3.5	70.25 ± 44.93	60.74 ± 46.48	57.31 ± 35.68	39.91 ± 18.17	23.28 ± 10.14
Amazonia	8	60.51 ± 43.92	14.32 ± 11.63	9.67 ± 6.02	9.53 ± 8.17	5.92 ± 2.96
	11	22.74 ± 18.24	9.31 ± 6.97	8.24 ± 4.08	5.21 ± 4.76	5.49 ± 2.16
	3.5	112 ± 57.95	89.37 ± 49.88	40.91 ± 16.53	51.40 ± 31.42	26.73 ± 12.33
Forastero	8	51.86 ± 39.43	34.02 ± 15.50	39.42 ± 26.36	11.35 ± 9.42	14.04 ± 7.60
	11	29.53 ± 21.36	17.19 ± 8.24	13.93 ± 7.33	9.89 ± 7.89	19.76 ± 6.60
	3.5	71.91 ± 61.07	77.99 ± 38.77	61.28 ± 27.69	52.53 ± 43.69	11.28 ± 14.06
Amelonado	8	27.82 ± 11.32	29.60 ± 19.93	17.43 ± 14.75	67.57 ± 20.91	7.74 ± 2.63
	11	21.26 ± 11.57	13.58 ± 8.20	10.81 ± 4.88	8.95 ± 5.75	4.18 ± 2.77

*Descriptive values = mean ± standard deviation

Determination of the cocoa pod firmness under different probe treatments. Firmness serves as a vital mechanical indicator of the cocoa pod maturity and damage resistance. The study showed an inverse relationship between the probe size and firmness across the cultivars, with scatter plots illustrating these findings for different probe diameters (Figure 2). The 3.5 mm probe produced the highest peak firmness values, followed by the 8 mm and 11 mm probes. This trend aligns with classical contact mechanics, where stress is inversely proportional to the contact area. Smaller probes reduce the contact area, thereby increasing the localised stress for the same applied force. As a result, the measured firmness appears higher, not necessarily because the material is stronger, but due to stress concentration effects (Mohsenin 1986; Bourne 2002).

The yield stress of the *Amazonia* pods declined from 9.085 MPa at Day 0 to 4.189 MPa at Day 8 (54% reduction; $P < 0.05$), while *Forastero* retained 4.844 MPa at Day 8, indicating slower mechanical softening. The corresponding deformation energy declined from 561.97 $J.m^{-2}$ to 162.93 $J.m^{-2}$ in *Amazonia* ($r = 0.996$; $P < 0.001$), demonstrating a strong link between the post-harvest softening and energy absorption capacity. These quantitative differences demonstrate that the softening kinetics vary significantly among cultivars, which has direct implications for mechanised processing. Equipment calibrated using a single cultivar may either underperform or cause excessive damage when applied to others, necessitating cultivar-specific calibrations (Bart-Plange and Baryeh 2003; Nwakuba et al. 2022). The differences in the softening among cocoa cultivars are due to microstructural and biochemical factors. The faster softening observed in *Amazonia* compared to *Forastero* can be attributed to the differences in the microstructural composition and biochemical activity. Cultivars with a lower lignin content and weaker cell wall architecture are more susceptible to enzymatic degradation, particularly by pectinases and cellulases, which accelerate the breakdown of middle lamella structures. This results in reduced intercellular adhesion and the rapid loss

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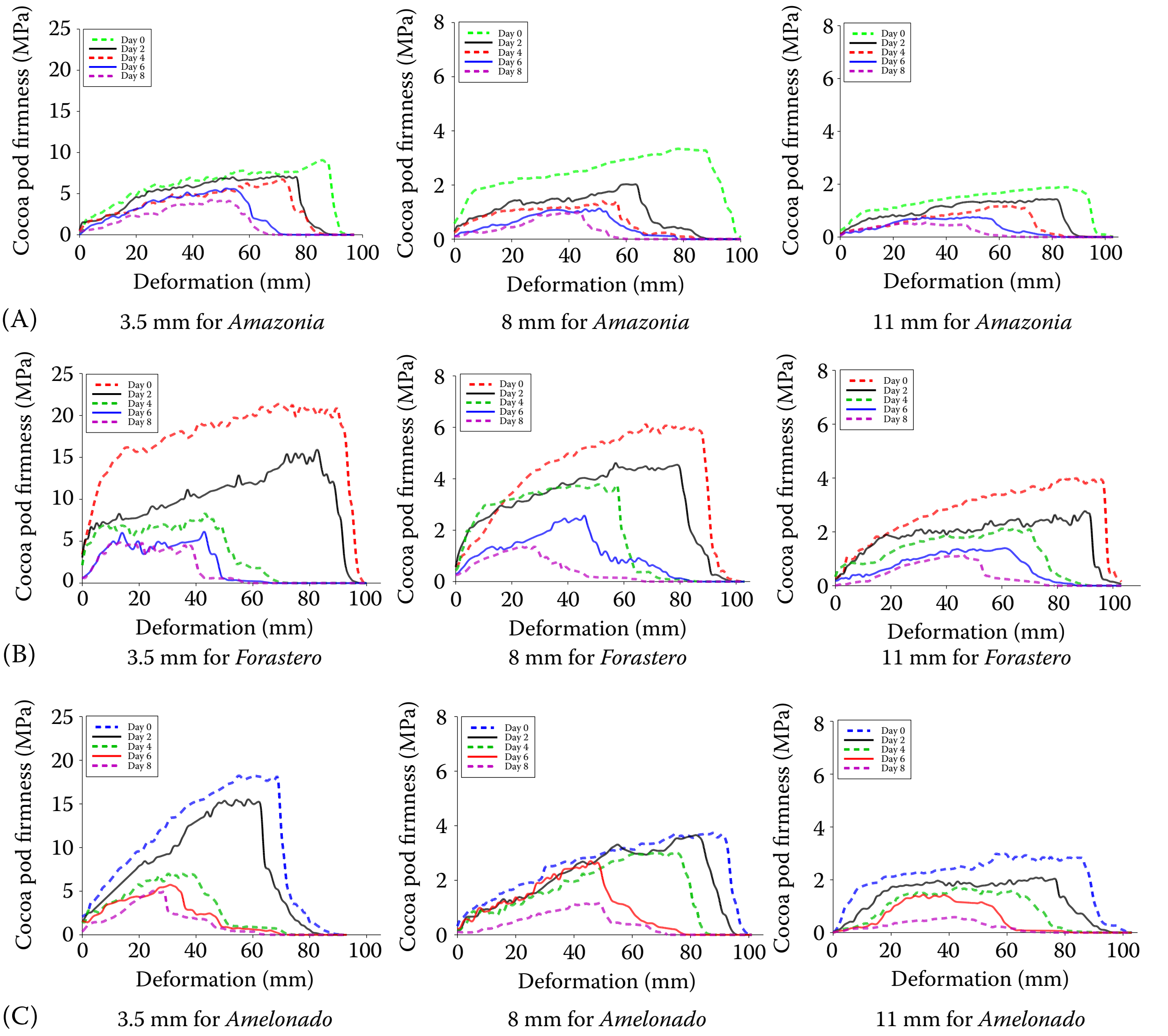

Figure 2. Firmness profiles for all cultivars
(A) *Amazonia*, (B) *Forastero*, (C) *Amelonado* under 3.5, 8 and 11 mm probe diameters

of mechanical strength. In contrast, *Forastero* likely possesses a more compact fibre network and higher lignification, contributing to its greater resistance to structural degradation during storage. These structural differences explain the variation in the mechanical behaviour observed during storage. Complex multipeak force-deformation profiles under the 8 mm probe suggest structural heterogeneity in the cocoa pod husk, linked to the sequential penetration of the epicarp and mesocarp layers, showing layer-dependent mechanical responses in fruit tissues (Vicente et al. 2007). The post-harvest storage led to reduced firmness in all the cultivars (2–4 days), with *Amazonia* losing about 60% firmness by Day 6 due to the enzymatic degradation of the polysaccharides, weakening the lamella cohesion and reducing the tissue rigidity. The rapid decline aligns with the enzymatic degradation of polysaccharides, weakening middle lamella cohesion and tissue rigidity (Brummell and Harpster 2001). Similar ageing-induced reductions in the mechanical strength of cocoa pod husks were reported by Murray et al. (2021), confirming that the post-harvest physiology strongly influences the structural integrity. *Forastero* retained higher firmness throughout the storage period, signifying enhanced resistance to biochemical softening processes. This indicates cultivar-spe-

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cific differences in the cell wall metabolism and structural resilience.

Deformation energy analysis. The deformation energy quantifies the mechanical energy absorbed by the cocoa pods during penetration, reflecting the structural integrity, elasticity, and tissue resistance to mechanical loading. The quantitative analysis of the deformation energy for all the post-harvest delays for all the cultivars is presented in Table 2. A significant reduction in deformation energy was observed with the increasing probe diameter, decreasing by 68–72% from 3.5 mm to 8 mm and by an additional 29–36% from 8 mm to 11 mm across the cultivars ($P < 0.05$).

This trend confirms that smaller probes induce higher localised stress, resulting in greater energy absorption prior to tissue failure. Mechanically, this indicates that the material undergoes more sensitivity to macroscopic surface degradation to penetration per unit area, reflecting the localised stiffness rather than the overall structural strength (Mohsenin 1986; Bourne 2002). Cultivar differences were evident, with the deformation energy following the order *Forastero* > *Amelonado* > *Amazonia*. The higher energy absorption observed in *Forastero* indicates greater structural integrity, likely associated with higher fibre density and pod wall composition. Structural variation as a determinant of the mechanical strength has been reported in cocoa and other agricultural materials (Bart-Plange and Baryeh 2003; Nwakuba et al. 2022). The post-harvest storage reduced the deformation energy in all the cultivars, particularly within the first 2–4 days, reflecting tissue softening and loss of turgor pressure (Brummell and Harpster 2001). Similar aging-induced reductions in mechanical strength of cocoa pod husks were reported by Murray et al. (2021), confirming that postharvest physiology strongly influences structural integrity. Forastero retained higher firmness throughout the storage period, signifying enhanced resistance to biochemical softening processes. This indicates cultivar-specific differences in cell wall metabolism and structural resilience.

The average deformation energy across the cultivars and probe diameters was analysed, with the baseline representing the undamaged condition of the cocoa pods (Figures 3–5). Figure 3A illustrates the firmness behaviour under a 3.5 mm probe, which produced the highest deformation peak, corresponding to a firmness value of 5.8773 MPa. The 3.5 mm probe demonstrates a decline in firmness indicating structural weakening of the pod, with a biphasic curve revealing elastic deformation followed by failure and stress concentration during loading.

Figure 3B,C demonstrates that the deformation energy response for the 8 mm and 11 mm probes results in a maximum firmness of 1.4370 MPa and 0.9908 MPa. The deformation energies absorbed by the *Amazonia* cocoa pods are 346.8 $J.m^{-2}$, 97.4 $J.m^{-2}$, and 68.30 $J.m^{-2}$ for probes of 3.5, 8, and 11 mm, respectively, with significant reductions observed between the probe sizes. The results further showed that the deformation energy decreases by 71.90% from the 3.5 mm to 8 mm probe, and 29.89% from the 8 mm to 11 mm probe.

Figure 4A–C illustrates the average deformation energy levels for the 3.5, 8 and 11 mm probe diameters. The firmness of the *Forastero* pods declined with the increasing deformation energy, signalling

Table 2. Quantitative analysis of the deformation energy

Cultivar	Probe diameter (mm)	Deformation energy ($J.m^{-2}$)				
		Day 0	Day 2	Day 4	Day 6	Day 8
Amazonia	3.5	561.9669	425.1507	343.8773	239.4854	162.9262
	8	242.0271	47.2408	38.1231	33.5011	20.9687
	11	136.4685	55.8581	46.9257	34.7616	21.9441
Forastero	3.5	1 688.488	983.1029	368.1705	205.5821	160.4002
	8	414.8488	243.7368	197.0808	93.7507	42.1305
	11	265.765	119.8464	120.3031	69.2486	39.5259
Amelonado	3.5	939.0801	539.4127	183.8514	160.7744	129.2204
	8	250.369	207.1763	156.8958	99.4122	38.7156
	11	212.5523	135.7861	86.4543	53.6925	20.9223

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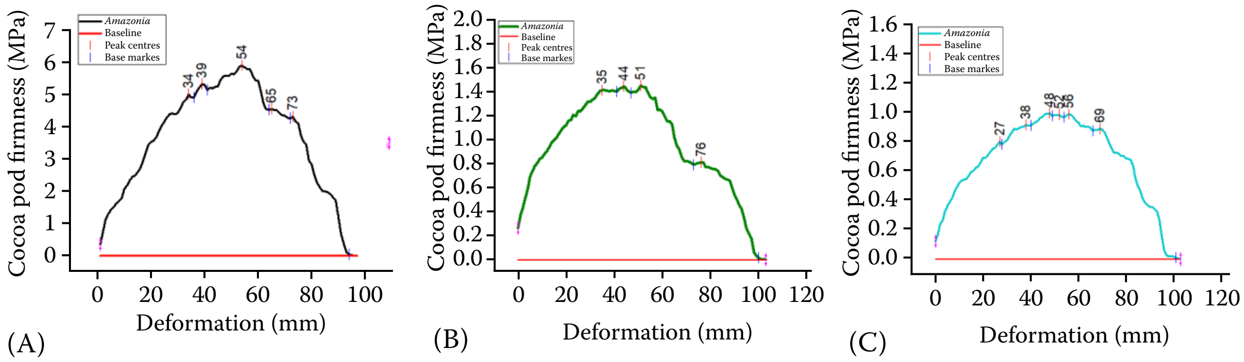

Figure 3. Firmness-deformation characteristics of *Amazonia* cocoa pods under probe diameter (A) 3.5 mm, (B) 8 mm, and (C) 11 mm

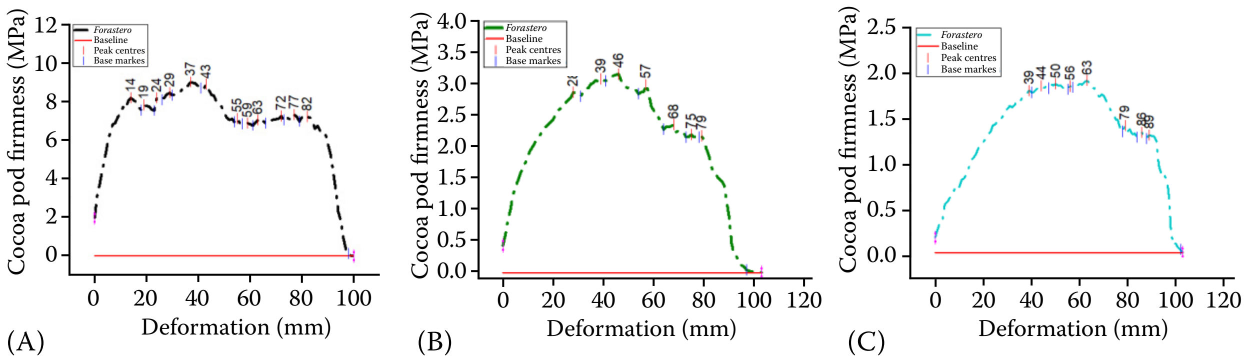

Figure 4. Firmness-deformation characteristics of *Forastero* cocoa pods under probe diameter (A) 3.5 mm, (B) 8 mm, and (C) 11 mm

a transition from elastic resistance to structural failure. The pods absorbed average deformation energies of 681.6 J.m^{-2}, 212.8 J.m^{-2}, and 135.2 J.m^{-2} under the 3.5 mm, 8 mm, and 11 mm probes, respectively. The highest firmness was observed at 8.9937 MPa for the 3.5 mm probe, indicating strong elastic behaviour. As the probe diameter increased, the firmness profile displayed less defined peaks and reduced energy accumulation, indicating tissue damage. The deformation energy declined due to significantly from the 3.5 mm probe (220.29% higher than 8 mm) to the 11 mm probe (by 36.44% from 8 mm).

Figure 5A–C demonstrates the deformation profiles for the *Amelonado* cocoa pods, indicating energy absorption of 250.5 J.m^{-2}, 156.1 J.m^{-2}, and 101.9 J.m^{-2} with probes of 3.5 mm, 8 mm,

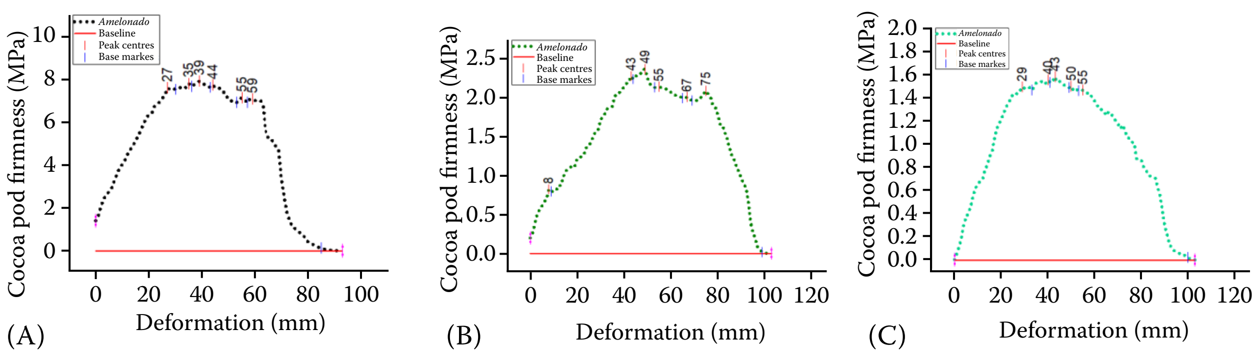

Figure 5. Firmness-deformation characteristics of *Amelonado* cocoa pods under probe diameter (A) 3.5 mm, (B) 8 mm, and (C) 11 mm

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and 11 mm, respectively. The energy decreases by 39.87% from 3.5 mm to 8 mm and 32.33% from 8 mm to 11 mm. The findings have direct applications in the design of automated cocoa pod processing systems, where probe-based sensing can be used for real-time quality evaluations. The deformation energy provides a practical basis for developing non-destructive grading systems and optimising machine calibration across cultivars.

Effects of probe size, cultivar, and post-harvest storage on cocoa pod firmness and deformation energy. Figure 6 illustrates the relationship between the deformation energy, firmness, probe diameter, and post-harvest storage time for *Amazonia* cocoa.

Increasing the storage duration resulted in a progressive reduction in both the firmness and deformation energy, while smaller probe diameters consistently produced higher firmness values than larger diameters. The decline in firmness and deformation energy reflects the progressive tissue softening driven by biochemical processes, including the enzymatic depolymerisation of the cell wall material and loss of turgor pressure. These changes reduce both the force required for penetration and the energy absorption capacity of the tissue. The data further demonstrate that deformation energy and pod firmness decrease with the increasing post-harvest delay and probe size with significant differences (P = 0.0365) and (P = 0.0261), respectively. Figure 7 demonstrates the relationship between the deformation energy, firmness, probe diameter, and storage duration in cocoa pods. The reduction in mechanical strength is primarily attributed to the enzymatic degradation of the cell wall polysaccharides, including pectin and cellulose, which weakens the middle lamella cohesion and reduces the tissue rigidity (Brummell and Harpster 2001; Vicente et al. 2007). The firmness also declined

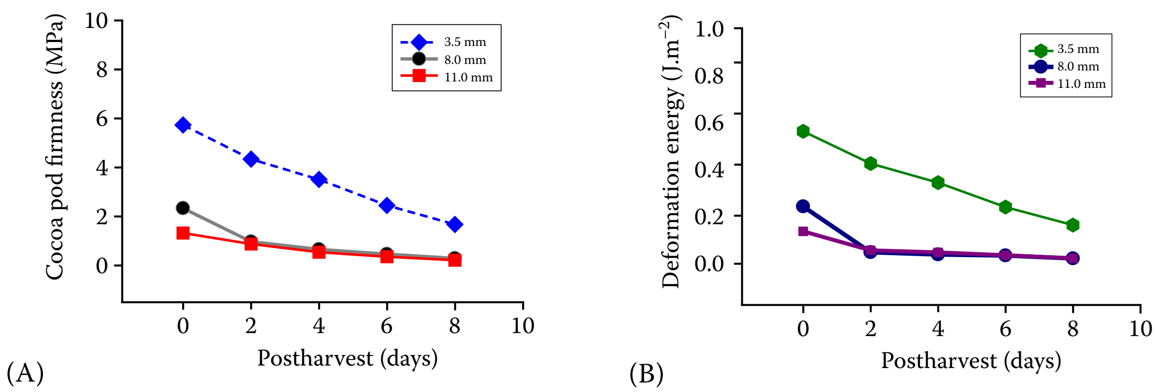

Figure 6. Effects of postharvest delay on mechanical properties of *Amazonia* cocoa pods
(A) Firmness, and (B) deformation energy

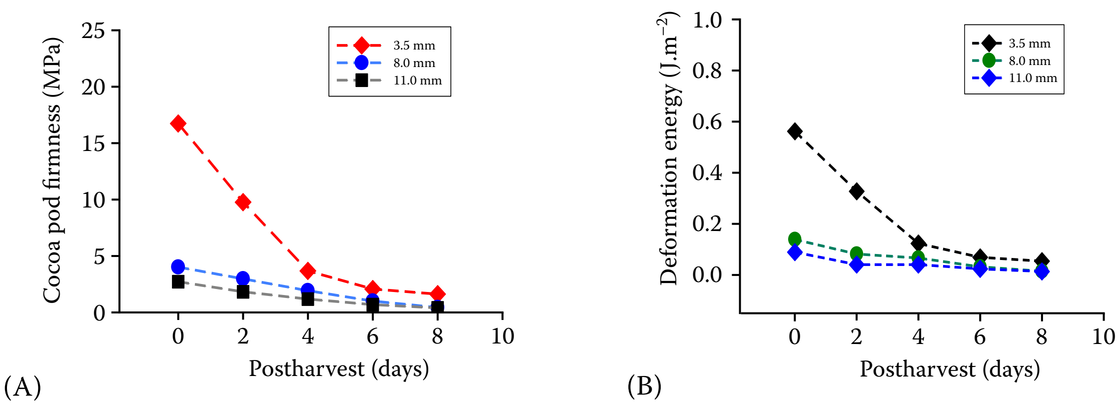

Figure 7. Effects of postharvest delay on mechanical properties of *Forastero* cocoa pods
(A) Firmness, and (B) deformation energy

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due to the increasing probe diameter due to the reduced stress concentration. The storage time led to progressive softening, particularly within the first 2–4 days. Similar ageing-induced reductions in mechanical strength were reported for cocoa pod husks by Murray et al. (2021). During storage, the firmness and deformation energy decreased. Smaller probes primarily measure the localised surface firmness due to the limited penetration area, whereas larger probes interact with a broader portion of the tissue, providing a more integrated measure of the bulk toughness and internal structural integrity. The probe-dependent variation in the measured firmness agrees with the penetration mechanics theory, where smaller indenter diameters produce higher apparent stress values due to stress concentration effects (Bourne 2002). The post-harvest delay weakens the cocoa pod structure, reducing the force and energy required for penetration. The statistical analysis demonstrates that the deformation energy and pod firmness decline with the longer post-harvest delays and larger probe sizes, showing significant differences of (P = 0.0133) and (P = 0.0473), respectively.

In the *Amelonado* cultivar, the deformation energy and firmness vary with the probe diameter and storage duration. Figure 8A,B shows that the 3.5 mm probe consistently yields the highest values of both responses, due to the increased localised stress associated with the reduced contact area.

The probe firmness declined progressively post-harvest, with a pronounced reduction within the first 2–4 days, followed by a plateau at low levels by days 4–5, indicating early structural degradation. The deformation energy showed a similar trend, decreasing significantly at the early storage stages before stabilising at lower values, with a consistent probe diameter ranking (3.5 > 8 > 11 mm). A strong positive correlation was observed between the firmness and deformation energy, indicating that the reductions in the firmness were associated with the corresponding decreases in the energy absorption capacity. The statistical analysis confirmed significant effects of the storage duration and probe diameter (P = 0.0012 and P = 0.0203, respectively). The rapid decline observed, particularly in the *Amazonia* cultivar, aligns with the reported effects of tissue ageing and cell wall degradation in cocoa pod husks (Murray et al. 2021). Notably, the 60% reduction in firmness by Day 6 in *Amazonia* highlights cultivar-dependent differences in the post-harvest physiological stability and mechanical integrity.

Correlation analysis between firmness and deformation energy. Pearson's correlation coefficients between the firmness and deformation energy ranged from r = 0.9478 to 0.9999 across the probe diameters and cultivars (P < 0.05), confirming that deformation energy is a reliable quantitative predictor of the mechanical strength. The correlation analysis is presented in Table 3.

The pooled Pearson's correlation analysis revealed strong positive relationships between the firmness and deformation energy across the *Forastero, Amazonia,* and *Amelonado* cultivars, all with statistically significant P-values (Table 4). The results indicate a strong linear association between the two variables, suggesting that both respond similarly to structural degradation processes. This relationship implies that the deformation energy may serve

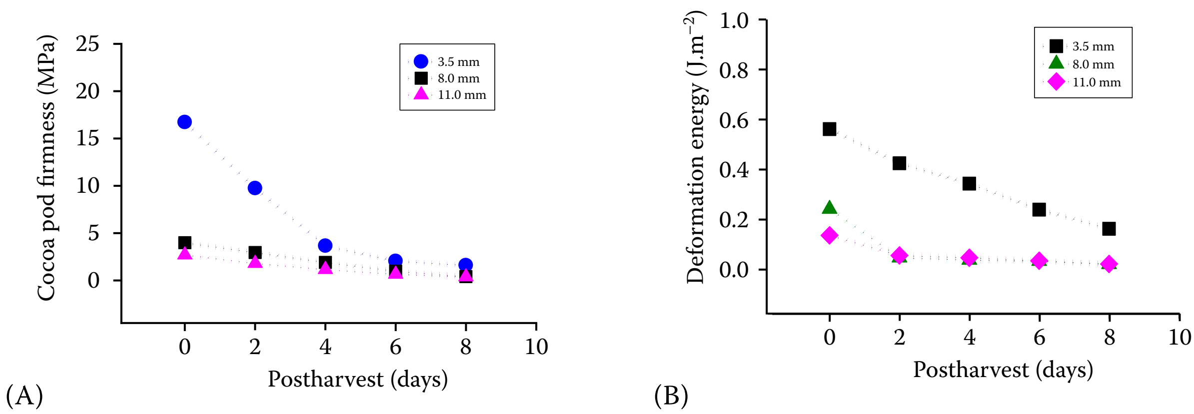

Figure 8. Effects of postharvest delay on mechanical properties of *Amelonado* cocoa pods
(A) Firmness, and (B) deformation energy

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Table 3. Pearson's correlation analysis between the firmness and deformation energy

Cultivar	Probe diameter (mm)	r	P-values
	3.5	0.9999	1.20×10^{-6}
Amazonia	8	0.9767	4.25×10^{-3}
	11	0.9478	1.42×10^{-2}
	3.5	0.9999	1.20×10^{-6}
Forastero	8	0.9836	2.51×10^{-3}
	11	0.9563	1.09×10^{-2}
	3.5	0.9815	3.01×10^{-3}
Amelonado	8	0.9999	1.20×10^{-6}
	11	0.9999	1.20×10^{-6}

as a proxy indicator of the firmness, reducing the need for direct stress-based measurements. The observed correlations support the potential application of probe-based, non-destructive measurement approaches for automated firmness assessment in post-harvest cocoa quality control systems.

The strong correlations ($r > 0.94$) suggest that the deformation energy can serve as a reliable proxy for the firmness; however, calibration across cultivars and probe geometries remains necessary to ensure measurement consistency. While earlier studies assessed the rupture force and stiffness independently (Maduako and Faborode 1994; Fonsso et al. 2019), these findings demonstrate the potential of the deformation energy as a reliable non-destructive proxy for firmness measurements, supporting its application in sensor-based post-harvest quality evaluation systems.

Regression analysis of cocoa pod penetration force by PLSR model. Post-harvest delays complicate the analysis of force-deformation curves, as prolonged storage increases the cellular degradation in pod husks, thereby reducing the penetration resistance and affecting the tissue thickness. To minimise the influence of these time-dependent instabilities, sub-intervals containing the most informative variations in the penetration resistance were selected instead of the full measurement range. Based on a study by Lu et al. (2023), which demonstrates a direct relationship between the intensity variations and peak strength, the optimal input intervals were determined.

Partial Least Squares Regression (PLSR) modelling was utilised to estimate the firmness using the measured data averaged over all the penetrometer diameters for each cocoa cultivar. The scatter plots of the PLSR modelling of the cocoa pod's firmness is presented in Figure 9. The PLSR models demonstrated improved prediction accuracy with the increasing probe diameter. For *Forastero*, R^2 increased from 0.7779 (3.5 mm) to 0.8118 (11 mm), while the RMSE declined from 1.5193 to 1.4036 MPa. The improved predictive performance observed with larger probes indicates that increasing the contact area reduces the influence of the local structural heterogeneity. This results in smoother force-deformation signals and more stable input variables for the PLSR model, thereby enhancing the prediction accuracy (Asuero et al. 2006; Chicco et al. 2021). The findings are directly applicable to the design of probe-optimised, automated firmness sensing systems for mechanised cocoa handling. *Forastero* showed the best model performance, while *Amazonia* exhibited the lowest prediction metrics in correlation and error (Table 5). The superior performance of the *Forastero* model reflects its more uniform mechanical structure and slower degradation rate, which reduce the data variability. In contrast, the rapid and uneven softening observed in *Amazonia* introduces noise into the dataset, limiting the model accuracy. Generally, the higher the coefficient of deformation, the lower the Root Mean Square Error, and the better the performance for a given data set. The variance in the data set was consistently explained by the models (P-values significant). Variations across the post-harvest days were observed (P = 0.0113, 0.0017, 0.0002). The cocoa cultivar type and probe diameter impacted the model accuracy, with *Forastero* showing superior performance and predictability. The improvement in the PLSR prediction accuracy with the increasing probe diameter indicates that larger probes reduce the signal variability caused by localised tissue heterogeneity. Similar trends have been reported in fruit firmness modelling studies, where the increased contact area enhances the

Table 4. Pooled Pearson's correlation analysis between the firmness and deformation energy (Vursavus et al. 2014)

Cultivar	r	P-values
Amazonia	0.9960	4.32×10^{-15}
Forastero	0.9988	1.35×10^{-18}
Amelonado	0.9835	4.77×10^{-11}

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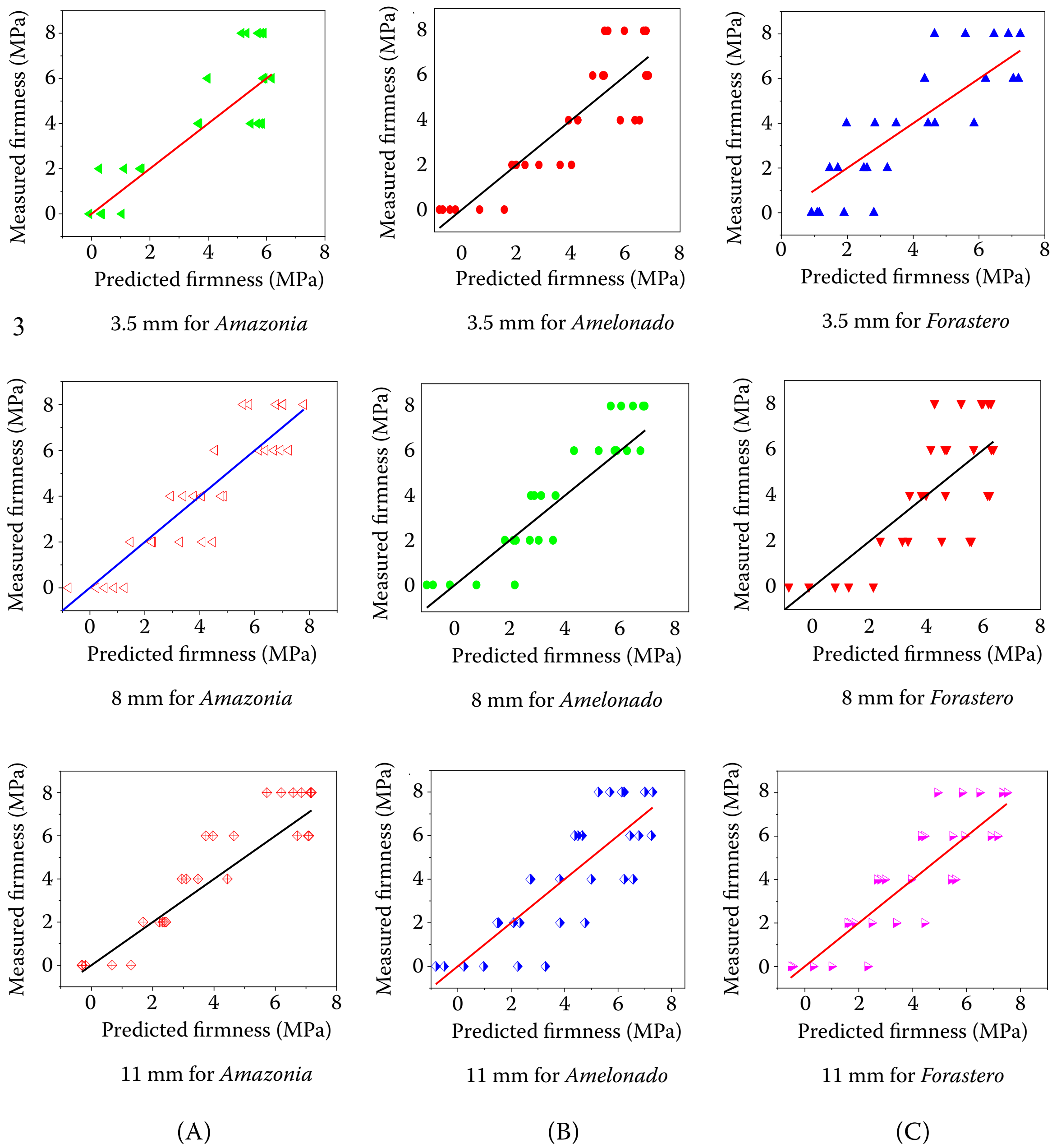

Figure 9. Scatter plots of Partial Least Squares Regression (PLSR) for firmness prediction of cocoa cultivars (A) *Amazonia*, (B) *Amelonado*, and (C) *Forastero* under probe diameters 3.5, 8, and 11 mm
PLSR – Partial Least Squares Regression

prediction robustness (Asuero et al. 2006; Chicco et al. 2021). This study confirms that these principles apply to cocoa pods and provides cultivar-specific performance benchmarks.

Varietal differences, probe diameters and postharvest delay effects on the Cocoa pod yield stress. *Forastero* exhibited the highest yield stress, followed by *Amelonado*, with *Amazonia* having the lowest (Table 6), reflecting genetic and structural variations among the cocoa cultivars. Cultivars with stronger and more compact cellular structures tend to exhibit higher resistance to mechanical deformation (Mohsenin 1986; Bart-Plange and Baryeh 2003). The yield stress declined significantly ($P < 0.05$) in all the cultivars during storage; *Forastero* resisted softening better than *Amelonado* and *Amazonia.* The smaller penetrator diameters increased the yield stress. For example, *Amazonia* dropped from

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Table 5. Predictive metrics for the cocoa pod firmness

Cocoa cultivar	Probe tip diameter (mm)								
	coefficient of determination (R^2)			Root Mean Square Error			*F*-value		
	3.5	8	11	3.5	8	11	3.5	8	11
Amazonia	0.5806	0.6806	0.7604	2.0915	1.8252	1.5788	5.311	8.174	12.214
Amelonado	0.7517	0.7569	0.7610	1.6829	1.5923	1.5785	7.968	11.943	12.218
Forastero	0.7779	0.7957	0.8118	1.5193	1.4623	1.4036	13.495	14.871	16.470

Table 6. Cocoa pod yield stress analysis

Cultivar	Probe diameter (mm)	Cocoa pod yield stress (MPa)				
		Day 0	Day 2	Day 4	Day 6	Day 8
	3.5	21.383	15.759	8.295	6.133	4.844
Forastero	8	6.1210	4.625	3.788	2.568	1.390
	11	4.0330	2.779	2.124	1.396	1.158
	3.5	18.254	15.468	6.985	5.738	5.042
Amelonado	8	3.736	3.660	3.002	2.695	1.150
	11	2.989	2.089	1.701	1.439	0.585
	3.5	9.085	7.141	6.736	5.634	4.189
Amazonia	8	3.338	2.029	1.390	1.118	1.009
	11	1.889	1.441	1.185	0.758	0.541

9.085 MPa at Day 0 to 4.189 MPa at Day 8, whereas *Forastero* declined from 21.383 MPa to 4.844 MPa. These differences reflect the inherent variations in the cellular architecture, including the fibre density and level of lignification, which directly influence the resistance to plastic deformation. Cultivars with stronger intercellular bonding exhibit higher yield stress and greater resistance to mechanical failure (Murray et al. 2021). This observation agrees with the indentation theory and prior agricultural material studies demonstrating that smaller probe diameters increase the measured yield stress due to localised stress amplification (Mohsenin 1986; Bourne 2002).

Limitations of the study. This study primarily examined the mechanical properties of cocoa pods, lacking direct microstructural and biochemical analyses, including histological imaging, which could reveal cultivar-specific behaviours. Constant storage conditions were used, unlike the fluctuating real-world environments affecting tissue degradation. Future research must combine histological techniques and biochemical assays to analyse cell wall changes and storage effects on the cocoa pod biomechanics for improved predictive models.

CONCLUSION

The present study systematically evaluated the effects of probe diameter, cultivar type, and post-harvest storage duration on the mechanical behaviour of cocoa pods using penetration testing. The results demonstrated that the probe diameter significantly influences measured mechanical properties due to stress concentration effects, with smaller probes producing higher firmness values. The post-harvest storage led to progressive reductions in the firmness and deformation energy, particularly within the first 2–4 days, reflecting the structural degradation of pod tissues. Significant cultivar-dependent differences were observed, with *Forastero* exhibiting the highest mechanical strength and slowest rate of softening, while *Amazonia* showed rapid degradation. These differences are attributed not only to mechanical responses, but also to the underlying biochemical and microstructural variations, including differences in the cell wall composition, fibre density, lignification, and enzymatic degradation rates. The very strong correlation between the firmness and deformation energy (r = 0.9478–0.9999; P < 0.05) confirms that the deformation

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energy is a reliable surrogate indicator of the cocoa pod firmness. Furthermore, the improved predictive performance of the Partial Least Squares Regression (PLSR) modelling with the increasing probe diameter highlights the potential for probe-optimised sensing systems in non-destructive quality assessment.

The novelty of this study lies in integrating the probe geometry, cultivar variability, and post-harvest storage effects into a unified mechanical framework while introducing the deformation energy as a robust, non-destructive indicator of pod firmness. This approach extends beyond traditional rupture-force-based assessments and provides improved predictive capabilities for cocoa pod quality evaluations. These findings have important practical implications for the design of automated cocoa pod processing systems, post-harvest handling equipment, and sensor-based quality monitoring tools.

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