Physical and mechanical properties of morula (*Sclerocarya birrea* subsp. *Caffra*) nuts

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Abstract: Morula nuts were characterized for several physical and mechanical properties relevant to food process engineering. Mean moisture content of the nuts which had been naturally dried under the sun was 7.65% (w.b.). Mean nut length, width and thickness were, respectively, 25.64, 21.99 and 18.03 mm, while the derived geometric mean and equivalent diameters were 21.62 and 21.72 mm, respectively. Mean surface and projected areas were 1 475.74 and 445.02 mm^2, respectively, while mean nut volume was 5 371.90 mm^3. Mean apparent density of the nuts was 811.30 kg m^{-3} while bulk density and bulk porosity were determined as 476.43 kg m^{-3} and 41.28%, respectively. Morula nuts are generally spherical, with mean sphericity of 84.40%, and aspect and flakiness ratios of 0.86, and 0.83, respectively. Mean angle of repose against a plywood surface was 19.13° while coefficient of friction against a galvanized iron surface was 0.24. Peak force upon mechanical compression in a texture analyser was 2 738.33 N, while energy expended during compression was 3 284.49 Nmm, with mean hardness being 774.02 N mm^{-1} and tensile strength recorded as 6.60 MPa. It may be concluded from these results that morula is a tough, moderately sized spherical nut whose density is lower than that of water, having high bulk porosity and low frictional properties.

Keywords: Morula nut, size, shape, density, frictional properties, mechanical properties

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[1] 1 Introduction

Morula (*Sclerocarya birrea* subsp. *Caffra*) is a large dioecious wild fruit tree of the Anardiaceae (mango) family. It is native to southern Africa but can be found in frost-free climatic regions of the entire African continent (Hall, 2002). It is known as morula among the Tswana people in Botswana, while the variant marula is also commonly used in other parts of southern Africa. It grows up to 9 – 12 m tall with the female tree bearing between 17 500 to 91 300 fruits annually, translating to yields of 315 to 1 643 kg per tree (Hall, 2002; Shackleton, 2002). In Botswana, the tree bears fruit during the summer months of December to February. The flesh of morula fruit is consumed upon ripening, providing a rich source of vitamin C (Wehmeyer, 1966), which has been shown to be relatively more stable to thermal treatment than vitamin C from mangoes and guava (Hiwilepo-van Hal et al., 2012). Its pulp is extracted to yield juice and it may also be fermented into an alcoholic beverage. The fruit contains a nut which encases its kernel or seed. The morula kernels contain between 20%-35% protein and 55%-65% fat which is high in unsaturated fatty acids (oleic, palmitic, stearic, and linoleic), making it a

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healthful source of these dietary components (Hall, 2002). The kernel may be roasted and eaten as a snack with a very delectable taste. Ahmed et al. (2015) report that morula kernel oil has peroxide value of zero which means that it is very stable to oxidation. In addition, recent studies in Botswana have evaluated the potential application of morula kernel oil as a biodiesel fuel source (Gandure and Ketlogetswe, 2011a, 2011b; Ejilah et al., 2012).

Morula kernels occur in two or three pieces embedded inside a tough woody nut which traditionally is cracked manually using stones as hammer and anvil. This is a slow, arduous task documented by McHardy (2002) to take individuals in communities in Maputaland, South Africa, on average 7.2 h to fill a one-litre container with kernels. In a similar survey, Shackleton and Shackleton (2002) documented longer processing time to fill a one-litre container of 12 hours on average, in Limpopo, South Africa. It is important to note that this kernel extraction process is also fraught with danger of injury to the worker's fingers. A suitable morula nutcracker is, therefore, needed to address these problems. Moreover, Mojeremane and Tshwenyane (2004) and Wynberg et al. (2002) have reported on the potential economic benefits that would accrue from the exploitation of morula, hence justifying the need to develop a suitable morula nutcracker. To facilitate the design of such a nutcracker, knowledge of the physical and mechanical properties of the nut is necessary yet non-existent in the literature, hence the need for the present report.

Determination of relevant properties of agricultural and food materials is a vital requirement for proper design and operation of handling, processing and storage machinery and equipment. Moisture content, a compositional property of agricultural materials, is often determined since it influences most of the engineering properties of these materials and needs to be reported as the base for their determination (Singh and Heldman, 2009). Dimensional properties of granular materials are important, for instance, in sizing of machines and apertures of their components (Irtwange, 2009; Kisaalita et al., 2010). Shape, surface and projected area, density and porosity of particulate food materials are utilised in heat and mass transfer calculations in agricultural and food processing applications (Henderson et al., 1997; Jimoh and Olukunle, 2012). Furthermore, frictional properties and data from mechanical compression studies are needed to determine machine component dimensions and power requirements for nut crackers (Kisaalita et al., 2010; Marey et al., 2017). Therefore, the objective of the present study was to characterize several physical and mechanical properties of morula nuts which would aid in design, fabrication and operation of morula nut processing and handling machinery such as a nutcracker.

2 Materials and methods

2.1 Fruit and nut processing

Ripe morula fruits were collected from trees growing wild in Sebele village situated in South-Eastern Botswana. Mature and ripe fruits which had fallen to the ground beneath the trees were picked and collected in 9-L plastic buckets and transported immediately at ambient conditions to the laboratory for processing.

Fruits were washed using tap water and punched using a table fork to remove the flesh, and then the slimy pulp covering the nuts was rubbed off by hand under water. After this the nuts were dried naturally in the sun for two weeks, which is the traditional drying procedure employed locally. The dried nuts were then collected and kept sealed in plastic bags at ambient temperature.

2.2 Analytical methods

2.2.1 Moisture content determination

The AOAC method 925.10 was followed to determine nut moisture content by oven drying at 130°C for 1 hour (AOAC, 2005).

2.2.2 Dimensional properties determination

Dimensions of 20 nuts were measured using a digital vernier calliper (TA, M5 0-300 mm model, China) of 0.01 mm precision and Equations 1 and 2 cited by Heidarbeigi et al. (2009) were then used to compute geometric mean

(D_g) and equivalent (D_e) diameters of morula nuts in millimetres:

$$D_g = \sqrt[3]{LWT} \tag{1}$$

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

where, L is length, W is width, and T is thickness, all measured in millimetres.

Nut shape was described using sphericity index (φ) as percentage, aspect (R_a) and flakiness ratios (R_f) being calculated using Equations 3-5 (Sahin and Sumnu, 2006; Encyclopaedia Britannica, 1978):

$$\varphi = \left(\frac{\sqrt[3]{LWT}}{L}\right) \times 100 = (\frac{D_q}{L}) \times 100 \tag{3}$$

$$R_a = \frac{W}{L} \tag{4}$$

$$R_f = \frac{T}{W} \tag{5}$$

2.2.3 Determination of nut area and volume

The surface (S) and projected (A_p) areas of the nuts in mm^2, and volume (V) in mm^3 were calculated using Equations 6 – 8 after Mirzabe et al. (2013):

$$S = \pi D_g^2 \tag{6}$$

$$A_p = (\frac{\pi \mathrm{WL}}{4}) \tag{7}$$

$$V = (\frac{\pi D_q^3}{6}) \tag{8}$$

2.2.4 Density and porosity determination

Apparent density (ρ_{app}) is the density of a material including all the pores within the material (Rahman, 2014; Sahin and Sumnu, 2006). It was calculated using Equation 9 and expressed in kg m^{-3}:

$$\rho_{app} = \frac{M_{nut}}{V_{nut}} \tag{9}$$

where, M_{nut} is the mass of each nut measured in kg on a weighing scale and $Vnut$ is the volume of the nut in m^{-3} as determined by liquid displacement in toluene (Irtwange and Igbeka, 2002).

Bulk density (ρ_{bulk}) of the nuts was determined in triplicate by weighing the nuts packed in a tin can of predetermined volume (Heidarbeigi et al., 2009), and calculated in kg m^{-3} using the Equation 10:

$$\rho_{bulk} = \frac{mass\ of nuts\ packed}{volume\ of\ bulk} \tag{10}$$

Porosity (ε) was computed as a percentage from the apparent and bulk densities using Equation 11 (Sahin and Sumnu, 2006):

$$\varepsilon = (1 - \frac{\rho_{bulk}}{\rho_{app}}) \tag{11}$$

2.2.5 Frictional properties

Static angle of repose on plywood surface was determined by filling an open sided cylindrical plastic vessel with nuts while it stood on the test surface. The vessel of 156 mm height and 105 mm internal diameter was raised slowly to let the nuts flow out to form a circular pile, whose height (H) and diameter (D) in mm were measured using a ruler (Irtwange and Igbeka, 2002; Mirzabe et al., 2013). The angle of repose (θ_r) in degrees was then computed using Equation 12:

$$\theta_r = \tan^{-1}\left(\frac{2H}{D}\right) \tag{12}$$

The static coefficient of friction (μ) of morula nuts against a galvanized iron surface was determined after the method of Mirzabe et al. (2013). An open-ended plastic cylinder of 156 mm height and 105 mm diameter was placed onto the test surface and filled with morula nuts. The cylinder was raised slightly so as not to contact the test surface. Then the test surface was gradually tilted using a screw mechanism until the cylinder started to slide over the surface. The angle of inclination (α) was calculated from the vertical elevation and horizontal length of the tilted surface, using trigonometric rules. The static coefficient of friction was obtained from α using Equation 13:

$$\mu = \tan \alpha \tag{13}$$

2.2.6 Mechanical properties

Compression tests using a round, flat aluminium plate of 140 mm diameter was conducted on the Lloyd Instruments LR 10K *Plus* universal materials testing machine (Ametek, Inc, West Sussex, UK). The length and width of each nut was measured using a vernier calliper before loading onto the test table, and the 10 kN crosshead was programmed to compress the nuts at a speed of 30 mm min^{-1} to 20% strain. Peak force, tensile strength and energy absorbed by the nuts on compression were computed using the pre-installed NEXYGENPlus

Data Analysis Software. Hardness was calculated by dividing the peak force by extension during compression and expressed in N mm^{-1} (Sirisomboon et al., 2007).

2.3 Data processing

Microsoft Excel Spreadsheet (Microsoft 365, Release 16.0) and the R Statistical Environment, version 4.1.3 (R Core Team, 2022) were used to, respectively, capture raw data and to compute several statistical indices to describe it.

3 Results and discussion

3.1 Morula moisture content

Mean moisture content of nuts was 7.65%±0.36% (w.b.) which is suitable for long-term storage of most dried foods for which a range of 7%-14% may be considered ”safe” (Golob, 2007). Morula nuts are known to keep well at ambient conditions in southern Africa, where relative humidity of the environment is generally low. Moyo et al. (2009) compared moisture content of freshly extracted morula kernels to those extracted from nuts after 12 months of storage and reported a reduction from 11.1% to 4.9%, showing that the nut has low hygroscopicity.

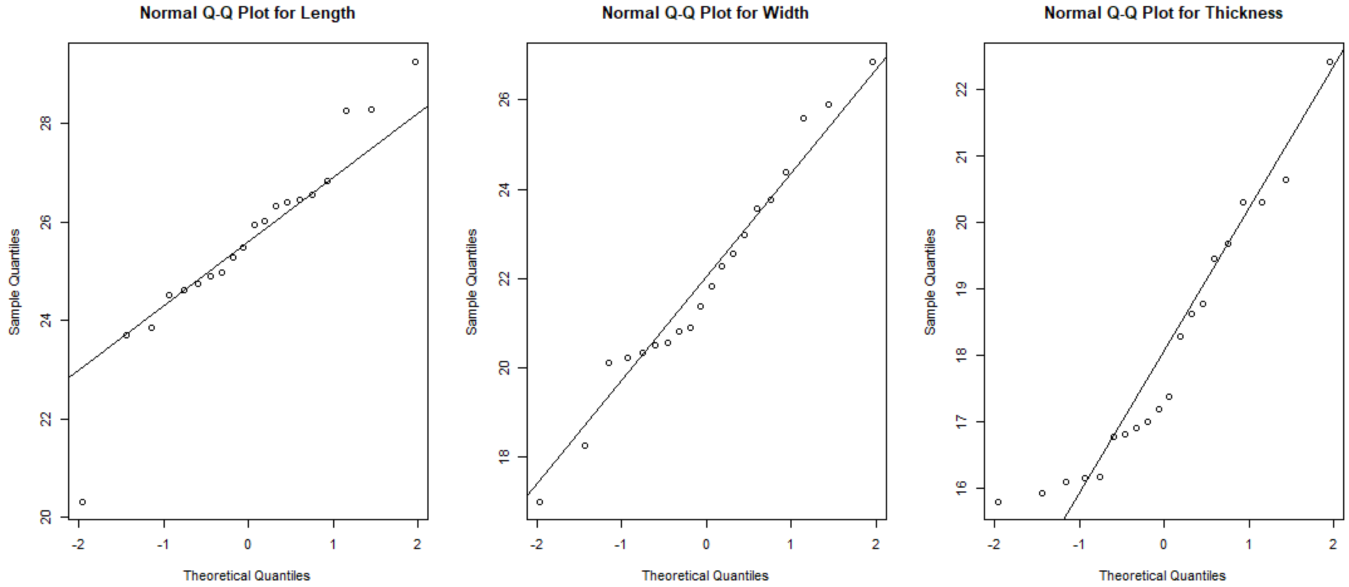

Figure 1 Normal Q-Q plots for morula axial dimensions

Table 1 Statistical summary of dimensional properties of morula nuts

Property	Mean	Minimum value	Maximum value	Standard Deviation	Kurtosis	Skewness
L, mm	25.64	20.32	29.27	1.93	2.20	-0.64
W, mm	21.99	17	26.87	2.51	-0.15	0.16
T, mm	18.03	15.79	22.42	1.90	-0.37	0.72
Dg, mm	21.62	18.04	25.02	1.60	0.56	0.03
De, mm	21.72	18.04	25.17	1.62	0.62	-0.07
Φ, %	84.40	77.95	91.33	3.86	-1.03	-0.09
Ra	0.86	0.76	1.02	0.08	-0.07	0.78
R_f	0.83	0.60	1.0	0.11	-0.47	-0.28
S, mm^2	1 475.74	1 022.58	1 967.34	217.42	0.54	0.28
A_p, mm^2	445.02	271.31	596.6	72.51	0.83	-0.35
V, mm^3	5 371.90	3 074.82	8 205.24	1 187.25	0.68	0.51

3.2 Dimensional properties

Sample versus theoretical quantile (Q-Q) plots for the length, width and thickness of the nuts are presented in Figure 1, which showed the data to have a normal distribution. A summary of statistical indices of the axial dimensions and the derived size and shape descriptors is presented in Table 1. Both the Q-Q plots and statistical indices showed nut length to be negatively skewed while width and thickness dimensions showed slight positive skewness. Length, width and thickness values ranged from 20.32 to 29.27 mm, 17 to 26.87 mm, and 15.79 to 22.42 mm, respectively.

Geometric mean and equivalent diameters ranged, respectively, from 18.04 to 25.02 mm, and 18.04 to 25.17 mm. Comparatively, morula nut size is similar to that of almond nuts, for which Mirzabe et al. (2013) reported geometric mean diameter range of 16.17 to 26.36 mm, and a mean value of 20.20 mm. Geometric mean diameter is a measure of size that summarises three linear dimensions into one, while the equivalent diameter is the diameter of a sphere having the same volume as the particle (Takayama et al, 1991; Sahin and Sumnu, 2006). The closeness in magnitude between the geometric mean and equivalent diameters suggests that the nut closely resembles a sphere in shape. Geometric mean and equivalent diameters find many applications in equipment design and in heat mass transfer computations (De Baerdemaeker et al., 1999; Sahin and Sumnu, 2006).

Sphericity, aspect and flakiness ratio values ranged, on average, between 77.95% to 91.33%, 0.76 to 1.02, and 0.6 to 1.0, respectively, showing that the nuts are spherical in shape since sphericity is >67% and the aspect and flakiness ratios are both greater than 0.67, the cutoff value above which a material can be termed as spherical (Encyclopaedia Britannica, 1978). Ogundahunsi et al. (2016) have employed size and shape parameters of dika nuts to create appropriately sized and shaped groves in the cracking trays of a motorised dika nut cracker.

The surface area, projected area and volume values ranged, respectively, from 1,022.58 to 1 967.34 mm^2, 271.31 to 596.6 mm^2, and 3 074.85 to 8 205.24 mm^3. Projected area data is needed in aerodynamic conveyance calculations (Yildirim and Tarhan, 2016).

3.3 Density, porosity and frictional properties

As is shown in Table 2, morula nuts had mean apparent and bulk densities of 811.30 and 476.3 kg m^{-3}, respectively, indicating that the nuts would float on water. Bulk porosity which was calculated from the density data was 41.28% which is a high value attributable to the presence of depressions on the nut surface which introduces voids. This is in contrast with morama bean which has a tough but smooth cortex, whose bulk porosity is reported as 25.76% (Emesu and Mabuza, 2014), while Sirisomboon et al. (2007) have reported much higher porosity for jatropha nuts of 56.73%. Density data is useful in many physical processes and operations involving heat and mass transfer (Henderson et al., 1997; Singh and Heldman, 2009).

Morula nut frictional properties are also presented in Table 2 with results showing that mean angle of repose was 19.13° as measured on a plywood surface and coefficient of friction against a galvanized iron surface was 0.24. These values suggest that morula nuts have fairly low cohesion among themselves and that they experience low friction against the surfaces tested. Angle of repose of particulate materials is important in the design and computation of operational parameters of agricultural and food processing, storage and conveyance systems and machinery (Sahin and Sumnu, 2006; Labiak and Hines, 1999; Degirmencioglu and Srivastava, 1996). In the design of an almond kernel extraction machine, Marey et al. (2017) have employed the coefficient of friction – in conjunction with dimensional properties – to constrain the radius of steel rollers used to crack the nuts.

Table 2 Density and frictional properties of naturally sun-dried morula nuts

Property	N	Mean	Standard Deviation
ρ_{app}, kg m^{-3}	16	811.30	77.39
ρ_{bulk}, kg m^{-3}	3	476.43	10.34
ε, %	N/A	41.28	N/A
θ_r	6	19.13	3.79
μ	6	0.24	0.03

3.4 Mechanical properties

Mechanical properties from compression of morula nuts in a texture analyser are presented in Table 3, with results revealing the nuts as very tough. Mean peak force to achieve compression to 20% strain was 2 738.33 N, with energy expended during the compression being, on average, 3 284.49 Nmm. Hardness was found to range between 170.15 and 1 240.27 N mm^{-1}, while tensile strength values ranged between 1.35 and 11.10 MPa. The peak force recorded during morula compression to 20% strain is 1.7 times more than the force required to crack Argan – deemed to be one of the toughest nuts in the world – which needed 1 575.6 N to crack (Kisaalita et al., 2010). Furthermore, Ledbetter (2008) reported a value of 874.4 N as the highest strength of eight ascensions of almonds examined for shell cracking strength, suggesting that nut crackers used in processing almonds would not be suitable to crack morula nuts. From a design standpoint, Marey et al. (2017) have used the maximum compressional force required to break almond nuts to compute the power requirement for an almond nut cracker.

Table 3 Summary of mechanical properties of morula nuts

Property	Mean	Minimum value	Maximum value	Standard Deviation
Peak force, N	2 738.33	675.85	4 148.89	955.12
Energy, Nmm	3 284.49	425.33	6 475.4	1 634.38
Tensile strength, MPa	6.60	1.35	11.10	2.44
Hardness, N mm-1	774.02	170.15	1 240.27	286.52

4 Conclusions

Morula nut dimensional, density, frictional and mechanical properties have been characterised. The nuts are deemed to be moderatly sized with average geometric mean diameter of 21.62 mm, similar to that of almond nuts. They are spherical in shape, having mean sphericity of 84.40%, with mean aspect and flakiness ratios of 0.86 and 0.83, respectively. Nut apparent and bulk densities were lower than water density at 811.30 and 476.43 kg m^{-3}, respectively, and they exhibited high bulk porosity of 41.28%. Morula nuts have low cohesion among themselves with angle of repose on plywood being, on average 19.13°, while coefficient of friction against a galvanised surface was low at 0.24 on average. Morula nuts are tougher than argan, opined by Kisaalita et al. (2010) as one of the toughest nuts in the world. Mean peak force to achieve 20% strain on compression of morula nuts was 2 738.33 N, with 3 284.49 Nmm energy absorbed in the process. Tensile strength and hardness were, on average, 6.60 MPa and 774.02 N mm^{-1}, respectively.

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