

Development of Predictive Mass and Volume Models for African Star Apple Fruits

Oyefeso, B. O. ¹; Akwunwa, I. J. ¹; Ajayi, P. E. ¹; Akintola, A. ²; Fadele, O. K. ³; and Ogunlade, C. A. ⁴

¹Department of Agricultural and Environmental Engineering, University of Ibadan, Ibadan, Nigeria.

²Department of Agricultural and Bio-Environmental Engineering, Oyo State College of Agriculture and Technology, Igboora, Nigeria. ³Department of Agricultural Engineering, Federal College of Forestry Mechanization, Afaka, Kaduna, Nigeria. ⁴Department of Agricultural Engineering, Osun State University, Osogbo, Osun State, Nigeria.

Corresponding author: oyefesobabatunde@gmail.com

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Abstract

Physical properties provide a vivid description of their characteristics which can be used in classifying crops. Accurate prediction of mass and volume, among other important physical properties, is crucial in the design of systems for sorting, grading and packaging of fruits and vegetables. This study therefore, focused on determining some physical attributes of African star apple and developing mathematical models to estimate the mass and volume of the fruits based on selected geometrical attributes. A total of 150 fresh African star apples were used in this study. The physical properties determined include mass, volume, axial dimensions, mean diameters and the projected areas along the three mutually-perpendicular axes. Regression analysis was carried out to develop the predictive mathematical models. The average length, width and thickness of African star apple fruits were 45.01 ± 2.28 , 43.88 ± 2.52 , and 44.22 ± 2.30 mm, while the projected areas ranged from 1094.33 to 1951.187 mm². The average mass and volume were 57.36 ± 7.46 g, and 54.75 ± 7.34 cm³, respectively. Models based on individual axial dimensions showed moderate correlation ($R^2 = 0.514-0.632$), with length-based models being the best among single-variable models. The longitudinal projected area models demonstrated a more predictive capability amongst all projected area models ($R^2 = 0.607$). The most accurate prediction was achieved by the mass model based on volume ($R^2 = 0.9902$), indicating that mass can be accurately predicted using volume measurements. These predictive mathematical models will facilitate the development of automated sorting and grading equipment, ultimately reducing processing costs and improving efficiency in African star apple value chain operations.

Keywords: African Star Apple, Physical Properties, Mass/Volume Modelling, Geometrical Attributes.

Introduction

African star apple (*Chrysophyllum albidum* G. Don), also known as *agbalumo* among the native Yoruba-speaking Nigerians, is a tropical fruit that belongs to the family of *Sapotaceae* found in the region of West Africa including Nigeria, Benin, Ivory Coast, and Cameroon (Nartey *et al.*, 2021). *Agbalumo* is grown primarily for its edible fruits, which are

consumed in larger quantities for their vitamins and mineral content required in proper body build-up. It is also prepared into jams, jellies, syrups, beverage drinks, and soups using various local methods (Ibrahim. *et al.*, 2017). Its plant has nutritional and medicinal value, offering therapeutic purposes when used in trado-medicine to cure ailments such as malaria, diarrhea, and even skin infections (Ajayi *et al.*, 2020). *Agbalumo* is used as a raw material for industries producing seed oil, which is used as a feedstock to convert waste into economic value (Adepoju, 2014).

Agbalumo undergoes various unit operations in its handling, packaging and processing. The extraction processes involved in converting its seed into seed oil, entails a series of unit operations such as cleaning, drying, winnowing, and grinding (Akpan *et al.*, 2006; Sayyar *et al.*, 2009). Many of these unit operations are still being done manually, and various resultant challenges are still apparent. Therefore, mechanization of these unit operations through the effective development of processing machines is necessary.

Data on the observable characteristics of *agbalumo* fruit are essential for adequately designing postharvest handling equipment and processing machines. Therefore, it is important to establish reliable mathematical models among mass, volume, axial dimensions, and areas that can serve several important purposes in the automation of design and processing operations (Tabatabaefar, 2002). Grading based on the mass of fruit is essential in ensuring uniform weight and optimum packaging configurations, reducing packaging and transportation costs (Shahir *et al.*, 2015), while volume of fruits and vegetables can be used to monitor yield during harvesting to predict harvesting time and ensure proper design of appropriate packaging materials (Hahn *et al.*, 2000).

Numerous studies have been conducted to predict physical properties with the help of predictive mathematical models created based on the relationships established between the physical attributes and the geometrical characteristics of the crops (Oyefeso, 2018). Mass, volume, dimensions, and projected areas are the core attributes that are important in developing post-harvest machinery, especially in grading systems for categorizing fruits (Naderiboldaji *et al.*, 2009). The development of models that could predict the mass and volume of agricultural products based on the dimensions and projected areas will give a good description of the size and shape of the products, and this will also be a tremendous help in the design of processing machines as well as sorting and handling equipment for the products (Raji and Oyefeso, 2021). Predictive mathematical models have been established for agricultural products based on physical attributes. Oyefeso and Raji (2024) reported that mass models have been developed by various researchers for various crops which include kiwi fruits, bananas, cantaloupes, apples, tangerines, pomegranates, and apricots. Models for estimating mass and volume have also been developed for citrus fruits (Khanali *et al.*, 2007), some cultivars of potato tubers (Tabatabaefar, 2002; Oyefeso and Raji; 2018), *Tacca* tubers (Raji and Oyefeso; 2021), tannia (*Xanthosoma sagittifolium*) cormels (Oyefeso and Raji, 2024) African bush mango (Oyefeso *et al.*, 2025), Himalayan pears (Akuleti *et al.*, 2025) and Assam lemon (Nickhil *et al.*, 2025). Despite the nutritional and economic value of African star apple (*agbalumo*), it has been under-researched in terms of postharvest engineering. There is also dearth of information on standardized model linking the linear

dimensions or projected areas, which are easily measurable parameters, with the mass and volume of the fruit. This creates some limitations in the integration of such geometry-based models in the automation of sorting and grading systems for the fruit. This study was therefore, designed to determine selected physical attributes of *agbalumo* and develop predictive mathematical models for estimating the mass and volume of the fruits based on the geometrical attributes, with a view to providing information which will help in developing automated systems for sorting and grading the fruits.

Materials and Methods

Agbalumo fruits used in this study were purchased from Oje Market in Ibadan, Oyo State, Nigeria. One hundred and fifty *agbalumo* fruits used in this study were cleaned and segregated into two sections based on gravimetric analysis and were adequately labelled and documented for easy identification. All measurements were carried out in triplicates.

Measurement of gravimetric properties

The mass of each sample was measured using an electronic weighing balance (METRA, model TL-5000), and the volume was measured using water displacement method as described by Lorestani *et al.* (2014). The density of the fruit was calculated as the ratio of the mass of the fruit to the actual volume measured by water displacement method (Raji and Oyefeso, 2021).

Measurement of geometrical attributes

The axial dimensions were obtained as length (L), width (W), and thickness (T) as method described by Tabatabaeefar (2002) and Ahemen and Raji (2017) using a digital vernier caliper (Carrera Precision, model CP8812-T 12-inch, USA). The Arithmetic Mean Diameter (AMD) of the fruit was estimated using Equation 1, while the Geometric Mean Diameter (GMD) and Equivalent Mean Diameter (EMD) were determined using Equations 2 and 3, respectively (Raji and Ahemen, 2011; Vivek *et al.*, 2017; Oyefeso *et al.*, 2025). The projected areas along the three mutually perpendicular axes were calculated using Equations 4, 5, and 6, respectively, while the criterion projected area was calculated using Equations 7 (Oyefeso, 2021; Oyefeso *et al.*, 2025).

$$AMD = \frac{L+W+T}{3} \quad (1)$$

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

$$EMD = [L \times \left(\frac{W+T}{2}\right)^2]^{\frac{1}{3}} \quad (3)$$

$$PA_L = \frac{\pi \times L \times W}{4} \quad (4)$$

$$PA_W = \frac{\pi \times W \times W}{4} \quad (5)$$

$$PA_T = \frac{\pi \times T \times W}{4} \quad (6)$$

$$CPA = \frac{PA_L + PA_W + PA_T}{3} \quad (7)$$

Where: L is the length (mm); W is the width (mm); T is the thickness of the fruit (mm); AMD is the Arithmetic Mean Diameter (mm); GMD is the Geometric Mean Diameter (mm); EMD is the Equivalent Mean Diameter (mm); PA_L , PA_W and PA_T (mm^2) are the projected areas along the longitudinal, cross-sectional and transverse orientations, respectively; CPA is the criterion projected area (mm^2).

Model development

A total of 150 *agbalumo* fruits were used for the study, of which 100 fruits were used to develop the predictive models, while the remaining 50 *agbalumo* fruits were used to validate the models. The data analysis tool in Microsoft Excel (2013 version) was used to carry out the descriptive statistics on the data obtained while regression analysis was carried out to determine the most suitable mathematical models between the dependent variables (mass and volume) and one or more independent variables related to the physical characteristics of the fruits. There are different regression model types that could represent the relationships that exist between the dependent variable (mass/volume) and the independent variables (geometrical attributes) and some of these models include linear, exponential, logarithmic, polynomials and power regression trends (Oyefeso and Raji, 2018). The most suitable mathematical models were determined on the basis of highest coefficient of determination (R^2). The mass/volume prediction models for *agbalumo* fruits were based on the three categories namely the axial dimensions (L, W, T, AMD, GMD, EMD), projected areas (PA_L , PA_W , PA_T and CPA) and volume (for mass prediction only).

Results and Discussion

The summary of the measured physical properties of *agbalumo* fruits are presented in Table 1 while the developed mass and volume models are presented in Tables 2 and 3, respectively. The prediction models created were based on both linear and non-linear regressions to estimate ASA's mass and volume.

Geometric attributes of *agbalumo* fruits

The average length, width, and thickness of the *agbalumo* fruits were 45.01 ± 2.28 , 43.88 ± 2.52 , 44.22 ± 2.30 , respectively. The AMD, GMD, and EMD of the fruits were within the ranges 38.34-49.75, 38.33-49.75, and 38.33-49.75 mm, respectively. The AMD, GMD, and EMD for the fruits were quite close, indicating that *agbalumo* fruits are approximately spherical and relatively uniform in dimensions. The projected areas namely PA_L , PA_W and PA_T were within the ranges of 1153.56-1951.19, 1094.33-1916.65 and 1124.53-1923.64 mm^2 , respectively. The projected areas are of close range indicating relative uniformity in the size and shape of the fruits.

Table 1: Selected physical characteristics of African star apple

Physical Properties	Mean	Maximum	Minimum	Standard deviation
Length (mm)	45.009	50.28	39.34	2.275
Width (mm)	43.883	49.39	37.32	2.521
Thickness (mm)	44.222	49.57	38.35	2.304
AMD (mm)	44.371	49.747	38.337	2.367
GMD (mm)	44.37	49.745	38.328	2.364
EMD (mm)	44.369	49.745	38.33	2.366
PA _L (mm ²)	1551.87	1951.187	1153.561	4.507
PA _W (mm ²)	1513.06	1916.65	1094.33	4.993
PA _T (mm ²)	1524.75	1923.635	1124.532	4.563
CPA (mm ²)	1572.47	1964.571	1184.559	8.78
Mass (g)	57.3566	69.35	40.86	7.461
Volume (cm ³)	48.329	66.45	38.53	7.495
Density (g/cm ³)	1.048	1.044	1.06	1.015

Table 2: Mass models for African star apple based on selected physical properties

Model No.	Classification	Independent Variable	Relation	R ²
1	First	L (mm)	$M = 0.0121L^2 - 1.0982L + 66.29$	0.668
2		W (mm)	$M = -0.095L^2 + 10.935L - 241.75$	0.515
3		T (mm)	$M = -0.064T^2 + 7.997T - 170.32$	0.514
4		L, W, T (mm)	$M = -51.141 + 1.810L - 0.325W + 0.988T$	0.623
5		AMD (mm)	$M = -0.077AMD^2 + 9.428AMD - 208.32$	0.598
6		GMD (mm)	$M = -0.077GMD^2 + 9.421GMD - 208.15$	0.598
7	Second	PA _L (mm ²)	$M = -2E-05PA_L^2 + 0.1084PA_L - 54.873$	0.607
8		PA _W (mm ²)	$M = -3E-05PA_W^2 + 0.115PA_W - 60.726$	0.516
9		PA _T (mm ²)	$M = -2E-05PA_T^2 + 0.109PA_T - 55.027$	0.530
10		PA _L , PA _W and PA _T	$M = 0.05150 PA_L - 0.04374 PA_W + 0.02778 PA_T - 3.4941$	0.619
11		CPA (mm ²)	$M = -3E-05CPA^2 + 0.116CPA - 61.507$	0.564
12	Third	V (m ³)	$M = 0.9795V - 1.4361$	0.9902

Table 3: Volume models for African star apple based on selected physical properties

Model No.	Classification	Independent Variable	Relation	R ²
1	First	L (mm)	$V = 0.0107L^2 - 0.8826L + 59.559$	0.662
2		W (mm)	$V = -0.0868W^2 + 10.1561W - 225.99$	0.514
3		T (mm)	$V = -0.06T^2 + 7.596T - 163.48$	0.518
4		L, W, T (mm)	$V = -52.2518 + 1.84558L - 0.44913W + 1.04525T$	0.632
5		AMD (mm)	$V = -0.0709AMD^2 + 8.824AMD - 196.82$	0.602
6		GMD (mm)	$V = -0.0709AMD^2 + 8.824AMD - 196.82$	0.602
7	Second	PA _L (mm ²)	$V = -2E-05PA_L^2 + 0.1025PA_L - 52.606$	0.612
8		PA _W (mm ²)	$V = -2E-05PA_W^2 + 0.1082PA_W - 57.641$	0.515
9		PA _T (mm ²)	$V = -2E-05PA_T^2 + 0.1045PA_T - 53.522$	0.532
10		PA _L , PA _W , PA _T	$V = 0.053PA_L - 0.0467PA_W + 0.0294PA_T - 1.6116$	0.629
11		CPA (mm ²)	$V = -2E-05CPA^2 + 0.11CPA - 59.23$	0.566

Gravimetric properties of African star apple

The average mass, volume, and density of the fruits are 57.36 ± 7.46 , 54.75 ± 7.34 and 1047.69 kg/m³. The results obtained from models 1 to 3 for determining mass and volume using axial dimensions (L, W, and T) have a lower R² from Tables 2 and 3. The prediction from multiple regression of the axial dimensions produced a greater R² of 0.632 for both mass and volume models; GMD and AMD, which are independent variables, also produced an approximate R² value of 0.600 for both mass and volume. It depended on the three axial dimensions, which created complexity in computing. In light of this, mode number 1, which is length based on tables 2 and 3, was recommended because it would enhance computing speed.

Classification of mass and volume models for African star apple

The mass models were presented in Table 2, while their corresponding volume models were presented in Table 3. The most suitable models of all the different regression models are reported in this study.

First Classification models (Axial dimensions)

Among the first classification, models numbered 1 to 6 in Tables 2 and 3, mass and volume models L, W, and T have relatively high R² needed to develop models 5 and 6, making sorting more complex. The mass and volume models based on the length (L) had the highest R² among the single variable models 1, 2, and 3 in Tables 2 and 3. This indicates that the prediction of the mass and volume of the African star apple is better obtained using the length than its two other primary axial dimensions (W and T). Figures 1 and 2 show the mass and volume models based on the longest dimension (length) of the fruit, respectively.

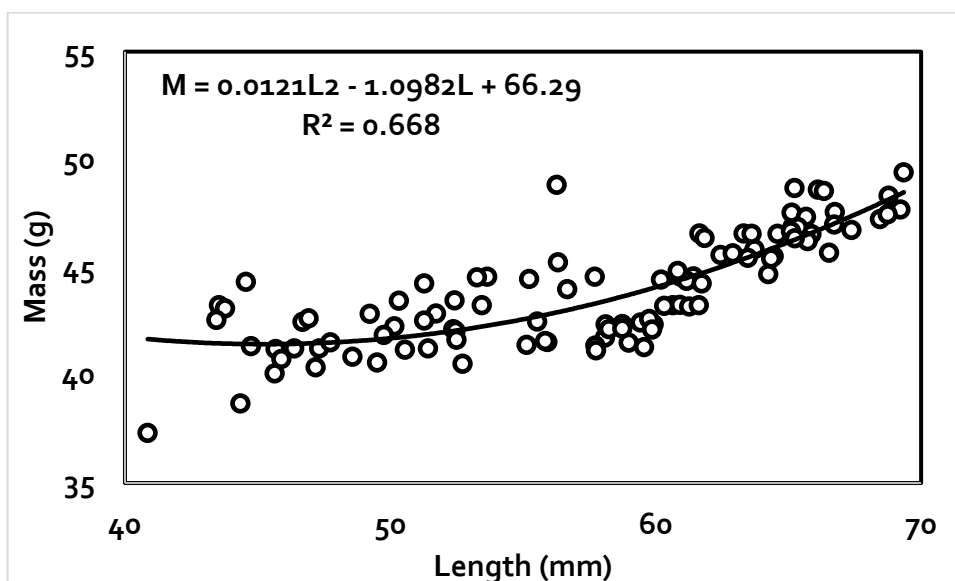


Figure 1: Mass model based on the length of the fruit

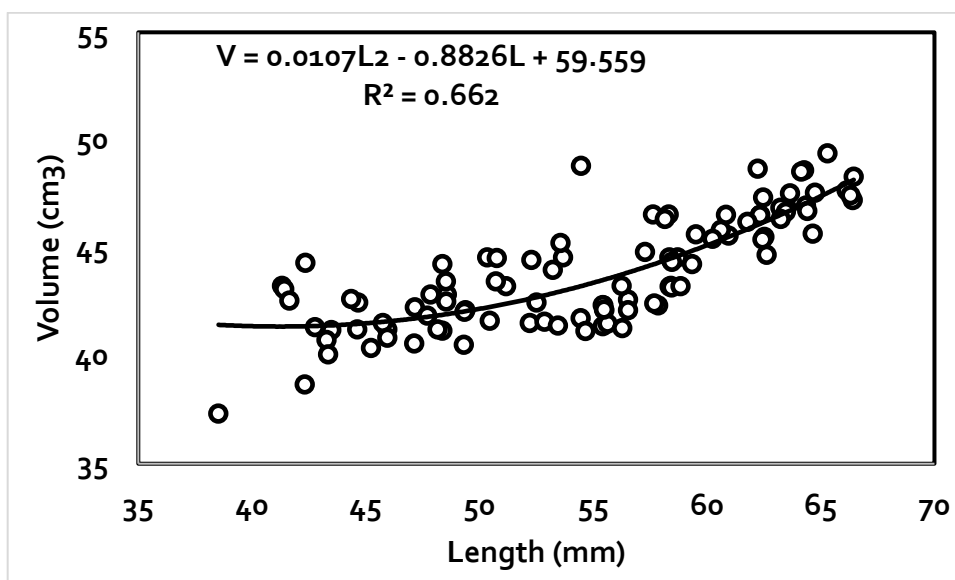


Figure 2: Volume model based on the length of the fruit

The second classification model (Projected area)

The mass and volume models are based on the projected areas. Sorting based on the area can be cumbersome since it is obtained from the axial dimensions (L , W , and T). The mass and volume models with a single independent variable based on PA_L gave more reliable results ($R^2 = 0.607$ and 0.612) for both models. The mass and volume based on the criterion area also had a higher R^2 value, as presented in Tables 2 and 3, respectively, which indicates that it was also suitable for accurately predicting the mass and volumes of African star apples (Oyefeso and Raji, 2024). The predictive mass and volume models based on the projected areas along the longitudinal axis of the fruit are presented in Figures 3 and 4, respectively.

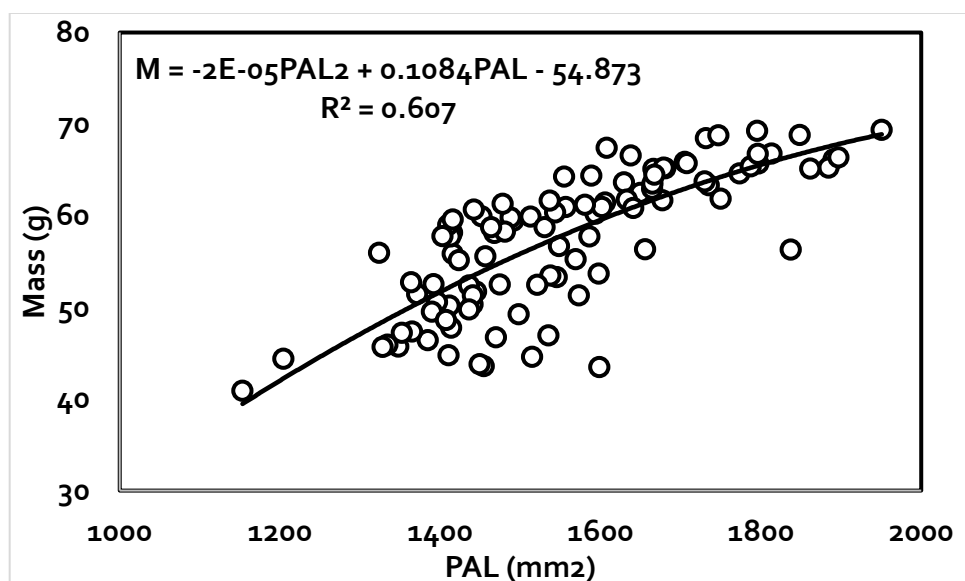


Figure 3: Mass model based on the PAL of the fruit

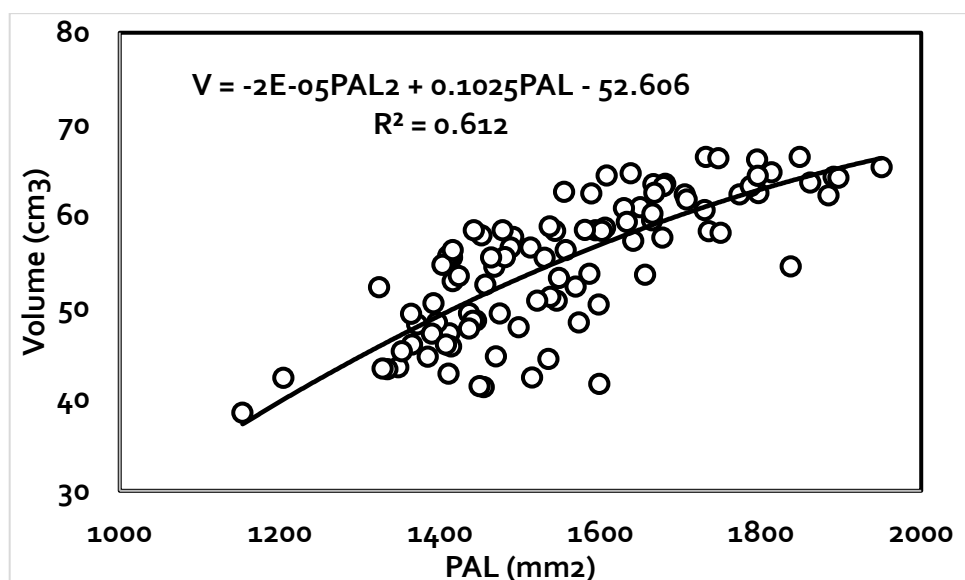


Figure 4: Volume model based on the PAL of the fruit

Third classification models (Volume)

The classification obtained a predictive mass model on the volume of African star apples. The mass model was numbered 12 in Table 2, with the highest R^2 (0.9902). Figure 5 shows the predictive mass model based on the volume of the fruits. The mass of African star apples can be accurately predicted using their volume. This agrees with the findings of Tabatabaefar (2002), Meisami-asl *et al.* (2009), Oyefeso and Raji (2024) and Oyefeso *et al.* (2025).

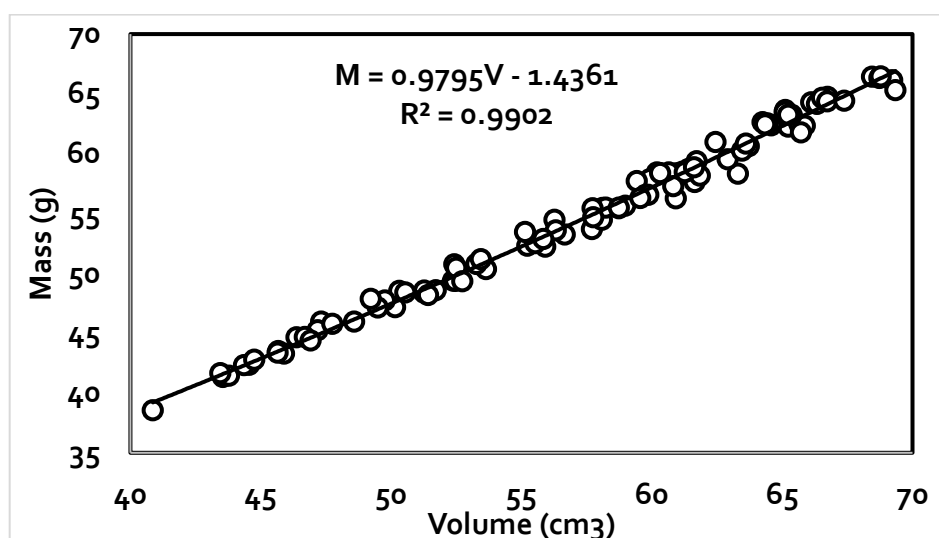


Figure 5: Predictive mass model based on the volume of the fruits

The developed mass and volume models based on the various geometrical attributes of African star apple can be implemented in the development of an electronic weight-based grading system which can sort the fruits based on the predicted mass compared to the designated grade classes, as well as an image-based grading system which uses either a two or three-dimensional images of the fruit to estimate the projected areas or volume and classify the fruits based on the predicted mass of the fruit. Such systems would involve capturing of the fruit image, extraction of the geometrical attributes from the captured image, comparing predicted values to set grade boundaries (depending on commercial standards) and the fruit can be diverted accordingly via servo-controlled gates. Proper design of the systems for handling, sorting and grading of African star apple fruit can be ensured with the aid of the predictive mass and volume models.

Conclusions

Some physical properties of African star apples, namely the length, width, thickness, AMD, GMD, EMD, projected areas along the principal axes, mass and volume, were determined in this study. Predictive models for estimating the mass and volume of the fruits were developed based on some of the measured geometrical attributes. Based on the findings in this study, it was observed that a fair relationship (average correlation) existed between the mass/volume of the fruits and the individual axial dimensions (length, width, and thickness) and the projected areas along the transverse and longitudinal orientations as independent variables. The mass of the fruits can be reliably estimated using its volume, with R^2 in excess of 0.9908. Volume-based mass prediction models are therefore, strongly recommended for incorporated into automated African star apple fruit grading equipment, where only volume (from images or sensors) needs to be measured, significantly reducing the need for costly weighing systems. This will enhance non-destructive measurements, offering

practical applications in mechanized postharvest handling, processing and quality control systems for the fruits.

Based on the findings in this study, it is recommended that:

- i. a database of the determined properties namely the linear dimensions, projected areas, mass and volume have been created and can serve as a guide in the design of processing machines and post-harvest handling equipment for African star apple;
- ii. the developed mass and volume models should be incorporated into automated grading prototypes to determine their performance under real life situations;
- iii. machine learning models can be trained using the dimensional data and actual mass/volume values obtained in this study for better generalization of the models for different varieties and maturity stages of the fruits with the potential of being deployed for selective harvesting.

Data Availability

The data supporting the conclusions of this study are available and can be released upon request.

Conflicts of Interest

The authors declare that there is no conflict of interests.

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