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Strength properties of the Bambara kernel (*Vigna subterranean*) as influenced by the moisture content and kernel size

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Abstract: The fracture resistance of food grains is an essential piece of information required for the optimum design and development of agricultural post-harvest machinery. In this study, the strength properties of two varieties of Bambara kernels (TVSU-1395 and TVSU-1353) were examined in terms of the mean rupture force, absorbed energy, and deformation as affected by the moisture content and kernel size. To achieve this, a quasi-compressive force was applied on the two varieties of Bambara kernels of varying moisture contents (5.43%, 7.24%, 9.01%, 11.54%, and 13.62% wb) and kernel sizes (small, medium, and large) in between the loading compartments of a universal Testometric device at a 20 mm/min loading rate. The experiments take ten treatments with 20 replications subjected factorially to a completely randomised design (CRD) into consideration. The results revealed that the force needed to initiate the kernel fracture increased with an increase in the kernel size and moisture content from 101.44 to 235.06 N and 74.69 to 190.49 N for TVSU-1395 and TVSU-1353, respectively; whereas the energy at the kernel fracture point increased in a range of 0.074 to 0.401 J and 0.062 to 0.141 J for TVSU-1395 and TVSU-1353, respectively. The kernel deformation increased with the moisture content and size from 0.654 to 3.746 mm. These infer that the large kernel size of the TVSU-1395 variety at a 5.4% moisture content had greater compressive strength than the TVSU-1353 variety. The kernel moisture and size exhibited a strong correlation ($0.958 \le R^2 \le 0.997$) with the strength parameters. The results of this study will help the food industry in designing energy-efficient post-harvest equipment for Bambara kernel processing. Further studies may consider the strength attributes of Bambara kernels at varying rates of loading, kernel orientations, and varieties to optimise the best process conditions for the post-harvest handling of different Bambara cultivars and develop labour-saving decorticating machines.

Keywords: compressive force; rupture, energy; deformation; yield strength

The Bambara (*Vigna subterranean*) is an African home-grown leguminous food crop, grown mostly by rural farmers across the African continent. In Nigeria, just as in many African countries, the Bambara nut is generally cultivated by small-hold farmers, typically women, in small land fragments

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and is often intercropped with maize, sorghum, and the cowpea (Alhassan and Egbe 2013). These impoverished farmers, according to Ibeawuchi (2007) and Orhevba et al. (2016), practice intercropping because of the increased rate of changes in the weather conditions, varied soil forms, population density, and socio-economic dynamics. Leguminous crops including the Bambara are known for enriching the soil with atmospheric nitrogen, consequently, giving rise to low fertiliser requirements for successive crops. As a result of this and its low vulnerability to insect and pest attack (Alozie et al. 2009), the Bambara is ideal for resource subsistent farmers who have, through continuous cultivations, chosen different Bambara nut cultivars with desirable qualities, such as providing a high yield and a bunchy growth tendency. Fumen et al. (2018) noted that the Bambara nut is known for various production benefits over other grains in the legume family, as it can thrive in poor soil conditions and has the prospect of producing a bountiful yield under improved soil conditions.

Commercially, the Bambara nut occupies the third position in ranking as the most preferred leguminous grain next to the groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculate*) (Orhevba et al. 2016). It is rich in basic food nutrients such as carbohydrates, iron, protein, calcium, potassium, sodium, oil, and energy. The nut, therefore, is taken as a complete balanced diet as revealed by the biochemical examination of the carbohydrate, protein, fat, and mineral substances. The food product was discovered to be richer in protein than the groundnut, soybean, and cowpea with protein levels of 65%, 74% and 64%, respectively (Pliestic et al. 2006; Orhevba et al. 2016). According to Mpotokwane et al. (2008), the Bambara nut has lost its relevance in many African regions as a result of the increased market availability of the groundnut. In Nigeria, the production of Bambara nuts has remained low, as it is estimated to vary averagely between 100 000 to 168 700 metric tonnes (Orhevba et al. 2016). Whereas in zones like the Sahel and Sudan Savannah, there is a decline in the market availability (production) of the crop primarily as a result of drought, but has an increased production rate in the Southern Guinea Savannah probably as a result of the crop's present increased income yield.

The Bambara nut has various economic benefits such as being a food for human consumption, a feed for livestock, a raw material for agro-industrial products, and healthy (Oluwole et al. 2007; Vurayai et al. 2011). It could be used in the production of high-quality extruded snacks. Orhevba et al. (2016) reported that in the South-east zone of Nigeria, the consumption of freshly harvested and dried Bambara products as food snacks is prominent and highly cherished in the form commonly known as "okpa" (Bambara nut paste). It is usually prepared after dehulling the kernel pods, crushed into a flour and homogeneously mixed with palm oil, water, salt, pepper and other food ingredients.

Bambara kernels are often subjected to various forms of mechanical forces during their shelling operation (to separate the bounded kernels), transportation, and storage. The shelling of the dried Bambara pods is traditionally undertaken by different means depending on the geographical zone and production capacity (Orhevba et al. 2016; Fumen et al. 2018). The shelling of the pods can be accomplished by mortar and pestle, hitting the pods with sticks on a flat hard surface, and the use of stones and concrete slabs to crush the pods. The local shelling techniques, according to Oluwole et al. (2007), are associated with a high seed damage rate, are laborious and sluggish. When these randomly applied shelling forces exerted on the kernel exceed certain limits, the pods fail typically in the form of interior and exterior cellular structure rupture. Damaged kernels make it possible for the entrance of organisms that cause decay, thereby reducing the market value and viability of the kernel. Therefore, the shelling or breakage of Bambara pods is a function of some physical characteristics like the applied force, moisture content, kernel size, and pod orientation (Fumen et al. 2018). Kernel damage due to cell rupture is, therefore, the main cause of quality shortfall in food grain markets. Thus, the strength property of the Bambara kernel is imperative not only for the ease of design and development of efficient machinery and equipment for post-harvest operations (such as harvesting, decortication, transportation, cleaning, sorting, grading, packing, drying, aeration, grinding, oil expelling, storage, *etc.*) as well as for the optimisation of process and crop variables, but also by food scientists, processors, plant breeders and allied scientists who may find novel applications for them (Kalkan et al. 2011). The strength property is also a good indicator of the kernel quality, resistive ability, and rupture characteristics at varying loading rates during

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post-harvest operations. This property and other physical properties of the Bambara kernel are affected by several factors like the moisture content, size of the kernel, and variety.

Several works have been reported in the literature on the strength properties of seeds and kernels, such as popcorn (Kalkan et al. 2011), the groundnut kernel (Uyeri and Uguru 2018), cumin seeds (Saiedirad et al. 2008), African oil bean seeds (Aremu et al. 2014), wheat and barley seeds (Dursun and Güner 2003), and neem seeds (Sacilik et al. 2003). Paulsen (1978) reported on the fracture resistance of soybeans under compressive loading at varying moisture contents of 9% to 20% dry basis (db). The maximum kernel hardness was obtained at a moisture range of 12–16% db, which shows the best moisture content regime for the absorbed energy. Samples loaded in the vertical orientation had less energy requirement for kernel rupture than the samples in the horizontal hilum orientation. The quantity of force needed to cause fraction in the pumpkin seed coat varied proportionally with the moisture content in the range of 5.1–10.5% db and decreased continuously to a moisture level of 21.7% db (Saiedirad et al. 2008). It was also observed that the seed coat rupture increased with an increase in the moisture content from 5.1 to 21.7% db. The rupture energy of the pumpkin seed loaded in the vertical position was considerably higher than that in the horizontal position. There was an increase in the absorbed energy of the seed in the two studied loading orientations with a moisture content up to 15% db, beyond which the energy absorbed was reduced. Kang et al. (1995) stated that at an increased moisture content and loading rate of the wheat kernel, the rupture strain and rupture energy diminished.

Similarly, the influence of the moisture content on some engineering characteristics of peanut kernels was investigated by Aydin (2007). His report demonstrated that the kernel rupture strength was moisture-dependent with a maximum value of 13.22 $N \cdot mm^{-2}$ at an 11.3% db moisture content. Braga et al. (1999) investigated the effects of the moisture content, nut size, and loading orientation on the mechanical behaviour of macadamia nuts under compressive loading. The obtained results showed that the needed force, deformation, and rupture energy of macadamia nuts were enhanced and were functions of the moisture content and nut size when the nuts were placed at right angles to the split plane. Saiedirad et al. (2008) observed that the mechanical strength of cumin seeds reduced with an increasing moisture content. They added that small seeds at a 5.7% moisture level under horizontal loading had greater strength at a maximum compressive force of 60.05 N than larger seeds at a 15% moisture content. The moisture content and kernel sizes perform meaningful roles in the design of engineering systems, and they change substantially amongst food crops, populations or varieties (Xiao et al. 2015).

Recent works on the shelling of food grains using mechanical devices reveal that the product moisture and kernel size are important parameters influencing the compressive efficiency and mechanical behaviour of biomaterials. Currently, there is a scarcity of information on the influence of the moisture content and kernel size on the strength properties of different varieties of Bambara kernels. This present study tries to close the research gap by estimating the compressive load-bearing capacities of two common cultivars of Bambara kernels at different kernel sizes and moisture content levels. A higher mechanical strength of Bambara kernel against damage is a guarantee for the effective post-harvest mechanisation. The propagation and development of new Bambara kernel varieties, as well as the strength characteristics under various loading types to which the grain may be subjected when in use, would be a good guide for selecting the most suited variety. Therefore, the specific objective of this study is to investigate the impact of the moisture content and kernel size on the strength properties of Bambara kernels.

MATERIAL AND METHODS

Sample preparation and moisture variation

The empirical study was conducted using two common varieties of dried Bambara nut kernels (TVSU-1395 and TVSU-1353), sourced from the Genetic Resources Centre, Ibadan, Nigeria (latitude 7°30'N and longitude 3°54'E). The studied varieties (Figure 1) are extensively cultivated in Nigeria because of their high disease-resistance index and kernel yield. A sample size of 700 g of each of the studied kernel varieties was meticulously removed of impurities: stalks/chaffs, stones, dirt, unformed and defective kernels, etc. The viable kernels were put in separate storage containers at room temperature for the equidistribution of the sample mois-

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Figure 1. The studied dried Bambara kernel varieties: TVSU-1395 (A) and TVSU-1353 (B)

ture (Sahoo and Srivastava 2002; Sangamithra et al. 2016). The initial moisture levels of the kernel samples were estimated gravimetrically using a handful (representative) kernel sample of 5 g (AOAC 2005; Nwakuba and Okafor 2020) at 105 °C for 24 h in an oven dryer (Memmert Ule500, Gemini Lab, Germany), and the mean moisture values was obtained as 5.43 and 5.38 % wet basis (wb) for TVSU-1395 and TVSU-1353, respectively. The kernel moisture levels were varied to five (5) different desired moisture levels (5.27 to 13.62% wb) by adding an estimated measure of distilled water expressed as Equation (1) (Seifi and Alimardani 2010; Kalkan et al. 2011; Sangamithra et al. 2016). Afterwards, the moist Bambara kernels were carefully mixed and wrapped in different air-tight glass containers and stored in a refrigeration system at a temperature of 5 °C for 7 days of the homogeneous moisture distribution in the kernels (Abalone et al. 2004; Kalkan et al. 2011).

$$Q_w = \frac{m_\kappa\left(x_2 - x_1\right)}{100 - x_2} \qquad (1)$$

where: Q_w – calculated amount of distilled water (kg); m_κ – initial mass of the kernel sample (kg); x_1, x_2 – initial and final kernel moisture levels, respectively (% wb).

All the kernels' geometric and gravimetric properties, as well as their compressive resistance variables, were calculated at the varying moisture levels. A random selection of 100 units of viable kernel samples from the bulk sample was used for the tests.

Kernel size measurements

Figure 2 schematically illustrates the measurements of the principal dimensions of the selected Bambara kernel varieties based on the three mutually perpendicular axes, *viz*: the major (length, ϕ_a), intermediate (width, ϕ_b), and minor (thickness, ϕ_c) diameters were performed using a vernier calipers (Fisher Scientific, Pittsburgh) with a sensitivity ± 0.01 mm. In this experimental study, the Bambara kernels were categorised into three size groups: large, medium, and small (Table 1).

Measurements of the principal axes were performed by turning the kernels in three different directions: along the length of the kernel which represents the major diameter; across the length, or along the shorter kernel length, (intermediate diameter), and the thickness, – minor diameter. The axial numerical measurements of the kernel samples are related to the choice of the sorter sieve diameter, as well as the hole diameter and clearance between the roller and the concave components of the pod shelling machine. The geometric mean

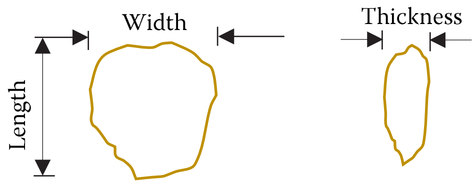

Figure 2. Typical axial measurements of a Bambara kernel sample

Table 1. Size categories of the sample Bambara kernels (ϕ_a –length; ϕ_b – width; ϕ_c – thickness)

Kernel variety	Small	Medium	Large
		(mm)	
	$\phi_a < 11.01$	$11.01 \leq \phi_a \leq 14.95$	$\phi_a > 14.95$
TVSU-1395	$\phi_b < 10.14$	$10.14 \leq \phi_b \leq 13.14$	$\phi_b > 13.14$
	$\phi_c < 9.46$	$9.46 \leq \phi_c \leq 12.92$	$\phi_c > 12.92$
Mean sphericity ratio	0.915 ± 1.2	0.919 ± 0.7	0.921 ± 1.1
	$\phi_a < 10.22$	$10.22 \leq \phi_a \leq 14.72$	$\phi_a > 14.72$
TVSU-1353	$\phi_b < 8.94$	$8.94 \leq \phi_b \leq 12.91$	$\phi_b > 12.91$
	$\phi_c < 8.56$	$8.56 \leq \phi_c \leq 11.53$	$\phi_c > 11.53$
Mean sphericity ratio	0.867 ± 1.1	0.872 ± 0.7	0.875 ± 0.5

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diameter ($\bar{\phi}_g$) and arithmetic mean diameter ($\bar{\phi}_a$) of each kernel variety are expressed in Equations (2) and (3), respectively (Abalone et al. 2004; Jibril et al. 2016; Fumen et al. 2018). The measured values of the principal axes were used to determine the geometric parameters of the kernel samples, whereas the coefficient of variation (*CV*) was used to compare the distributed axial values (Equation (4)).

$$\bar{\phi}_g = 3\ \ (\phi_a \times \phi_a \times \phi_a) \qquad (2)$$

$$\bar{\phi}_a = \pi\bar{\phi}_g^2 \qquad (3)$$

$$CV = \mathrm{SD}/\bar{x} \qquad (4)$$

where: SD – standard deviation; $\bar{x}$ – mean axial values (mm).

Thousand weight kernel (TWK). The mass of one thousand kernels was determined by weighing 100 viable kernels per variety of the studied sample using a digital weighing balance with a sensitivity, 0.01 g. In determining the TWK, the sample mass was extrapolated to 1 000 kernels by multiplying by a factor –10 (Ndirika and Oyeleke 2006; Jibril et al. 2016; Sangamithra et al. 2016).

Kernel surface area. The surface area (A_s) of the Bambara kernels was determined by the expression (Altuntaş et al. 2005; Orhevba et al. 2016):

$$A_s = \pi\bar{\phi}_g^2 \qquad (5)$$

Gravimetric characteristics

Volume. The volume of the kernel samples (V_κ) at the varying moisture content levels were calculated by considering the axial dimensions of the kernel varieties using the expression described by Seifi and Almandine (2010):

$$V\kappa = 1/4\ [\pi/6 \times \phi_a\ (\phi_b + \phi_c)^2],\ \mathrm{mm}^3 \qquad (6)$$

Sphericity ratio (ϕ_k). This refers to the ratio of the surface area of a sphere with an equal volume as that of the kernel to the surface area of the kernel (Sangamithra et al. 2016). It is expressed as:

$$\phi_k = \frac{(\phi_a \times \phi_b \times \phi_c)^{1/3}}{\phi_a} \qquad (7)$$

Kernel compressive test

The test for the strength attributes of the Bambara kernels was conducted with the use of a universal testing machine (Testometric, England; ± 0.001 N, 0.001 mm), at the Crop Processing Laboratory of the National Centre for Agricultural Mechanization, Ilorin, Nigeria. The machine is made up of three key components: a load compartment linked to an immobile upper plate; a lower movable plate attached to a driving element, and a digital computer stocked with data acquisition software applications. Each of the Bambara kernel varieties at different moisture levels was properly positioned in between the parallel plates (loading compartment) of the device, and a quasi-compressive force was applied at a constant deformation rate of 20 mm·min^{-1} through the lower plate by the drive element (Altuntaş et al. 2005; Seifi and Alimardani 2010) until the kernel sample fractured (Figure 3). The load-cell mounted on the immobile upper plate detected the applied force on the kernel sample, whose value increased with time until the kernel yielded and the data were transmitted to the data collation and processing unit to obtain a force-time relationship. The individual kernel deformation during the quasi loading up to the time of rupture is one of the strength characteristics of the Bambara kernels.

A plot of the force-deformation curve was generated by the Testometric device. The compressive loading was terminated when a rupture condition occurred as indicated in the bio-yield point in the auto-generated force-deformation plot. From the test, the strength parameters of the Bambara kernels, expressed as the rupture force, deformation at rupture, elasticity modulus, and rupture energy, were estimated by the machine's auto-plot. Steffe (1996) and Kalkan et al. (2011) reported that the rupture point of bio-materials is associated with

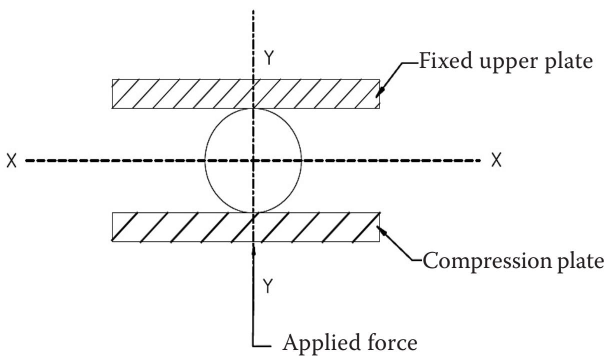

Figure 3. Kernel placement during the quasi-compressive loading

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the macroscopic collapse of the cell structure, denoted as the sample breaking point. The sample toughness (rupture energy) ζ_E, is referred to as the work needed for the Bambara kernel to rupture (fail), denoted as the area bounded by the force-deformation curve extending to the point of the kernel rupture. This was achieved using the installed software in the Instron Testometric machine. The kernel toughness is expressed as the ratio of absorbed energy to kernel volume (Mohsenin 1986; Kalkan et al. 2011):

$$\zeta_E = E_a/v_\kappa \quad (8)$$

where: E_a – kernel absorbed energy (J); v_κ – kernel volume (mm^3).

The kernel hardness was computed as the ratio of the rupture force to the amount of deformation at the point of the kernel rupture (Olaniyan and Oje 2002; Kalkan et al. 2011).

$$\psi_\kappa = \zeta_F/\zeta_D \quad (9)$$

where: ζ_F – rupture force (N); ζ_D – deformation at rupture (mm).

Statistical analysis

The experimental tests considered ten (10) treatments (which were comprised of ten separate kernel samples) at five (5) moisture content levels (5.43–13.62% wb); two (2) kernel varieties (TVSU-1395 and TVSU-1353); and three (3) size groups (small, medium, and large). The treatments were randomised factorially using the Completely Randomised Design (CRD), with a total of 20 replications and 60 treatment combinations and the mean values were recorded. A total of 600 kernels were subjected to a quasi-static compression test with ten kernels selected at random for each treatment run and the mean values were reported. The obtained results were tested for the degrees of variation ($P < 0.01$, $P < 0.05$) with the use of the SPSS 20.0 Statistical software®. Comparison of the least significant differences (LSD) in the kernels' strength parameters and interaction effects were tested and the treatment means were separated using Duncan's new multiple range test at a 0.95 level of confidence (Nwakuba et al. 2020, 2021).

RESULTS AND DISCUSSION

The analysis of variance (ANOVA) of the experimental data, as presented in Table 2, signifies that the moisture content and kernel size of the two studied varieties had a significant statistical influence on the strength properties of the Bambara kernel ($P < 0.01$). The mean force required to cause the kernel rupture was found to be 136.10 N, ranging between 74.69 N ≤ ζ_F ≤ 235.06 N, whereas the mean value of the kernel rupture energy was estimated as 0.16 J, ranging from 0.062 J ≤ ζ_E ≤ 0.401 J. The mean deformation of the kernel at rupture point was obtained as 2.34 mm over a range of 0.65 to 3.75 mm. Also, from Table 2, the interaction influence of the kernel variety and size, ($v \times s$) was not significant on the parameters of the strength properties of the Bambara kernels; whereas the interaction influence of the moisture content and kernel size, ($m \times s$) was statistically significant on the rupture energy only ($P < 0.01$). Statistically, the significant interaction influence of three experimental

Table 2. Analysis of variance of the variables of the strength properties of the Bambara kernels

Source of variation	Degree of freedom	Rupture force (N)	Rupture energy (J)	Deformation at rupture (mm)
Treatment	29	15.07*	4.38*	2.18*
Moisture content (*m*)	4	$8.17 \times 10^{-3*}$	$5.26 \times 10^{-2*}$	$7.04 \times 10^{-4*}$
Kernel variety (*v*)	1	$6.47 \times 10^{-5*}$	$4.13 \times 10^{-2*}$	$5.08 \times 10^{-3*}$
Kernel size (*s*)	2	$2.71 \times 10^{-7*}$	$3.4 \times 10^{-1\text{ns}}$	$2.01 \times 10^{8*}$
Interaction ($m \times v$)	(4)	$1.01 \times 10^{-4**}$	$1.21 \times 10^{-3**}$	$2.03 \times 10^{-5*}$
Interaction ($m \times s$)	(8)	$3.74 \times 10^{-2\text{ns}}$	$1.94 \times 10^{-3*}$	$4.28 \times 10^{-2\text{ns}}$
Interaction ($v \times s$)	(2)	0.946^{ns}	0.877^{ns}	0.261^{ns}
Interaction ($m \times v \times s$)	(8)	1.622^{ns}	$12.56 \times 10^{-4*}$	$6.67 \times 10^{-5*}$
Error	58	–	–	–
Total	87	–	–	–

*,**significant difference at $P < 0.05$, 0.01; ns – not significantly different; *CV* – 2.14%

https://doi.org/10.17221/94/2021-RAE

variables, ($m \times v \times s$), on the kernel rupture energy and deformation at rupture were only recorded at a 1% level of probability.

In the succeeding paragraphs and sub-sections, the influences of each experimental variable on the strength characteristics (rupture force, rupture energy, and deformation at rupture) of the Bambara kernel are exhaustively discussed.

Moisture content

The data analysis showed that amongst the studied two quantitative parameters (moisture content and kernel size), the moisture content demonstrated dominance over the strength characteristics of the Bambara kernels under compressive loading. The force needed to cause the kernel rupture (yield), ζ_F at varying moisture content levels and kernel sizes is given in Figure 4. An increase in the kernel moisture content diminished the ζ_F-values for each kernel size. As illustrated in Table 3, at a 5.4% moisture content, the rupture force (ζ_F) was 164.95 N. According to Duncan's new multiple range tests, this is significantly ($P \leq 0.01$) greater than the rupture force needed at a 13.62% moisture content, which is about 1.5 times. This possibly could be as a result of a softer product kernel at an increased moisture content level, thus a lower rupture force requirement. The works of Saiedirad et al. (2008), Konak et al. (2002), and Sadowska et al. (2013) are consistent with this assertion. They noted that an increase in moisture content value renders the sample kernels more susceptible to cracking; therefore, less rupture force is required. Aremu et al. (2014) studied the effects of the moisture content and loading orientation on the mechanical properties of the African oil bean seed (*Pentaclethra macrophylla* Benth) and stated that an increase in the moisture content (from 15.76 to 34.43% wb), reduced its mechanical properties (except the modulus of elasticity) which varied between 362.04 ≤ ζ_F ≤ 168.82 N; 1.783 ≤ ζ_E ≤ 0.623 J; and 1.529 ≤ ε ≤ 3.528 × 10^6 Pa for the rupture force, rupture energy, and modulus of elasticity, respectively.

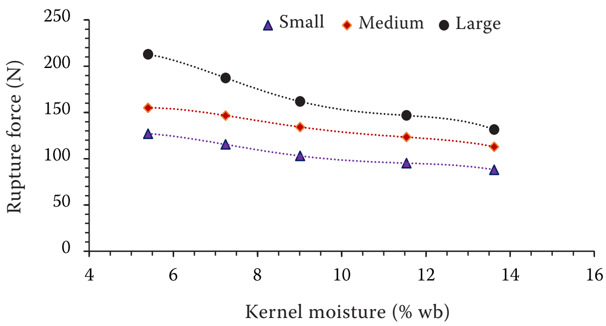

Figure 4. Influence of the moisture content and kernel size on the mean rupture force

However, from all the evaluated moisture contents, the maximum kernel rupture force (235.06 N) was recorded for the large-size TVSU-1395 kernel variety at a 5.4% moisture content, whereas the minimum rupture force of 74.69 N at a 13.62% moisture content was obtained for the small-size TVSU-1353 kernel variety (Table 4). This is an indication of the weakened moisture-induced kernel structure

Table 3. Mean evaluation of the strength parameters of the Bambara kernels in different size groups and moisture content levels

	Strength parameter		
	rupture force (N)	rupture energy (J)	deformation at rupture (mm)
Kernel size group (mm)			
Small	105.75[a]	0.12[a]	1.73[a]
Medium	134.46[b]	0.18[a]	2.34[a]
Large	168.08[c]	0.20[a]	2.96[ab]
Moisture content (% wb)			
5.4	164.95[a]	0.11[a]	2.80[a]
7.24	149.82[b]	0.13[a]	2.62[a]
9.01	133.06[bc]	0.15[a]	2.37[a]
11.54	121.77[c]	0.19[ab]	2.10[a]
13.62	110.89[d]	0.28[b]	1.83[ab]

Treatment means with the least common alphabetic letter are not significant ($P < 0.05$) based on Duncan's new multiple range test

https://doi.org/10.17221/94/2021-RAE

at higher moisture contents; thus, reducing the kernel's resistive strength to mechanical compression.

At varying kernel moisture contents and sizes, the mean amount of the energy absorbed by the kernels under quasi-loading to the point yield/rupture is given in Figure 5. An abrupt reduction in the rupture energy of the kernels was observed from 0.28 to 0.07 J as the level of moisture content is raised from 5.4 to 13.62% ($P < 0.01$). The maximum and minimum absorbed energy values were recorded for the small and large-sized kernels, respectively. This reveals that the larger sizes of kernels will be deformed more during the compressive loading as a result of the greater quantity of energy absorbed. From Table 4, the TVSU-1395 variety had more absorbed energy than TVSU-1353. This statistical significance of the TVSU-1395 nut ($P < 0.01$) may be due to its soft kernel coat nature and matrix structure enabling it to take up more energy at higher moisture content levels. This property of the Bambara kernel has the potential of reducing the proportion of cracked kernels during the post-harvest processing.

Table 4. Descriptive statistics for the strength properties of the Bambara kernels at different size groups, varieties, and moisture contents

Kernel size	Kernel variety	Moisture content (% wb)	Rupture force (N)	Rupture energy (J)	Deformation at rupture (mm)
Small	TVSU-1395	5.4	138.89^{a}	0.074^{a}	2.498^{a}
		7.24	124.68^{ab}	0.10^{b}	2.367^{a}
		9.01	112.75^{b}	0.13^{b}	2.228^{a}
		11.54	108.15^{bc}	0.16^{b}	1.748^{b}
		13.62	101.44^{c}	0.19^{b}	1.267^{c}
	TVSU-1353	5.4	115.19^{a}	0.062^{a}	2.135^{a}
		7.24	106.15^{b}	0.069^{a}	1.822^{ab}
		9.01	93.27^{bc}	0.076^{ab}	1.509^{b}
		11.54	82.26^{c}	0.13^{b}	1.082^{c}
		13.62	74.69^{c}	0.18^{b}	0.654^{d}
Medium	TVSU-1395	5.4	189.45^{a}	0.198^{a}	3.746^{a}
		7.24	181.13^{a}	0.208^{b}	3.503^{a}
		9.01	172.81^{b}	0.218^{b}	3.259^{a}
		11.54	159.48^{c}	0.262^{b}	2.951^{b}
		13.62	146.15^{d}	0.315^{c}	2.643^{b}
	TVSU-1353	5.4	120.62^{a}	0.064^{a}	1.603^{a}
		7.24	112.26^{ab}	0.083^{b}	1.556^{a}
		9.01	95.73^{b}	0.101^{bc}	1.509^{ab}
		11.54	87.18^{bc}	0.136^{c}	1.372^{b}
		13.62	79.81^{c}	0.17^{d}	1.235^{c}
Large	TVSU-1395	5.4	235.06^{a}	0.183^{a}	3.959^{a}
		7.24	212.17^{b}	0.228^{ab}	3.745^{a}
		9.01	189.23^{bc}	0.273^{b}	3.430^{ab}
		11.54	179.27^{c}	0.337^{bc}	2.983^{b}
		13.62	169.31^{d}	0.401^{c}	2.815^{c}
	TVSU-1353	5.4	190.49^{a}	0.089^{a}	3.175^{a}
		7.24	162.53^{b}	0.094^{a}	3.121^{b}
		9.01	134.56^{c}	0.098^{a}	2.684^{c}
		11.54	114.24^{d}	0.112^{b}	2.523^{c}
		13.62	93.91^{e}	0.141^{c}	2.361^{c}

Treatment means with a similar letter in the same column have no statistical difference at $P < 0.01$ according to Duncan's new multiple range test (DNMRT)

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Conversely, the absorbed energy is dependent upon the force and kernel deformation at the point of yield. This inverse relationship of the absorbed energy with the kernel moisture content is due to the small amount of yield force required at an increased moisture content occasioned by the kernel's soft texture. The reports of Kalkan et al. (2011), Aremu et al. (2014), and Uyeri and Uguru (2018) for popcorn kernels, African oil bean seeds, and groundnut kernels, respectively, are in line with our observations.

The influence of the different moisture contents of the Bambara kernels and sizes on the deformation at the rupture point is illustrated in Figure 6. For each of the size categories, the kernel deformation increased with the increasing moisture content, but had a slight decrease at a 9.01% moisture content and marginally increased again with an increase in the moisture content. Most plant-based materials are elastic during the initial phase of compressive loading and increase in the viscoelasticity as the moisture content increases. The depression at the 9.01% moisture content indicates the sensitivity of the Bambara kernels to damage. Kalkan et al. (2011) and Vursavus and Ozguven (2004) reported a related behaviour for popcorn and apricot pits, respectively. Therefore, the large kernels of the TVSU-1395 variety at a higher moisture content will encounter greater deformation than the TVSU-1353 variety, thereby causing unavoidable mechanical damage. This is due to the larger elastic modulus resulting in greater deformable power under mechanical load.

Kernel characteristics

The sphericity (ϕ_k) values of the Bambara kernels, which varied between 87.2% (TVSU-1353) to 92.1% (TVSU-1395) are given in Table 1. A statistical significance ($P < 0.05$) in the ϕ_k values occurred amongst the studied kernel varieties. It could be observed that the variety with the maximum mean sphericity was TVSU-1395. Balami et al. (2012) reported that the ϕ_k values for most food grains span between $0.32 \leq \phi_k \leq 1.0$; implying that the lower the ϕ_k value, the more regular the object becomes. According to Eke et al. (2007), a ϕ_k value above 70% indicates the degree of closeness of the seed geometry to a sphere. Similar observations for jack beans, Bambara groundnuts, maize kernels, and cowpeas have been reported (Eke et al. 2007; Mpotokwane et al. 2008; Ndukwu and Adama 2012; Sangamithra et al. 2016). Therefore, given the obtained high sphericity values, which permits the kernels to roll instead of sliding on a platform is the veritable property of food grains considered for the optimal design of process machines (such as grain cleaners and sorters) and components, such as hoppers, discharge chutes, as well as other storage equipment like traditional rhombus, recent grain silos (Fumen et al. 2018). Consequently, the TVSU-1395 kernel had a more regular shape than the TVSU-1353 one. The shape of the Bambara kernel can best be illustrated with the geometric attributes adopted by Olayanju and Lucas(2004): an irregular short longitudinal length > the lateral conic tapered near the apex. Therefore, the Bambara kernel can be described as an irregular short conic food grain.

The mean values of the principal measurements of the Bambara kernels, *viz.*, the length, width, and thickness, as well as the geometric and arithmetic mean diameters, surface area, volume, and kernel mass for the studied moisture ranges (5.27 to 13.62% wb) are summarised in Table 5. It is obvious

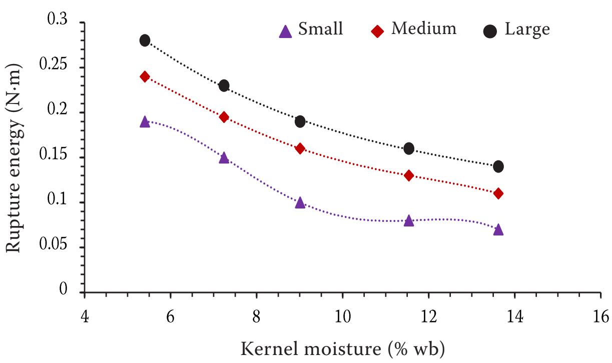

Figure 5. Influence of the moisture content and kernel size on the mean rupture energy

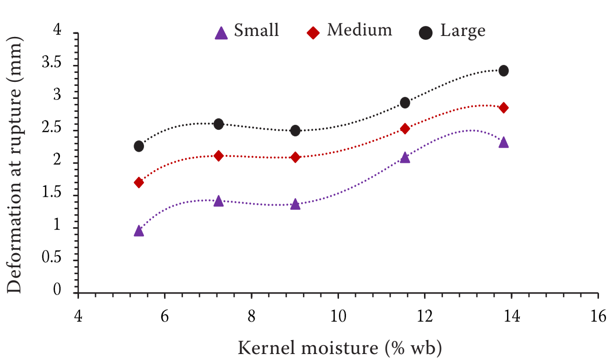

Figure 6. Influence of the moisture content and kernel size on the mean deformation at the rupture point

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Table 5. Mean values of the axial dimensions of the two Bambara kernel varieties (TVSU-1395 and TVSU-1353) at varying moisture levels

Kernel variety	m (% wb)	Length (ϕ_a) (mm)	Width (ϕ_b) (mm)	Thickness (ϕ_c) (mm)	Volume (cm^3)	Mass (g)	$\bar{\phi}_g$ (mm)	$\bar{\phi}_a$ (mm)	A_s (mm^2)
TVSU-1395	5.43	12.78 ± 0.78^{a}	11.59 ± 0.71^{a}	11.16 ± 0.75^{a}	1.01 ± 0.08^{a}	1.38 ± 0.17^{a}	11.85 ± 0.67^{a}	3.95 ± 0.22^{a}	442.0 ± 56.76^{a}
	7.24	13.2 ± 0.76^{ab}	11.87 ± 0.65^{b}	11.38 ± 0.62^{ab}	1.19 ± 0.18^{ab}	1.40 ± 0.21^{ab}	12.12 ± 0.57^{ab}	4.04 ± 0.19^{ab}	462.42 ± 43.54^{b}
	9.01	13.41 ± 0.80^{bc}	12.13 ± 0.65^{bc}	11.58 ± 0.65^{bc}	1.34 ± 0.30^{bc}	1.48 ± 0.19^{b}	12.35 ± 0.60^{bc}	4.12 ± 0.20^{b}	479.88 ± 45.89^{c}
	11.54	14.36 ± 0.94^{c}	13.08 ± 0.75^{c}	12.08 ± 0.79^{c}	1.42 ± 0.37^{c}	1.53 ± 0.22^{bc}	13.13 ± 0.68^{c}	4.38 ± 0.23^{bc}	543.03 ± 56.34^{d}
	13.62	14.84 ± 0.38^{cd}	13.59 ± 0.62^{cd}	12.49 ± 0.58^{cd}	1.53 ± 0.28^{d}	1.66 ± 0.25^{c}	13.57 ± 0.63^{cd}	4.82 ± 0.17^{c}	578.58 ± 43.25^{e}
TVSU-1353	5.43	12.92 ± 0.91^{a}	10.89 ± 0.81^{a}	10.22 ± 0.71^{a}	0.93 ± 0.25^{a}	1.00 ± 0.19^{a}	11.28 ± 0.69^{a}	3.76 ± 0.23^{a}	401.15 ± 48.47^{a}
	7.24	13.24 ± 0.98^{ab}	11.04 ± 0.91^{ab}	10.49 ± 0.76^{ab}	1.00 ± 0.18^{ab}	1.16 ± 0.25^{ab}	11.52 ± 0.75^{ab}	3.84 ± 0.25^{ab}	418.77 ± 55.29^{b}
	9.01	13.94 ± 1.25^{bc}	11.63 ± 1.02^{bc}	10.90 ± 0.95^{bc}	1.13 ± 0.26^{bc}	1.31 ± 0.28^{b}	12.08 ± 0.94^{bc}	4.03 ± 0.31^{b}	460.75 ± 71.56^{c}
	11.54	14.25 ± 1.20^{c}	11.88 ± 1.06^{cd}	11.05 ± 0.91^{c}	1.17 ± 0.31^{c}	1.39 ± 0.28^{bc}	12.31 ± 0.94^{c}	4.10 ± 0.31^{bc}	478.78 ± 73.31^{d}
	13.62	14.88 ± 0.96^{cd}	12.19 ± 1.02^{d}	11.51 ± 0.83^{d}	1.24 ± 0.11^{cd}	1.42 ± 0.24^{c}	12.75 ± 0.86^{d}	4.16 ± 0.37^{c}	495.63 ± 65.14^{e}

m – moisture content; A_s – kernel surface area; $\bar{\phi}_g$ – geometric mean diameter; $\bar{\phi}_a$ – arithmetic mean diameter; mean values ± SD; ^{a,b,c,d}for each column, the mean followed by similar alphabetic letters are not significantly different at a 1% level of probability ($P \leq 0.01$)

from the table that an increase in the kernel moisture level gave rise to a corresponding increase in the mean values of the kernel size. Each of the principal axes seemed to depend linearly on the moisture content (Figure 7) with meaningful statistical changes at $P \leq 0.01$ between the values. The values of coefficient of variation (*CV*) of 0.35, 0.10, and 0.22 were calculated for the kernel length, width, and thickness, respectively. The coefficient of variation, however, is an indispensable statistical parameter for estimating the mesh/aperture size and cylinder clearance for cleaning, grading, sorting, threshing, and size reduction operations (Fumen et al. 2018). The mean values for the lengths, widths, and thicknesses of the two kernel varieties (TVSU-1395 and TVSU-1353) were respectively obtained as 13.72 ± 0.73 mm and 13.85 ± 0.91 mm; 12.45 ± 0.66 mm and 11.53 ± 0.94 mm; 11.74 ± 0.75 mm and 10.83 ± 0.82 mm. These axial dimensions were found to be at par with the results of Ogunsina (2014) and Fumen et al. (2018) for Bambara nuts seeds, and are relatively lower than those of cashew nuts, filbert kernels, and almond seeds (Pliestic et al. 2006; Ogunsina 2014; Fumen et al. 2018). It can be further deduced from Tables 1 and 6 that the TVSU-1353 variety with the larger major diameter is comparatively longer than the TVSU-1395 one. This physical attribute is valuable in kernel handling, sorting and grading, as well as evaluating the screen size of the processing equipment. In addition, the mean kernel arithmetic and geometric diameters varied proportionally with the moisture content for both varieties. Their values ranged between $11.57 \leq \bar{\phi}_g \leq 13.16$ mm and $3.86 \leq \bar{\phi}_a \leq 4.49$ mm, respectively, as the kernel moisture rose from 5.4–13.62% wb. Similar findings were reported for the hazelnut,

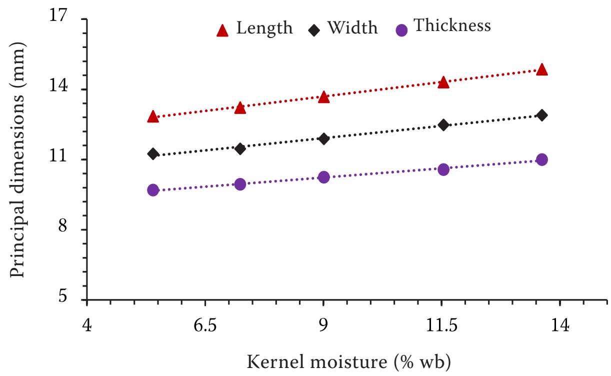

Figure 7. Variation of the principal measurements of the Bambara kernels with the moisture content

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Table 6. Regression relationships of the strength properties of the Bambara kernels as a function of the size and moisture level

Strength parameter	Kernel variety	Relationship	R^2
Rupture force (ζ_F, N)	TVSU-1395	$\zeta_F = 38.24 - 9.65\ m + 2.14 \times 10^{-2} m^s + 3.18 \times 10^{-2} s^2 + 1.12 \times 10^{-2}(ms)$	0.994
	TVSU-1353	$\zeta_F = 33.69 - 6.01\ m + 5.32 \times 10^{-2} m^s + 7.22 \times 10^{-2} s^2 + 3.07 \times 10^{-2}(ms)$	0.984
Rupture energy (ζ_E, J)	TVSU-1395	$\zeta_E = 17.75 - 11.083\ m + 4.13 \times 10^{-2} m^s - 4.32 \times 10^{-2} s^2 + 1.27 \times 10^{-2}(ms)$	0.997
	TVSU-1353	$\zeta_E = 12.96 - 9.15\ m + 7.31 \times 10^{-2} m^s - 6.54 \times 10^{-2} s^2 + 1.66 \times 10^{-2}(ms)$	0.988
Deformation at rupture (ζ_D, mm)	TVSU-1395	$\zeta_D = 1.92 - 0.51\ m + 1.73 \times 10^{-2} m^s - 5.36 \times 10^{-2} s^2 + 6.26 \times 10^{-2}(ms)$	0.977
	TVSU-1353	$\zeta_D = 3.53 - 1.28\ m + 2.81 \times 10^{-2} m^s - 8.21 \times 10^{-2} s^2 + 7.73 \times 10^{-2}(ms)$	0.958

m – moisture content; s – kernel size; R^2 = coefficient of determination

soybean grains, maize kernels (Guner et al. 2003; Tavakoli et al. 2009; Seifi and Alimardani 2010; Sangamithra et al. 2016).

It was observed that variety TVSU-1395 had a larger mean kernel mass of 1.66 g than variety TVSU-1353 of 1.42 g, due to differences in their microstructural arrangements. Variety TVSU-1395 has a higher moisture absorbing capacity than variety TVSU-1353, probably due to its characteristic permeable outer coat, hence, a larger specific mass and volume. The study of the size, mass, and volume indices of plant-based materials are of great importance as these physical attributes are applied in the design of equipment for post-harvest unit operations, such as cleaning, separating, and conveying, and adopting the aerodynamic principles, drag and friction coefficients. Thus, the kernel mass is a valuable index for estimating the relative quantity of the dockage, waste products per quantity of processed material. It can also be useful in evaluating the efficiency of a system or process amongst other benefits. Similarly, Table 5 revealed that the kernel volume for the TVSU-1395 variety was higher with a mean value of 1.53 cm^3 than the TVSU-1353 variety. Knowledge of the kernel volume can be applied in the design of hoppers, discharge chutes and other parts of agricultural material handling equipment. The research findings showed that the surface area of food grains exerts a huge impact on the flow rate of air applied in the pneumatic separation of particulate materials from the debris (Asoiro et al. 2012).

Kernel size influence on the strength property. Statistically, amongst the three groups of kernel sizes, there was a significant change ($P < 0.05$) as illustrated in Table 4. All the strength parameters of the two kernel varieties had an increasing trend with an increase in the kernel size. The strength properties of the TVSU-1395 kernels were statistically greater than those of the TVSU-1353 kernels (Table 4). This is maybe credited to variations in the structural make ups of the two Bambara varieties. The influence of the kernel size on the relative deformation of the Bambara kernel shown in Table 3 exhibited an increasing trend in the relative kernel deformation at the rupture point with the kernel size such that the mean rupture force of the small kernel sizes was about 0.63-fold (> ½) of the large sizes. This portrayed that a greater structural deformation will be experienced by the large-sized kernel group at a low moisture content level for the TVSU-1395 variety, thus creating additional compressive loading. This kernel behavioural pattern may be ascribed to the greater rupture resistance as a result of the increased kernel size. This result was corroborated by the work of Saiedirad (2008), in which the force and energy needed to fracture cumin seeds increased with an increasing seed dimension.

The interaction influence of the kernel size and moisture on the rupture force revealed that a greater difference amongst the size groups was obtained at a 5.4% moisture level (Table 3). The kernel size did not significantly influence the rupture force at a 13.62% moisture content. The same applies to the rupture energy and deformation at the rupture point. The rupture energy at the 13.62% moisture content increased with the kernel size. This is perhaps a result of an upturn in the moisture content in the kernel which has the potential of increasing the elasticity modulus thereby making the large kernels suffer more deformation when subjected to compressive loads, thus producing an upsurge in the kernel rupture energy. The data analysis shows that the interaction influence of the kernel variety and size ($v \times s$) on the strength parameters was insignificant at both probability lev-

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els. A similar finding was observed by Uyeri and Uguru (2018) for groundnut kernels. Taking the variety and size interaction influence into consideration, the maximum change in the kernel strength property amongst the different size categories was attributed to the TVSU-1395 variety.

The results of this study show that a strong correlation exists between the strength parameters and the experimental variables (moisture content and kernel size). The regression functions are presented in Table 6 for the kernel variety. The relationships are characterised by a high determination coefficient ($R^2 > 0.95$), signifying a strong correlation between the kernel strength property and the experimental variables. These regression functions are useful in estimating the amount of yield force, energy, and deformation on the food materials, especially during size reduction operations, seed shelling and deppodding, and kernel loading in transport and storage, *etc.*

CONCLUSION

This experimental study focused on the influence of moisture content and kernel size on the strength property of TVSU-1395 and TVSU-1353 Bambara kernel varieties. The obtained results substantiate the sensitivity of Bambara kernels to mechanical injury as a result of changes in moisture content, kernel variety, and size, as well as their mechanical strength capability to absorb deformation. These factors greatly control the rupture force of the Bambara kernel which affect its mechanical damage during post-harvest operations. Therefore, the strength property of the Bambara kernel's resistance ability to compressive force is a veritable attribute for optimum design of its handling and processing machines. Knowledge gained from this study can be applied to the quantitative evaluation of the product kernel texture as well as inherent damages that may arise during crop harvesting and processing operations. Therefore, given the outcomes of this research, the following conclusions can be drawn:

(*i*) A mean sphericity of 89.7% was obtained for the studied kernel size groups, with a maximum mean sphericity obtained for the TVSU-1395 variety, indicating a more regular kernel shape than the TVSU-1353 variety.

(*ii*) An increase in the kernel axial dimensions, mass, and volume were functions of the product moisture content. The mean values for the kernel lengths, widths, and thicknesses of the two varieties (TVSU-1395 and TVSU-1353) were respectively found to be 13.72 ± 0.73 and 13.85 ± 0.91 mm; 12.45 ± 0.66 and 11.53 ± 0.94 mm; 11.74 ± 0.75 and 10.83 ± 0.82 mm.

(*iii*) The mean arithmetic and geometric diameters of the kernel samples had a proportional increase with the moisture content. They varied between $11.57 \leq \bar{\phi}_g \leq 13.16$ and $3.86 \leq \bar{\phi}_a \leq 4.49$ mm, respectively. The kernel volume ranged from 0.93 to 1.53 cm^3, with the TVSU-1395 variety volume having a higher mean value of 1.53 cm^3 than the TVSU-1353 variety.

(*iv*) The kernel size and moisture content had noteworthy influences on the strength properties of the two studied Bambara varieties. The results revealed that, for each size group, the moisture content had a diminishing effect on the rupture force and absorbed energy of the kernels.

(*v*) There was a declining and increasing trend, respectively, in the strength and deformation ability of the Bambara kernel based on the comparison theory of the energy-carrying ability of wet kernels to dry ones which is greater than the moisture-laden ones, resulting in higher resistive strength to rupture during quasi-state loading.

(*vi*) The TVSU-1395 kernel variety gave a maximum kernel rupture force of 235.06 N and a maximum absorbed energy at kernel rupture (0.401 J) at moisture content levels of 5.4% and 13.62%, respectively.

(*vii*) A significant interaction effect of the moisture content and kernel size on the strength property of the Bambara kernel was revealed at a 5.4% moisture content ($P < 0.05$).

(*viii*) The moisture content and kernel size showed a strong statistical correlation with the strength parameters of the Bambara kernels with high R^2 values greater than 0.95 ($0.958 \leq R^2 \leq 0.997$).

The engineering significance of the research results indicates the importance of sorting Bambara kernels into different size groups before their post-harvest processing for energy savings as well as estimating the relative amount of physical damage in the Bambara kernel. The kernel behaviour at varying moisture contents expresses its strength to withstand mechanical or physical damage (bruises, crack/abrasion, slip, etc.) at any stage of kernel processing; during transportation, and storage as they suffer under dead load which may be in the form of static, impact, and fluctuating loads, all acting separately or jointly.

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Further studies may take the strength characteristics of Bambara kernels under varying loading rates, kernel orientations, and varieties into account to optimise the best process conditions for the post-harvest handling of different Bambara cultivars and develop efficient decorticating machines.

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