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ORIGINAL RESEARCH ARTICLE

PREDICTION OF MASS AND VOLUME OF *TACCA INVOLUCRATA* TUBERS USING PHYSICAL CHARACTERISTICS

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ABSTRACT

Knowledge of physical properties of crops is necessary for the development of processing machines. Relationships between the various physical properties of crops could also be useful in ensuring proper handling and more efficient design of processing machineries. This study was therefore, aimed at developing mathematical models for predicting the mass and volume of Tacca involucrata tubers using some physical characteristics of the crop. Physical characteristics of Tacca tubers at average moisture content of 73.3% (wet basis) namely axial dimensions, Arithmetic Mean Diameter (AMD), Geometric Mean Diameter (GMD), projected areas along the three mutually-perpendicular axes, criterion area (Ac), mass and volume were determined. Out of 240 samples used in the study, data from 120 samples were used for development of the prediction models while the remaining were used for validation of the developed models. Data analysis tool in Microsoft Excel (2013 version) was used to carry out regression analysis and develop the predictive models. Statistical parameters namely correlation coefficient, coefficient of determination, root mean square error and mean bias error were used to determine the goodness of fit of the predictive models. The mass and volume models were divided into three classifications namely: single and multiple variable regression models based on axial dimensions; single and multiple variable regression models based on the projected areas; single variable regression model based on volume (for mass prediction only). Average length, width, thickness, AMD and GMD of the tubers were 71.88, 57.22, 46.71, 58.60 and 57.57 mm respectively while average criterion area, longitudinal, cross-sectional and transversal projected areas were 2614.24, 2580.61, 2097.04 and 3165.07 mm^2 respectively. Average mass and volume of the tubers were 129.30 g and 111.55 cm^3 respectively. All the developed models performed well in predicting the mass and volume of Tacca tubers (R^2 ≥ 0. 905) except for those based on the axial dimensions as single independent variables (R^2 ≤ 0.890). The predicted mass and volume of Tacca tubers were not significantly different (p ≤ 0.05) from the experimentally observed values for all the classifications considered. Mass and volume modelling based on a single variable of any of the projected areas was the most convenient modelling for Tacca tubers since it involves the use of a single image capturing device and the whole measurement could therefore, be automated. The developed models would be useful for automated sorting and packaging of Tacca tubers.

1.0 Introduction

Tacca (*Tacca involucrata*, Schum. and Thonn.) is an important member of the root and tuber crops which serve as staple foods in many parts of the tropics. Although the crop is grown at subsistent level in the Eastern part of Nigeria, it is yet to be domesticated in many regions of Africa where it is still found predominantly in the wild and reproduces asexually on its own at a later period (Raji and Ahemen, 2011). It is noteworthy that some parts of the plant are useful for various purposes while the tuber is well known for its starch which has almost zero percentage fat content and therefore, suitable for industrial uses especially in the pharmaceutical industries (Omojola, 2013; Raji and Ahemen, 2011). Its tuber and starch are traditionally used for treatment of diarrhoea and bleeding (internal and external). Its stems are also useful for making mats while the leaves are used for treatment of nausea and vomiting (Ofoefule *et al.,* 2004).

Tacca tuber processing involves a lot of unit operations which are largely carried out manually in the developing countries where the crop is available for use. The increasing global demand for its starch necessitates commercialisation of its production which inevitably requires mechanization of its processing and handling operations (Ahemen and Raji, 2017). Knowledge of the engineering properties of the tubers is therefore, needed as they constitute essential data for the design of machineries for processing and handling operations (Mohsenin, 1986).

Sizing by weighing mechanism is recommended for the irregular-shaped products (Stroshine and Hamann, 1994) which is typical of most agricultural products. Determining the relationships among mass, axial dimensions and projected areas may also be useful and applicable in the automation of sorting processes for agricultural products (Stroshine and Hamann, 1994; Pathak *et al*., 2020). Though these relationships or models may be cumbersome to establish, once established, they can easily be used to quickly predict the unknown parameters in the relationships.

Axial dimensions, projected areas, mass and volume of agricultural products are important parameters in sorting and grading machines (Naderiboldaji *et al*., 2009). Crops are often graded on the basis of size and the projected area, although it may be more economical to develop a machine which would grade by mass or volume of the product. Therefore, this will necessitate establishing relationships between mass or volume and other physical attributes of the crops (Khanali *et al*., 2007; Jahromi *et al*., 2007a).

Mathematical modelling helps to develop functional relationships between different crop variables and thereby, make it easy to predict the values of the dependent (unknown) variables based on the different values of the independent (known or measured) variable(s). The development of models that could be used to predict the mass and volume of agricultural products based on the dimensions and the projected areas will give a good description of the size and shape of the products and this will be of tremendous help in the design of processing machines as well as sorting and handling equipment for the products.

Several researches have been carried out to predict some physical properties of interest using developed regression models based on the geometrical attributes of the crops. Some of these studies include development of mass models for kiwi fruit (Lorestani and Tabatabaeefar, 2006), date fruit (Jahromi *et al*., 2007a), pomegranate fruit (Khoshnam *et al*., 2007), apple (Meisami-asl *et al.,* 2009), fava beans (Lorestani and Ghari, 2012), potato (Berberoglu et al., 2014), Sohiong fruit (Vivek *et al*., 2017), persimmon fruits (Subbarao and Vivek, 2017), apricot fruit (Rashidi *et al*., 2018), Belleric myrobalan fruit (Pathak *et al*., 2020), Indian coffee plum (Barbhuiya *et al*., 2020) and pepper berries (Azman *et al*., 2021). Mass and volume prediction models were developed for tangerine fruit (Khanali *et al.,* 2007), citrus fruits (Omid et al., 2010), sweet cherry (Khadivi-Khub and Naderiboldaji, 2013), and Nigeria-grown sweet and Irish potatoes

(Oyefeso and Raji, 2018). Mass and surface area of bergamot fruits were also predicted based on axial dimensions, projected areas and volume (Jahromi *et al.*, 2007b). All these studies were carried out for prediction of various properties such as mass, volume, surface area etc with varying degrees of success in the development of their predictive models. However, there appears to be scarcity of information on prediction models for Tacca tuber which are useful in its automated sorting and handling. This study therefore, aimed at developing mathematical models for predicting mass and volume of Tacca tuber which are grown in Nigeria using some of their physical characteristics. This is with the ultimate aim of generating data which could serve as a quick guide in the design of sorting and handling equipment for the tubers.

2. Materials and Methods

2.1 Sample preparation

Some Tacca tubers were randomly selected and purchased from a pit storage stock harvested within a period of one month from Tse-Ikyor and Tse-Adawa villages, Benue State, Nigeria. The study was conducted on 240 tubers which were sorted into different fractions based on their weights and labelled to enable proper identification and documentation of data from the samples.

2.2 Moisture content determination

Moisture content of the tuber was determined according to ASABE (2003) standard method which involved drying the samples in an oven maintained at temperature of 103 ± 2°C until constant weight was attained (Ahemen and Raji, 2017).

2.3 Determination of geometrical attributes

The physical characteristics determined include mass, volume, length (L), width (W), thickness (T), Arithmetic Mean Diameter (AMD), Geometric Mean Diameter (GMD), projected areas along the three mutually-perpendicular axes (PA_L, PA_W and PA_T) and the Criterion Area (A_C).

The individual mass of each of the Tacca tubers was measured using an electronic weighing balance (A&D Co. LTD, AND EK-6100i model, Japan) with an accuracy of 0.1g. Volume of each of the tubers was obtained using the water displacement method (Mohsenin, 1986; Khanali *et al.*, 2007; Jahromi *et al.*, 2007).

The axial dimensions (L, W and T) were measured with the aid of a digital Vernier calliper (Carrera Precision model CP8812-T 12-Inch, United States) having an accuracy of 0.01 mm. The three mutually-perpendicular axes were determined by allowing each tuber crop to drop freely under gravity and then rest on its natural axis. At this natural resting position, the axial dimensions along the three mutually-perpendicular axes were obtained as length (the longest dimension), width (the axial dimension perpendicular to the length) and thickness (the axial dimension which is perpendicular to both length and width) (Tabatabaeefar, 2002; Raji and Ahemen, 2011; Ahemen and Raji, 2017). The three mutually perpendicular axes of the tubers are illustrated in Figure 1.

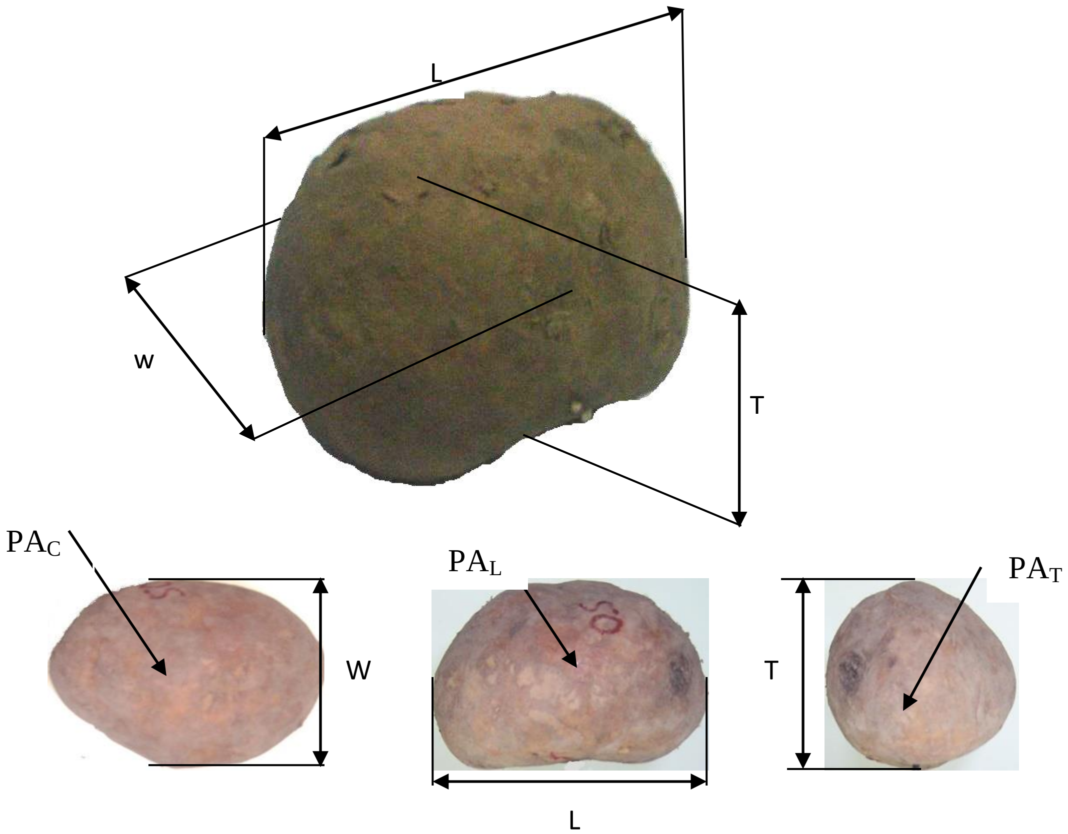

Figure 1: Major axial dimensions and projected areas of Tacca tubers

AMD and GMD were calculated from the measured axial dimensions according to Equations 1 and 2 respectively (Pathak *et al*., 2020).

$$AMD = \frac{L+W+T}{3} \tag{1}$$

$$GMD = (L \times W \times T)^{\frac{1}{3}} \tag{2}$$

where: AMD = Arithmetic Mean Diameter (mm); GMD = Geometric Mean Diameter (mm); L = length or longest diameter of the tuber (mm); W = width or the axial dimension perpendicular to the length (mm); T = thickness or diameter which is perpendicular to both length and width (mm).

Forty samples were selected at random for developing mass and volume models based on the projected areas. The projected areas along the three mutually-perpendicular axes PA_L (along the longitudinal plane), PA_C (along the cross-sectional plane) and PA_T (along the transverse plane) were obtained by image processing (Khanali *et al*, 2007; Jahromi *et al*., 2007). The image processing technique involved the acquisition of the images of the tubers using a digital camera and the projected areas were then obtained by reading the images in portable pixel map (ppm) format as input into an algorithm developed in Fortran 95 programming language. An image acquisition lighting box (Figure 2) was constructed to flood the samples with light and ensure proper capturing of the images by preventing shadow-casting. The algorithm extracted the total number of pixels making up the acquired image enclosed in a rectangle of known area and the number of pixels making up the projection of Tacca tuber in the image. The projected area was calculated within the algorithm according to Equation 3.

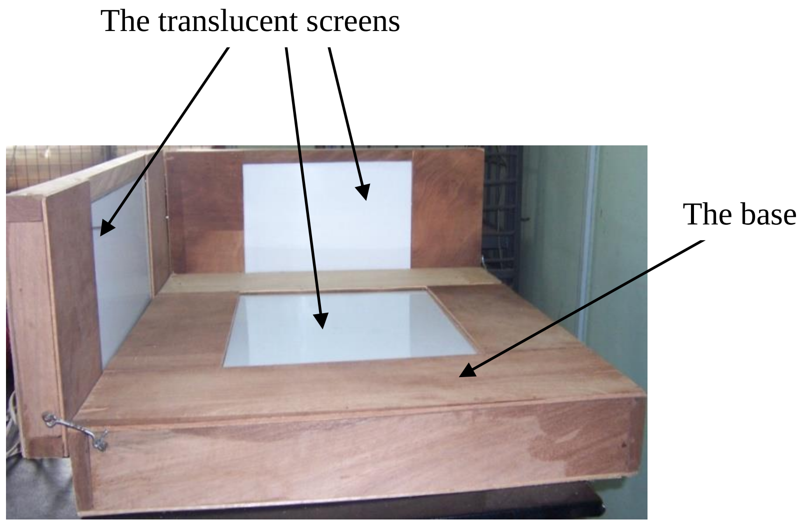

Figure 2: The image acquisition lighting box

$$PA = \frac{N_{PP}}{N_{TP}} \times A_R \tag{3}$$

where: PA = Projected area of the tuber (mm^2); N_{PP} = Number of pixels of tuber projection; N_{TP} = Total number of pixels making up the enclosing rectangle; A_R = Area of the smallest enclosing rectangle (mm^2). Table 1 shows the areas of the smallest enclosing rectangle for the acquired images along the longitudinal, cross-sectional and transverse orientations.

Table 1: Areas of the smallest circumscribing rectangles for the acquired images

S/N	Orientation	Projected Area (mm^2)	Area of Circumscribing Rectangle (mm^2)
1	Longitudinal	PA_L	$L \times T$
2	Cross-sectional	PA_C	$L \times W$
3	Transverse	PA_T	$W \times T$

The Criterion Area (A_c) of the tubers was calculated according to Equation 4 (Tabatabaeefar, 2002).

$$A_c = \frac{PA_L + PA_C + PA_T}{3} \tag{4}$$

where: Ac = Criterion Area (mm^2); PA_L = projected area along the longitudinal plane (mm^2); PA_C = projected area along the cross-sectional plane (mm^2) and PA_T = projected area along the transverse plane (mm^2).

2.4 Development of the prediction models

Out of the 240 tubers used in this study, data from 120 samples were used for actual development of the prediction models while the remaining 120 samples were used for validation of the developed models. All the data were averaged over three replications. Mathematical models for predicting the mass and volume of Tacca tubers were developed by regression analysis using the Data analysis tool in Microsoft Excel (2013 version). The regression analysis involved estimating the likely relationship between the dependent variables (mass and volume) and one or more physical properties of the tubers as independent variable(s).

Different regression models that were suggested in analysing the data obtained include linear ($y = a + b_1x_1 + \cdots + b_nx_n$), exponential ($y = ae^{bx}$), logarithmic ($y = a\ln x$), power ($y = ax^b$) and polynomials of order 2 to 6 ($y = b_nx^n + b_{n-1}x^{n-1} + \cdots + b_1x + k$). However, the regression models that best describe the relationships that exist between the dependent and independent variables are the only ones presented in the study. Suitability and adequacy of fit of the developed mass and volume models were determined on the basis of highest coefficients of determination (R^2) and lowest error estimates.

The mass and volume models were divided into three classifications based on the independent variables as follows:

i. single and multiple variable regression models based on axial dimensions namely length (L), width (W), thickness (T), AMD and GMD of the tubers for the first classification;
ii. single and multiple variable regression models based on the projected areas (PA_L, PA_C, PA_T and A_C) for the second classification;
iii. single variable regression model based on volume (for mass prediction only) for the third classification. The mass of the tuber was predicted using the measured volume and a simple linear regression obtained is of the form shown in Equation 5.

$$M = k + a_1V \tag{5}$$

Where: M = mass of Tacca tubers (g); V = volume of Tacca tubers (cm^3); k = intercept on the M-axis; a_1= slope or gradient of the equation.

Model validation involved using the developed models to estimate the mass and volume of the tubers and then determining the closeness of the predicted values to the experimental or observed values. Highest coefficient of determination (R^2) and lowest error estimates namely mean bias error (MBE) and root mean square error (RMSE) were used as the basis for determining the goodness of fit of the developed models. Values of R^2, MBE and RMSE for the data were calculated using Equations 6, 7 and 8 respectively.

$$R^2 = \frac{\sum_{i=1}^{N}(Y_{(exp,i)} \times Y_{(pre,i)})^2}{(\sum_{i=1}^{N}(Y_{(exp,i)})^2) \times (\sum_{i=1}^{N}(Y_{(pre,i)})^2)} \tag{6}$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(Y_{(pre,i)} - Y_{(exp,i)}) \tag{7}$$

$$RMSE = [\frac{1}{N}\sum_{i=1}^{N}(Y_{(pre,i)} - Y_{(exp,i)})^2]^{\frac{1}{2}} \tag{8}$$

where: $Y_{(exp,i)}$ is the ith experimentally observed value; $Y_{(pre,i)}$ is the ith predicted value; N is the number of observations.

3. Results and Discussion

The minimum and maximum values of the measured physical properties of Tacca tubers at average moisture content of 73.3 ± 1.2% (wet basis) are as presented in Table 2. These physical properties include the axial dimensions (length, width, thickness, AMD and GMD), projected areas, criterion area, mass and volume of the tubers. These data are of significance in the design of processing machines and handling equipment for the tubers. Accurate packaging of the tubers based on mass or volume could also be ensured based on these physical characteristics.

Table 2: Some physical properties of Tacca tubers

Physical Characteristics	Number of Samples	Range
L (mm)	240	34.81 – 114.24
W (mm)	240	20.05 – 94.58
T (mm)	240	24.22 – 70.70
AMD (mm)	240	29.72 – 97.92
GMD (mm)	240	28.82 – 97.36
PA_L (mm^2)	40	602.77 – 5,277.89
PA_C (mm^2)	40	588.94 – 4,283.63
PA_T (mm^2)	40	840.44 – 6,792.78
A_C (mm^2)	40	677.38 – 5451.43
M (g)	240	14.80 – 566.40
V (cm^3)	240	13.00 – 460.00

3.1 Mass and volume prediction models

Mass and volume prediction models developed based on the three classifications are as presented in Tables 3 and 4 respectively. Statistical parameters (R, R^2, RMSE and MBE) for validation of the mass and volume models are presented in Tables 5 and 6 respectively.

There were no significant differences ($p \leq 0.05$) between the predicted and experimentally observed values of mass and volume of Tacca tubers.

Table 3: Mass models for Tacca tubers based on the selected geometrical attributes

Model No.	Classification	Independent variable	Relation	R^2
1	First	L (mm)	$M = 0.003L^{2.484}$	0.890
2		W (mm)	$M = 0.072W^2 - 2.757W + 42.331$	0.854
3		T (mm)	$M = 0.011T^{2.416}$	0.762
4		L, W, T (mm)	$M = -213.572 + 2.278L + 1.501W + 2.044T$	0.930
5		AMD (mm)	$M = 0.103(AMD)^2 - 5.960(AMD) + 112.470$	0.987
6		GMD (mm)	$M = 0.111(GMD)^2 - 6.478(GMD) + 123.230$	0.980
7	Second	PA_L (mm^2)	$M = 0.0008(PA_L)^{1.506}$	0.986
8		PA_C (mm^2)	$M = 0.0005(PA_C)^{1.601}$	0.982
9		PA_T (mm^2)	$M = 0.0011(PA_T)^{1.428}$	0.985
10		PA_L, PA_c, PA_T (mm^2)	$M = -56.347 + 0.027(PA_L) + 0.018(PA_C) + 0.022(PA_T)$	0.982
11		Ac (mm^2)	$M = 0.007(A_c)^{1.516}$	0.996
12	Third	V (cm^3)	$M = 1.121V + 3.045$	0.965

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Table 4: Volume models for Tacca tubers based on the selected geometrical attributes

Model No.	Classification	Independent variable	Relation	R^2
1	First	L (mm)	$V = 0.002L^{2.499}$	0.881
2		W (mm)	$V = 0.065W^2 - 2.615W + 42.952$	0.840
3		T (mm)	$V = 0.010T^{2.403}$	0.738
4		L, W, T (mm)	$V = -183.640 + 1.889L + 1.423W + 1.667T$	0.905
5		AMD (mm)	$V = 0.086(AMD)^2 - 4.722(AMD) + 86.046$	0.955
6		GMD (mm)	$V = 0.093(GMD)^2 - 5.229(GMD) + 97.230$	0.949
7	Second	PA_L (mm^2)	$V = 0.0011(PA_L)^{1.446}$	0.984
8		PA_C (mm^2)	$V = 0.0007(PA_C)^{1.538}$	0.982
9		PA_T (mm^2)	$V = 0.0016(PA_T)^{1.367}$	0.978
10		PA_L, PAc, PA_T (mm^2)	$V = -42.546 + 0.020(PA_L) + 0.019(PA_C) + 0.017(PA_T)$	0.979
11		Ac (mm^2)	$V = 0.001(A_c)^{1.454}$	0.992

Table 5: Comparison of predicted and observed mass of Tacca tubers

Model No.	Model type	Independent variable	R	R^2	MBE	RMSE
1	Power	L (mm)	0.959	0.920	-1.517	18.354
2	Quadratic	W (mm)	0.906	0.822	1.669	26.727
3	Power	T (mm)	0.861	0.742	-2.848	32.229
4	Linear (multiple)	L, W, T (mm)	0.972	0.945	4.273	15.789
5	Quadratic	AMD (mm)	0.993	0.985	0.353	7.700
6	Quadratic	GMD (mm)	0.990	0.980	0.512	8.921
7	Power	PA_L (mm^2)	0.992	0.984	0.274	9.860
8	Power	PA_C (mm^2)	0.990	0.980	-0.143	11.004
9	Power	PA_T (mm^2)	0.992	0.983	-0.183	9.975
10	Linear (multiple)	PA_L, PAc, PA_T (mm^2)	0.991	0.982	0.018	10.385
11	Power	Ac (mm^2)	0.997	0.994	0.076	6.074
12	Linear	V (cm^3)	0.979	0.959	-1.457	12.911

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Table 6: Comparison of predicted and observed volume of Tacca tubers

Model No.	Model type	Independent variable	R	R^2	MBE	RMSE
1	Power	L (mm)	0.940	0.883	-3.097	19.647
2	Quadratic	W (mm)	0.907	0.822	2.711	23.547
3	Power	T (mm)	0.834	0.695	-2.025	30.679
4	Linear	L, W, T (mm)	0.957	0.916	1.926	16.529
5	Quadratic	AMD (mm)	0.975	0.950	1.701	12.484
6	Quadratic	GMD (mm)	0.971	0.943	1.809	13.372
7	Power	PA_L (mm^2)	0.988	0.977	-0.201	9.642
8	Power	PA_C (mm^2)	0.987	0.975	-0.102	10.116
9	Power	PA_T (mm^2)	0.988	0.976	-0.249	9.879
10	Linear (multiple)	PA_L, PAc, PA_T (mm^2)	0.989	0.979	-0.011	9.173
11	Power	Ac (mm^2)	0.994	0.987	0.056	7.266

3.1.1 First classification models (axial dimensions, AMD and GMD)

Mass and volume models based on axial dimensions as single independent variable numbered 1, 2 and 3 in Tables 3 and 4 had low fitness with low R^2 and higher MBE and RMSE. This thereby indicates that no single axial dimension can be reliably used to predict mass and volume of Tacca tubers. However, mass and volume models based on length gave better results than the ones based on width and thickness. Mass and volume models based on multiple regression of the three axial dimensions (L, W and T) had relatively good fitness with R^2 of 0.930 and 0.905 respectively. Models on the basis of AMD and GMD as independent variables gave consistently high R^2 ($\geq$ 0.958). This clearly indicates that these models can consistently predict the mass and volume of the tubers with high level of accuracy. However, the models are multi-variate, relying on all the three axial dimensions in their computations and are therefore, more complex than those that are univariate.

Although mass and volume of the tubers may not be effectively predicted on the basis of any of the axial dimensions individually due to low R^2, it can be suggested that the models having length as the independent variable can still be adopted. These models (based on length) are preferred to the models that consider all the three mutually-perpendicular axial dimensions despite their lower R^2 values, because it is more practicable, less cumbersome and faster to handle and compute. Variations in mass and volume of the tubers against length as the independent variable are presented in Figures 3 and 4 respectively.

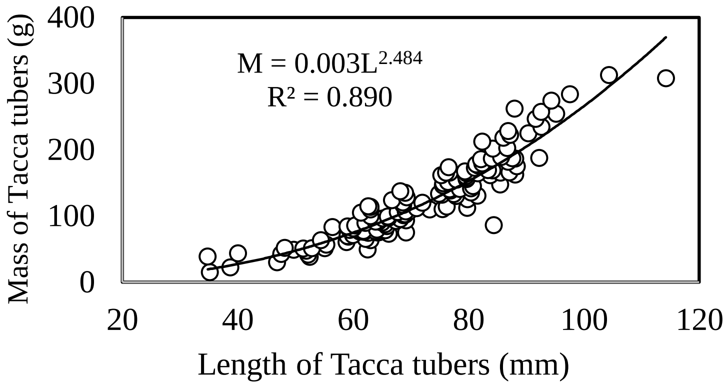

Figure 3: Mass model of Tacca tubers on length at average moisture content of 73.3% (wet basis)

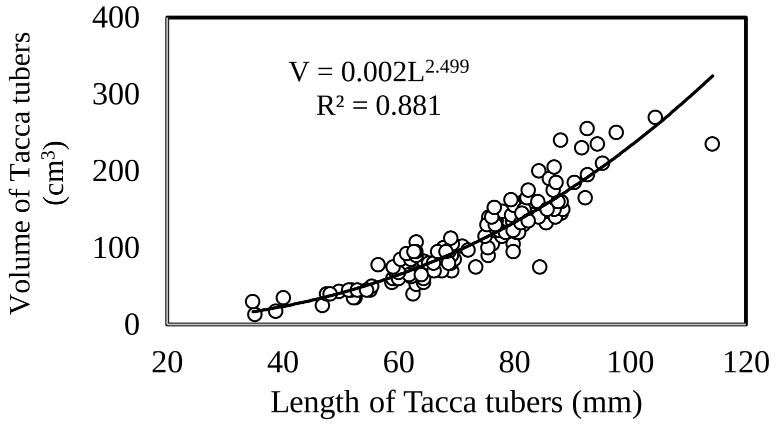

Figure 4: Volume model of Tacca tubers on length at average moisture content of 73.3% (wet basis)

3.1.2 Second classification models (projected and criterion areas)

Mass and volume models developed based on second classification involving the projected and criterion areas are presented in Tables 3 and 4, as models numbered 7 to 11. These models gave very consistent and relatively higher R^2 and could therefore, be suggested as the best models to be adopted for the estimation of mass and volume of Tacca tubers. Models based on the Criterion Area (A_c) also had consistently high R^2, indicating their suitability for accurately predicting the mass and volume of Tacca tubers. However, the models rely on all the three projected areas along mutually-perpendicular axes which makes them more cumbersome to compute. Best predictive mass and volume models (with highest R^2) in the second classification for the tubers were those on the basis of PA_L as the independent variable and their plots are presented in Figures 5 and 6 respectively.

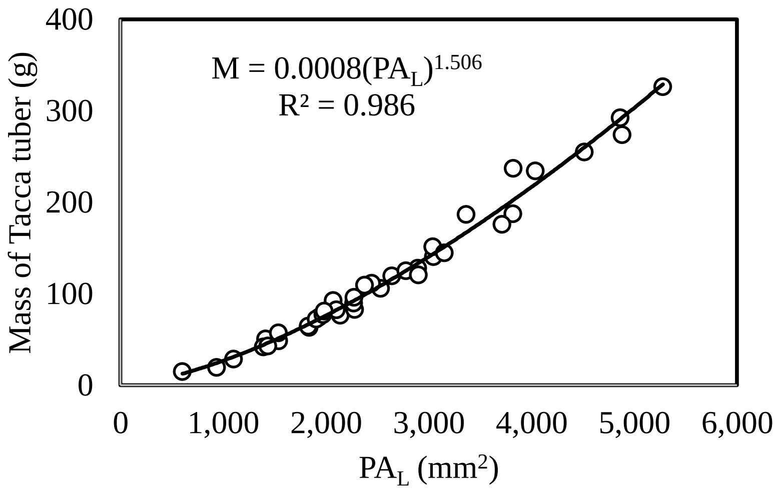

Figure 5: Mass model of Tacca tubers on PA_L at average moisture content of 73.3% (wet basis)

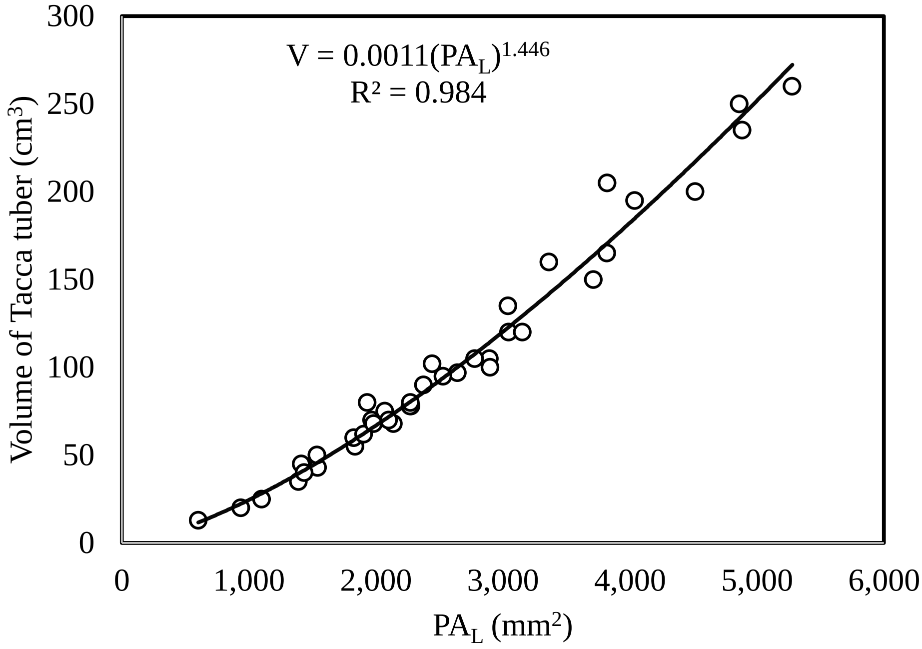

Figure 6: Volume model of Tacca tubers on PA_c at average moisture content of 73.3% (wet basis)

3.1.3 Third classification Models (Volume)

This classification was considered only for predicting the mass of the tubers with volume as the independent variable. The mass models based on volume is numbered 12 on Table 3. Variations in mass against the volume of the tubers are presented in Figure 7. For the third classification, the mass model had R^2 of 0.961 which indicates a high level of accuracy in its prediction and could therefore, be recommended for adoption in predicting the mass of the tubers.

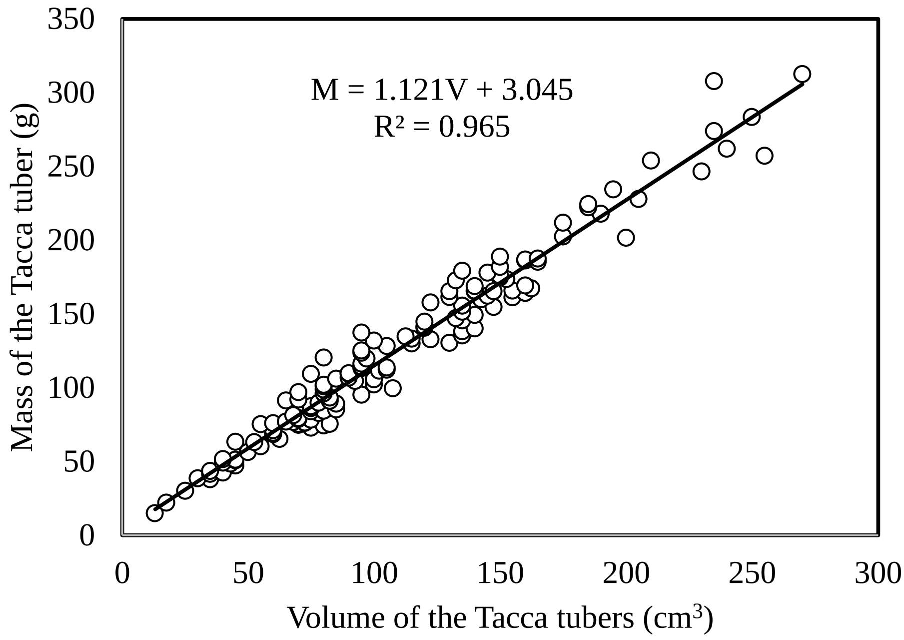

Figure 7: Mass model of Tacca tubers on volume at average moisture content of 73.3% (wet basis)

4. Conclusions

Selected physical properties of Tacca tubers were determined in this study and predictive models were determined based on these physical characteristics to estimate the mass and volume of the tubers. Length, width, thickness, arithmetic mean diameter (AMD) and geometric mean diameter (GMD) ranged from 34.81 to 114.24, 20.05 to 94.58, 24.22 to 70.70, 29.72 to 97.92 and 28.82 to 97.36 mm respectively. Longitudinal, cross-sectional, transversal and criteria projected area of the tubers ranged from 602.77 to 5277.89 mm^2, 588.94 to 4283.63, 840.44 to 6792.78 and 677.38 to 5451.43 mm^2 respectively. Mass and volume of the tubers ranged from 14.80 to 566.40 g and 13.00 to 460.00 cm^3 respectively.

Mass and volume models developed based on the length and projected area along the longitudinal plane (PA_L) were the best models on the basis of a single variable of axial dimension and projected area respectively. The predictive models based on AMD, GMD and criterion area had consistently high correlation and error estimates, although they are more cumbersome to compute since they depend on multiple attributes in their computations. There existed a very good correlation between mass and volume of the tubers, thereby indicating that mass of the tubers can be reliably predicted with the volume. Mass and volume modelling based on a single variable of any of the projected areas can be considered as the most reliable and convenient modelling for Tacca tubers since it involves the use of a single image capturing device and the whole measurement could therefore, be automated. The models developed in this study will be useful for automated sorting and packaging of Tacca tubers.

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