

Effect of maturity and the colour parameters on the cocoa opening force using the existing mechanical system

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Abstract: The study assessed the mechanical and colorimetric properties of cocoa (*Theobroma cacao* L.) pods at various maturity stages to improve the mechanised pod-opening efficiency. Thirty pods, each replicated three times, underwent compressive loading and colour analysis using the CIE Lab* colour space to correlate the colour attributes with mechanical resistance. The pod maturity significantly ($P < 0.05$) influenced the opening force and compressive strength: unripe pods required the highest mean force (1 222 N) and strength (0.316 N.mm⁻²), while aged pods needed only 346 N and 0.094 N.mm⁻². The longitudinal orientation yielded higher and more consistent force response than the transverse orientation, with the ANOVA confirming significant differences ($P < 0.05$). The colour parameters, especially yellowness (b^*) and hue angle (H^*), were strongly and negatively correlated with the mechanical properties ($r \geq -0.99$, $P \leq 0.05$), making them reliable non-destructive indicators of maturity. The Partial Least Squares Regression (PLSR) models validated the predictive power of the combined colour and mechanical data, with the longitudinal orientation producing the highest model accuracy across all the maturity levels. Combining the colour-based maturity assessment with mechanical testing provides a robust framework for designing automated, maturity-sensitive cocoa pod-opening systems that optimise the efficiency and reduce bean damage during post-harvest handling. The research approach provided an outstanding quantitative assessment.

Keywords: colour space analysis; compressive strength; orientation effects; postharvest mechanisation; ripeness indicators

Theobroma cacao L. (cocoa) plays a crucial role in global agriculture. Efficient post-harvest processing, particularly the opening of cocoa pods to extract the beans, is essential for maximising the yield and maintaining bean quality to acceptable standards. Cocoa pods exhibit considerable variability in size, shape, shell thickness, and internal structure, all of which evolve with the maturity and

influence their mechanical response during opening. Previous studies have shown that immature pods possess higher moisture content and lower lignification, while mature pods develop harder shells due to the increased lignin deposition and reduced water content, resulting in greater resistance to fracture (Carter et al. 2017). Universal testing machines (UTMs) have therefore been widely

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applied to characterise the breaking force, compressive strength, and fracture behaviour under controlled loading conditions, with the pod maturity and loading orientation identified as critical factors influencing the rupture behaviour (Maduako and Faborode 1994; Fonsso et al. 2016). Immature pods have a higher moisture content and fewer lignified tissues, which results in lower mechanical resistance. Mature pods, on the other hand, have harder shells due to the increased lignin and decreased water content, which require more force to split effectively. Recent research into cocoa pod mechanisation has focused on the force characteristics across the maturity stages and differences in cultivars. Empirical data show a clear relationship between pod maturity and the required opening force. For example, Carter et al. (2017) discovered that immature pods required 180–250 N on average to induce fracture, whereas fully developed pods required more than 400 N due to the shell tissue density. These discoveries emphasise the importance of a maturity-sensitive design in automated pod-breaking machines. Mechanised methods like Universal Testing Machines are increasingly used to assess the cocoa pod mechanical properties such as the compressive strength, deformation, and fracture points under controlled loading conditions. In cocoa research, UTMs have been utilised to exert axial or lateral forces on pod samples to mimic the actual opening forces. Fonsso et al. (2016) used a UTM to determine the rupture force of cocoa pods of the *Criollo*, *Forastero* and *Trinitario* varieties following the Hertz theory. In a similar study, Vankayalapati et al. (2016) researched the uniaxial compression loading and cutting behaviour of cocoa pods using a UTM machine. Similarly, Ekinici et al. (2010), Sorensen et al. (2015) used UTM data to quantify the peak force needed for pod rupture, showing correlations between the maturity and pod resistance. Also, Maduako and Faborode (1994) further examined how the orientation and loading directions affect the failure pattern of cocoa pods. Universal Testing Machines have been utilised to assess the mechanical characteristics of various agricultural products, including cashew nuts (Sanchez et al. 2024). Cashew shells, like cocoa pods, demand a careful force application to prevent kernel damage. Research by Ogunsina and Bamgboye (2013) applied UTM testing to determine the cracking forces and discovered a significant influence of the nut orientation, size, and

maturity on the shell failure. The parallels in force behaviour propose that similar testing methodologies and design approaches can be adapted for cocoa pods. Despite extensive studies on the mechanical behaviour of cocoa pods, limited attention has been given to integrating objective colour-based maturity indicators with mechanical resistance and orientation-dependent opening behaviour. Furthermore, the absence of standardised maturity-sensitive design parameters restricts the optimisation of automated cocoa pod opening systems. Therefore, the aim of this study is to generate new knowledge on the combined effects of the cocoa pod maturity and loading orientation on the opening force, compressive stress, and deformation energy, while quantitatively linking these mechanical responses to the CIE L^* , a^* , b^* colour parameters. The study further seeks to establish the colorimetric attributes as reliable non-destructive predictors of the pod mechanical resistance, thereby providing a scientific basis for the development of automated, maturity-sensitive cocoa pod opening technologies.

MATERIAL AND METHODS

Preparation of cocoa samples. The cocoa pods, collected directly from the farm, were thoroughly washed with water and cleaned with a soft brush to remove any dirt and contaminants. The stalk ends were gently removed with a knife to prevent damage to the pod shell and also enable the easy positioning of the pod within the fixtures of the Universal Testing Machine. The cocoa pods were categorised into unripe, ripe, and aged maturity stages based on the external colour characteristics as summarised in Table 1.

Experimental set-up and procedure. The mechanical characteristics of cocoa pods at three maturation stages: aged, ripe, and unripe were assessed with a Hegewald & Peschke Universal

Table 1. Pod physical characteristics at different maturity stages

| Maturity | Physical characteristics |
|----------|-------------------------------|
| Unripe | fully green |
| Ripe | mix of green and yellow |
| Aged | fully yellow with black spots |

Testing Machine (Model: Inspekt Table 50 kN) at the wood testing lab of the Council for Scientific and Industrial Research-Forestry Research Institute of Ghana (CSIR-FORIG) in Kumasi. The UTM is a 50 kN electromechanical testing system with a servo drive, offering precise force measurements and programmable testing via LabMaster software. Standard laboratory conditions (ambient temperature: $25 \pm 2^\circ\text{C}$, relative humidity: $60 \pm 5\%$) were used for all the experiments. *Theobroma cacao* cocoa pods were obtained from Tafo in the Eastern region. The pods were carefully chosen to maintain consistent sizes and weights, and to ensure they were free from defects. A vernier calliper was used to measure the length, width, and thickness of each cocoa pod, unripe, ripe, and aged, before the start of the experiment. The compressive force of a total of 45 cocoa pods, comprising 15 cocoa pods per maturity stage, was measured in this study from both the lateral and longitudinal orientations. The cocoa pod deformation in both lateral and longitudinal orientations remains elastic under compressive loading until the peak load causes a macroscopic crack. When this crack reaches the shell-bean interface, it leads to an explosion, significantly decreasing the pod resistance. The cocoa pod resistance is measured until a macroscopic crack appears, causing the universal testing machine to stop loading. The cocoa pod samples with macroscopic cracks and deformation are shown in Figure 1.

Colorimetric evaluation of cocoa pods. Three values that form the foundation of a three-dimensional representation system created by the International Commission on Illumination (CIE) define the colour: L^* , a^* , b^* , where L^* represents the light-dark spectrum, a^* denotes the red-green spectrum, and b^* signifies the yellow-blue spectrum of visible light. If the chromaticity a^* and b^* values are zero (0), it indicates a grey colour. The L^* value ranges from zero for black to 100 for perfect white. An L^* value of 0 indicates that the specimen absorbs visible light, while an L^* value of 100 signifies that the specimen reflects all the incident light. The colour of the unripe cocoa pod was used as the reference state colour. The total colour difference was determined by the Euclidean distance between the reference and ageing colour states, as given by Equation (1) (Palus 1998):

$$\Delta E_{L^*a^*b^*} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

where: ΔL^* , Δa^* , and Δb^* are the differences of the initial and final values [reference (unripe) and ageing (ripe and over-ripe)] of L^* , a^* , b^* , respectively.

The chroma is a quantitative colour attribute that quantifies the vividness or dullness of a material. A higher C value indicates a higher colour intensity or saturation of the material. The chroma is determined using Equation (2) (Jha 2010):

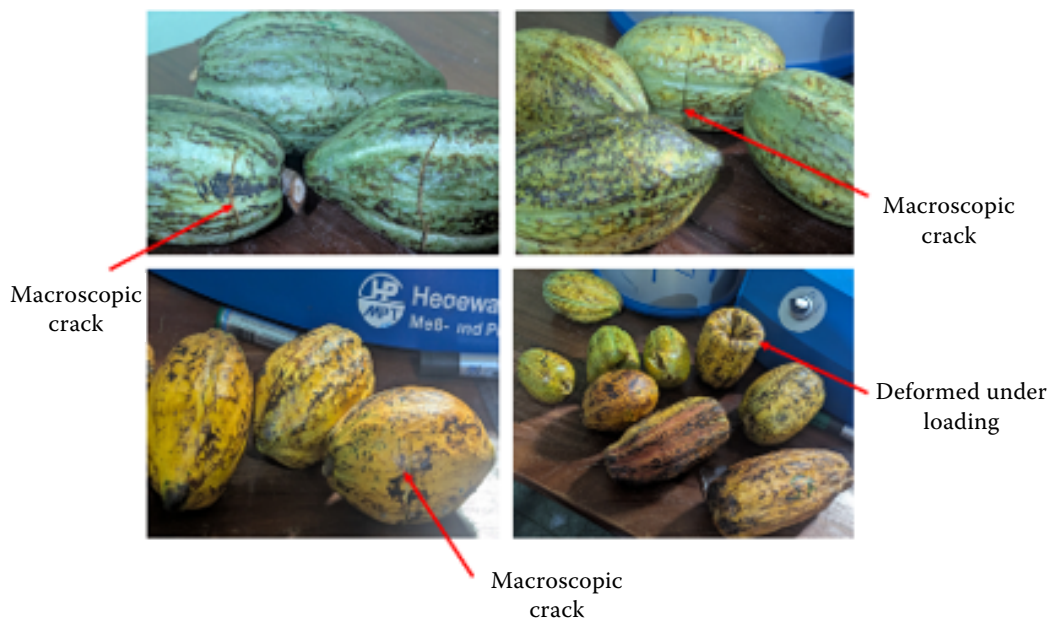


Figure 1. Samples after compression loading

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$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \tag{2}$$

Samples of the cocoa pods at different maturity stages used in the colorimetric evaluation are presented in Figure 2. Conversely, the hue (H) is a qualitative colour parameter which quantifies the extent to which the colour appearance of a material aligns with the primary colours of red-purple when $H = 0^\circ$, $H = 90^\circ$, yellow, $H = 180^\circ$, bluish-green, and $H = 270^\circ$, blue, respectively. The hue angle is determined using Equation (3) (Cantrell et al. 2010):

$$H = \arctan\left(\frac{b^*}{a^*}\right) \tag{3}$$

Statistical evaluation of the cocoa pod response to compression loading. To obtain sufficient information on the compressive forces observed, a partial least squares regression (PLSR) analysis was carried out. PLSR can easily handle data matrices, such as the measured forces, where each item is characterised by hundreds of factors. This method can generate the most reliable models and retrieve pertinent information from a vast data matrix. The prediction accuracy is assessed using the root mean square error of the prediction set

(RMSEP) and the coefficient of determination R^2 of the prediction set (R_k). The degree of correlation between the measured and predicted values is indicated by the (R_k). It is calculated using Equation (4) (Asante et al. 2021):

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

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 $\overline{S_{ip}}$ – predicted by the i^{th} and the average values of the predicted values, respectively; N – the number of samples.

The RMSE of the predicted values S_{ip} for observation i , of a regression's dependent variable, T_{ip} is computed for N different predictions as the square root of the mean of the squares of the deviations.

It is given by Asante et al. (2021):

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



Figure 2. Photos of cocoa pod at different maturity stages used in the research: (A) unripe, (B) ripe, and (C) aged

Determination of the deformation energy. The deformation energy is the energy absorbed by a material during deformation under mechanical stress, quantified as the area under the force-deformation curve until failure or permanent deformation. For biological materials such as cocoa pods, the deformation energy provides an essential measure of their structural strength, firmness, and resistance to mechanical damage during processing. In this study, cocoa pods under different maturity stages were subjected to compressive loading using a Universal Testing Machine (UTM). The resulting compressive force plunger displacement curves were analysed and the area under the curve was used to determine the deformation energy using the trapezoidal rule function of OriginLab 2019b software, where adjacent peak points are connected by straight lines creating a series of trapezoids. The total area which is the sum of all the trapezoids is the deformation energy. For a dataset where the row index (i) corresponds to the value (y_i), the deformation energy (area under the curve) is approximated by Equation (6):

$$D_{Energy} = E \approx \sum_{i=1}^{N-1} \frac{(y_i + y_{i+1})}{2} \times (x_{i+1} - x_i) \quad (6)$$

where: $(x_i + 1 - x_i)$ – the spacing between the row indices, or the time interval in a signal.

RESULTS AND DISCUSSION

Effects of maturity on cocoa pod opening force.

The force-deformation responses of cocoa pods at different maturity stages under lateral and longitudinal compression are presented in Figure 3. Clear

differences in the mechanical behaviour were observed as the pod maturity progressed. Unripe cocoa pods exhibited high rigidity, characterised by steep force-deformation slopes and high peak forces prior to fracture. This behaviour indicates a stiff, structurally intact pericarp that resists deformation until failure. Similar responses have been reported for immature cocoa pods and other hard-shelled agricultural products, where intact fibrous tissues contribute to their high mechanical resistance (Maduako and Faborode 1994; Ogunsina and Bamgboye 2013).

In contrast, ripe pods demonstrated more ductile deformation behaviour, with lower peak forces and greater deformation prior to failure. This ductility reflects physiological changes during ripening, including the enzymatic degradation of cell-wall components, a reduction in tissue stiffness, and the redistribution of internal moisture. Aged pods showed the lowest resistance to deformation and early loss of structural integrity, indicating advanced tissue weakening. Similar maturity-dependent softening trends have been reported for cocoa pods and other fruits undergoing post-harvest ageing (Amanquah 2013; Fonsso et al. 2016).

Mechanical responses were orientation-dependent, reflecting the anisotropic structure of cocoa pod tissues. Although longitudinal loading yielded more consistent force responses and superior PLSR model performance, lateral loading absorbed greater deformation energy, particularly in unripe pods, indicating enhanced resistance to fracture propagation. This confirms the anisotropic mechanical nature of cocoa pods, which arises from the alignment of fibrous tissues along the longitudinal axis. Comparable orientation-dependent mechanical behaviour has been documented in carob pods

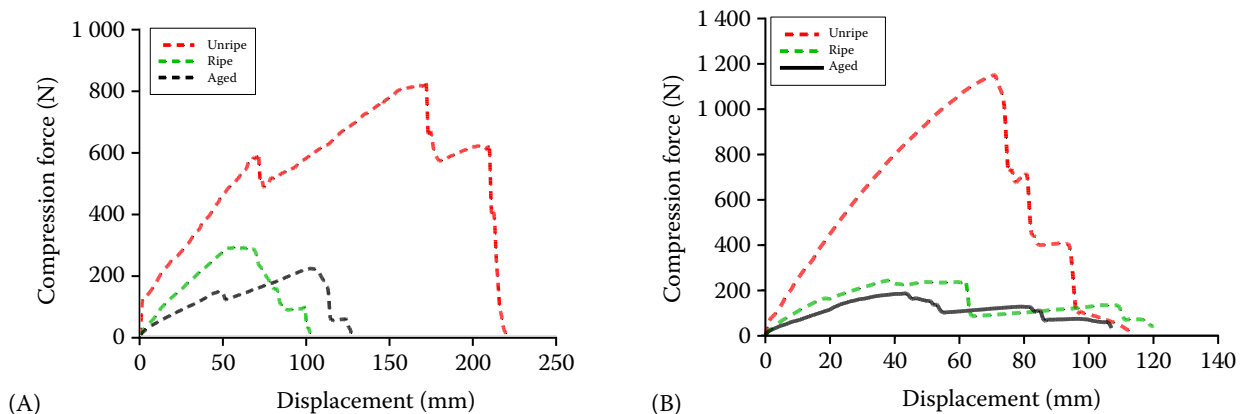


Figure 3. Force-deformation curve of cocoa pods under (A) lateral position and (B) longitudinal position

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and cashew nuts, where the load-bearing capacity is greater along the fibre-aligned directions (Ekinci et al. 2010; Ogunsina and Bamgboye 2013). The literature confirms that the fibre orientation influences the longitudinal resistance across maturity. The average maximum opening force and compressive strength values for cocoa pods at different maturity stages are presented in Table 2.

The unripe pods exhibited the highest mean opening force (1 222 N) and compressive strength (0.316 N·mm⁻²), indicating superior structural integrity and resistance to external loading. These values reflect the presence of intact, highly ordered cell wall structures and higher moisture-induced turgidity in unripe pods, which enhance resistance to deformation and fracture. The ripe pods showed a marked reduction in the mechanical resistance, with a mean opening force of 355 N and compressive strength of 0.117 N·mm⁻². This reduction corresponds to the onset of ripening processes, including the depolymerisation of hemicellulose, and the weakening of intercellular bonding. Similar reductions in fracture resistance during fruit ripening have been reported for cocoa pods and other agricultural materials (Maduako and Faborode 1994; Hu et al. 2020).

The aged pods recorded the lowest mechanical values (346 N and 0.094 N·mm⁻²), indicating advanced structural degradation. However, the rela-

tively small difference between the ripe and aged pods shows that the most pronounced mechanical weakening occurs during the transition from the unripe to ripe stages, while further ageing results in only a marginal strength loss (Amanquah 2013).

This distinction is important for mechanised pod-opening systems, as it identifies the maturity stage with the greatest variability in opening force requirements. The experimental results underscore the maturity's crucial impact on the pod-opening resistance, revealing a significant decline in the mechanical properties; Pearson correlation analysis was used to explore relationships between the mechanical properties and colorimetric characteristics across the developmental stages using Equation (7) (Mohammadzadeh et al. 2025):

$$r = \frac{[n(\sum xy) - \sum x \sum y]}{\sqrt{[n(\sum x^2) - (\sum x)^2][n(\sum y^2) - (\sum y)^2]}} \quad (7)$$

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 the squares of the dependent and independent variables. The correlation coefficient (*r*) and *P*-values are presented in Table 3.

Table 2. Mechanical properties of cocoa pods at different maturity stages

| Descriptive parameters | Maximum force (N) | | | Compressive strength σ (N·mm ⁻²) | | |
|------------------------|-------------------|--------|--------|---|-------|-------|
| | unripe | ripe | aged | unripe | ripe | aged |
| Maximum | 2 100 | 845.05 | 585.6 | 0.454 | 0.307 | 0.180 |
| Minimum | 54.75 | 165.8 | 185.65 | 0.015 | 0.06 | 0.043 |
| SD | 643.45 | 184.36 | 113.23 | 0.146 | 0.071 | 0.041 |
| Mean | 1 222.22 | 355.25 | 345.62 | 0.316 | 0.117 | 0.094 |

Table 3. Pearson correlation analysis (colourimetric parameters and mechanical properties)

| Parameters | Maximum force (N) | | Compressive strength σ (N·mm ⁻²) | |
|-----------------------|-------------------|----------|---|----------|
| | <i>r</i> | <i>P</i> | <i>r</i> | <i>P</i> |
| <i>L</i> * | -0.9994 | 0.0222 | -0.9925 | 0.0782 |
| <i>a</i> * | -0.7840 | 0.4263 | -0.8355 | 0.3704 |
| <i>b</i> * | -0.9970 | 0.0492 | -0.9999 | 0.0068 |
| <i>C</i> * | -0.9920 | 0.0805 | -0.9993 | 0.0245 |
| <i>H</i> ^o | -0.9973 | 0.0470 | -0.9869 | 0.1030 |

The Pearson correlation analysis (Table 3) shows strong negative relationships between the selected colour attributes and mechanical resistance, indicating that colour development is closely associated with structural weakening. In particular, the b^* (yellowness) and chroma (C^*) exhibited statistically significant negative correlations with both maximum opening force and compressive strength. This indicates that as cocoa pods become increasingly yellow and more colour-saturated, their mechanical strength declines (Amanquah 2013). This trend is consistent with previous studies, which have shown that chlorophyll degradation and carotenoid accumulation during ripening coincide with the enzymatic softening of fruit tissues (Schröder 2003; Hu et al. 2020).

The hue angle (H°) was also significantly correlated with the maximum force, further confirming its relevance as a maturity indicator (Salinas-Hernandez et al. 2013). The significant correlation for L^* and a^* (Table 3) show that these parameters are sensitive to changes in mechanical behaviour. Similar findings have been reported in studies on the fruit ripeness assessment, where b^* , C^* , and H° were identified as more reliable indicators of internal structural changes than lightness alone (Ilahy et al. 2018; Gong et al. 2024). These results demonstrate that colorimetric parameters can serve as effective non-destructive indicators of the mechanical resistance, which is particularly valuable for automated sorting and mechanised pod-opening applications.

Effects of compressive loading on the cocoa pods. To determine changes on the pod surface due to compressive loading, the compressive stress was calculated using Equation (8) (Thompson and Rough 2021):

$$\sigma_{cs} = \frac{O_F}{A_{cp}} \quad (8)$$

where: σ_{cs} – the compressive stress; O_F – the opening force; and A_{cp} – the average contact area of the cocoa pod.

The compressive stress profiles of cocoa pods under lateral and longitudinal loading orientations are shown in Figure 4. The unripe pods exhibited the highest compressive stress and displacement prior to failure, indicating greater resistance to crack initiation and propagation. This multi-phase fracture behaviour is typical of fibrous biological materials with intact structural networks (Ogunsina and Bamgboye 2013).

As the maturity progressed, the ripe and aged pods exhibited lower compressive stress and reduced displacement before failure, reflecting the progressive degradation of cell-wall integrity. Ripe and aged pods showed decreased compressive stress and displacement before failure, indicating cell-wall degradation. Longitudinal loading produced slightly higher stress values, but differences between orientations decreased with maturity (Table 4).

This convergence suggests that the directional strength is gradually lost as the structural components degrade. Similar maturity-related reductions in anisotropy have been reported for agricultural materials subjected to compressive loading (Sanchez et al. 2024).

Correlation between the mechanical properties and changes in the cocoa pod colour. The colour characteristics of the cocoa pods at different maturity stages are presented in Table 5. The unripe pods were characterised by low lightness

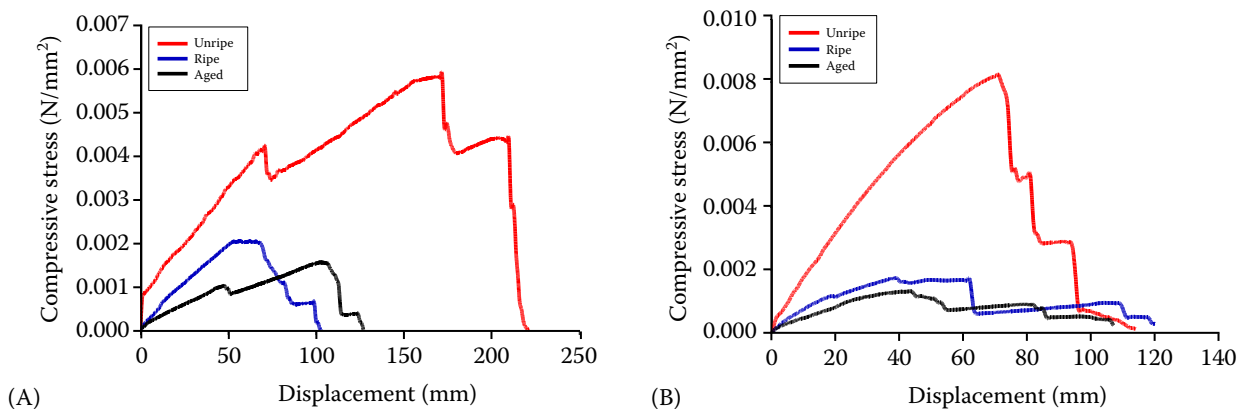


Figure 4. Compressive stress profile of the cocoa pod under (A) lateral, and (B) longitudinal orientation

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Table 4. Average compressive stress on pods at different maturity stages

| Cocoa samples | Compressive stress (N.mm ⁻²) | |
|---------------|--|--------------|
| | lateral | longitudinal |
| Unripe | 0.003776 | 0.003981 |
| Ripe | 0.00118 | 0.001018 |
| Aged | 0.000879 | 0.000774 |

($L^* = 22.93$) and negative a^* values, corresponding to dark green colouration and high mechanical resistance. As the pods matured, increases in the L^* , a^* , b^* , and chroma values were observed, indicating a transition towards brighter and more saturated colours. These colour changes coincided with substantial reductions in the mechanical strength. The ripe pods exhibited a significant decrease in the opening force and compressive strength, while the aged pods showed the lowest mechanical resistance alongside the highest colour saturation.

The inverse correlation between the colour development and mechanical strength has often been ascribed to the degradation of chlorophyll, the synthesis of carotenoids, and the enzymatic breakdown of structural carbohydrates occurring during ripening as previously noted by (Schröder 2003; Afoakwa et al. 2008). The large total colour difference (ΔE^*) between the unripe and ripe pods further supports the use of colour as an indicator of physiological maturity and internal structural disorganisation. Similar conclusions have been reported for cocoa pods and other fruits, where the colour evolution closely reflects the internal mechanical changes (Moretti et al. 2023).

Regression analysis under different pod opening orientations by the PLSR model. The partial least squares regression (PLSR) modelling revealed that the longitudinal loading orientation provided superior predictive performance compared to the lateral orientation (Table 6). The higher coefficient of determination (R^2), lower RMSE, and higher F-values under longitudinal loading indicate improved model robustness and statistical reliability. This improved performance can be attributed to the alignment of the fibrous tissues along the longitudinal axis, which produces more consistent mechanical responses under compression.

The results have important practical implications for machine design and development. The opening force scatter plots of the PLSR model for both the lateral and longitudinal orientations are presented in Figure 5.

Similar improvements in predictive modelling under fibre-aligned loading conditions have been reported for carob pods and cashew nuts (Ekinci et al. 2010; Ogunsina and Bamgboye 2013). These findings have important implications for the design of mechanised cocoa pod-opening systems, suggesting that the longitudinal orientation offers greater consistency and reduced risk of bean damage.

Colour evolution of cocoa pods. The cocoa pod colour changed significantly with maturity. The lightness (L^*) increased from 22.93 in the unripe pods to 33.34 in the overripe pods, reflecting a transition from dark green to light green and finally to yellow (Figure 2). This change is caused by the chlorophyll degradation and carotenoid accumulation during ripening, with the higher chlorophyll content in the unripe pods reducing the reflectance

Table 5. Colour characteristics of the cocoa pods at different maturity stages

| Maturity stages | L^* | a^* | b^* | C^* | H angle |
|-----------------|-------|-------|-------|-------|-----------|
| Aged | 33.34 | 10.97 | 43.22 | 44.59 | 75.73 |
| Ripe | 39.83 | 1.62 | 40.98 | 41.01 | 87.71 |
| Unripe | 22.93 | -3.74 | 19.80 | 20.15 | -79.28 |

Table 6. PLSR prediction metrics

| Lateral orientation | | | Longitudinal orientation | | |
|---------------------|--------|---------|--------------------------|--------|---------|
| R^2 | RMSE | F-value | R^2 | RMSE | F-value |
| 0.9050 | 0.5600 | 3.1630 | 0.9300 | 0.4813 | 4.4800 |

PLSR – Partial Least Squares Regression; RMSE – Root Mean Square Error

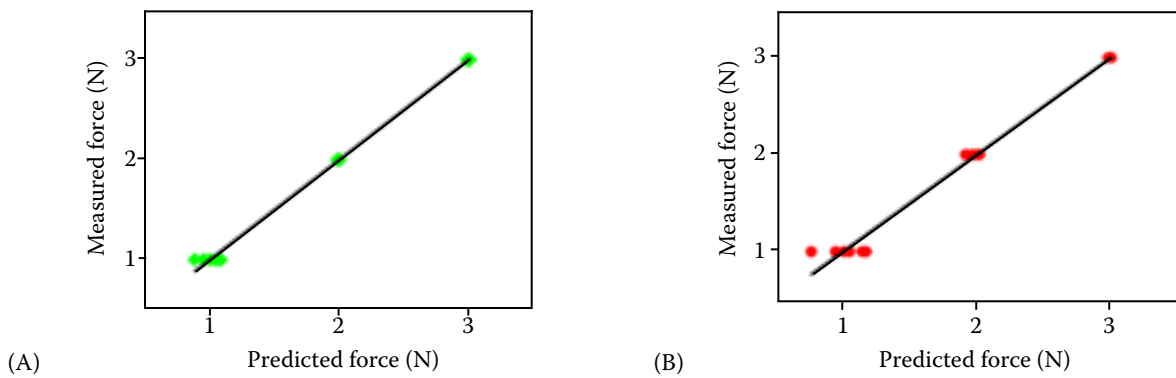


Figure 5. Opening force scatter plots under (A) lateral, and (B) longitudinal orientation

and resulting in darker colouration (Schröder 2003; Afoakwa et al. 2008; Hu et al. 2020). The large total colour differences (ΔE^*) between the maturity stages indicate visually distinct transitions that are physiologically meaningful. Similar relationships between the colour evolution and internal structural changes have been reported for cocoa pods and other fruits (Moretti et al. 2023).

Deformation energy analysis. The deformation energy behaviour of cocoa pods under lateral and longitudinal loading orientations is presented in Figures 6–8, with the quantitative values summarised in Table 7. The unripe pods absorbed significantly higher deformation energy than the ripe and aged pods, indicating greater resistance to the initiation and propagation of fracture cracks. The baseline indicates the undamaged state of the cocoa pods. The maximum compressive forces peaked at 815.52 N for the unripe pods, with decreasing forces for the ripe (287.63 N) and aged (218.8 N) pods, showing structural strength loss. The energy absorption was 117.1944 J, 17.15576 J, and 15.7310 J, respectively. As the maturity increases, the deformation energy and mechanical resistance decrease. The compressive forces under loading were 1 145.83 N (unripe), 243.01 N (ripe), and 182 N (aged). The unripe pods exhibited 85.36% greater deformation energy compared to the ripe ones; the ripe pods surpassed the aged ones by 8.30%.

As the cocoa pods transition from unripe to aged, their compressive force and deformation energy decreased, with deformation energy values of 63.9624 kJ, 17.1928 kJ, and 11.6651 kJ, respectively.

Under lateral loading, the deformation energy decreased by 85.36% from the unripe to ripe

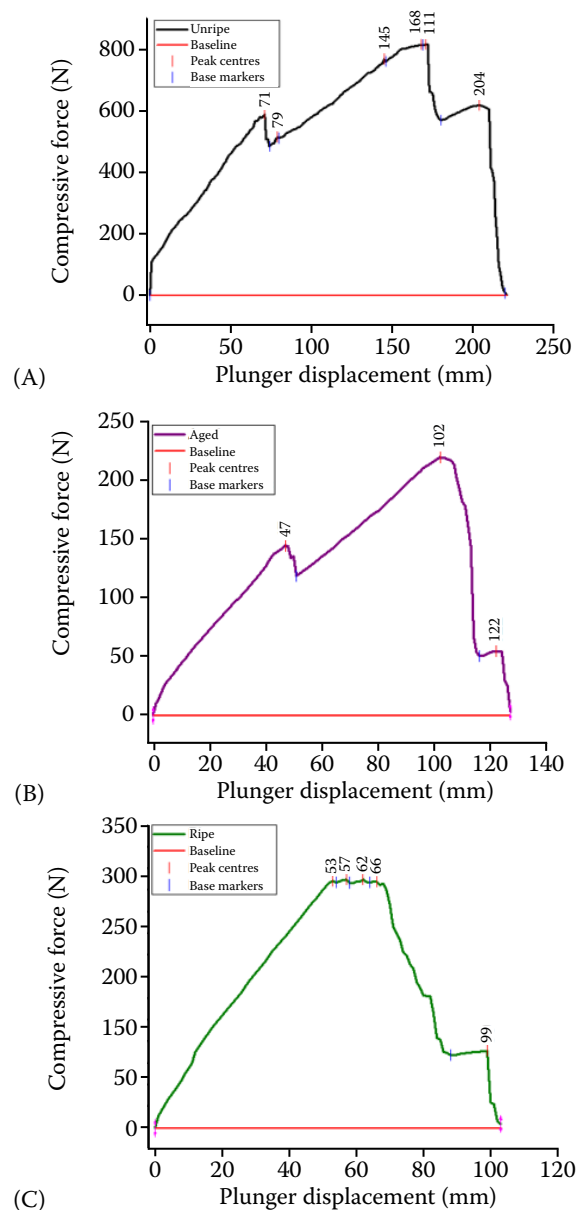


Figure 6. Deformation energy for the (A) unripe, (B) ripe, and (C) aged under lateral orientation

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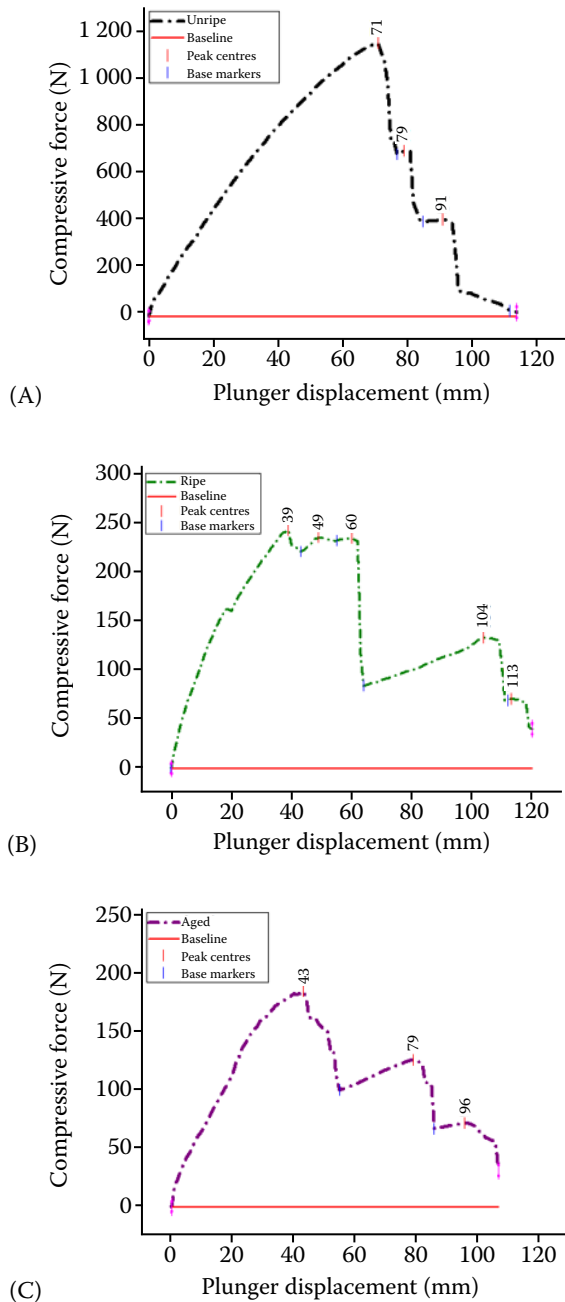


Figure 7. Deformation energy for (A) unripe, (B) ripe, and (C) aged under longitudinal orientation

pod, while, under longitudinal loading, a reduction of 73.12% was observed. These reductions reflect the progressive softening of pod tissues due to the enzymatic degradation of the cell wall components and moisture loss during maturation. Similar maturity-dependent reductions in the deformation energy have been reported for various agricultural products subjected to compressive

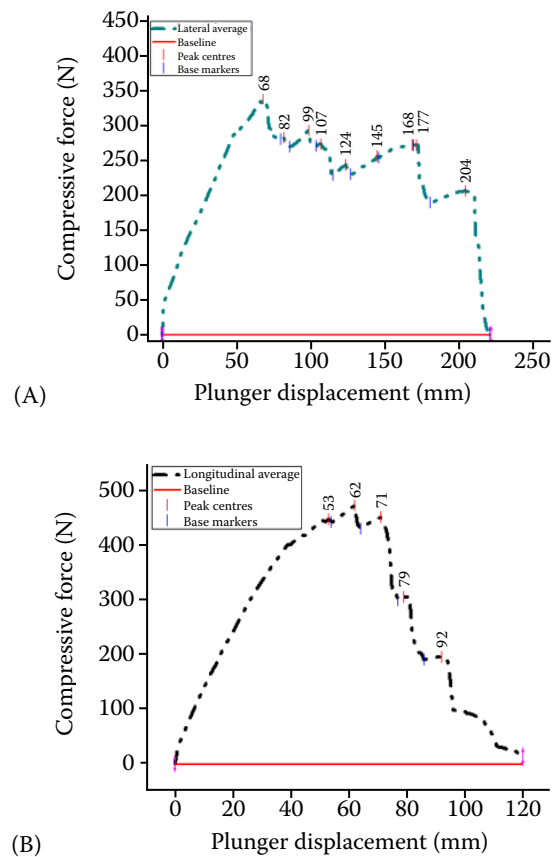


Figure 8. Average deformation energy (A) lateral, and (B) longitudinal orientation

Table 7. Quantitative values of the deformation energy

| Maturity stages | Deformation energy (J) | |
|-----------------|------------------------|--------------|
| | lateral | longitudinal |
| Unripe | 117.19442 | 63.96238 |
| Ripe | 17.15576 | 17.19284 |
| Aged | 15.73128 | 11.66509 |

loading (Ogunsina and Bamgboye 2013; Sanchez et al. 2024). The deformation energy declines with maturity in both orientations, revealing that the mature pods reduced mechanical energy absorption. The orientation affects the behaviour, aiding the design of efficient pod opening systems with minimised bean damage.

Table 7 presents the quantitative analysis of the deformation energy across the maturity stages and loading orientations. The deformation energy decreased significantly with the maturity ($P = 0.0307$). The unripe pods showed 85.36% higher energy

than the ripe ones, which was 8.30% higher than the aged ones. The lateral orientation had 38.15% higher average energy than the longitudinal orientation ($P = 0.0024$). These results indicate that both the maturity and loading direction strongly affect the pod's capacity to absorb mechanical energy before fracture, consistent with the observed reductions in compressive strength and opening force as the pods mature (Ogunsina and Bamgboye 2013; Sanchez et al. 2024).

The quantitative analysis on the deformation energy (Table 7) proved to be a sensitive indicator of the cocoa pod maturity and mechanical susceptibility. From an engineering perspective, this parameter provides valuable insight for optimising pod-opening mechanisms to minimise the energy consumption while reducing the mechanical damage to cocoa beans. This highlights the practical relevance of linking the pod mechanical properties, maturity stage with pre-treatment processes for mechanised processing (Ogunsina and Bamgboye 2013; Sanchez et al. 2024).

CONCLUSION

In this study, the mechanical and colorimetric properties of cocoa pods at different maturity stages were examined using a universal testing machine. The study generated new quantitative findings regarding the combined influence of the cocoa pod maturity, colour variation, and loading position on the mechanical opening behaviour. The results show a notable negative correlation between the pod maturity and mechanical resistance, as the unripe pods display the greatest opening force, compressive stress, and deformation energy. The longitudinal alignment consistently yielded greater force responses and enhanced predictive precision, validating its effectiveness for mechanised pod-opening uses. A major result of this study is the discovery of strong, statistically significant correlations between the colorimetric parameters, particularly the b^* , chroma, and hue angle (H°), and the mechanical properties. These results clearly indicate that the cocoa pod colour can act as a dependable non-invasive sign of the mechanical strength and maturity level. Integrating a colour parameter analysis with the mechanical properties and partial least squares regression modelling establishes a novel framework for creating intelligent, maturity-responsive cocoa

pod opening systems. The research enhances the existing knowledge by connecting the physiological colour alterations to the mechanical breakdown processes and behaviour that depend on the orientation and maturity, offering a scientific foundation for refining automated cocoa pod processing methods intended to boost the efficiency and minimise cocoa bean damage during post-harvest processing. Future studies should focus on creating non-invasive optical maturity sensors, incorporating machine learning for immediate force prediction, examining the pod structure, and connecting the mechanical characteristics to the post-harvest bean quality.

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