Journal of Halal Science and Research (JHSR)
Vol. 7, No. 2, Month September, Year 2026, Page 170 – 178
doi: 10.12928/jhsr.v7i2.17088

P-ISSN: 2715-6214
E-ISSN: 2964-4909

Physical characterization and mass modeling of dried fermented cocoa beans: Implications for halal processing

Putri Rousan Nabila[1*], Satria Bhirawa Anoraga[1,4], Sang Norma Lintang Asmara[1], Jhauharotul Muchlisyiyah[2], Jamilu Suleiman[3]

[1]*Department of Bioresources Technology and Veterinary, Vocational College, Universitas Gadjah Mada, Blimbing Sari, Caturtunggal, Depok, Sleman, Special Region of Yogyakarta, 55281, Indonesia*
[2]*Department of Food Science and Biotechnology, Faculty of Agricultural Technology, Universitas Brawijaya, Jl. Veteran, Ketawanggede, Lowokwaru, Malang City, East Java, 65145, Indonesia*
[3]*Department of Agricultural and Bio-Environmental Engineering, Faculty of Engineering, Federal University Dutsin-Ma, Katsina-Kankara Road, Dutsin-Ma, Katsina, 5001, Nigeria*
[4]*Field Research Center, Universitas Gadjah Mada, Wates, Kulon Progo, Special Region of Yogyakarta, 55651, Indonesia*
**Corresponding author: rousannabila@ugm.ac.id*

ABSTRACT

This study characterized dried fermented cocoa beans and developed empirical regressions to predict individual-bean mass from simple geometric descriptors. Length, width, and thickness were measured with high-resolution calipers, then used to derive geometric mean diameter, projected areas in three orthogonal orientations and their criterion average, spheroidal volumes, and surface area. Four model families linear, quadratic, logarithmic, and power—were fitted under a fixed significance level. A clear performance hierarchy emerged. The quadratic model based on geometric mean diameter provided the strongest prediction ($R^2 = 0.990$), followed by thickness ($R^2 = 0.945$). Furthermore, the width in logarithmic form ($R^2 = 0.955$) also performed a strong prediction. Area-based models confirmed the centrality of geometry: the criterion projected area achieved $R^2 = 0.956$, single-view PAL reached $R^2 = 0.899$, and surface area derived from geometric mean diameter matched the best volume model ($R^2 = 0.961$). Volume surrogates assuming prolate and oblate spheroids performed competitively ($R^2 = 0.961$ and 0.948, respectively). These findings indicate that a geometry-based approach can support rapid and consistent grading with minimal instrumentation. In halal cocoa-processing systems, the models may also support standardized raw-material acceptance, batch documentation, and traceability by providing reproducible physical criteria for recording and separating cocoa-bean lots. The approach therefore offers a practical basis for sorter configuration, intake quality control, and transparent process documentation where rapid mass estimation is required.

Article History
Submitted: July 14, 2026
Revised: September 26, 2026
Accepted: September 29, 2026
Published: September 30, 2026

Keywords
Cocoa beans, Dimension mass modeling, Halal traceability, Physical characteristics, Quadratic regression.

© 2026 The Author(s). Published by Universitas Ahmad Dahlan.
This is an open–access article under the CC–BY–NC–SA license.

INTRODUCTION

Cocoa beans are globally recognized as the primary raw material for producing chocolate liquor, cocoa butter, and cocoa powder, which serve as essential ingredients in confectionery, beverages, and other food products (Chaudhary et al., 2025). Originating from the Amazon basin of South America, cocoa cultivation has expanded to various tropical regions, including Africa and Southeast Asia, due to favorable climatic conditions and strong economic demand (Esan et al., 2025). Postharvest processing

P-ISSN: 2715-6214
E-ISSN: 2964-4909

of cocoa beans is a complex sequence involving pod breaking, seed fermentation, and drying, which significantly influences bean quality and flavor development (Subroto et al., 2023). Among these steps, fermentation is particularly critical, as it facilitates the biochemical reactions responsible for generating flavor precursors and reducing undesirable bitterness. The subsequent drying phase stabilizes these precursors, ensuring that the beans maintain optimal chemical and physical characteristics for subsequent industrial processing (Santander et al., 2025). Roasting further enhances desirable volatile compounds while improving brittleness and dehulling efficiency. Uniformity in cocoa bean quality, shaped by genetic variety, fermentation control, and precise drying, plays a decisive role in maintaining consistent flavor, texture, and aroma during chocolate manufacturing (Putri et al., 2024). A high degree of uniformity also contributes to process predictability and consumer satisfaction by minimizing variability during roasting and grinding operations. Maintaining this uniformity from farm to factory requires comprehensive attention to postharvest handling and process standardization (Lima et al., 2024).

Knowledge of the physical and mechanical properties of agricultural commodities is crucial for designing and optimizing postharvest systems. Dimensions, volume, surface area, and density affect how materials behave during cleaning, transport, drying, and storage (Sanchez et al., 2024). For cocoa beans, such parameters determine the efficiency of dehulling, nib separation, roasting, and oil extraction operations. Reliable data on these properties guide engineers in specifying equipment geometry for conveyors, elevators, and dryers to ensure uniform flow and minimal damage (Looh et al., 2025). Despite cocoa's industrial significance, few studies have comprehensively documented its physical properties, particularly after fermentation and drying. International grading standards use physical indicators including bean count per 100 g, uniformity, and absence of visible defects like mold or cracks (Federation of Cocoa Commerce, 2019). These parameters not only reflect quality but also influence the design of screens, feeders, and dehullers. Accurately quantifying such properties helps refine equipment configuration, enhances postharvest efficiency, and ensures consistent quality assurance throughout cocoa processing.

Research on the physical characterization and mass modeling of fruits and nuts has generated valuable data for agricultural engineering. Studies on date (Khodabakhshian & Emadi, 2016), kinnow mandarin (Mahawar et al., 2019), Terminalia chebula (Pathak et al., 2019), Kendu (Panda et al., 2020), and pepper berries (Azman et al., 2021) have established correlations between geometric features and product mass. Most employed regression models—linear, quadratic, or power—to predict mass using easily measurable dimensions such as surface area, volume, or geometric mean diameter. High coefficients of determination were often achieved; for instance, Azman et al. (2021) reported $R^2 = 0.995$ for pepper berries based on actual volume, while Mahawar et al. (2019) obtained $R^2 = 0.956$ using geometric mean diameter for kinnow mandarins. Panda et al. (2020) also found strong mass–volume correlations for Kendu fruits, and Pathak et al. (2019) measured Terminalia chebula with longitudinal axes averaging 31.08 mm and mass from 1.73 to 9.79 g. Collectively, these studies confirm that empirical models offer practical, low-cost tools for mass estimation, improving grading precision and reducing manual effort. Their success across multiple commodities suggests similar modeling can be applied to other irregular-shaped agricultural products to enhance automation and throughput in postharvest operations.

Although mass modeling has advanced in other crops, little is known about the geometric and physical behavior of dried fermented cocoa beans. Information on Indonesian varieties remains limited, creating a barrier to designing locally adapted processing systems. Bean morphology varies with genotype, fermentation time, and drying intensity, factors that alter dimensions, density, and surface structure. These variations affect flowability, packing efficiency, and heat transfer during roasting or grinding (Haruna et al., 2025). Quantifying such parameters is crucial for quality assessment and mechanical design. Dimensions such as length, width, thickness, and sphericity are key indicators of maturity and quality, informing grading standards and enabling mechanized selection (Ghonimy et al., 2025). Examining the three-dimensional shape of beans from smallholder plantations, including those in Gunungkidul, Yogyakarta, provides insight into variability linked to cultivation and processing practices. These data are essential for designing conveyors, graders, and dryers suited to regional production characteristics (Onwude & Chen, 2021). Generating systematic data on these properties can

P-ISSN: 2715-6214
E-ISSN: 2964-4909

strengthen postharvest efficiency, support technology development, and enhance competitiveness in Indonesia's cocoa sector.

Cocoa beans are plant-derived materials, but their use in halal food production also requires control over the processes through which they are received, stored, transported, and transformed into cocoa ingredients (Sentellas & Saurina, 2023). Halal assurance extends beyond the origin of the raw material because processors must maintain traceability and prevent uncontrolled mixing or contamination throughout production and distribution (Bachtiar et al., 2025). In cocoa processing, consistent identification and recording of incoming bean lots can support this requirement. Physical parameters such as mass, dimensions, volume, surface area, and projected area provide measurable criteria for classifying raw materials and documenting their movement through grading, storage, roasting, and further processing (Bannor et al., 2026). Reliable mass-prediction models may therefore complement halal traceability systems by supporting standardized intake records, batch separation, equipment calibration, and process consistency.

To address this knowledge gap, the present work characterizes the physical attributes of dried fermented cocoa beans and models their relationship with mass through empirical regression analysis. Measurements include weight, length, width, thickness, sphericity, volume, surface area, and projected area, evaluated using linear, quadratic, and power models to identify the most accurate predictive relationships. The resulting models provide technical information for grading, handling, equipment design, and raw-material standardization. They may also support halal cocoa-processing systems by providing reproducible physical criteria for batch recording, raw-material segregation, and traceability. This study therefore connects cocoa-bean engineering properties with the operational controls required for consistent and transparent food processing.

RESEARCH METHOD

Materials

The cocoa beans that have been fermented and dried under the same conditions were bought from a local farmer in Patuk, Gunungkidul, Special Region of Yogyakarta, Indonesia. Dried fermented cocoa beans were brought to the laboratory within two hours. To determine their physical characteristics, a random selection of healthy, uninjured samples was made. It is recommended to gather more cocoa beans than is necessary for the sample to standardize the sample in the lab (selection of cocoa beans that were possibly damaged during transport or otherwise) (Rossetti et al., 2022). All experiments in the laboratory were conducted at room temperature (25 ± 2℃).

Methods

Measurements of Physical Properties

The mass of each cocoa bean (M) was determined using an electronic balance with a precision of 0.001 g. Three primary dimensions—length (L), width (W), and thickness (T)—were measured as shown in Figure 1 using a digital vernier caliper with an accuracy of 0.01 mm. The sphericity (Φ) and geometric mean diameter (Dg) of the beans were then calculated using Equations 1 and 2 as described by Tscheuschner (1987).

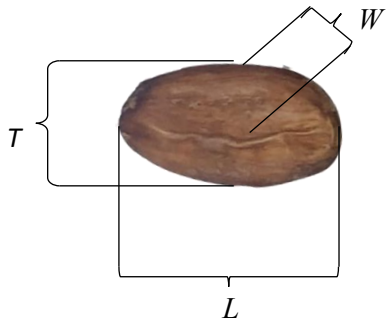


Figure 1. Principal dimensions of the cocoa beans.

P-ISSN: 2715-6214
E-ISSN: 2964-4909

$$Dg = (LWT)^{\frac{1}{3}} \quad (1)$$

$$\phi = \frac{(LWT)^{\frac{1}{3}}}{L} \quad (2)$$

To estimate bean volume, the analysis derived two separate volume measures. First, the cocoa bean geometry was approximated using idealized spheroidal forms, namely oblate and prolate spheroids, denoted as V_{obl} and V_{pro}, respectively. Based on these geometric assumptions, volume values were computed using Equations (3) and (4), as described in previous studies (Khodabakhshian & Emadi, 2016; Pathak et al., 2019):

$$V_{obl} = \frac{4\pi}{3}\left(\frac{L}{2}\right)\left(\frac{W}{2}\right)^2 \quad (3)$$

$$V_{pro} = \frac{4\pi}{3}\left(\frac{L}{2}\right)\left(\frac{W}{2}\right)\left(\frac{T}{2}\right) \quad (4)$$

The surface area, defined as the total external area of the three-dimensional bean structure, was calculated using Equation (5) following established methods (Azman et al., 2021).

$$SA_{sp} = \pi D_g^2 \quad (5)$$

Projected areas normal to the principal axes—thickness (PA_T), length (PA_L), and width (PA_W)—were determined using Equations (6) through (8). The criterion projected area (CPA) was subsequently obtained as the average of these three projections using Equation (9), in accordance with the approach proposed by Azman et al. (2020):

$$PA_L = \frac{\pi LW}{4} \quad (6)$$

$$PA_T = \frac{\pi TW}{4} \quad (7)$$

$$PA_W = \frac{\pi WW}{4} \quad (8)$$

The criterion projected area (CPA) was then defined as the arithmetic mean of the three views and was calculated using Equation (9):

$$CPA = \frac{PA_L + PA_T + PA_W}{3} \quad (9)$$

Regression Analysis and Mass Modelling

Mass prediction was conducted using four groups of regression approaches derived from dimensional attributes, projected areas, volume estimates, and surface area measurements, following established modeling frameworks (Khodabakhshian & Emadi, 2016; Pathak et al., 2019). First, single-variable regressions were developed to relate cocoa bean mass to basic linear dimensions, including length (L), width (W), thickness (T), and geometric mean diameter (Dg). Second, mass estimation was performed using projected areas obtained from different bean orientations as well as the criterion projected area (CPA). Third, cocoa bean volume was approximated by assuming prolate and oblate spheroidal geometries, and these volume estimates were then used as independent variables in single-parameter regression models. Fourth, surface area was also evaluated as a sole predictor of cocoa bean mass. Experimental data were fitted using four functional forms: linear, quadratic, logarithmic, and power models. These formulations are presented in Equations (10) – (13). In these expressions, M denotes the cocoa bean mass (g), X represents the independent variable corresponding to dimensional, volumetric, projected area, or surface measurements, and a, b, and c are regression coefficients determined through curve fitting.

$$M = a + bX \quad (10)$$

$$M = aX^2 + bX + c \quad (11)$$

$$M = a + b\ln(x) \quad (12)$$

$$M = aX^{\mathrm{n}} \quad (13)$$

P-ISSN: 2715-6214
E-ISSN: 2964-4909

Data Analysis

Statistical software like SigmaPlot (Version 12.0) was used to analyze data and make predictions about the mass using a significance level of 1%. The coefficient of determination (R^2) was used to assess the accuracy of the regression model. The preferred specification was the one with the highest R^2 within each predictor class.

RESULT AND DISCUSSION

Physical Properties of Cocoa Beans

The cocoa bean from Indonesia remains difficult to export as a halal product (Aini & Go, 2026); this may be caused by its unclear traceability. Table 1 presents the mean value and standard deviation (SD) for the physical properties of cocoa beans, which were determined using standard procedures. Figure 2 shows the cocoa bean samples of this research. The samples showed compact seeds with mean linear dimensions of L=15.19 cm, W = 7.79 cm, and T = 7.77 cm, alongside Dg = 9.7 cm and a moderate spread in volumes (V_{pro} = 493 cm^3; V_{obl} = 495 cm^3) and surface area (S_{asp} = 298.74 cm^2). The projected areas clustered around PA_L = 93.32 cm^2, PA_T = 47.95 cm^2, and PA_W = 47.81 cm^2, yielding a CPA = 63.02 cm^2 (Table 1). These magnitudes sit within the broad ranges described for edible legumes and cocoa-like seeds. For instance, haricot beans commonly span 11.1 – 13.1 cm in length and 6.2 – 8.4 cm in width (Wodajo et al., 2021), overlapping our width–thickness band, while kidney bean cultivars reach 11.5 – 16.5 cm (L), 6.7 – 7.8 cm (W), and 4.7 – 6.1 cm (T) (Wani et al., 2017), illustrating comparable axial scaling across botanically distinct but similarly sized seeds. Cocoa studies further emphasize that surface-derived metrics (Dg, S, Φ) covary with morphological class (ellipsoid of revolution), which frames our volumes near the prolate/oblate limits. Together, these references provide a realistic boundary for our measured geometry and support using L–W–T derived proxies as the foundation for mass modeling (Alamilla et al., 2024; Koua et al., 2019; Sandoval et al., 2019). The values of projected areas are essential for the development and design of grading system machines (Mahawar et al., 2019).



Figure 2. Cocoa bean samples.

Table 1. Physical properties of cocoa beans.

Parameter	Mean	Maximum	Minimum
L (mm)	15.19 ± 2.33	23.1	10.91
W (mm)	7.79 ± 0.77	9.97	6.3
T (mm)	7.77 ± 0.74	10.16	6.1
Mass (g)	0.41 ± 0.12	0.90	0.21
Geometric Mean Diameter (D_g) (mm)	9.7 ± 0.96	12.69	7.76
Sphericity (Φ)	0.65 ± 0.006	0.07	0.05
V_{obl} (mm^3)	494.83 ± 156.39	1050.8	252.99
V_{pro} (mm^3)	492.73 ± 153.97	1070.82	244.96
Sasp (mm^2)	298.74 ± 60.33	506.08	189.29
PA_L (mm^2)	93.32 ± 20.64	161.1	58.32
PA_T (mm^2)	47.95 ± 9.24	79.51	30.16
PA_W (mm^2)	47.81 ± 9.19	81.03	29.20
CPA (mm^2)	63.02 ± 12.29	107.21	39.23

P-ISSN: 2715-6214
E-ISSN: 2964-4909

Mass modelling

Table 2 reports cocoa bean mass modeling based on dimensions, volume estimates, surface area, and projected area variables. The coefficient of determination (R^2) was used to assess model accuracy, with higher values reflecting better model fit.

Table 2. The most accurate and precise models for predicting the mass of cocoa beans based on a set of independent variables.

Dependent Parameter	Independent Parameter	Model Equation	Regression			Statistical Parameter
			a	b	c	R^2
M (g)	L (mm)	Quadratic	6×10^{-6}	0.0015	0.002	0.858
M (g)	W (mm)	Logarithmic	2×10^{-4}	- 0.0112	0.234	0.955
M (g)	T (mm)	Quadratic	3×10^{-4}	- 0.0279	0.924	0.945
M (g)	Dg (mm)	Quadratic	10^{-4}	- 0.0092	0.229	0.990
M (g)	V_{obl} (mm^3)	Quadratic	2×10^{-13}	6×10^{-7}	0.071	0.948
M (g)	V_{pro} (mm^3)	Quadratic	10^{-13}	7×10^{-7}	0.037	0.961
M (g)	S_{asp} (mm^2)	Quadratic	2×10^{-10}	6×10^{-6}	0.022	0.961
M (g)	PA_L (mm^2)	Quadratic	10^{-9}	4×10^{-5}	- 0.029	0.899
M (g)	PA_T (mm^2)	Quadratic	10^{-8}	$- 3 \times 10^{-5}$	0.192	0.818
M (g)	PA_W (mm^2)	Quadratic	10^{-10}	$- 9 \times 10^{-7}$	0.126	0.799
M (g)	CPA (mm^2)	Quadratic	5×10^{-9}	3×10^{-5}	0.005	0.956

Modelling based on fruit dimensions

Dimension-based mass prediction favored the quadratic form. Among single axes, width (W) generated the highest goodness of fit (R^2 = 0.955), while thickness (T) also performed strongly, consistent with reports that dorsal–ventral build governs kernel fullness and mass deposition in related botanicals (Khodabakhshian & Emadi, 2016; Panda et al., 2020; Pathak et al., 2019). Diameter-based prediction strengthened this pattern: the geometric mean diameter (D_g) fitted the quadratic specification in Equation (14) with R^2 = 0.99, offering a compact, high-fidelity surrogate for tri-axial growth:

$$M = 0.0001X^2 - 0.0092X + 0.229 \quad (14)$$

where X denotes Dg (mm), and M denotes single-bean mass (g). Logarithmic alternatives produced lower R^2 across dimensions, a result consistent with nonuniform proportionality between size and mass in cocoa beans, as noted for similar seeds under variable morphology (A'Bidin et al., 2020; Shahbazi et al., 2026). These outcomes support a practical recommendation to use W when only a single axis is feasible and adopt Dg when caliper triads or machine vision can estimate a diameter proxy. This hierarchy preserves accuracy with minimal sensing burden and aligns with prior evidence that thickness- or diameter-centered models capture the physical drivers of mass most effectively (Khodabakhshian & Emadi, 2016; Panda et al., 2020; Pathak et al., 2019).

Modelling based on fruit volume

Volume predictors showed clear superiority of the quadratic form (Table 2). The prolate spheroid approximation delivered the highest goodness of fit (V_{pro}, R^2 = 0.961), with the oblate spheroid remaining competitive (V_{obl}, R^2 = 0.948). The best-fit equations are:

$$M = 0.0000000000002X^2 - 0.0000006X + 0.071 \quad (15)$$

$$M = 0.0000000000001X^2 - 0.0000007X + 0.037 \quad (16)$$

where X denotes the estimated geometric volume (mm^3), and M denotes single-bean mass (g). The performance gap indicates that a prolate assumption better reflects the average axial proportions of the beans, while the oblate form remains suitable for lots with broader midsections. Quadratic volume–mass mappings align with reports for other botanicals, including Terminalia chebula, Kendu, pomelo, and pepper berries, where parametric spheroidal volumes approximate true volume closely enough for

P-ISSN: 2715-6214
E-ISSN: 2964-4909

reliable mass prediction under stable shape factors (Azman et al., 2021; Panda et al., 2020; Pathak et al., 2019; Salihah et al., 2015). This evidence supports a practical rule to apply the V_{pro} model when length dominates over width and thickness (elongated lots), and pivot to V_{obl} when transverse axes widen, without sacrificing predictive strength or implementation simplicity.

Modelling based on fruit project areas

Among area predictors, the quadratic model based on the criterion projected area (CPA) achieved the highest accuracy (R^2 = 0.956), indicating that integrating three orthogonal silhouettes reduces orientation noise. Equation (17) expresses the mass–area relationship:

$$M = 0.000000005X^2 - 0.00003X + 0.005 \quad (17)$$

where X denotes projected area (mm²), and M denotes single-bean mass (g). For single-view proxies—PA_W, PA_L, and PA_T—the quadratic form outperformed linear, power, and S-curve alternatives (Table 2); applying Equation (17) to each proxy generates consistent predictions across views. Among these proxies, PA_L delivered the strongest single-view performance (R^2 = 0.899), followed by PA_T (R^2 = 0.818) and PA_W (R^2 = 0.799). A tiered deployment follows: use CPA with Equation (17) for calibration or premium grades where misclassification costs are high; use PA_L with Equation (17) on high-throughput lines where single-view imaging is preferable. This unified specification streamlines parameter management, preserves a common closed form across area inputs, and clarifies the trade-off between accuracy (CPA) and acquisition cost (single view), while remaining compatible with a geometry-centered grading workflow.

CONCLUSION

This study demonstrates that simple, rigorously defined geometry can deliver accurate, line-ready estimates of cocoa-bean mass. Consequently, such traceability data is essential to support and fulfill the requirements for halal product certification. These results support a Dg-centric pipeline that minimizes sensing burden yet preserves accuracy. All predictors were derived from readily captured dimensions; processors can integrate this framework into sorter setup, intake QC, and early-stage process design without specialized hardware. The models are easy to recalibrate and compatible with routine validation. Therefore, it can be concluded that empirical, single-parameter regressions anchored in Dg provide a robust foundation for mass grading of dried, fermented cocoa beans, while area and volume descriptors extend the toolkit where operating constraints or quality targets differ. This compact approach enables rapid adoption and creates a coherent bridge between measurement, quality assurance, and unit-operation engineering. In addition, the standardized physical measurements and predictive models developed in this study may support batch identification, raw-material segregation, and process documentation, thereby strengthening technical traceability within cocoa-processing operations. Although these models do not establish halal compliance by themselves, they can contribute to transparent and consistent process control as part of broader halal traceability and quality assurance systems.

REFERENCES

A'Bidin, F. N. Z., Shamsudin, R., Basri, M. S. M., & Dom, Z. M. (2020). Mass modelling and effects of fruit position on firmness and adhesiveness of banana variety *Nipah*. *International Journal of Food Engineering*, *16*(10). https://doi.org/10.1515/ijfe-2019-0199

Aini, N., & Go, R. T. (2026). Key factors influencing the competitiveness of Indonesian halal product exports: A prospective analysis with MICMAC approach. *Journal of Halal Science and Research*, *7*(1), 63–76. https://doi.org/10.12928/jhsr.v7i1.13924

Alamilla, P. G., Baeza, A. T., Arrazate, C. H. A., Alamilla, R. G., & Lanestosa, A. C. (2024). Determination of geometric properties of cocoa beans (Theobroma cacao L.). *Agro Productividad*. https://doi.org/10.32854/agrop.v17i5.2582

Azman, P. N. M. A., Shamsudin, R., Che Man, H., & Ya'acob, M. E. (2021). Mass modelling of pepper berries (Piper nigrum L.) with some physical properties. *Food Research*, *5*(S1), 80–84. https://doi.org/10.26656/fr.2017.5(S1).047

P-ISSN: 2715-6214
E-ISSN: 2964-4909

Azman, P. N. M. A., Shamsudin, R., Man, H. C., & Ya'acob, M. E. (2020). Some physical properties and mass modelling of pepper berries (Piper nigrum L.), variety Kuching, at different maturity levels. *Processes*, *8*(10), 1314. https://doi.org/10.3390/pr8101314

Bachtiar, W. F., Masruroh, N. A., Asih, A. M. S., & Sari, D. P. (2025). Halal food sustainable traceability: A multi-group consumer-centric acceptance and preference analysis. *Journal of Islamic Marketing*, *16*(12), 3682–3710. https://doi.org/10.1108/JIMA-12-2024-0610

Bannor, R. K., Oppong-Kyeremeh, H., & Chaa Kyire, S. K. (2026). Behavioural and institutional drivers of traceability system adoption in the Ghanaian cocoa supply chain. *Cleaner Logistics and Supply Chain*, *19*, 100330. https://doi.org/10.1016/j.clscn.2026.100330

Chaudhary, V., Mongia, G., & Drake, M. (2025). Approaches to determine the flavor and flavor chemistry of cocoa beans and cocoa liquor. *Journal of Food Science*, *90*(9). https://doi.org/10.1111/1750-3841.70481

Esan, V. I., Oke, G. O., Olaide, A., Ayoola, M. O., Obisesan, I. A., & Oluranti, O. O. (2025). Knowledge on potential, production, and achievements of cocoa (*Theobroma cacao*) in Nigeria: Past, current status, and perspective. *CABI Agriculture and Bioscience*. https://doi.org/10.1079/ab.2025.0028

Federation of Cocoa Commerce. (2019). *FCC Quality Rules*. Federation of Cocoa Commerce.

Ghonimy, M., Alayouni, R., Alshehry, G., Barakat, H., & Ibrahim, M. M. (2025). Integrated physical–mechanical characterization of Fruits for Enhancing Post-Harvest Quality and Handling Efficiency. *Foods*, *14*(14), 2521. https://doi.org/10.3390/foods14142521

Haruna, L., Abano, E. E., Teye, E., Lukeman, M., Tukwarlba, I., Yeboah, W., Nukafo, D., & Agyei, K. J. (2025). Effects of different drying techniques on the post-harvest quality of fermented cocoa beans in Ghana. *Food Science & Nutrition*, *13*(9). https://doi.org/10.1002/fsn3.70715

Khodabakhshian, R., & Emadi, B. (2016). Mass model of date fruit (cv. Mazafati) based on its physiological properties. *International Food Research Journal*, *23*(5), 2070–2075.

Koua, B. K., Koffi, P. M. E., & Gbaha, P. (2019). Evolution of shrinkage, real density, porosity, heat and mass transfer coefficients during indirect solar drying of cocoa beans. *Journal of the Saudi Society of Agricultural Sciences*, *18*(1), 72–82. https://doi.org/10.1016/j.jssas.2017.01.002

Lima, G. V. S., Gonçalves, C. G. e, Pinto, A. S. O., Silva, E. M. da, Souza, J. N. S. de, & Rogez, H. (2024). Impact of post-harvest processing and roasting conditions on the physicochemical properties, phenolic compounds, and antioxidant capacity of cocoa beans from the Brazilian Amazon. *LWT*, *210*, 116825. https://doi.org/10.1016/j.lwt.2024.116825

Looh, G. A., Xie, F., Wang, X., Looh, A. N., & Hind, H. (2025). Grain kernel damage during threshing: A comprehensive review of theories and models. *Journal of Agricultural Engineering*. https://doi.org/10.4081/jae.2025.1674

Mahawar, M. K., Bibwe, B., Jalgaonkar, K., & Ghodki, B. M. (2019). Mass modeling of kinnow mandarin based on some physical attributes. *Journal of Food Process Engineering*, *42*(5). https://doi.org/10.1111/jfpe.13079

Onwude, D. I., & Chen, G. (2021). Advances in Postharvest Process Systems. *Processes*, *9*(8), 1426. https://doi.org/10.3390/pr9081426

Panda, G., Vivek, K., & Mishra, S. (2020). Physical characterization and mass modeling of Kendu (Diospyros melanoxylon Roxb.) fruit. *International Journal of Fruit Science*, *20*(sup3), S2005–S2017. https://doi.org/10.1080/15538362.2020.1851339

Pathak, S. S., Pradhan, R. C., & Mishra, S. (2019). Physical characterization and mass modeling of dried Terminalia chebula fruit. *Journal of Food Process Engineering*, *42*(3). https://doi.org/10.1111/jfpe.12992

Putri, D. N., De Steur, H., Juvinal, J. G., Gellynck, X., & Schouteten, J. J. (2024). Sensory attributes of fine flavor cocoa beans and chocolate: A systematic literature review. *Journal of Food Science*, *89*(4), 1917–1943. https://doi.org/10.1111/1750-3841.17006

Rossetti, A. G., Moura, C. F. H., Silva, E. de O., Vidal Neto, F. das C., Ribeiro, L. B., & Almeida, A. C. P. de. (2022). Sample size for the physical and physico-chemical characteristics of the cashew. *Revista Brasileira de Fruticultura*, *44*(6). https://doi.org/10.1590/0100-29452022614

P-ISSN: 2715-6214
E-ISSN: 2964-4909

Salihah, B. N., Shamsudin, R., & Norashikin, A. A. (2015). Mass modeling of Malaysian varieties pomelo fruit (Citrus grandis L. Osbeck) with some physical characteristics. *International Food Research Journal*, *22*(4), 488–493.

Sanchez, A., Pacheco Barragán, H. C., Urbano-T, J., Ayala-Garcia, C., Alvarez Solano, O. A., Maranon, A., Porras, A., & Hernandez, C. (2024). Physical, morphological, and mechanical properties of raw and steamed cashew nuts (Anacardium occidentale L.). *International Journal of Food Properties*, *27*(1), 224–244. https://doi.org/10.1080/10942912.2024.2304271

Sandoval, A. J., Barreiro, J. A., De Sousa, A., Valera, D., & Müller, A. J. (2019). Determination of the physical properties of fermented and dried Venezuelan Trinitrio cocoa beans (Theobroma cacao L.). *Revista Tecnica De La Facultad De Ingenieria Universidad Del Zulia*, *42*(2), 47–53. https://doi.org/10.22209/rt.v42n2a01

Santander, M., Chica, V., Correa, H. A. M., Rodríguez, J., Villagran, E., Vaillant, F., & Escobar, S. (2025). Unravelling cocoa drying technology: A comprehensive review of the influence on flavor formation and quality. *Foods*, *14*(5), 721. https://doi.org/10.3390/foods14050721

Sentellas, S., & Saurina, J. (2023). Authentication of cocoa products based on profiling and fingerprinting approaches: Assessment of geographical, varietal, agricultural and processing features. *Foods*, *12*(16), 3120. https://doi.org/10.3390/foods12163120

Shahbazi, F., Shahbazi, S., & Nadimi, M. (2026). Fruit impact damage: A review of contact theory in mathematical modeling for postharvest applications. *Journal of Food Processing and Preservation*, *2026*(1). https://doi.org/10.1155/jfpp/4493011

Subroto, E., Djali, M., Indiarto, R., Lembong, E., & Baiti, N. (2023). Microbiological activity affects post-harvest quality of cocoa (Theobroma cacao L.) beans. *Horticulturae*, *9*(7), 805. https://doi.org/10.3390/horticulturae9070805

Tscheuschner, H. (1987). Physical properties of plant and animal materials: Structure, physical characteristics and mechanical properties. *Food/Nahrung*, *31*(7), 702–702. https://doi.org/10.1002/food.19870310724

Wani, I. A., Sogi, D. S., Wani, A. A., & Gill, B. S. (2017). Physical and cooking characteristics of some Indian kidney bean (Phaseolus vulgaris L.) cultivars. *Journal of the Saudi Society of Agricultural Sciences*, *16*(1), 7–15. https://doi.org/10.1016/j.jssas.2014.12.002

Wodajo, D., Admassu, S., & Dereje, B. (2021). Geometric Characteristics and Mass-Volume-Area Properties of Haricot Beans (Phaseolus vulgaris L .): Effect of Variety Geometric Characteristics and Mass-Volume-Area Properties of. *International Journal of Food Properties*, *24*(1), 885–894. https://doi.org/10.1080/10942912.2021.1937210