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PHYSICAL CHARACTERIZATION AND MASS MODELING BY GEOMETRICAL ATTRIBUTES OF BLACK SAPOTE (*Diospyros nigra* (J.F.Gmel.) Perr.)

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ABSTRACT

The fruit of black sapote (*Diospyros nigra* (J.F.Gmel.) Perr.) has been consumed in Mexico and Central America since pre-Hispanic times. They contain antioxidant compounds, minerals, and vitamins, making them valuable for nutraceutical and agro-industrial applications. Despite this, there is no scientific information on the physical and mechanical characterization of the fruit that helps in the design and development of protocols and equipment for storage, handling, processing, and added value for a better use of the fruit. In the present work, the physical and mechanical qualities of physiologically ripe black sapote fruit from the State of Hidalgo, Mexico, were characterized after one day of storage after harvest under environmental storage conditions. Models were also determined for the prediction of the mass of the fruit using their dimensional characteristics, finding that the quadratic models based on the volume of the ellipsoid (R^2 = 0.8919) and width of the fruit (R^2 = 0.8252) were the most appropriate to predict their mass. Likewise, a maximum compressive load force of 869.99 N and an apparent modulus of elasticity of 0.0.088 MPa were determined.

Keywords: mechanical properties, modulus of elasticity.

INTRODUCTION

The black sapote (*Diospyros nigra* (J.F.Gmel.) Perr.) is a fruit native to Mesoamerica. It is a member of the Ebenaceae family and has been consumed since prehispanic times (García-Díaz *et al.*, 2015). Its high phenolic compound content and nutritional value (Morton, 1987; Moo-Huchin *et al.*, 2014) make it ideal for use in nutraceutical and agro-industrial applications. However, its high perishability has limited its commercialization outside of the production regions, so it is currently underutilized. This is due to its architecture and intense metabolic activity, causing farmers to lose up to 40 % of its value before they reach the consumer (Kitinoja *et al.*, 2011). In this regard, in Mexico, a sown area of 2488 ha was recorded in 2021, with a production of 18 482 Mg (SIAP, 2023).

The study of the physical characteristics of fruits and their relationships is necessary for the design, development, and optimization of various equipment suitable for harvesting, post-harvest processing, and material handling (Miraei Ashtiani *et al.*, 2014; Jaiswal *et al.*, 2017). The determination of the mass, length, width, thickness, volume, and projected areas of the fruits is essential in the development of calibration systems and marketing since fruits with similar weight and uniform shape have a high acceptance by the consumer in the market (Panda *et al.*, 2020).

Fruit classification systems could be optimized by knowing the relationship between their physical properties and mass (Vivek *et al.*, 2018), since their geometric properties are easily measurable and their modeling could reduce classification time as well as work and costs in industries (Demir *et al.*, 2020). Several studies have shown the advantage of modeling the mass of fruits, as it has been for *Neolamarckia cadamba* (Roxb.) Bosser, *Fragaria x Ananasa* Duch., *Laurocerasus officinalis* Roem., *Euryale ferox* Salisb., *Phyllanthus emblica* L., *Haematocarpus validus* (Miers) Bakh.f. ex Forman, *Psidium guajava* L., *Flacourtia jangomas* (Lour.) Raeusch., *Diospyros melanoxylon* Roxb., *Terminalia chebula* Retz, and *Citrus reticulata* L. (Mahawar *et al.*, 2019; Pathak *et al.*, 2019; Barbhuiya *et al.*, 2020; Panda *et al.*, 2020; Altuntas and Mahawar, 2021; Bibwe *et al.*, 2022; Birania *et al.*, 2022; Gaurav *et al.*, 2022; Tomar and Pradhan, 2022; Panda *et al.*, 2022; Sasikumar *et al.*, 2021).

Fruits bruise during the transfer and storage stages due to the pressure exerted by heavy loads. Such damage reduces the quality of the product and increases the waste rate (Jahanbakhshi *et al.*, 2018). Because of this, it is important to study the mechanical properties of the fruits, which are defined as those that are related to the behavior of the materials when applying forces characteristic of deformation stress under static and dynamic loads. It is necessary to determine the physical-mechanical properties of each particular fruit due to the close relationship between these properties and their degree of susceptibility to different types of mechanical damage (Pérez-López *et al.*, 2014). In this sense, the American Society of Agricultural Engineers of the United States has developed guidelines such as Standard S368.4 DEC00 (ASAE, 2005), which deals with the compression test of agricultural products and served as the basis for the tests in the present study.

According to the Food and Agriculture Organization (FAO, 2003), there is a general demand for quality food in terms of nutritional value and safety, as well as appearance, freshness, and presentation. The fruit of *D. nigra* has a high nutritional value for its vitamin, mineral, and antioxidant content. However, their physical and mechanical properties are unknown, limiting proper post-harvest management. Also, *D. nigra* fruit has a ripening process with climacteric behavior (Arellano-Gómez *et al*., 2005), so the fruit is harvested before ripening, which should be completed in a warehouse under controlled conditions of temperature and humidity.

The objective of this work was to characterize the physical and mechanical properties of freshly harvested *D. nigra* fruit in physiological maturity, in particular the dimensions, color, maximum compression load, maximum deformation by compression, and apparent modulus of elasticity, in addition to determining models that allow the estimation of its mass. The results of the research can be applied to the design of post-harvest processes that allow the reduction of damage and waste in the fruit of *D. nigra*, particularly those from the State of Hidalgo, Mexico.

MATERIALS AND METHODS

For the present study, 108 physiologically ripe and undamaged *D. nigra* fruit were collected; 46 were harvested 270 days after anthesis on January 26, 2022, and the remaining 62 were picked 260 days after anthesis on January 10, 2023. The fruit was obtained from a single wild tree incorporated into a family orchard, provided with no agronomic management (only weed control) in the Municipality of Atlapexco, Hidalgo, Mexico (21° 2′ 22.34″ N, 98° 20′ 48.55″ W), where the climate is humid semi-warm with rains all year round (72.1 %) and humid semi-warm with abundant rains in summer (27.9 %). After each harvest, the fruit was immediately packed in plastic nets and transported to the Materials Laboratory of Chapingo Autonomous University in the municipality of Texcoco, State of Mexico, Mexico, where the measurements were made.

Physical property characterization

The physical and mechanical properties of the fruit were characterized at a temperature of 21.19 ± 0.42 °C and a relative humidity (RH) of 39.39 ± 4.93 % on January 26, 2022. On January 10, 2023, the harvested fruit was characterized at a temperature of 19.76 ± 0.31 °C and a relative humidity (RH) of 45.12 ± 4 %. The moisture content was determined following the AOAC Method 925.10 (AOAC, 2005) using a digital balance (Ohaus; NJ, USA) with a sensitivity of 0.001 g. Mass was calculated using an Ohaus digital balance with a sensitivity of 1 g.

Color was determined with a portable colorimeter (X-rite; MI, USA), obtaining the luminosity L* (100 = white, 0 = black), a* (positive = red, negative = green), and b* (positive = blue, negative = yellow) values. The average values of three records reported in the equipment were considered the reported coordinates of each sample. The data was captured and processed in Adobe Photoshop® CS3 Extended (ASI, 2007) to determine the red, green, and blue (RGB) coordinate model. Subsequently, the data was processed to obtain the polar coordinates C* and H° using Microsoft Excel through the following equations (McGuire, 1992):

for a* and b* positives:

$$Tono\ (h^o) = arctan\,\frac{b^*}{a^*}$$

for a* negative and b* positive:

$$Tono\ (h^o) = 180 + arctan\frac{b^*}{a^*}$$

$$Croma\ (C^*) = (a^2 + b^2)^{1/2}$$

A digital Vernier (Truper, Mexico) with 0.01 millimeters (mm) accuracy was used to obtain the dimensions of length (L), width (W), and thickness (T) of the fruit (Figure 1). The results were expressed in terms of mm.

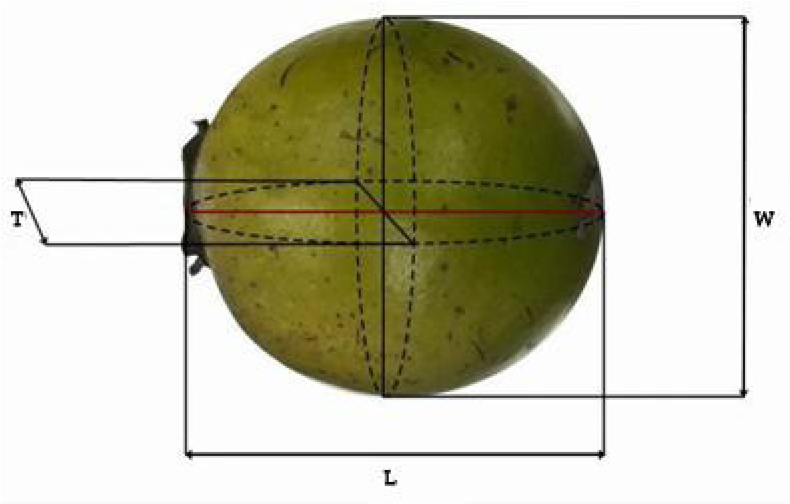


Figure 1. Length (L), width (W), and thickness (T) of black sapote (*Diospyros nigra* (J.F.Gmel.) Perr.) fruit.

The dimensional parameters were calculated using the following equations (Panda *et al*., 2020):

$$d_g = (L * W * T)^{1/3}$$

where d_g represents the geometric mean diameter (mm);

$$d_a = \frac{L + W + T}{3}$$

where d_a represents the arithmetic mean diameter (mm); and

$$d_e = \left[\frac{L * (W + T)^2}{4} \right]^{1/3}$$

where d_e represents the equivalent average diameter (mm).

The shape of the fruit was determined by calculating the sphericity, the aspect ratio of the fruit, the relationship between the thickness and width of the fruit (F_R), and the relationship between length and width (E_R), using the following equations:

$$\varphi = \frac{(L * W * T)^{1/3}}{L} * 100$$

where φ represents sphericity;

$$A_R = \frac{W}{L}$$

where A_R represents the aspect ratio;

$$F_R = \frac{T}{W}$$

where F_R represents the flaking index; and

$$E_R = \frac{L}{W}$$

where E_R represents the elongation index.

Projected areas perpendicular to thickness, length, and width were calculated using the following equations (Vivek *et al*., 2018):

$$P_T = \frac{\pi * W * T}{4}$$

where P_T represents the projected area perpendicular to the thickness (mm^2) of the fruit;

$$P_T = \frac{\pi * L * W}{4}$$

where P_L represents the projected area perpendicular to the length (mm^2) of the fruit;

$$P_W = \frac{\pi * W * W}{4}$$

where P_W represents the projected area perpendicular to the width (mm^2) of the fruit; and

$$CPA = \frac{P_L * P_T * P_W}{3}$$

where *CPA* represents projected area criteria (mm^2).

The fruit surface was calculated by reference to the following expression:

$$S_a = \pi * d_g^2$$

where S_a represents the surface area (mm^2) of the fruit.

The volume was calculated as a measure of a flattened spheroid, an elongated spheroid, and ellipsoid volume referring to the following equations (Shahbazi and Rahmati, 2013):

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

where V_{obl} is the volume of the flattened spheroid (mm^3) of the fruit;

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

where V_{prl} is the volume of the prolonged spheroid (mm^3) of the fruit; and

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

where V_{ellip} represents the ellipsoid volume (mm^3) of the fruit.

Mass modeling of fruit

The mass modeling of the *D. nigra* fruit, according to their physical properties, was performed using six empirical models: linear, quadratic, power, S-curve, exponential, and multiple linear (equations 1 to 6, respectively), which have been previously reported for the modeling of fruit mass (Mahawar *et al.*, 2019; Pathak *et al.*, 2019; Barbhuiya *et al.*, 2020; Panda *et al.*, 2020; Altuntas and Mahawar, 2021; Bibwe *et al.*, 2022; Birania *et al.*, 2022; Gaurav *et al.*, 2022; Tomar and Pradhan, 2022; Panda *et al.*, 2022; Sasikumar *et al.*, 2021).

$$M = \beta_0 + \beta_1 X \quad (1)$$

$$M = \beta_0 + \beta_1 X + \beta_2 X^2 \quad (2)$$

$$M = \beta_0 X^{\beta_1} \quad (3)$$

$$M = \beta_0 + \beta_1 \frac{1}{X} \quad (4)$$

$$M = \beta_0 e^{\beta_1 X} \quad (5)$$

$$M = \beta_0 + \beta_1 L + \beta_2 W + \beta_3 T \quad (6)$$

where M is the mass (g), X is the physical property of the *D. nigra* fruit, and β_0, β_1, β_2, and β_3 are the adjustment constants of the curves.

Mechanical properties

Compression tests were applied within parallel plates of 15 cm in diameter to determine the mechanical properties of the maximum compression load (N), Hencky deformation, and apparent modulus of elasticity (MPa) of the fruit (Bourne, 2002). The equipment used was an INSTRON (Universal Testing Machine) model 3382 (INSTRON, Norwood, MA, USA) with a crosshead speed of 50 mm min^{-1} (ASAE, 2005) and a load cell of 100 kN. The fruit was placed in horizontal orientation (transverse axis) on a platform. The load was applied until the fracture. The INSTRON machine was simultaneously connected to a computer with BLUEHILL® Software, which provides the compression load and compression extension values for each fruit evaluated.

From this data, the instantaneous compression stress-Hencky deformation curve was generated for each sample, taking into consideration the radial height of the fruit and the surface area of the compression plate. The apparent modulus of elasticity and Hencky deformation were calculated according to the following equations (Nedomová *et al.*, 2017):

$$E = \frac{\sigma}{\varepsilon_H} = \frac{\frac{F}{A_{instant}}}{\varepsilon_H}$$

$$\varepsilon_H = -\ln\left(1 - \frac{compression\ extension}{h}\right)$$

$$A_{instant} = \frac{A * h}{h - compression\ extension}$$

where E is the apparent modulus of elasticity of the fruit, ε is the fruit tension, ε_H is the Hencky deformation in the fruit, F is the force applied during compression, A is the area of the disc that makes contact with the surface of the fruit, $A_{instant}$ is the instant area, and h is the radial height of the fruit.

Statistical analysis

Statistical indices, including mean, minimum, maximum, standard deviation, and coefficient of variation, were calculated using R programming (version 4.1.2) (R Core Team, 2017). The raw data on physical properties were used to obtain mass models (regression models between mass and physical characteristics), regression coefficients (R^2), and standard error of estimates (SEE). All model coefficients were analyzed with F-tests and t-tests with α = 0.05. The best model fit was decided based on the highest R^2 value and lowest SEE.

RESULTS AND DISCUSSION

Physical characteristics

The moisture content determined for the fruit of *D. nigra* harvested on January 26, 2022, was 80.62 ± 1.68 %. For the fruit harvested on January 10, 2023, the moisture content was 76.45 % ± 3.77 %. These moisture values match those of 71 to 83 % moisture previously reported by Morton (1987).

The average results of color measurement of the fruit in the CIE-L*a*b* color space, as well as the color palette of epicarps, mesocarps, and seeds (Table 1) show a bright green and light-yellow color were observed in the epicarp and mesocarp, respectively, which coincides with Ledesma and Campbell (2001), who mentioned that the color of the pulp of the unripe fruits of *D. nigra* is golden-yellow. Regarding the seeds, an average of 6 ± 3 seeds per fruit of a dark brown color were obtained (Table 1), with an average weight of 1.23 ± 0.14 g and a length of 22.07 ± 2.57 mm, which coincides with Morton (1987), who mentions that there can be from 1 to 10 seeds per fruit, which are flat, smooth, brown, and 1.9–2.54 cm long.

The physical parameters of the fruit (Table 2), as well as the distributions obtained for the mass (M), length (L), width (W), and thickness (T) of the analyzed lot of *D. nigra* fruit (Figure 2), showed a natural variation in the dimensions of the fruit of up to 30.68 %. This variation is important to know and consider in the design of postharvest processes such as drying and packaging, among others (Pathak *et al.*, 2020).

Table 1. Rectangular chromatic coordinates and color palette of black sapote (*Diospyros nigra* (J.F.Gmel.) Perr.).

Part of the fruit	Parameters					
	L*	a*	b*	Tone (h°)	Croma (C*)	Color
Epicarp	51.46 ± 4.40	-5.91 ± 2.14	38.95 ± 4.81	278.82 ± 3.35	39.47 ± 4.70	
Mesocarp	55.12 ± 7.20	7.31 ± 2.39	40.60 ± 7.22	259.93 ± 1.81	41.27 ± 8.09	
Seed	21.57 ± 5.83	11.95 ± 1.28	12.27 ± 1.95	224.76 ± 6.63	17.08 ± 2.16	

Table 2. Black sapote (*Diospyros nigra* (J.F.Gmel.) Perr.) fruit dimensions.

Property	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation (%)
M (g)	74.74	318.55	160.70	43.55	27.10
L (mm)	56.10	106.60	81.05	8.74	10.70
W (mm)	50.50	88.20	66.94	6.88	10.28
T (mm)	54.95	91.70	70.30	6.76	9.62
d_e (mm)	39.10	90.53	72.30	7.00	9.68
d_g (mm)	54.42	90.13	72.34	6.18	8.54
d_a (mm)	54.50	90.80	72.69	6.18	8.50
P_L (mm^2)	2225.07	6781.60	4284.25	743.69	17.36
P_W (mm^2)	2002.96	6109.80	3555.94	738.64	20.77
P_T (mm^2)	2256.80	6352.25	3729.67	740.20	19.85
CPA (mm^2)	2161.61	6035.91	3851.43	707.60	18.37
S_A (mm^2)	9305.24	25 521.64	16 557.42	2832.61	17.11
V_{ellip} (mm^3)	84 404.41	383 386.40	203 389.88	51 900.63	25.52
V_{ops} (mm^3)	75 979.01	373 512.49	169 734.38	52 075.70	30.68
V_{prl} (mm^3)	83 217.70	481 945.63	235 110.24	63 840.41	27.15
f	79.51	106.78	89.89	7.26	8.08
A_R	0.70	1.08	0.83	0.10	12.13
F_R	1.00	1.18	1.05	0.04	3.84
E_R	0.92	1.44	1.22	0.14	11.36

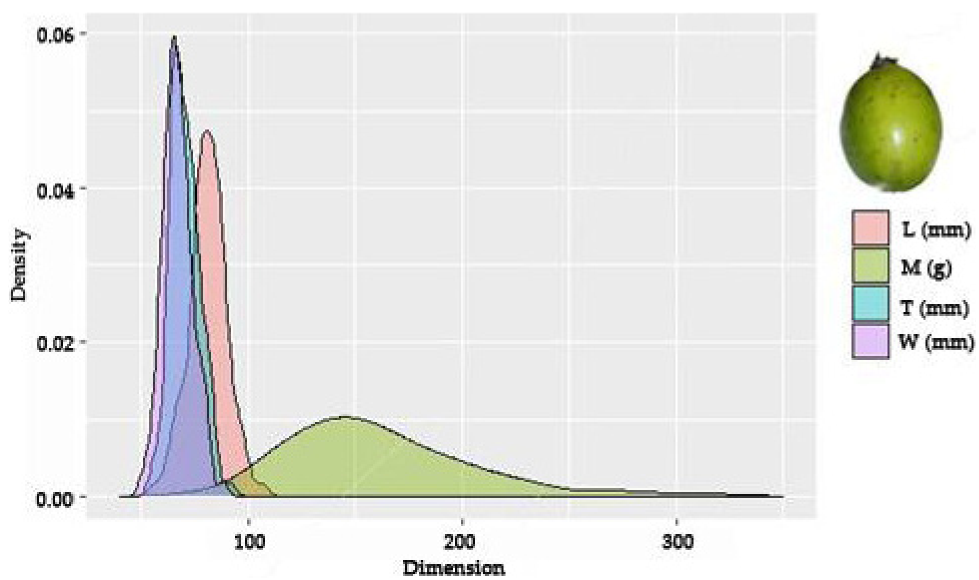


Figure 2. Distributions of mass (M), length (L), thickness (T), and width (W) of black sapote (*Diospyros nigra* (J.F.Gmel.) Perr.) fruit.

Mass modeling of the fruit

The quadratic (Equation 1) and multiple linear (Equation 4) models were selected as the best models for all physical attributes due to their high coefficients of determination (R^2) and low standard error of estimates (SEE) (Table 3). The F test values for these models were also significant ($p < 0.05$).

Table 3. Coefficients and the standard error of estimates (SSEs) of the models tested for the calculation of the black sapote (*Diospyros nigra* (J.F.Gmel.) Perr.) fruit mass.

Independent parameter(s)	Model	R^2	SSE	β_0	β_1	β_2	β_3
W	Quadratic	0.8252	18.41	7.85×10^{1}	-3.19×10^{0}	6.53×10^{-2}*	--
T	Quadratic	0.7979	19.80	1.19×10^{2}	-4.40×10^{0}	7×10^{-2}*	--
d_e	Quadratic	0.8798	15.27	6.21×10^{2}*	-1.92×10^{1}*	1.75×10^{-1}*	--
d_g	Quadratic	0.8780	15.38	5.12×10^{2}*	-1.62×10^{1}*	1.6×10^{-1}*	--
d_a	Quadratic	0.8644	16.22	5.21×10^{2}*	-1.63×10^{1}*	1.55×10^{-1}*	--
P_L	Quadratic	0.7627	21.57	7.16×10^{1}	8.84×10^{-3}	6.71×10^{-6}*	--
P_w	Quadratic	0.8251	18.42	-3.57×10^{0}	3.92×10^{-2}*	1.88×10^{-6}	--
P_T	Quadratic	0.8381	17.72	1.66×10^{1}	4.16×10^{-2}*	1.53×10^{-6}	--
CPA	Quadratic	0.8914	14.51	4.84×10^{1}	1.48×10^{-3}	6.96×10^{-2}*	--
SA	Quadratic	0.8763	15.32	8.01×10^{1}*	-4.28×10^{-3}	5.37×10^{-7}*	--
V_{ellip}	Quadratic	0.8919	14.55	3.40×10^{1}	4.64×10^{-4}*	7.38×10^{-10}*	--
V_{osp}	Quadratic	0.8393	17.65	1.67×10^{1}	9.23×10^{-4}*	-4.01×10^{-10}	--
L, W, and T	Multiple linear	0.8852	15.08	-3.12×10^{2}*	1.21×10^{0}*	2.50*	2.94*

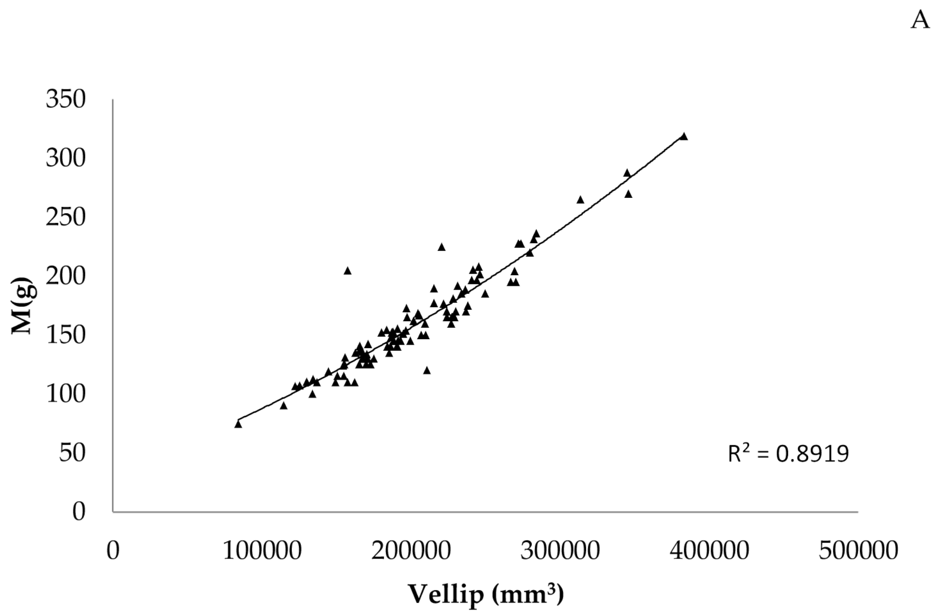
*Model coefficients (βi) are significant ($p < 0.05$) according to the t-test obtained in the R programming environment.

The model that uses the ellipsoid volume (V_{ellip}) as the independent variable has the highest R^2 value and lowest SEE (Equation 7 and Figure 3A); therefore, it is suggested as the best fit.

$$M = 4.639 \ x \ 10^{-4} \ V_{ellip} + 7.375 \ V^2_{ellip}; \ R^2 = 0.891, \ SEE = 14.55 \qquad (7)$$

Similar results regarding the estimation of fruit mass based on ellipsoid volume (V_{ellip}) within a quadratic model have been reported as a suitable physical property for mass modeling of the fruit *Haematocarpus validus, Euryale ferox*, *Diospyros melanoxylon*, *Terminalia chebula,* and *Citrus reticulata* (Mahawar *et al.*, 2019; Pathak *et al.*, 2019; Panda *et al.*, 2020; Sasikumar *et al.*, 2021; Gaurav *et al.*, 2022), with R^2 values of 0.945, 0.879, 0.955, 0.970, and 0.955, respectively.

Likewise, the model that uses only fruit width (W) as an independent variable shows R^2 values of 0.8252 and SSE of 18.41 (Equation 8 and Figure 3B), which could also be



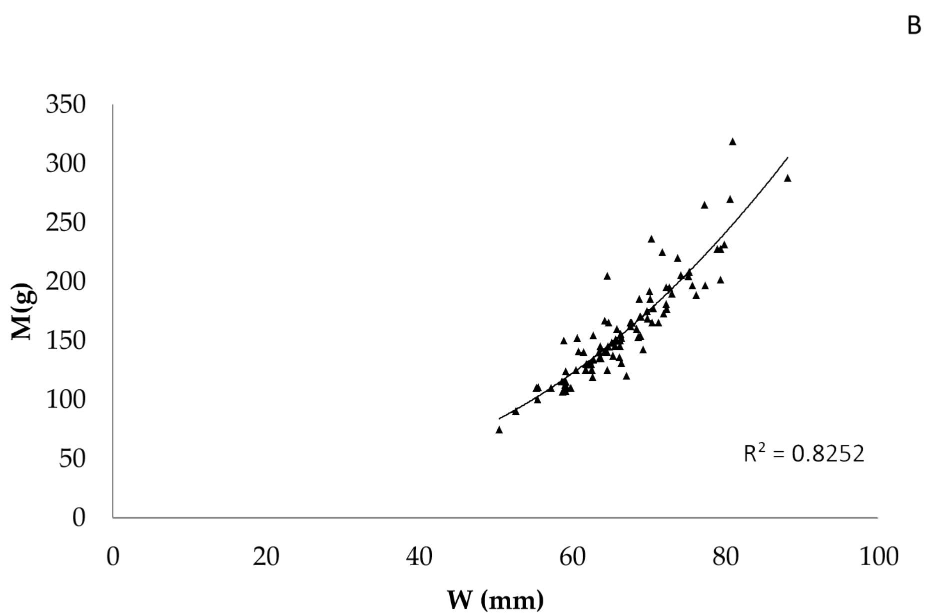


Figure 3. Quadratic mass models of black sapote (*Diospyros nigra* (J.F.Gmel.) Perr.) fruit. A: model based on ellipsoid volume (V_{ellip}); B: based on width (W).

considered a suitable model if a higher speed and lower processing costs of *D. nigra* fruit and data are sought.

$$M = 0.065\ W^2;\ R^2 = 0.825,\ SEE = 18.41 \quad (8)$$

Fruit width was reported as a suitable physical property for mass modeling in the case of *Prunus avium* fruit by being the most appropriate model among the three one-dimensional models they tested, with an R^2 value of 0.825 (Khadivi-Khub and Naderiboldaji, 2013).

Mechanical properties

The obtained values for maximum compression load, maximum Hencky deformation, and apparent elasticity (Table 4) show that freshly harvested nigra fruits are not damaged when the compression force is less than 399.7 N. Likewise, the compression load vs. extension and the instantaneous compressive stress vs. Hencky deformation curves obtained for a sample showed that *D. nigra* fruits present a typical linear viscoelastic behavior (Figure 4) (Severa, 2008).

Table 4. Values obtained for the mechanical properties of black sapote (*Diospyros nigra* (J.F.Gmel.) Perr.) fruit.

	Maximum compressive load (N)	Maximum Hencky's strain (%)	Apparent modulus of elasticity (MPa)
Minimum	399.72	21.82	4.75×10^{-2}
Maximum	1623.75	54.69	1.50×10^{-1}
Average	869.99	41.77	8.77×10^{-2}
Standard deviation	234.80	5.01	2.53×10^{-2}
Coefficient of variation (%)	26.99	12.18	$2.88 \times 10^{+1}$

The results show that the force that the physiologically mature fruit of *D. nigra* with one day of post-harvest storage can tolerate, up to the breaking point, is approximately 869.99 N, which is higher than the force reported for other fruits such as banana (*Musa acuminata* var. *Cavendish*), with a value of 194 N (Jahanbakhshi *et al*., 2020), and tomato (*Solanum lycopersicum*) (V. Canyon, Early Ch), with a value of 57.85 N (Lak *et al*., 2018). The value obtained for the apparent elastic modulus is 0.088 MPa, which is higher than other fruits, such as banana with a value of 0.007 MPa (Jahanbakhshi *et al*., 2020), and tomato (*Solanum lycopersicum*) (V. Canyon, Early Ch) with 0.05 MPa (Lak *et al*., 2018), and lower than fruits such as orange, with a reported value of 0.584 MPa (Gharaghani and Maghsoudi, 2018).

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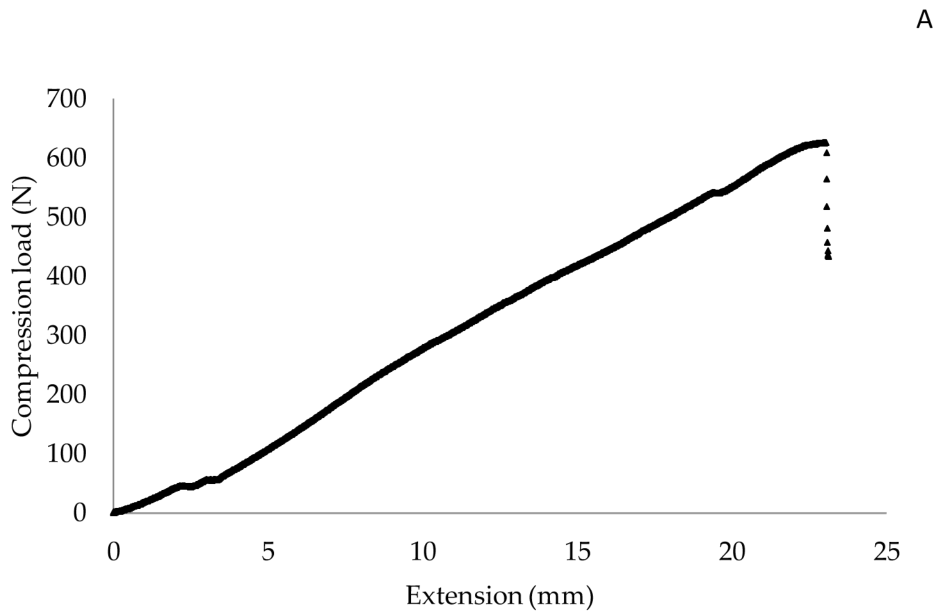

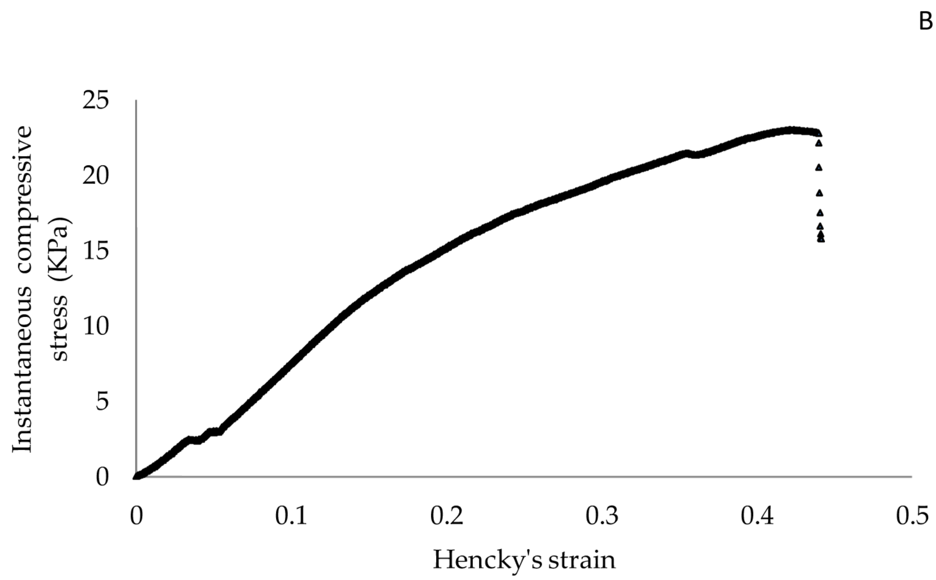

Figure 4. Compression test graphs for *Diospyros nigra* (J.F.Gmel.) Perr. A: compression load vs. extension; B: instantaneous compressive stress vs. Hencky's strain.

CONCLUSIONS

The physical and mechanical properties of black sapote (*Diospyros nigra* (J.F.Gmel.) Perr.) fruit at physiological maturity with one day of storage from the State of Hidalgo, Mexico, were characterized. In the models evaluated, all physical properties and their coefficients were statistically significant. The second-order polynomial model was the most suitable, with the highest R^2 values, indicating a strong correlation between the characterized physical variables and fruit mass. The models that use the ellipsoid volume (V_{ellip}) and the fruit's thickness (W) as independent variables are recommended for modeling mass; the latter requires fewer resources and only requires determining one dimension of the fruit. Black sapote fruit withstands a maximum compression load of 869.99 N at breakage. The data obtained can be used to design, develop, and manufacture different sorting, packing, transport, and processing machines for this fruit. However, due to morphological variation between locations, it is still necessary to study the mechanical, physical, and chemical characteristics as well as the compounds present in *D. nigra* fruits, including fruit from other areas. This will help identify any correlations between the various existing morphologies.

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