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Effect of Maturity Stages on Physical Properties of Cocoa (*Theobroma cacao L.*) Pods

Babatunde Oluwamayokun Soyoye[1], Nazmi Mat Nawi[2,3]*, Mohamad Ariffin Zulkifli[2], Guangnan Chen[4], Nurfadzilah Madian[2,5], Ahmad Faiz Mokhtar[2], Siti Nooradzah Adam[2] and Dimas Firmanda Al Riza[6]

[1]*Agricultural and Environmental Engineering Department, School of Engineering and Engineering Technology, Federal University of Technology, Akure, Nigeria*
[2]*Institute of Plantation Studies, Universiti Putra Malaysia 43400 Serdang, Selangor Malaysia*
[3]*Department of Biological and Agricultural Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[4]*School of Agriculture and Environmental Science, University of Southern Queensland, Toowoomba, QLD 4350, Australia*
[5]*Division of Cocoa Upstream Technology, Cocoa Research and Development Centre, Malaysian Cocoa Board, Jalan Jengka 23. P. O. Box 34, 28000, Temerloh, Pahang, Malaysia*
[6]*Biosystems Engineering Department, Faculty of Agricultural Technology, Universitas Brawijaya, Jalan Veteran, Malang 65145, Indonesia*

ABSTRACT

Cocoa is one of the main plantation crops in Malaysia. Significant efforts have been made to modernise the industry using mechanisation and automation technologies. Thus, determination of the physical properties of cocoa pods at different maturity stages is paramount for an appropriate design and development of a post-harvest machinery system for pod breaking, sorting and grading. This study investigated the effect of five different maturity stages (unripe, under-ripe, ripe, very-ripe and over-ripe) on the physical properties of cocoa pods. A total of 80 cocoa pods (Clone PBC140) were used as samples, where 16 pods represented each maturity stage. For the unripe stage, the largest mean dimensional values were 172.45, 89.3 and 111.18 mm for the pods' length, diameter and geometric mean diameter, respectively. The highest mean values of 0.66 and 0.54 for the over-ripe stage were recorded for sphericity and aspect ratio, respectively. The geometric mean diameter, weight and

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E-mail addresses:
bosoyoye@futa.edu.ng (Babatunde Oluwamayokun Soyoye)
nazmimat@upm.edu.my (Nazmi Mat Nawi)
ariffin@myinvent.com.my (Mohamad Ariffin Zulkifli)
Guangnan.Chen@usq.edu.au (Guangnan Chen)
nurfadzilah@koko.gov.my (Nurfadzilah Madian)
faiz_mokhtar@upm.edu.my (Ahmad Faiz Mokhtar)
snadzah@upm.edu.my (Siti Nooradzah Adam)
dimasfirmanda@ub.ac.id (Dimas Firmanda Al Riza)
* Corresponding author

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firmness were found to be inversely proportional to the maturity stages. The advanced maturity stages experience greater colour intensity, as reflected in the chroma *(C*)* and higher L^*, a^* and b^* values. This study has found that the colour and texture of the cocoa pods change throughout their maturity. In conclusion, the results reported in this study can be used as a reference for designing and developing a machinery system for post-harvest fruit processing.

Keywords: Cocoa fruits, colour intensity, dimensional analysis, firmness, maturity stages

INTRODUCTION

Cocoa (*Theobroma cacao L.*) is one of the most prominent and lucrative plantation crops commonly grown in tropical regions worldwide. In the last decade, world cocoa production has reached 4.48 million tonnes annually, valued at USD98.38 billion, with a steady production increment of 3% annually (Beg et al., 2017). Cocoa is a perennial tropical crop that continuously produces pods throughout the year to fulfil tremendous demand for cocoa-based products, especially chocolates. Cocoa beans are the main cocoa product used to produce chocolate and its derivatives, including cosmetics, foods and pharmaceutical products (Subroto et al., 2023). In addition, it was revealed that cocoa, rich in flavonoids, has also been used in the medical industry due to its ability to reduce high blood pressure and increase the suppleness of blood vessels (Avendaño-Arrazate et al., 2018).

Typically, a cocoa pod is an ovoid indehiscent fruit 15–30 cm long and 8–10 cm wide, available in various shapes such as oblate, spherical, elliptical and oblong (Ramji et al., 2018). The skin surface of a cocoa pod can be smooth or rough during its immature state with green and red colours, depending on its genotype (Avendaño-Arrazate et al., 2018). Generally, unripe cocoa pods have green or reddish-purple skin, which changes to yellowish or reddish-orange when they mature (Motamayor et al., 2013). The colour of cocoa pods is one of the indicators of their maturity level, and farm workers widely use it to decide when to harvest the crop. Harvesting is an initial field operation which could influence the quality level of cocoa beans during post-harvest processing (Apriyanto, 2016). Ideally, only fully ripe pods should be harvested for optimum yield and quality of cocoa beans (Rojas et al., 2020). However, since the maturity level of cocoa during harvesting is subjectively determined by visual inspection, it is difficult to ensure that all the harvested cocoa pods are at optimum maturity levels. Sometimes, slightly overripe and underripe cocoa pods are also harvested.

After harvesting, cocoa pods will be sent to a processing centre for post-harvest processing. Post-harvest processing of cocoa pods includes sorting, breaking, splitting, fermenting, drying, and storage (Forte et al., 2023). Post-harvest handling is a crucial step to be considered because it can greatly affect the yield of cocoa beans (Subroto et al., 2023). Unfortunately, in most countries, labourers still carry out post-harvest processing manually.

Post-harvest processing of cocoa should be modernised to cope with the growing demand using mechanisation and automation technologies, which could reduce the drudgery to workers, thus increasing the efficiency of the process (Arulmari et al., 2021). In specific terms, mechanisation technology is needed to replace labourers, especially during the post-harvest processing of matured cocoa pods, which involves handling, sorting, cleaning, grading, pod breaking and drying.

The physical properties of cocoa pods during harvest should be quantified to develop specific machinery for processing equipment. Among the typical physical properties of the pods to be measured are size, volume, mass, density, friction angle, angle of repose, curvature, sphericity, colour, and firmness (Arulmari et al., 2021). Various types of cleaning, grading, separation, and conveying equipment were designed and constructed based on the physical properties of the targeted crops (Sandoval et al., 2019). Thus, this study was carried out to investigate the effect of different maturity stages of cocoa pods on their physical properties. The findings of this study will provide useful data for the design and development of various cocoa processing machines.

MATERIALS AND METHODS

Materials Acquisition and Preparation

Cocoa pod samples from clone PBC140 were carefully selected for experimentation. The clone was chosen because it has a fine and unique flavour as well as good agronomic traits (Haya et al., 2021). A total of 80 cocoa pods, with 16 pods for each maturity stage [unripe *(UR),* under-ripe *(DR),* ripe *(RP),* very-ripe *(VR)* and over-ripe *(OR)*] were acquired from the Cocoa Research and Development Centre, Malaysian Cocoa Board (MCB), Jengka, Pahang, Malaysia. The fruits were carefully chosen to guarantee they were free from being infested by pests and diseases, and their size and weight were remarkably uniform. Subsequently, the maturity stages of the harvested cocoa pods were determined and classified by a senior research officer from the Centre based on the characteristics as presented in Table 1. Before the commencement of the experiment, the fruits were cleaned with a soft brush, labelled and numbered to assist the identification process. The dimensional parameters such as the length, diameter and weight were taken and recorded immediately after harvesting on the farm. Then, the fruits were immediately transported to a laboratory at the Institute of Plantation Studies, Universiti Putra Malaysia, for laboratory analysis. All the laboratory experiments were concluded within 24 hours after harvesting.

Table 1
Characteristics of the cocoa pods at different maturity stages

Maturity Stage	Characteristic
Unripe (UR)	Fully green
Under-ripe (DR)	More green than yellow
Ripe (RP)	Mix of green and yellow
Very-ripe (VR)	More yellow than green
Over-ripe (OR)	Fully yellow

Determination of Physical Properties

The physical properties of each cocoa pod sample, such as length, *L* and diameter, *D*, were measured using digital vernier callipers (Mitutoyo Corporation, Kawasaki, Kanagawa, Japan. Model 500-196-20). In contrast, the weight was measured using an electronic balance (A&D GF-10K, precision weighing balance, USA, sensitivity: ±0.03 g). The diameter was measured in the middle of the pod, perpendicular to its length. The geometric mean diameter (*GMD*), sphericity (*S*), aspect ratio (R_a) and surface area (S_A) were determined using Equations 1 to 4.

$$Geometric\ mean\ diameter\ (GMD) = \sqrt[3]{(L \times D^2)} \quad [1]$$

$$Sphericity\ (S) = \frac{GMD}{L} \quad [2]$$

$$Aspect\ ratio\ (R_a) = \frac{L}{D} \quad [3]$$

$$Surface\ area\ (S_a) = \pi(GMD) \quad [4]$$

Where *L* is the length while *D* is the diameter of the pod (m), respectively.

Colour Measurement

The colour of the cocoa pod samples was measured using a colorimeter (CR-400, Minolta Corp, Osaka, Japan) with a measuring head of 8 mm in diameter and calibrated with standard white tiles. Before the measurement, the colorimeter was calibrated to values Y = 85.40, X = 0.3184 and y = 0.3356 as recommended in the manual at room temperature. The colour readings of the cocoa pods were measured from six different portions of each fruit. The mean of these measurements was determined, and the colour description of the fruits was described as the CIE values where lightness (L^*) was represented from 0 (black) to 100 (white), redness (a^*) was represented by red to green components of the colour, where +ve a^* (positive) is more to red values and –ve a^* (negative) is more to green values, yellowness (b^*) was represented by yellow to blue components of the colour, where +ve b^* (positive) more to yellow values and –ve b^* (negative) more to blue values, chroma (C^*) was represented by saturation or vividness of the colour, and hue (h°) was the actual colour which varies continuously from 0° to 360°. A h° of 0° or 360° corresponds to red, 90° to yellow, 180° to green, and 270° to blue (Ly et al., 2020). After taking the first three readings, the last three were taken after 180° rotation of the samples, giving six readings for each cocoa pod sample.

Moisture Content Measurement

Moisture content was determined using an air oven method according to the Association of Official Analytical Chemists (AOAC) standard (Rojas et al., 2020). Each of the cocoa pod samples was weighed using an electronic balance (Mettler Toledo Model- JS1203C, Columbia. sensitivity: ± 0.0002 g) and placed in a petri dish inside a recirculating oven (Memmert GMBH, Model-30-1060, Germany). The samples were dried for 24 h in the oven at 70ºC, and the dry weight was recorded. The sample was dried and weighed again every 3 h until a constant weight was obtained. The moisture content was determined based on a wet-weight basis method (MC%, w.b.) using Equation 5.

$$Moisture\ content\ (\%)w.b. = \frac{W_2 - W_3}{W_2 - W_1} \quad [5]$$

Where W_1 is the weight of the petri dish, W_2 is the weight of the petri dish with the sample before drying, and W_3 is the weight of the petri dish with the sample after drying.

Firmness Determination

The firmness of the cocoa pod samples was measured using an Instron Universal Testing Machine fitted with a 6.0 mm diameter plunger tip and 5 kg load cell (GY-1, G-tech Ltd., China). Figure 1 illustrates the intact cocoa pod which was placed on the plate before the Instron probe was allowed to punch the fruit to 5 mm depth at a crosshead speed of 20 mm min^{-1} into each punch, following the same speed applied by Wang et al. (2019). The firmness readings were recorded in Newton (N) using Instron Merlin Software version M12- 13664-EN. These measurements were made at three points per fruit to represent the pods' upper, middle and lower portions.

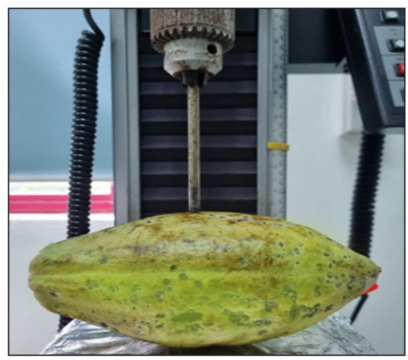

Figure 1. Firmness test using Instron Universal Testing Machine

Statistical Analysis

A one-way analysis of variance (ANOVA) complemented with Turkey (honestly significant difference) HSD Post Doc tests were used to establish the significant effect of maturity stages on the properties of the cocoa pods. All the data analyses were done using Statistical Package for Social Sciences (SPSS) software (Version 25.0, SPSS Inc. Chicago, USA).

RESULTS AND DISCUSSION

Dimensional Characterisation

The dimensional results reveal the differences in the physical morphologies of the fruits at different maturity stages, as presented in Table 2. The size of the cocoa pods was determined based on their length and diameter. The length and diameter of the pods ranged from 152 to 198 mm and 81 to 99 mm, respectively, for the *UR* category; 151 to 195 mm and 80 to 99 mm, respectively, for *DR* maturity stage; 145 to 181 mm and 77 to 93 mm respectively for *RP* category; 142 to 181 mm and 77 to 93 mm respectively for *VR* category and 136 to 194 mm and 74 to 99 mm respectively for *OR* maturity stages. The largest mean dimensional values of 172.45 mm, 89.30 mm and 111.18 mm were recorded for the length, diameter and geometric mean diameter of the cocoa pods for *the UR* maturity stage, respectively. The least 159.45 mm, 85.15 mm and 104.92 mm were recorded for the *OR* maturity stage. In contrast, the least values of 159.45 mm, 85.15 mm and 104.92 mm for the same categorical order were recorded for the *OR* maturity stage, respectively. This finding shows that the dimensional values decreased as the maturity level increased.

There is no significant difference in the diameter of the cocoa pods for all maturity stages. In addition, at the maturity stages of *DR, RP* and *VR*, the length exhibits no significant difference in the mean values. However, the maturity stages of *UR* and *OR* show significant differences in the pods' length and geometric mean diameters (P>0.05). The findings align with the published study by Bojacá et al. (2019), who reported that a decrease in the dimensional parameters of the fruits was a sign that fruit growth does not occur during the ripening process. In addition, Doaré et al. (2020) reported that fruit development depended on climatic factors such as temperature and genetic variation in the fruiting cycle. The results of ANOVA reveal that the effect of maturity stages on the geometric mean diameter of the cocoa pods was significantly different (P<0.05). The geometric mean diameter of the cocoa pods decreased as the maturity stage increased from *UR* to *OR* category.

Table 2
Dimensional properties of the cocoa pod samples

Property	Variation	Maturity Stage				
		UR	***DR***	***RP***	***VR***	***OR***
Length (mm)	Min	152.00	151.00	145.00	142.00	136.00
	Max	198.00	195.00	200.00	181.00	194.00
	Mean	172.45^{b}	168.15^{ab}	171.00^{ab}	164.95^{ab}	159.45^{a}
	SD	11.91	12.13	15.12	11.88	16.05
Diameter (mm)	Min	81.00	80.00	79.00	77.00	74.00
	Max	99.00	99.00	95.00	93.00	99.00
	Mean	89.30^{a}	87.05^{a}	87.60^{a}	86.70^{a}	85.15^{a}
	SD	4.85	5.36	4.07	5.16	6.08
Geometric mean diameter (mm)	Min	100.78	99.69	96.73	94.43	91.46
	Max	122.63	121.28	121.35	115.28	123.89
	Mean	111.18^{b}	108.38^{ab}	109.43^{ab}	107.40^{ab}	104.92^{a}
	SD	6.09	6.50	6.04	6.39	8.14

Note. $^{a\text{-}b}$ Equal letters in a column mean that there are no significant differences based on the Tukey-HSD test (P>0.05)

In the same trend, the highest mean values of 0.66 and 0.54 were recorded for sphericity and aspect ratio for the *OR* maturity stage, respectively (Table 3). In contrast, the lowest mean value of 329.61 mm^2 was obtained for the surface area of the *OR* maturity stage, and the highest surface area of 349.27 mm^2 was recorded for the *UR* maturity stage. At all maturity stages, no significant difference was recorded for sphericity and aspect ratio. However, there was a significant difference in surface area between *UR* and *OR* maturity stages (P>0.05).

Table 3
Sphericity, aspect ratio and surface area of the cocoa pod samples

Parameters	Variation	Maturity Stage				
		UR	***DR***	***RP***	***VR***	***OR***
Sphericity	Mean	0.65 ^{a}	0.65 ^{a}	0.64 ^{a}	0.65 ^{a}	0.66 ^{a}
	SD	0.02	0.02	0.03	0.02	0.02
Aspect ratio	Mean	0.52 ^{a}	0.52 ^{a}	0.51 ^{a}	0.53 ^{a}	0.54 ^{a}
	SD	0.03	0.03	0.04	0.03	0.03
Surface area (mm^2)	Mean	349.27 ^{b}	340.48 ^{ab}	343.78 ^{ab}	337.42 ^{ab}	329.61 ^{a}
	SD	19.12	20.43	18.99	20.08	25.59

Note. $^{a\text{-}b}$ Equal letters in a column mean that there are no significant differences based on the Tukey-HSD test (P > 0.05)

Firmness

The summary of the firmness level of the cocoa pods at different maturity stages is presented in Table 4. It is evident from the Table that the firmness level decreased as the maturity stages increased from *UR* to *OR* categories. It shows that firmness is inversely proportional to the maturity stages. The mean maximum value of 148.30 N was recorded for the firmness of *UR* pods, while the mean minimum value of 130.44 N was recorded for the firmness of *OR* pods. The results agree with the report by Rojas et al. (2020), which also showed a significant decrease in fruit firmness as the maturity state of cocoa pods increased. Yapo et al. (2013) reported that the decrease in firmness in relation to maturity stages may be related

Table 4
Descriptive analysis of the firmness values for different maturity stages

Maturity Stage	Max (N)	Min (N)	Mean (N)	SD
UR	198.86	107.82	148.30^b	23.50
DR	199.64	107.32	145.79^b	22.61
RP	199.48	89.47	142.38^{ab}	28.39
VR	200.03	75.66	138.03^{ab}	26.49
OR	188.52	73.16	130.44^a	24.83

Note. $^{a\text{-}b}$ Equal letters in a column mean that there are no significant differences based on the Tukey-HSD test (P>0.05) to the bark's high fibre and pectin contents, which can degrade to ethylene-independent components and affect the fruit texture. In addition, Torres et al. (2015) also stated that the decrease in firmness with respect to maturity is more pronounced in climacteric fruits like bananas and papaya.

Moisture Content and Weight

The results of the moisture content and weight of cocoa fruits at different maturity stages are presented in Table 5. The moisture content does not significantly differ from one another within the group and at different maturity stages (P>0.05). In contrast, a significant difference occurred between the weight of cocoa fruit between *UR* and *OR* maturity stages (P>0.05). Loss of weight and moisture content were observed as the maturity stage increased. The early increase in moisture content of the cocoa fruit may be attributed to the fact that the maturity stages of *UR* to *DR* might be termed a developmental stage where moisture is required for metabolic reactions.

Table 5
The effect of maturity stages on moisture content and weight

Maturity Stage	Moisture Content (%)		Weight (g)	
	Mean	SD	Mean	SD
UR	85.84[a]	1.84	643.91[a]	95.89
DR	86.50[a]	0.91	586.74[ab]	94.69
RP	86.48[a]	1.02	576.89[abc]	104.44
VR	85.44[a]	1.15	523.51[bc]	88.14
OR	83.78[b]	1.51	494.07[c]	113.43

Note. [a-c] Equal letters in a column mean no significant differences based on the Tukey-HSD test (P>0.05).

Consequently, as the maturity stage of *RP* was attained, the moisture content began to decrease due to fruit shrinkage. The fruit had completed its developmental stage, attained maturity, and was ready to be harvested. Rojas et al. (2020) reported that the moisture content of cocoa pods showed a significant decrease in values as the maturity level increased. In addition, Lopez and Dimick (1995) recommended that the over-ripe pods should not be utilised because they tend to be dry, and their beans have the potential to germinate inside the pods and are susceptible to a fungal disease.

Colour Measurement

The colour parameters of the cocoa pod samples at different maturity levels are presented in Table 6. The samples from the *OR* maturity stage have higher values for L^* (58.90), followed by the *VR* maturity stage (58.84) and the least L^* values were obtained at the *UR* maturity stage (51.66). It is evident from Table 6 that the maturity stages and L^* values exhibit direct proportionality (*L** increased as the maturity stage increased). The result aligns with the report by Lockman et al. (2019), who reported that the *L** increased from 53.87 to 59.71 as the maturity level increased. The same trend was also observed for the values of *b** and the chrome *C** and there were significant differences in all maturity stages for the colour index of *b** and *C** (P>0.05). Rojas et al. (2020) also reported that the cocoa pods exhibited a significant increase in *a*, b** and *C** as their ripeness increased. The authors also reported that the *L** increased as the ripeness increased, showing that the brightness of the bark increased as the maturity stages increased.

Table 6
Colour parameters of the cocoa pods at different maturity stages

Maturity Level	Variation	Colour Parameters				
		L^*	a^*	b^*	C^*	$h^*(^o)$
UR	Mean	51.66^a	-6.96^a	18.15^a	19.48^a	-68.99^a
	SD	4.56	1.31	1.65	1.67	3.78
DR	Mean	53.05^a	-7.23^a	20.98^b	22.28^b	-68.69^a
	SD	4.18	1.65	3.89	3.72	16.89
RP	Mean	56.48^b	-6.42^a	27.58^c	28.44^c	-74.34^a
	SD	4.11	2.07	5.48	5.23	17.36
VR	Mean	58.84^c	-4.06^b	33.75^d	34.19^d	-67.67^a
	SD	3.78	3.43	4.38	4.13	46.63
OR	Mean	58.90^c	4.63^c	40.53^e	41.17^e	39.36^b
	SD	3.99	6.14	5.25	5.85	72.95

Note. $^{a-e}$ Equal letters in a column mean that there are no significant differences based on the Tukey-HSD test (P>0.05)

The *UR, DR, RP,* and *VR* maturity stages have negative (-ve) values of *a**, which shows the presence of green pigments in the samples, while positive (+ve) *a** values were recorded for the *OR* maturity stage. The results justified the visual classification of the cocoa fruits when the pod is fully yellow and fully matured (*OR* maturity stage). For hue (h°), the *OR* maturity stage was the only sample with positive (+ve) values (tan $\theta = +$ve). The h° value of 39.36° was recorded for the *OR* maturity stage, and this falls in the first quadrant, making the samples showcase yellow pigments to complement the *a** results. There is no significant difference in the hue angle or colour index of all the maturity stages except in the *OR* maturity stage with a mean value of 39.36 °hue (P>0.05).

CONCLUSION

This study has quantified the physical properties of the cocoa pods (clone PBC140) at different maturity stages. This study investigates considerable physical differences between the maturity stages (*UR, DR, RP, VR* and *OR*). The cocoa pods in early maturity stages have the largest length, polar diameter, weight and firmness values. The moisture content peaked between the *DR* and *RP* maturity stages and decreased as maturity progressed. The advanced maturity stages experienced greater colour intensity, as reflected in the chroma (C^*) and higher L^*, a^* and b^* values. The results showed that all the parameters considered in this study exhibit different patterns during the maturation process of the cocoa pods. It is also evident that the colour and texture of the fruits change throughout their maturity. In conclusion, the data presented in this study can be used as a reference for designing and developing a mechanisation system for the cocoa industry.

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