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ORIGINAL RESEARCH

# Development and evaluation of a mechanical model for the assessment of cocoa pod opening force

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## Abstract

Confronted with limited data on cocoa pod opening force and bean separation for optimization, several machines developed have faced challenges over the years. To address this challenge, a mechanical model for the pod opening force assessment was developed and evaluated using *Forastero*, *Amezonia***,** and *Amelonado* cocoa cultivars under 0, 2, 4, 6, and 8-day post-harvest delay. Ten *Forastero* pods were fixed one after the other between two parallel plates on the developed model on the first day of harvest. The pressure shaft was turned through a number of revolutions and the corresponding opening force was recorded using a sensor placed underneath the bottom plate for five pods under longitudinal and lateral orientations and repeated for the other postharvest delays. The process was replicated five times using *Amezonia* and *Amelonado* cultivars. Results showed that the opening force decreases with increasing postharvest delay. Terminal opening force for the *Forastero >Amezonia >Amelonado*. ANOVA showed no significant difference ($P > 0.05$) between successive postharvest delays for the *Forastero,* except 4-6 days ($P > 0.05$) for *Amelonado, and* 6-8 days ($P < 0.05$) for *Amezonia*. Therefore, the maximum postharvest delay for effective pod opening is 4 days for *Amelonado,* 6 days for *Amezonia* and 8 days for *Forastero.* The quantitative assessment of the PLSR model for the *Forastero* cultivar ($R^2$ = 0.70309; RMSE = 0.01404) is considerably better than the *Amezonia* cultivar ($R^2$= 0.68875; RMSE = 0.02134) and *Amelonado* cultivar ($R^2$ = 0.62312; RMSE = 0.01785). The technique highlighted the cultivar differences and provided excellent quantitative analysis.

**Keywords:** Cocoa Pod, Mechanical Load, Postharvest Delay, PLSR Model, Pod Orientation

## Introduction

The cocoa plant (*Theobroma cacao*) which is predominantly grown in Africa, Asia, and South America survives in warm and drizzling climates. Globally, cocoa is grown in a narrow belt of around 20 degrees on either side of the equator as it offers the perfect conditions for growing cocoa (Smith, 1960; Nyamora and Kanyeka, 2012). The cocoa tree needs high temperatures, humid conditions, and rainfall to grow successfully (Asante and Amuakwa-Mensah, 2014). *Theobroma* means "food of the gods" and is the source of many products that have sustained the whole world in diverse ways (Rusconi and Conti, 2010). In Ghana, the cocoa plant is the most important cash crop and serves as a principal agricultural revenue for smallholder farmers (Anderman *et al*., 2014). The revenue target from cocoa has been estimated to be about 70 – 90 % of annual household income in the growing counties (Asare *et al*., 2014). Nearly two-thirds of the world's cocoa beans come from West Africa, Fowler and Coutel (2017), with the Ivory Coast and Ghana being the two biggest producers (Woods, 2004). These two countries alone provide half of the world's cocoa (Higonnet *et al*., 2017). The main cocoa varieties grown in Ghana are namely the *Forastero*, *Amelonado*, and *hybrid Amezonia* (Adzaho, 2007; Amoah *et al*., 2017). These varieties have superior growth vigour and high bean yields. They are appreciable and tolerant to West African virus strains. The cocoa fruit comprises the pod, beans, placenta, and mucilaginous pulp (Joshy *et al*., *2015)*. The number of beans per pod is usually between 30 and 40 (Pod, 1989; Thompson *et al*., 2012). Usually, cocoa pods are oval and vary in size with the length typically between 200 and 320 mm. Its colour ranges from yellow or green to red-violet (Davies and Mohammed, 2014).

The pod varies significantly in thickness and the value depends on the cultivar. Figure 1, shows the cocoa fruit, beans with the pulp, as well as pod. Cocoa bean processing starts from harvesting. Harvesting starts approximately three years (hybrid/improved variety) or 4-5 years (traditional variety coming from the nursery) after planting (Edoh Adabe and Ngo-Samnick, 2014). Harvesting is done by cutting the fruit stalk with a machete, a pruning pole, shears, or a sickle (Edoh Adabe and Ngo-Samnick, 2014; Aliu and Ebunilo, 2012). After harvesting, the cocoa pod is split open and the bean is removed for the fermentation process to start. Traditionally, the opening of the pods to extract the beans is done within 3-7 days after harvesting depending on the size of the farm and labour availability. Once the beans have been fermented and dried, they can be processed (paste, powder, granules etc.,) to produce a variety of products or exported in its raw state (Achaw and Danso-Boateng, 2021). The opening of the cocoa pods whose aim is to extract the beans is a major challenge to many farmers (Joshy *et al*., 2015). Meanwhile, cracking to remove the beans is an integral part of the production chain. Therefore, getting accurate data on the required opening force to support efficient machine design and optimization of the performance is crucial. There are several techniques by which the cocoa pod can be broken with the main objective of carefully generating a crack to aid in the removal of the wet beans. These include using a wooden or any blunt object to hit the pod, hitting two pods against each other, or using a cutlass to split the pod open (Amoa-Awua, 2014). However, using the cutlass to split the pod open is the most prevalent traditional technique among the lot. Though the process is carefully and skillfully carried out, there is always the tendency of cutting through the pod and damaging the beans reducing the number of beans suitable for fermentation (Schwarz, 1928; Hancock and Fowler, 1994).

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The technique is time-consuming and dependent on the strength of manpower. Besides, farmers sometimes accidentally cut their fingers. Hence this exercise is not advisable. However, some farmers still believe the method is faster and more convenient (Aliu and Ebunilo, 2012). To eliminate drudgery, and reduce bean loss and the risk involved in removing cocoa beans, many efforts have been put in place over the years to mechanize and simplify the process. For instance, the Cocoa Research Institute of Nigeria (CRIN) which is an active producer of cocoa beans in West Africa constructed a cocoa pod splitter and reported a good performance (Choudary *et al*., 2019). A similar machine was built by Messers Christy and Norris Limited of England and tested at Cadbury Brothers Cocoa Plantation at Ikiliwindi, Cameroon (Adewumi and Fatusin, 2006). This machine required two people to operate. The pod is split open using a revolving ribbed wooden cone mounted vertically inside a ribbed cylindrical metal drum. The authors reported that an impact energy of 30.9 J is required to break one pod while 78.6 J is required for five pods at a time for a hammer speed of 3.13 m/s.

In another study, the existence of the Zinke cocoa-splitting machine which used several rotary jaws or toothed rollers was reported (Aliu and Ebunilo, 2012). The performance evaluation showed a bad result because the jaw crushes the husks further into tiny portions which makes separation difficult. Subsequently, Chamsing *et al*. (2006) and Aliu and Ebunilo (2012) assessed the performance of an impact-type hand-operated cocoa pod breaker at 3.13 m/s hammer speed and reported 93-100 % efficiency with less than 1 % seed damage. Similarly, Caleb and Akinnuli (2019) and Adu Otomfo (2014) evaluated an electrically powered cocoa pod-breaking machine at 6.6 m/s belt speed and reported 93 % efficiency with no seed damage. Further research work on the extraction of cocoa beans showed that the forces involved in breaking cocoa pods are shearing, compressive, and impact forces depending on the machine type and the process used (Josué *et al*., 2019). In Ghana, Afoakwa (2016) designed and developed a cocoa-splitting machine that could split open five cocoa pods at a time. The splitting knives were actuated by simple hydraulic mechanisms devoid of any major stresses and forces acting on them. These mechanisms were powered by simple hydrostatic hydraulic pumps with an 87.5 kW power rating. However, the machine can also operate on simple two-stroke internal combustion (IC) Engines.

To automate the production process, a Pinhalense cocoa pod breaker was developed in Brazil. The machine consists of a breaker which includes an agitator that starts the process of separating the beans from the husk, a conveyor belt, a cocoa bean pulp agitator and a pulper (García-León *et al*., 2021). The machine works automatically from the cocoa pod received through the splitting process, fermentation, drying and bean bagging (Afoakwa *et al*., 2013). Based on the literature reviewed it can be concluded that there is limited data on the required opening force, which could be used by machine developers for the optimal design of pod-breaking machines. Therefore, this study seeks to: (1) develop a mechanical model that could be used to effectively assess the opening force required to break the pod under continuous compressive loading, (2) assess the deformation (opening) force under the uniaxial compression test in both lateral and longitudinal axes for three cocoa cultivars under different post-harvest delays, (3) determine the cocoa cultivar with the highest resistance to compressive loading using the force at which opening occurs, and (4) predict the opening force for the three cocoa cultivars using partial least square regression (PLSR).

## Materials and Methods

### Description of study area and sampling

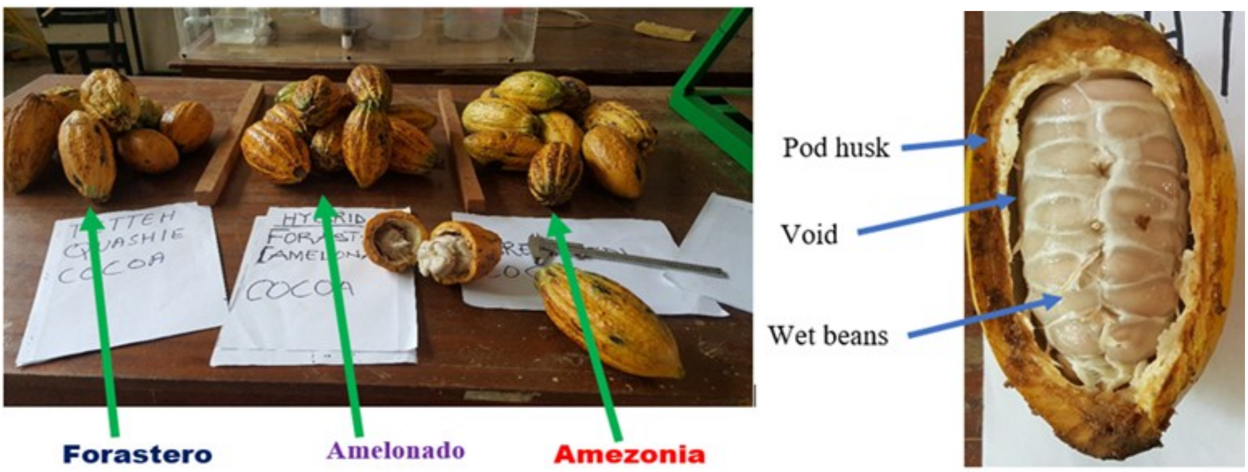
The design and fabrication of the mechanical model used for the opening force assessment and experiment were carried out at the Department of Agricultural and Biosystem Engineering workshop at the Kwame Nkrumah University of Science and Technology, Kumasi, which is located in the Ashanti Region of Ghana.

Three cocoa cultivars, namely Forastero, Amezonia and Amelonado, were used as experimental cultivar samples as shown in Figure 1. Matured, ripe and undamaged *Forastero*, *Amezonia* and *Amelonado* cocoa pods were harvested from the Cocoa Research Institute farm located in Tafo within the Eastern Region of Ghana. For each cultivar, various pod diameters (small, medium and large) were chosen and subjected to compressed loading in a lateral and longitudinal orientation.

### Development of cocoa opening force assessment model

#### *Development of the mainframe*

The developed cocoa opening force assessment model consists of a square base frame, four legs vertically inclined frame with a smaller square top frame that supports a pressure shaft (Figure 2). The turning of a horizontal arm fixed on top of the shaft provided linear motion to the shaft. This linear motion pushes a pressure plate fixed at the bottom end of the shaft downwards to provide the needed pressure required for the cocoa opening force assessment. The base frame, the four legs




(a) Different cocoa cultivars (b) Sectional view of a cocoa pod

**Figure 1** The nomenclature of cocoa and a sectional view showing the beans, pod and the void

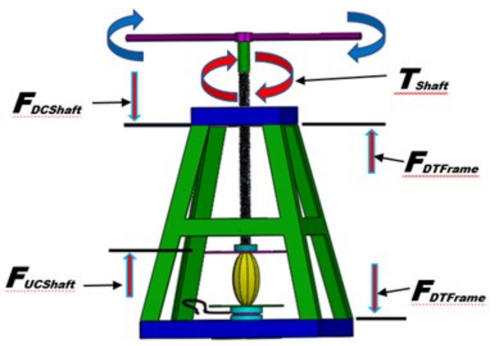



**Figure 2** Three-dimensional view of opening force assessment model with cocoa

vertically inclined frame and the top frame were all made from a 40 mm x 40 mm mild steel angle iron. The ends of the angle irons were used to form the base and the top frames were cut to 45° inwards to ensure easy joining at 90° to form a square section.

The four legs of the vertical frame were inclined at an angle of 15° to the vertical to enhance stability. To ensure that the force does not alter when the turning is halted for reading, the pressure shaft has a square thread formed on it and is screwed through a nut installed in the top frame. The bending moment diagram of the shaft was drawn to find out the maximum bending moment (M) on the shaft. Then the area moment of inertia (I) for the shaft was calculated. the maximum bending stress ($T_b$) was replaced with the given allowable stress for the shaft material. Finally, the diameter of the shaft was calculated. This was done because the shaft must have adequate torsional strength to transmit torque and not be overstressed. Besides, the shaft must sustain a combination of bending and torsional loads.

***Shaft design calculations***

The maximum shear stress theory or Guest's theory was used because the shaft material is mild steel which is one of the ductile materials commonly used for threaded shaft designs. According to the maximum shear stress theory (Talib *et al*., 2010), the maximum shear stress in the shaft is given by:

$$\tau_{\max} = \frac{1}{2}\sqrt{(\sigma_b)^2 + 4\tau^2} \quad (1)$$

Where $\tau$ = Shear stress induced due to twisting moment and $\boldsymbol{\sigma}_b$ = Bending stress (compressive) induced due to bending moment (Figure 3). The full length of the force lever on the shaft is, D = 400 mm. Half of the force lever on the shaft is represented by D/2(R) = 200 mm. The maximum measured resisting the force of the cocoa pod on the lever, $F_1 = 750\ N$ on the tight side and $F_2 = 550\ N$ on the slack side. The distance from the center line of the force lever to the centre of the nut is 70 mm. The maximum allowable shear stress ($\tau$) for mild steel is = 42 *MPa*. The torque transmitted by the shaft is given by:

$$T = (F_1 - F_2)\,R \quad (2)$$

Where $F_1$ is the force on the right side of the lever and $F_2$ is the force on the slack side of the lever.

Neglecting the weight of the shaft and force lever, the total force on the lever is:

$$F_r = (F_1 + F_2) \quad (3)$$

Therefore, the bending moment is given by:

$$M = (F_r * L) \quad (4)$$

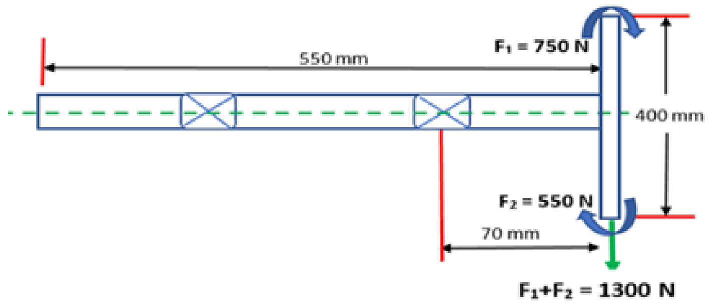



**Figure 3** Free body diagram of the shaft used to determine the maximum bending moment (M)

If d = Diameter of the shaft in mm, the equivalent twisting moment is given by:

$$T_e = \sqrt{M^2 + T^2} \quad (5)$$

But the equivalent twisting moment, $T_e$ is also given by:

$$T_e = \left(\frac{\pi}{16} * \tau * d^3\right) \quad (6)$$

Therefore,

$$d = \sqrt[3]{\frac{16T_e}{(\pi * \tau)}} \quad (7)$$

***Opening force (Uni-axial compression) assessment***

One whole cocoa pod sample for the *Forastero* was fixed into the developed opening model between two parallel plates in the longitudinal orientation on the first day after harvesting (Figure 4). The pod was compressed by turning the lever connected to the pressure shaft through 0.125 revolutions and the corresponding force was read from a sensory scale which was placed directly under the base of the mechanical model supporting the cocoa pod. The lever was further turned through 0.125 revolutions and the corresponding force readings were recorded until the cocoa pod (husk) crushes when the turning is stopped. The process was replicated using four other pods of the same cultivar. Five pods of the same cocoa cultivar (*Forastero*) were taken through the same process on the same day under lateral orientation bringing the total crushed pods to 10 pieces on the day (0) for the *Forastero*. Postharvest delay characterized as the day (0) represents the very day of harvesting the cocoa. Subsequently, the whole process was repeated after post-harvest delays of 2, 4, 6 and 8 days bringing the total samples to fifty (50) pods. The experimental evaluation process is presented in (Figure 4). The *Amezonia* hybrid and the *Amelonado* were also taken through the same force experimental procedures conducted on the forastero cultivar bringing the overall sample size to one hundred and fifty (150) cocoa pods.

The data collected was used to plot graphs to determine the variation in the opening force for the three cocoa cultivars. Subsequently, statistical models were developed using partial least square regression (PLSR) and the output was presented in the form of scatter plots. Finally, the correlation coefficient (R) and

(a) (b)

**Figure 4** (a) Model calibration, and (b) longitudinal orientation of the pod

and root mean square error (RMSE) between the measured force values and the predicted values were determined. The results obtained were used to determine the performance of the models.

**Statistical evaluation of cocoa pod response to compressive loading**

To obtain adequate information on the opening forces measured, Partial least square regression (PLSR) analysis was performed. PLSR can simply treat data matrices in which each item is described by hundreds of variables like measured forces. This technique can extract the relevant portion of the information for a large data matrix and produce the most dependable models. The coefficient of determination R square of the prediction set ($R_k$) and the root mean square error of the prediction set (RMSEP) are used to evaluate prediction precision. The ($R_k$) measures the degree of correlation between the predicted and measured values. The following expression computes it:

$$R = \frac{\sum_{i=1}^{N}\left(T_{im} - \overline{T}_{im}\right)\left(S_{ip} - \overline{S}_{ip}\right)}{\sqrt{\sum_{i=1}^{N}\left(T_{im} - \overline{T}_{im}\right)^2 * \sum_{i=1}^{N}\left(S_{ip} - \overline{S}_{ip}\right)^2}} \quad (8)$$

Where $T_{im}$ and $\overline{T_{im}}$ are the reference values of the $i^{th}$ sample and the average values of the reference values respectively; $S_{ip}$ and $\overline{S_{ip}}$ are the predicted values of the $i^{th}$ and the average values of the predicted values respectively; N is the number of samples. The RMSE of the predicted values $S_{ip}$ for observations; 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:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(S_{ip} - T_{im})^2}{N}} \quad (9)$$

## Results and Discussion

### Assessment of cocoa pod opening force

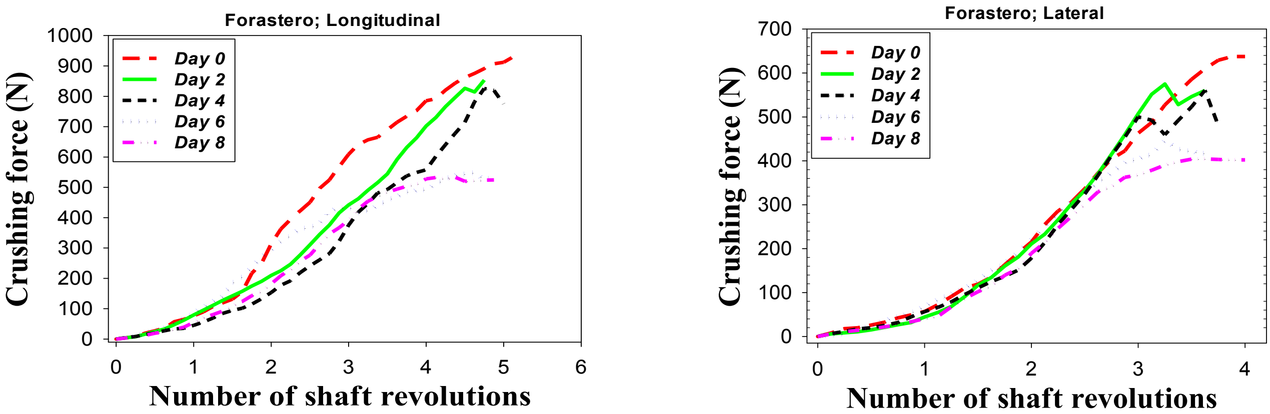
#### *Forastero* cocoa pod

The opening force assessed for the *Forastero*, *Amezonia* and *Amelonado* cocoa pods was carried out under longitudinal and lateral orientations for different postharvest delay conditions. The results for the *Forastero* under longitudinal and lateral orientations are shown in Figure 5. Furthermore, the results showed that the pod opening force increases gradually and linearly from 0 to 130 N with an increasing number of shaft revolutions. Subsequently, the opening force began to increase sharply from 130 N at about 1.5 shaft revolutions to a maximum of 975.1, 853.5, 825.5, 549.4 and 533.7 N at 5.75, 4.75, 5.00, 4.88 and 4.88 shaft revolutions for 0, 2, 4, 6 and 8-days postharvest delay respectively (Figure 5a). Due to closeness and overlaps that occurred (Figure 5), averages were computed and used to determine the differences. Average values of 475.66, 346.55, 314.78, 308.98 and 277.49 N were obtained for 0, 2, 4, 6 and 8-days postharvest delays. The trend showed that the average opening force decreases with increasing postharvest delay which was due to ripening and fermentation of the cocoa pod. Delaying the opening of the pod for 2, 4, 6 and 8 days decreases the opening force by 27.14, 33.82, 35.04, and 41.66 % respectively.

The results for lateral orientation for different postharvest delays were computed and plotted in Figure 5b. The 0, 2, 4, 6 and 8-day postharvest delay yielded maximum opening forces of 637.65, 575.11, 560.81, 446.36 and 404.76 N which occurred at 4.00, 3.62, 3.75, 3.62, and 3.63 shaft revolutions respectively (Figure 5b). Furthermore, 268.68, 227.62, 225.10, 207.38 and 202.71 N average opening forces were obtained for 0, 2, 4, 6 and 8-day postharvest delay respectively. The postharvest delay of 2, 4, 6 and 8 days decreases the average opening force by 15.28, 16.22, 22.82, and 24.55 % respectively.

***Forastero pod orientation effect on compressive loading***

Comparing the results for longitudinal and lateral orientations, a graph of the opening force averaged over the entire postharvest delay was plotted (Figure 6). There was an obvious rise in the opening force for both orientations which occurred at 1.5 shaft revolutions but terminated differently. The terminal values of (975.11 N; 5.37 shaft revolution) and (519.93 N; 4.00 shaft revolution) were obtained for longitudinal and lateral orientation respectively. The terminal opening force for the longitudinal was 46.68 % higher than that of the lateral. The higher opening force for the longitudinal orientation was because the




**(a)** **(b)**

**Figure 5** Opening force of Forastero cocoa pod for different postharvest delays under **(a)** longitudinal, and **(b)** lateral positioning

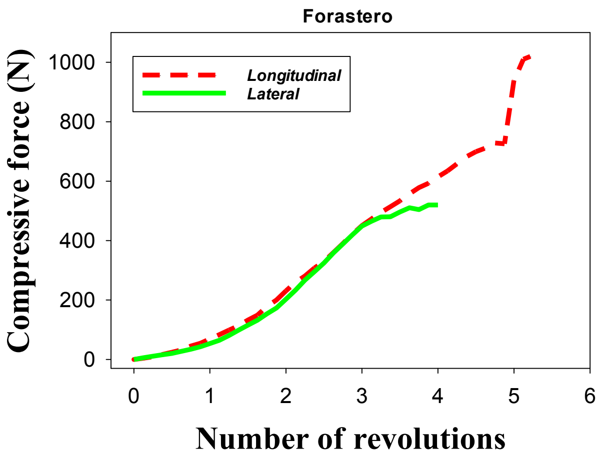



**Figure 6** Average opening force of *Forastero* cultivar for all postharvest delay under longitudinal and lateral positioning

fibre in the cells of the cocoa pod is aligned in the longitudinal direction which provides the cocoa pod with higher resistance to deformation, this result confirms earlier research (Joshy et al., 2015, Vankayalapati and Rajesh, 2016). Furthermore, the cocoa pod is narrow in the longitudinal orientation with a smaller cross-sectional area leading to higher resistance to the pressure coming from the shaft. Finally, the smaller cross-sectional area makes the distance from the centre of the cocoa pod axis where the force is acting to the circumference shorter at any cross-section. This condition allows a certain percentage of the pressure coming from the shaft to be dissipated. Therefore, more force needs to be applied to crush the cocoa pod under longitudinal orientation than the lateral orientation.

***Amezonia cocoa pod***

The opening force for the *Amezonia* cocoa pods under longitudinal and lateral orientations for different postharvest delay conditions is shown in Figure 7. There were closeness and overlaps among the curves for all the postharvest delays except the curve for the 8 days postharvest delay, which shows a lower trend and is separated from the others. The opening force increased steadily to a maximum of 701.4, 656.68, 638.39, 448.71 and 349.24 N for 0, 2, 4, 6 and 8-day postharvest delay respectively (Figure 7a). The average opening force varied from 346.05 N at the 8-day postharvest delay to 165.20 N at the day 0 delay. Delaying the opening of the pod for 2, 4, 6 and 8 days decreases the opening force by 7.34, 14.36, 25.97, and 52.26 % respectively.

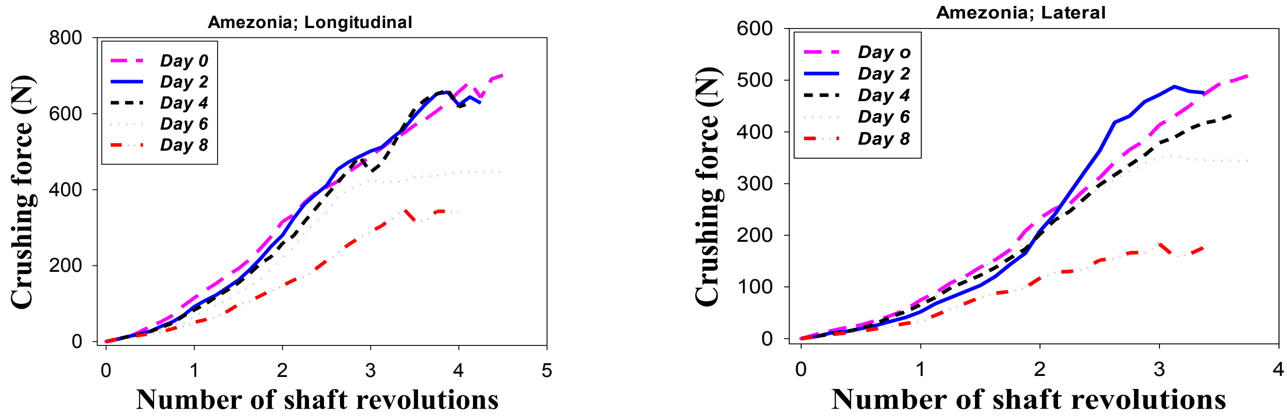
The results for lateral orientation for different postharvest delays were computed and plotted in Figure 7b. The 0, 2, 4, 6 and 8-day postharvest delay yielded maximum opening forces of 509.63, 487.75, 434.09, 355.12 and 183.20 N which occurred at 3.75, 3.12, 3.62, 3.13 and 3.00 shaft revolutions respectively (Figure 7b). Furthermore, 225.00, 200.41, 193.91, 188.73 and 89.39 N average opening forces were obtained for 0, 2, 4, 6 and 8-day postharvest delay respectively. The postharvest delay of 2, 4, 6 and 8 days decreases the average opening force by 10.93, 13.81, 16.12, and 60.27 % respectively.

***Amezonia pod orientation effect on compressive loading***

The *Amezonia* pod opening force averaged over the entire postharvest delay for the longitudinal and lateral orientation was plotted in Figure 8. The terminal opening values of (575.06 N; 4.5 shaft revolution) and (427.37 N; 3.75 shaft revolution) were obtained for longitudinal and lateral orientations respectively. The terminal opening force for the longitudinal was 25.68 % higher than that of the lateral. Similarly, average values of 293.05 N and 191.83 N were obtained for the longitudinal and lateral orientations respectively with a 34.54 % difference. This condition is similar to what happened when the opening force for the *Forastero* was assessed, which once again confirms that extra force needs to be applied to crush the cocoa pod along the longitudinal axis than along the lateral axis (Amoah et al., 2017).

***Amelonado cocoa pod***

The opening force for the *Amelonado* cocoa pods along the longitudinal and lateral axis for different postharvest delay conditions is shown in Figure 9. The opening force increased steadily to a maximum of 575.85, 527.64, 442.23, 298.81 and 206.40 N for 0, 2, 4, 6 and 8-day postharvest delay respectively (Figure 9a). The average opening force varied from 136.67 N at the 8-day postharvest delay to 346.04 N at day 0 delay. Delaying the opening of the pod for 2, 4, 6 and 8 days decreases the opening force by 10.70, 28.56, 52.79, and 63.39 % respectively. The results for lateral orientation for different postharvest delays were computed and plotted in Figure 9b. The 0, 2, 4, 6 and 8-day postharvest delay yielded maximum opening forces of 499.53, 434.78, 331.58, 248.19 and 183.45 N respectively. Furthermore, 222.23, 202.66, 191.93, 117.15 and 100.70 N average opening forces were obtained for 0, 2, 4, 6 and 8-day postharvest delay respectively. The postharvest delay of 2, 4, 6 and 8 days decreases the average opening force by 8.80, 13.63, 47.28, and 54.68 % respectively.




(a) (b)

**Figure 7** Opening force of *Amezonia* cocoa pod for different postharvest delays under (a) longitudinal, and (b) lateral positioning

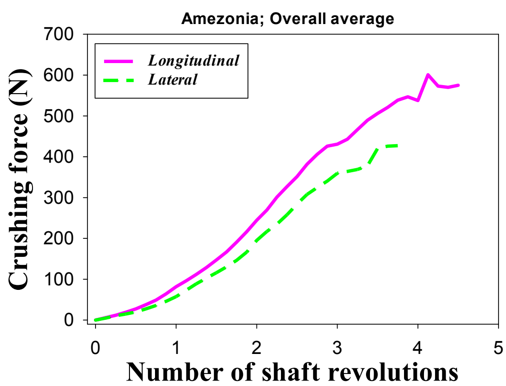
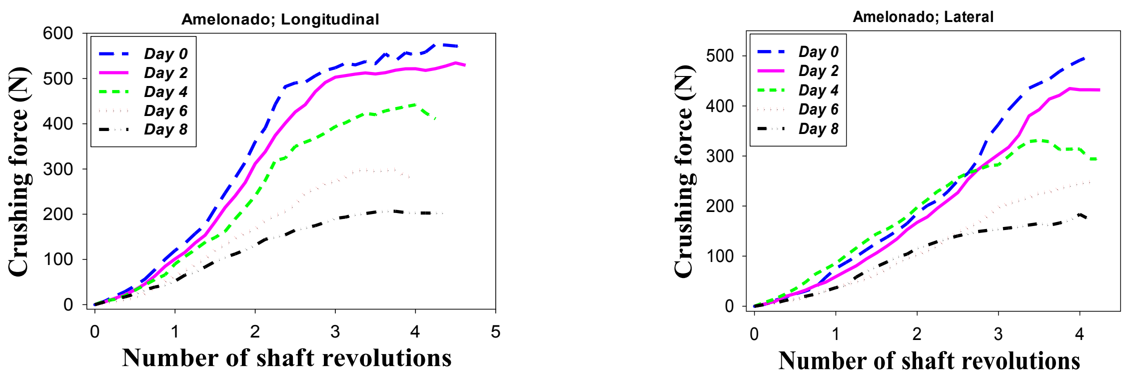



**Figure 8** Average opening force of *Amezonia* cultivar for all postharvest delay under longitudinal and lateral positioning

lateral axis for the different cocoa cultivars averaged over the entire postharvest delay were plotted (Figure 11). Comparing the results, it is clear that the terminal opening force was 975.11, 575.06 and 434.60 N for *Forastero*, *Amezonia* and *Amelonado* respectively (Figure 11a). Consequently, the terminal opening force for the *Forastero* was 41.03 % higher than that of the *Amezonia* with the Amezonia having 24.62 % higher than the *Amelonado* hybrid. Similarly, the number of shaft revolutions at which the opening force terminates were 5.38, 4.50 and 4.38 for *Forastero*, *Amezonia* and *Amelonado* respectively.

The pod opening forces assessed along the lateral axis for the different cocoa cultivars averaged over the entire postharvest delay were plotted (Figure 11b). Matching the results, it is clear that the terminal opening force was 529.93, 427.37 and 363.15 N for the *Forastero*, *Amezonia* and *Amelonado* respectively. Consequently, the terminal opening force for the *Forastero* was 17.80 % higher than that of the *Amezonia* with the *Amezonia* having 15.03 % higher than the *Amelonado* hybrid. Results show that the overall average pod opening force for the *Forastero* cultivar under each orientation was higher than *Amezonia* with the *Amelonado* cultivar being the least. This was because the pod for the *Amelonado* cultivar transforms faster from the brittle-like state at harvest to a more malleable state due to over-ripening and fermentation as postharvest delay increases. This statement confirms an earlier research conducted by Koné *et al*. (2021). It is therefore obvious that the resistance of the cocoa cultivar to compressive loading using the terminal opening force could be ranked as (*Forastero* > *Amezonia* >*Amelonado*).




(a) (b)

**Figure 9** Opening force of *Amelonado* cocoa pod for different postharvest delays under (a) longitudinal, and (b) lateral positioning

***Amelonado pod orientation effect on compressive loading***

The *Amelonado* pod opening force averaged over the entire postharvest delay for the longitudinal and lateral orientation was plotted in Figure 10. The terminal opening values of (434.60 N; 4.38 shaft revolution) and (363.15 N; 4.25 shaft revolution) were obtained for longitudinal and lateral orientations respectively. The terminal opening force for the longitudinal was 16.44 % higher than that of the lateral. The terminal values for the *Amelonado* cultivar were the same as the maximum values in the data set. Furthermore, the longitudinal and lateral orientations yielded 242.66 N and 170.64 N average values respectively with a 29.68 % difference.

**Comparison of cultivar resistance to compressive loading**

The pod opening forces assessed along the longitudinal and

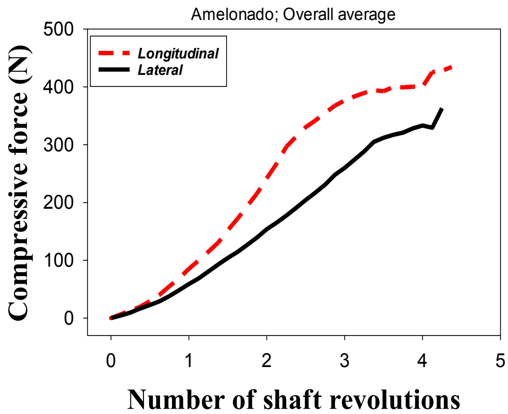
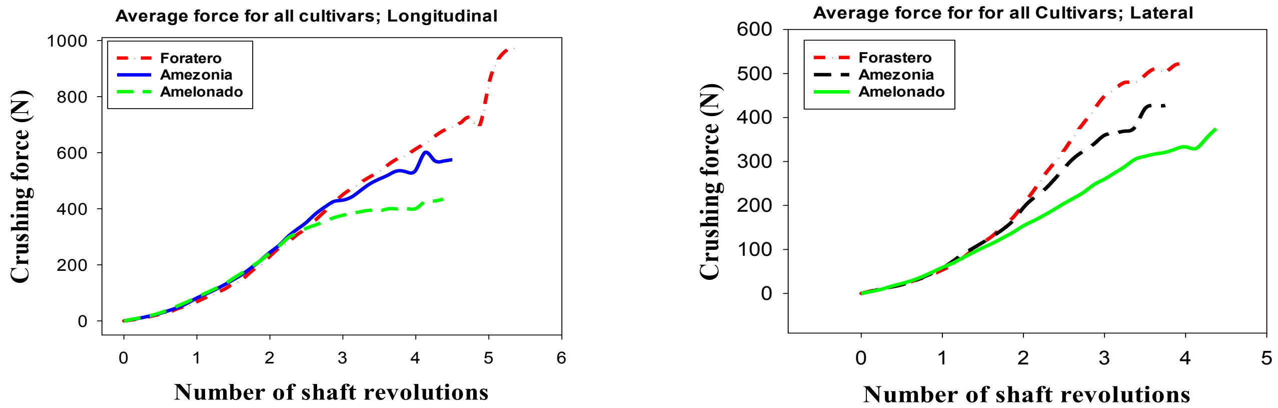



**Figure 10** Average opening force for the *Amelonado* (Hybrid) for all postharvest assessments along the longitudinal and lateral positioning.




(a) (b)

**Figure 11** Average pod opening force for all cultivars under (a) longitudinal, and (b) lateral orientations

**Optimum postharvest delay for effective cocoa pod opening**

The effect of 0, 2, 4, 6 and 8-day postharvest delays averaged over both orientations were computed and presented in Figure 12. In the case of the *Forastero*, successive postharvest delays of 0–2 days, 2–4 days, 4–6 days and 6–8 days, decreased the average opening force by 22.97, 7.03, 4.22 and 4.26 % respectively. Subsequently, analysis of variance performed on the data showed no significant differences ($p > 0.05$) between the successive postharvest delays (Table 1). This was because the ripening of the cocoa and subsequent deterioration of the pod was slow within the entire 8 days postharvest delay period leading to no significant change in the opening force. Therefore, the maximum postharvest delay for effective crushing is 8 days. In the case of the *Amezonia*, successive postharvest delays of 0–2 days, 2–4 days, 4–6 days and 6–8 days, decreased the average opening force by 14.89, 5.03, 4.12 and 48.11 % respectively with no significant differences ($p > 0.05$) except 6 –8 days ($p < 0.05$). Therefore, the maximum postharvest delay for effective crushing is 6 days (Table 1).

Furthermore, analysis of the *Amelonado* pod showed that successive postharvest delays of 0–2 days, 2–4 days, 4–6 days and 6–8 days, decreased the average opening force by 6.16, 16.37, 39.62 and 14.83 % respectively with no significant differences ($p > 0.05$) except 4–6 days ($p < 0.05$). This indicates that severe fermentation of the beans inside the pod which generate heat and causes the husk to decay begins after 4 days (Schwan and Wheals, 2004). The husk at this stage starts transforming which can clearly be seen physically hence reducing the pod's resistance to compressive loading. Therefore, the maximum postharvest delay for effective crushing is 4 days (Table 1). The colour of the cocoa pod begins to change from yellow to brown as the beans become mouldy and start to germinate inside the pod after the critical postharvest delay for a given cultivar (Maduako and Faborode, 1994, Nair, 2021, Belitz et al., 2009). Therefore, it is prudent to open the cocoa pod within 4, 6 and 8 days after harvest to avoid any appreciable beans loss for the *Amelonado*, *Amezonia* and *Forastero* respectively, confirming an earlier research by Vankayalapati and Rajesh (2016).

To determine the significance of postharvest delay on the opening force, an analysis of variance was performed on the average postharvest delay for all the cultivars. The results of the p-values which defines the probability of getting a result that is either the same or more extreme than the actual observations are presented in Table 1.

**Regression analysis of Cocoa pod opening force by PLSR model**

The variability features in the opening force make it difficult to segregate the force curve changes with different postharvest delays. The opening force is proportional to the degree of pod cell damage due to the postharvest delay period and thickness of the attenuating species in the material sample. This is because the husk could have more cell damage at a longer postharvest delay which weakens the resistance to compressive loading than at a shorter postharvest delay. It was required to select the subintervals which contain the most information on opening force changes instead of the whole interval so as to reduce the impact of instability features. Finding the best input intervals was based on a study by Noda (2018), which shows that there is a direct correlation between the intensity changes, and the strength of the peak (Zhang *et al*., 2017). In this study, four intervals were selected as follows: 0.125– 075 revolution, 1.125–1.750 revolution, 2.125–2.75 revolution, and 3.125–3.75 revolution. PLSR models were built after the interval selection, and Figure 13 shows the performance in the form of scatter plots.

The specific comparisons of the evaluation parameters were the R square and RMSE as shown in Table 2. The quantitative assessment result obtained for the PLSR model of the *Forastero* cultivar ($R^2$ = 0.70309, RMSE = 0.01404), is considerably better than the PLSR model of the *Amezonia* cultivar ($R^2$ = 0.68875, RMSE = 0.02134) and the PLSR model of *Amelonado* cultivar ($R^2$ = 0.62312, RMSE = 0.01785) respectively. The force prediction for *Forastero* was better than *Amezonia* and *Amelonado* cultivars due to differences in the pod thickness and cultivar resistance to compressive loading.

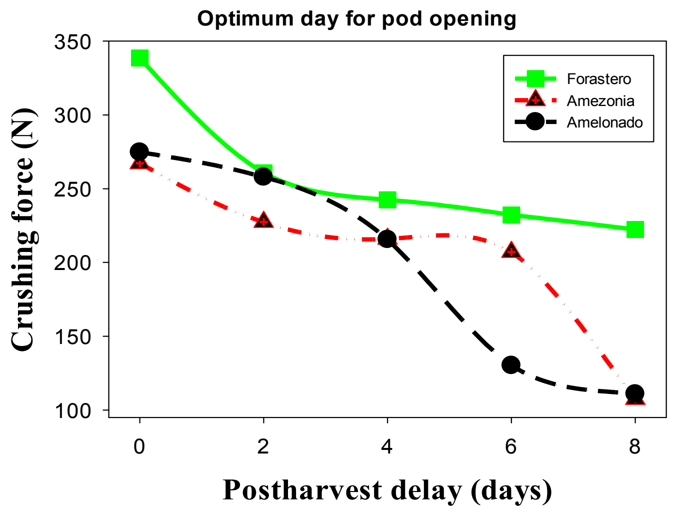


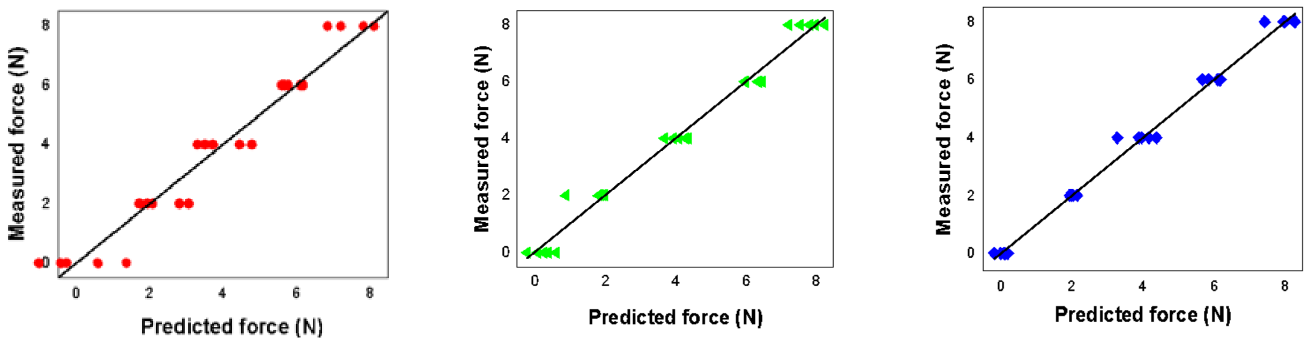

**Figure 12** The average opening force against postharvest delays for all cultivars

**Table 1** ANOVA on average postharvest delay for all cultivars

| Between Postharvest Delays | *P*-values | | |
|---|---|---|---|
| | *Forastero* | *Amezonia* | *Amelonado* |
| 0 – 2 | 0.0890 | 0.3273 | 0.6021 |
| 2 – 4 | 0.6449 | 0.7568 | 0.2855 |
| 4 – 6 | 0.7712 | 0.8076 | 0.0043 |
| 6 – 8 | 0.0883 | 0.0003 | 0.3243 |

**Table 2** PLSR Analysis

| Models | $R^2$ | RMSE |
|---|---|---|
| Forastero | 0.70309 | 0.01404 |
| Amezonia | 0.68875 | 0.02134 |
| Amelonado | 0.62312 | 0.01785 |




(a) (b) (c)

**Figure 13** Scatter plots of PLSR Analysis for (a) *Forastero*, (b) *Amezonia,* and (c) *Amelonado*

## Conclusion

A mechanical model for the assessment of Cocoa pod opening force has been developed and evaluated under compression test in both longitudinal and lateral orientations using three cocoa cultivars as experimental samples. The applied force drops sharply just after the pod has ruptured due to the internal partial void of the pod. The opening force decreases with increasing postharvest delay. The pod deforms instead of crushing after 4, 6, and 8 days for *Amelonado, Amezonia*, and *Forastero* respectively. This was because the ripening of the cocoa and subsequent deterioration of the pod begins after 4, 6, and 8-days respectively leading to a significant change in the opening force.

The resistance of the cocoa cultivar to compressive loading using the force at which the opening occurs has been determined and ranked as *Forastero* > *Amezonia* >*Amelonado*. The opening resistance and other mechanical properties of the pod could be affected by the compression rate and cocoa cultivar due to differences in thickness. The PLSR model showed that the *Forastero* cocoa cultivar had the highest correlation coefficient between the measured and the predicted values with the lowest RMSE and the *Amelonado* cocoa cultivar had the least performance. The technique applied in measuring the opening forces highlighted the cultivar differences and provided a measuring sequence and excellent quantitative analysis.

## Conflict of Interest Declarations

The authors declare that there is no conflict of interest with the information presented in this paper.

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