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Evaluation of the biophysical and mechanical properties of kenaf seeds in relation to processing application

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Abstract The geometry and strength characteristics of new varieties of kenaf seeds were determined to better understand the physical and mechanical properties of the seeds. These properties were important for handling and processing the seeds. Four varieties of new kenaf seeds, namely Cuba 108, Ifeken 400, Ifeken 700, and Ifeken D1 400 were evaluated with the corresponding moisture content of 8.61, 8.48, 5.25, and 5.96% wet basis. The average length, width, and thickness of kenaf seed ranged from 4.87 – 5.25 mm, 3.19 – 4.18 mm, 2.36 – 2.96 mm, respectively. While the mass, thousand seed mass, bulk, and true density ranged from 0.02 – 0.03 g, 22.89 – 27.50 g, 509.87 – 642.00 kg/m^3, 763.33 – 1021.74 kg/m^3, respectively. Furthermore, the compressive stress, load at rupture, energy at fracture, and toughness of the seed ranged from 0.609 - 1.106 MPa, 23.417 – 49.835 N, 0.016 – 0.063 J, and 0.069 – 0.272 N/mm, respectively. The analysis of variance showed that the physical and mechanical properties of the seeds varied significantly among the varieties.

Keywords: Kenaf seed, Compressive behaviour, Rupture behaviour, Energy, Seed toughness

Introduction

Kenaf plant has a unique structure with a single, straight, unbranched stem, leaves, and seed capsules, encompassing the seeds (Mohanty *et al*., 2004; Falana *et al.* 2020). Apart from the importance of the various components of the plant, the locally developed and available technologies for the processing of the fibres have influenced the desire of the farmers towards growing of the crop (Atta and Owolarafe, 2023). The capsules are about 1.9 – 2.5 cm long and 1.3 – 1.9 cm in diameter (Webber *et al*., 2002). These capsules are covered with hair-like materials that irritate when in contact with the skin. In the past decades,

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researchers have continued to explore the physical and mechanical properties of fruits, nuts, grains, and seeds. Some of these studies have been performed on different biomaterials, such as kenaf (Bakhtiari *et al*., 2011), sweet corn seed (Bülent *et al*., 2005), pigeon pea grains (Sangani and Davara, 2013), roselle (Sánchez-Mendoza *et al.,* 2008), and rice (Ohagwu and Akubuo (2014). However, there is a shortage of research on kenaf seeds' physical and mechanical properties, especially on the load-bearing capacity of the seeds.

Although Bakhtiari *et al.* (2011) investigated some moisture-dependent physical and mechanical properties of a kenaf seed, this study was limited to the seed geometry, angle of repose, and coefficient of static friction. They showed that as moisture content of the kenaf seed increased, the true density and bulk density decreased, and the static coefficient of friction, filling, and emptying angle of repose of kenaf seed increased linearly against the various surfaces, namely, stainless steel, aluminium, and glass. For sweet corn seed, Bülent *et al*. (2005) observed that variation of the seed's moisture content increased the thousand seed mass, the sphericity, the true density, and the porosity. Above all, the static coefficient of friction also increased linearly against the surfaces of different structural materials. Also, Sangani and Davara (2013) determined some properties of pigeon pea grains. It was observed that the bulk density and true density decreased, while the porosity and angle of repose increased when the moisture content increased. Similarly, Ohagwu and Akubuo (2014) stated that rice mechanical properties varied among varieties. Above all, it is essential to study the properties of agricultural materials with respect to their varieties which might also provide useful information that could attract the use of infrared thermography to monitor the storage condition of the seeds after harvest, since this has been found very useful for perishables like tomatoes (Atta *et al*., 2022).

The purpose was to determine some selected physical properties (seed geometry, mass, bulk and true density, porosity, angle of repose, and coefficient of static friction) and mechanical properties (compressive stress, rupture load, rupture energy, and toughness) of different varieties of kenaf seeds to better understand its loading and handling behavior.

Materials and methods

Determination of the physical properties of kenaf seed

The following properties of kenaf seed were determined from the seed geometry. This is because the parameters are vital for the design of kenaf handling and processing machines. Each procedure was replicated:

Size: it was specified on the seed's length, width, and thickness. The axial and lateral dimensions of the seeds were measured using a Vernier caliper with a precision of 0.01 mm. The procedure was evaluated for 100 randomly selected seeds for each kenaf variety. The geometric mean diameter and arithmetic mean diameter of the seed was calculated by using the equations (1) and (2) (Mohsenin, 1986; Rich and Teixeira, 2005; Garnayak *et al.,* 2008; Bakhtiari *et al*., 2011)

$$D_g = (L \times W \times T)^{1/3} \quad (1)$$

$$D_a = \frac{L + W + T}{3} \quad (2)$$

Where, L = length or largest intercept (mm), W = width or largest intercept normal to L (mm), T = thickness or largest intercept normal to L and W (mm).

Shape: this parameter is relevant for the design of the seed hopper and the seed metering device. This was expressed basically in sphericity. The mathematical expression used is given in Equations (3) as stated by Khan (2017)

$$D_s = \frac{D_g}{L} \quad (3)$$

Where, D_s = degree of sphericity,

Surface area: This was determined from the geometric mean using the equation described by Bakhtiari *et al*. (2011)

$$S_a = \pi D_g^2 \quad (4)$$

Bulk density: This was determined in the laboratory using a cylindrical container of a known volume. The container was filled with kenaf seeds without compaction and then weighed. The bulk density was calculated using Equation (5) described by Özgüven and Vursavuş (2005). All measurements were replicated five times.

$$B_d = \frac{W}{V} \quad (5)$$

Where, B_d = bulk density (kg/m^3), W = weight of kenaf seeds (kg), V = volume of wooden box (m^3)

True density: Toluene displacement method was used to determine the volume and true density of the kenaf seed (Mohsenin, 1986). A sample of 100 seeds randomly selected was weighed and immersed in a container filled with toluene. The volume of toluene displaced was measured to determine the volume of a single kenaf seed. The procedure was replicated five times. After that, the true density was calculated using the Equation described by Khan (2017)

$$T_d = \frac{W}{V} \quad (6)$$

Where, T_d = true density (g/cm^3), W = weight of grain (g), V = true volume occupied by the same grain (cm^3)

***Angle of repose*:** to determine the angle of repose, a cylinder with a discharge at the other end was filled with kenaf seed. The cylinder was removed gradually, leaving the kenaf seeds to form a cone. A stainless-steel scale was used to measure the height of the cone, and the angle of repose was calculated using Equation (7). This parameter is relevant for the design of the hopper, and the procedure was replicated five times.

$$\Phi = tan^{-1}\left(\frac{2h}{d}\right) \quad (7)$$

Where, Φ = angle of repose (degree), h = height of cone (cm), d = diameter of cone (cm)

***Coefficient of static friction*:** this was measured using an inclined plane method on a glass, mild steel, plywood, and stainless-steel surface. The kenaf seeds were separated on a horizontal surface, and the slope was increased gradually. The angle at which the seeds started to slip was recorded. All measurements were replicated five times. The coefficient of static friction was calculated using Equation (8).

$$C_{sf} = \tan\Phi \quad (8)$$

Where, C_{sf} = coefficient of static friction, Φ = angle of static friction (degree)

***Thousand seed weight*:** One thousand kenaf seeds were weighed on a digital weighing balance with a precision of 0.01 g.

***Porosity*:** The porosity of the kenaf seed was calculated using Equation (9) Bakhtiari *et al*. (2011).

$$\mu = \left(1 - \frac{B_d}{T_d}\right) \times 100 \quad (9)$$

where, μ = porosity (%), B_d = bulk density (kg/m^3), T_d = true density (kg/m^3)

***Moisture content*:** The moisture content of the kenaf seeds was determined using the oven drying method. The weighed samples were dried in a laboratory oven (Uniscope, Surgifriend Medicals, England) at 104°C for 24 hrs (ASABE, 2012). Equation (10) was used to determine the moisture content of the seeds.

$$\mathrm{M.C_{wb}} = \frac{\mathrm{W_i - W_f}}{\mathrm{W_i}} \times 100 \quad (10)$$

where, $M.C._{wb}$ = Moisture content of the sample on a wet basis (%), W_i = initial weight of the sample before oven drying (g), W_f = final weight of the sample after oven drying (g)

Determination of the mechanical properties of kenaf seed

To determine the dynamic behaviour of the kenaf seeds, the test materials were subjected to a uniaxial compression test using Universal Instron Testing Machine (UTM, Instron 3369K1781, 50 kN, USA). The purpose of the test is to draw the force-deformation curves of the four kenaf seed variety between two parallel plates at 8 mm/min (Akbarnia and Rashvand, 2019). The UTM consists of three main parts which are: screen, fixed jaw, and moving jaw. The test was carried out using randomly selected 20 samples of the kenaf seed varieties. Furthermore, the toughness of the kenaf seeds was determined by summing the area under the compressive stress-strain curve before the failure of the seeds during the test. All procedures were replicated three times.

Statistical analysis of the data

The data obtained from the physical and mechanical properties of the kenaf seeds were analyzed using the Microsoft Excel data analysis toolkit (2016) to establish whether there is a significant difference between the properties with respect to the varieties studied. Also, to determine the correlation between the geometry and the strength characteristics of the kenaf seeds.

A total of 12 accessions with two commercial varieties (Ifeken 400, Ifeken DI-400) of kenaf were selected for evaluation under rain at Institute of Agricultural Research and Training, Ibadan station in 2017 and 2018. Seeds of each genotype were planted in a four-row plot, 5 m each, at a spacing of 20 cm within row and 50 cm between rows in each of the two plantings. The trial was laid out in randomized complete block design with three replications. Four seeds were sowed per hill and thinned to 2 per stand to adjust the population density to 100,000 plants ha^{-1} at 3 weeks after planting (WAP). The plants were dosed with 60 kg ha^{-1} NPK fertilizer at 4 WAP. The plots were kept weed free throughout the trial. Cultural practices were applied according to the recommendation of IAR&T (2015).

Days to 50% flowering was taken for each genotype per plot. Agro-morphological data were also collected from 10 randomly selected plants per plot at 50%, flowering on plant height, as well as basal, middle and top stem diameters. The basal, middle and top stem diameters were at 5 cm above ground level, middle of the plant and 5 cm from the tip of the plant, respectively. The stem diameters were taken using vernier calipers (Falana *et al*., 2019a). All the plants in each plot were harvested after data collection at 50% flowering stage and fibres were extracted from the plants by retting process after cutting at the ground level. Freshly cut kenaf plants were tagged per plot and soaked in water for 14 days to obtain the fibres. The soaked plants were removed from the water and bast fibres were stripped from main stick (core) by hand. The bast fibre was washed in clean water and weighed after drying by direct sunshine for five days using a sensitive scale.

Fibre quality analysis

Samples of bast fibre of the 14 genotypes were taken to the laboratory for quality analysis on mechanical characteristics. The samples of different categories were prepared for tension test (tensile stress, e-modulus, extension and maximum load) using Universal Mechanical Testing Machine (Instron-Series 3369) available at the Centre for Energy Research Development, Obafemi Awolowo University, Ile-Ife. Samples were also spun into yarn and subjected to test for the determination of the quality ratio of the spun yarn. The set up was done in a completely randomized design with three replications. Data were also obtained on the tensile strength of yarn and yarn count of the samples.

Data analysis

Agro-morphological data collected on the field were pooled across the two years and subjected to analysis of variance (ANOVA) with the mechanical data taken in the workshop using SAS (2009). The Least Significant Difference was used to separate the means in both cases. Correlation coefficients were used to detect the relationships among the agronomic and mechanical characters. Bar charts were also employed to explain the variations among the genotypes with respect to their mechanical properties.

Results

Physical properties of kenaf seeds

Analyzing kenaf seed properties was significant for determining whether the properties vary among the seed's variety. One of the properties' relevance was designers of agricultural equipment used the properties to develop handling and processing machinery. In this study, the moisture content of Cuba 108, Ifeken 400, Ifeken 700, and Ifeken D1 400 of the kenaf seed varieties were 8.61, 8.48, 5.25, 5.96% wet basis, respectively. Result showed the physical properties of the four varieties of kenaf seeds studied (Table1). The kenaf seeds' length, width, thickness, and mass varied from 4.87 – 5.25 mm, 3.19 – 4.18 mm, 2.36 – 2.96 mm, and 0.02 – 0.03 g, respectively. Also, the thousand seed mass, arithmetic and geometric mean diameter, and surface area were in the range of 22.89 – 27.50 g, 3.48 – 4.03 mm, 3.32 – 3.86 mm, and 34.64 – 46.90 mm^2, respectively. Furthermore, the spherical coefficient expressed the sphericity of the seeds relative to the shape of a sphere. Ifeken

400 was observed to be more spherical with a corresponding value of 0.75, while Ifeken 700 was the least spherical with a corresponding value of 0.68.

Table 1. Physical properties of kenaf seeds

Properties	Kenaf Variety			
	Cuba 108	Ifeken 400	Ifeken 700	Ifeken D1 400
Length (mm)	5.25(0.21)	5.06(0.29)	4.87(0.32)	5.10(0.36)
Width (mm)	3.88(0.72)	4.18(0.51)	3.19(0.39)	3.50(0.38)
Thickness (mm)	2.96(0.71)	2.58(0.16)	2.36(0.16)	2.63(0.28)
Mass (g)	0.03(0.00)	0.03(0.00)	0.03(0.01)	0.02(0.01)
Thousand seed mass (g)	24.02(0.02)	24.95(0.05)	27.50(0.20)	22.89(0.16)
Arithmetic mean diameter (mm)	4.03(0.10)	3.94(0.20)	3.48(0.17)	3.74(0.23)
Geometric mean diameter (mm)	3.86(0.10)	3.78(0.24)	3.32(0.16)	3.60(0.23)
Surface area (mm2)	46.90(2.43)	45.16(5.06)	34.64(3.39)	40.88(5.28)
Spherical coefficient (dimensionless)	0.74(0.03)	0.75(0.05)	0.68(0.04)	0.71(0.05)
Bulk density (kg/m3)	621.82(0.34)	626.43(0.71)	642.00(0.51)	509.87(1.02)
True density (kg/m3)	783.33(0.41)	1021.74(1.43)	923.00(0.23)	763.33(1.43)
Porosity (%)	20.62(0.23)	38.60(0.49)	30.44(0.45)	33.20(0.71)
Moisture content (%) wb	8.61(0.05)	8.48(0.05)	5.25(0.04)	5.96(0.05)
Coefficient of Static Friction				
Glass Surface	0.56(0.07)	0.52(0.05)	0.59(0.07)	0.54(0.03)
Stainless Surface	0.57(0.05)	0.50(0.02)	0.60(0.09)	0.59(0.04)
Mild Steel Surface	0.56(0.05)	0.57(0.05)	0.63(0.02)	0.68(0.02)
Plywood Surface	0.54(0.05)	0.70(0.08)	0.67(0.03)	0.65(0.08)
Angle of repose (degree)	24.40(0.68)	27.74(0.06)	25.80(0.77)	23.50(0.13)

Values in parenthesis represent the standard deviation

The analysis of the variance indicated a significant difference in the mean of length, width, thickness, and mass of the kenaf seeds with respect to varieties ($P \leq 0.05$) as seen in Table 2. It could be observed that the value of the coefficient of static friction increased on all the surfaces respectively (Figure 1). The Cuba 108 kenaf seed variety slides easily because it is more spherical. Also, Ifeken 400 gave the highest resistance to the motion on a plywood surface. Overall, all the kenaf seed varieties moved quickly on a glass surface, but this surface is limited application in engineering design due to its fragility. Conversely, stainless steel or mild steel surfaces were more adequate for handling the seeds.

Table 2. Analysis of variance of the physical properties of kenaf seed

Parameters	Source of Variation	SS	df	MS	F	P-value	F crit
Length	**Between Groups**	**7.28704**	**3**	**2.429013**	**27.11764**	**5.702E-16***	**2.627441**
	Within Groups	**35.47098**	**396**	**0.089573**			
	Total	**42.75802**	**399**				
Width	**Between Groups**	**56.36711**	**3**	**18.78904**	**69.26508**	**5.007E-36***	**2.627441**
	Within Groups	**107.4201**	**396**	**0.271263**			
	Total	**163.7872**	**399**				
Thickness	**Between Groups**	**17.94902**	**3**	**5.983005**	**38.01241**	**1.314E-21***	**2.627441**
	Within Groups	**62.32886**	**396**	**0.157396**			
	Total	**80.27787**	**399**				
Mass	**Between Groups**	**0.001178**	**3**	**0.000393**	**11.96379**	**1.631E-07***	**2.627441**
	Within Groups	**0.012992**	**396**	**3.28E-05**			
	Total	**0.01417**	**399**				

SS – sum of squares; df – degree of freedom; MS – mean square; *p value<0.05, values assigned an asterisk are statistically significant at a level of 0.05%

Mechanical properties of kenaf seeds

The result of the strength characteristics of the kenaf seed is represented in Table 3. The maximum compressive stress of Cuba 108 was 1.1106 MPa, which was the highest among the kenaf seed varieties, while Ifeken 700 had the least compressive stress of 0.609 MPa. The trend was also similar for the maximum rupture load with the highest value as 49.835 N for Cuba 108. However, the energy required to rupture the seed was slightly higher than Ifeken 400 with a value of 0.063 J compared with Cuba 108, Ifeken D1 400, and Ifeken 700 with the corresponding values 0.062, 0.058, and 0.016 J, respectively. It was observed that Ifeken 400 kenaf seed was the toughest with a corresponding value of 0.272 N/mm, while Ifeken 700 was the weaker seed with a corresponding value of 0.069 N/mm.

Table 3. Strength characteristics of kenaf seed

Kenaf Variety	Compressive stress (MPa)	Rupture Load (N)	Rupture Energy(J)	Toughness (N/mm)
Cuba 108	**1.106(0.28)**	**49.835(16.71)**	**0.062(0.02)**	**0.265(0.04)**
Ifeken 400	**0.988(0.22)**	**24.860(5.91)**	**0.063(0.03)**	**0.272(0.02)**
Ifeken 700	**0.609(0.07)**	**23.417(6.38)**	**0.016(0.00)**	**0.069(0.01)**
Ifeken D1 400	**0.956(0.36)**	**42.821(19.57)**	**0.058(0.02)**	**0.247(0.01)**

Values in parenthesis represent the standard deviation

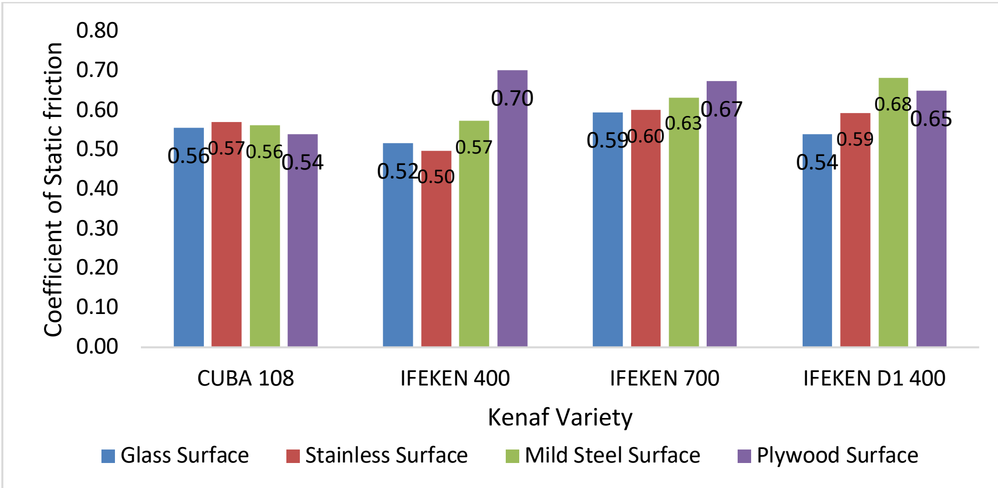

Figure 1. Coefficient of static friction on different surfaces

The results on the effects of kenaf variety, strength parameter, and their interaction along with within-group variability are shown in Table 4. It revealed that for the kenaf variety as a source of variation, the P-value was 0.848303, and the F critical value stood at 3.0088. Regarding the strength parameter, the P-value was extremely low at 8.53E-09, indicating a significant effect. In the case of interaction between kenaf variety and strength parameter, the P-value was high at 0.960461, and the F critical value was 2.508189. It showed no interaction between the kenaf variety, and the strength parameters measured.

The analysis of variance of the mechanical properties of kenaf seeds was affected by the kenaf variety (Table 4) which showed that the geometry of the samples was similar but behaves differently under the same loading condition. Also, the values of the properties obtained seem to be differed with slight dispersion, significantly affecting the properties of the kenaf seeds. The kenaf seed showed a similar trend of deformation under the same loading conditions, but the mechanical properties were varied between the kenaf seed varieties. Hence, the load-bearing capacity of the kenaf seeds differed between the varieties.

The correlation matrix for the physical and mechanical properties of kenaf seed revealed a complex interrelationship among these properties (Table 5). Length, width, and thickness of the seeds showed strong intercorrelations, with particularly high correlation between length and thickness (0.979). Compressive stress is notably correlated with all three physical dimensions, especially with length (0.957) and width (0.783). The rupture load showed a varied pattern of correlation, being moderately correlated with length (0.863) but only weakly with width (0.126), suggesting that seed width was significantly influenced the load at which rupture occurs. Rupture energy exhibited strong correlations with compressive stress (0.963) and width (0.829), indicating that both the size and the ability of the seed to withstand stress affected the energy required for rupture. Toughness displayed identical correlation values as rupture energy, strongly correlated with compressive stress (0.963), width (0.829), and length (0.851). This pattern suggested that the mechanical resilience of the seeds, as reflected in their toughness, is closely tied to their physical dimensions and their ability to withstand compressive forces. Hence, a linear regression model could be established to predict the compressive stress, rupture load, rupture energy, and toughness of the seeds (Figure 2).

The compressive stress-strain curve of the kenaf seeds is shown in Figure 3. It could be observed that the biomaterials exhibited a similar deformation trend, but Cuba 108 could withstand more stress than the other kenaf varieties This could be due to the robust geometry of the seed along the longitudinal and axial axis of the seed. Generally, the compressive stress increased with the arithmetic diameter of the seeds.

A direct relationship between the load and the deformation of the seeds is shown Figure 4. It was observed that Ifeken 700 failed swiftly when compared to other kenaf seeds. Cuba 108 resisted the highest load, but Ifeken 400 showed more resistance to load before failing. Above all, looking at the mechanical property of another component of kenaf, the values of the mechanical properties of the kenaf seeds are lesser than that of the fibers. These biophysical and strength characteristics were necessary because they translated into machine parameters relevant for the development of processing machinery. Therefore, they helped to prevent the damage or deformation of the seed during harvest and postharvest processes.

Table 4. Analysis of variance of the strength characteristics of kenaf seed

Source of Variation	SS	DF	MS	F	P-value	F crit
Kenaf variety	49.31778	3	16.43926	0.267287	0.848303	3.008787
Strength parameter	5467.018	2	2733.509	44.44438	8.53E-09*	3.402826
Interaction	86.99367	6	14.49895	0.23574	0.960461	2.508189
Within	1476.097	24	61.50404			
Total	7079.426	35				

SS – sum of squares; df – degree of freedom; MS – mean square; *p value<0.05, values assigned an asterisk are statistically significant at a level of 0.05%

Table 5. Correlation of the physical and mechanical properties of kenaf seed

	Length	Width	Thickness	Compressive stress	Rupture load	Rupture energy	Toughness
Length	1.000						
Width	0.608	1.000					
Thickness	0.979	0.538	1.000				
Compressive stress	0.957	0.783	0.893	1.000			
Rupture load	0.863	0.126	0.873	0.707	1.000		
Rupture energy	0.851	0.829	0.740	0.963	0.555	1.000	
Toughness	0.851	0.829	0.740	0.963	0.555	1.000	1.000

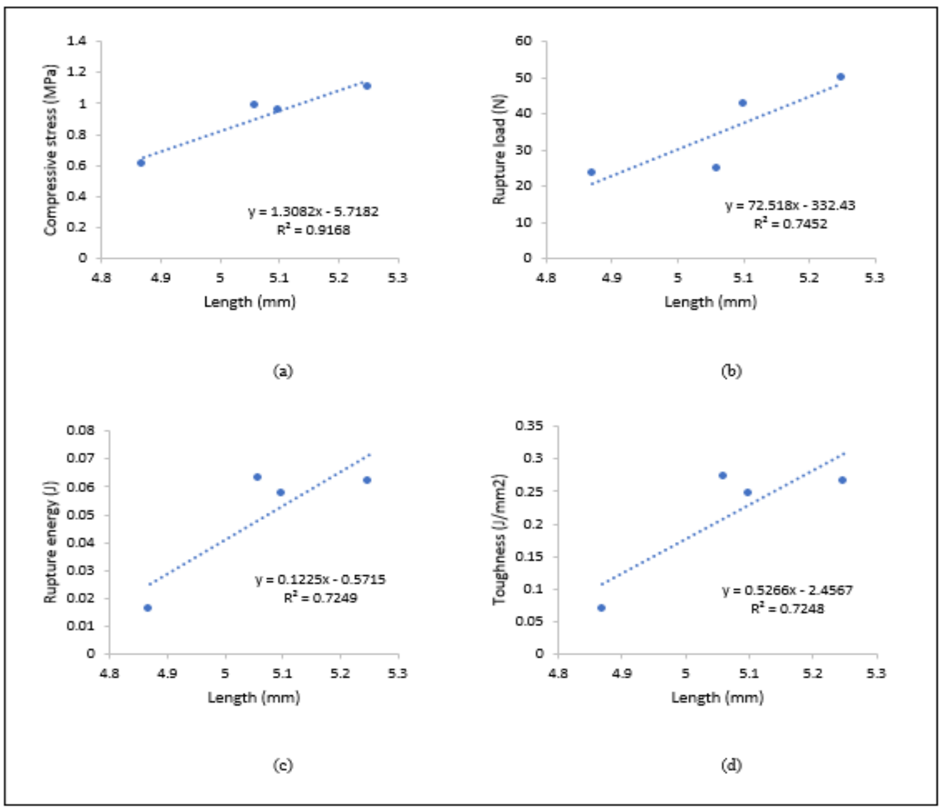

Figure 2. Relationship between seed length and (a) compressive stress (b) rupture load (c) rupture energy (d) toughness

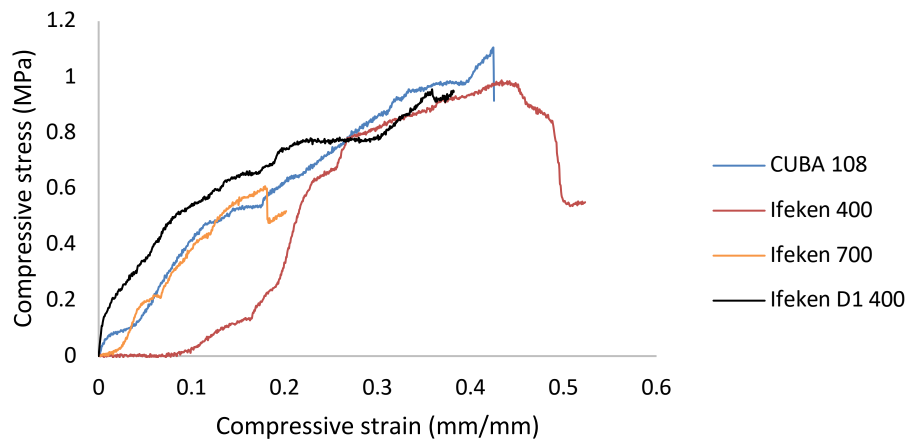

Figure 3. Compressive stress-strain curve of kenaf seed

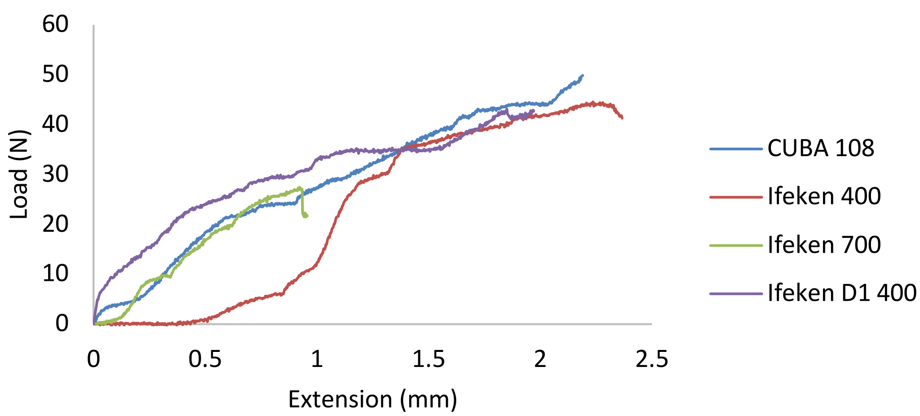

Figure 4. Compressive load-extension curve of kenaf seed

Discussion

Physical properties of kenaf seeds

The study on the physical and mechanical properties of kenaf seed varieties, including Cuba 108, Ifeken 400, Ifeken 700, and Ifeken D1 400 offered thorough understanding essential for agricultural and engineering purposes. The moisture content, a crucial factor influencing seed processing and storage, showed notable variation among the varieties, ranging from 5.25% to 8.61%. Bakhtiari *et al.* (2011) also investigated kenaf seeds (variety V36) and found similar variations in moisture content. It was reported that the moisture content of the seed ranged from 6.8% to 25.2% dry basis. However, when comparing the findings to those of Bülent *et al.* (2005) on sweet corn seeds (11.54 to 19.74% dry basis) and Ab Razak *et al.* (2011) on *Parkia speciosa* seeds (68.59 to 77.7% on wet basis), it was found that the moisture content of kenaf seed is low. The moisture content of the *Parkia speciosa* seeds is similar to kenaf stem (57.55 to 61.48%) reported by Falana *et al.* (2019b). It is clear understood that different seeds exhibit distinct moisture content. This variation was critical as moisture content significantly affected the seed behavior during various stages of handling.

The geometric characteristics of the kenaf seeds, such as length, width, thickness, and mass, displayed minimal dispersion across the varieties, suggested a degree of uniformity important for the design of sorting, grading, and processing machinery. The study also explored the sphericity of the seeds, and it was found that Ifeken 400 was the most spherical. Bülent *et al*. (2005) reported to increase sphericity with moisture content in sweet corn seeds, suggesting alterations in handling efficiency as seeds absorb moisture. Sacilik *et al*. (2003) reported a similar result (0.795) for hemp seeds. This factor affected seed interaction with machinery, and it is pivotal in designing equipment for efficient seeding and handling processes.

The coefficient of static friction is critical for understanding how seeds interact with various surfaces during processing. All the kenaf seeds move better on stainless and mild steel. Bakhtiari *et al.* (2011) indicated that the friction coefficient of kenaf seeds increases with moisture content across different surfaces. Bülent *et al*. (2005) extended this analysis to sweet corn seeds, showing a linear increase in friction coefficients against surfaces as moisture content rises. These findings underscored the need to consider the type of surface material in machinery design, with stainless steel or aluminum offering different advantages based on the specific seed properties.

Mechanical properties of kenaf seeds

The mechanical properties, including compressive stress and rupture load were significantly varied across the varieties. Cuba 108 showed the highest compressive stress, indicating a greater resistance to mechanical damage during processing. The energy required to rupture the seeds also differed, suggesting varying resilience levels among the varieties, which is importantly designed machinery that applies specific force levels without causing seed damage. The toughness of the seeds was found to vary, with Ifeken 400 emerging as the toughest. The rupture load was lower than 150 N reported by Ohagwu and Akubuo (2014) for a vertically loaded rice grain. This aspect is critical for understanding how the seeds withstand mechanical stresses during processing.

The study is also contextualized these findings by comparing the mechanical properties of kenaf seeds with other grains and stems, providing a broader perspective on the challenges in handling and processing kenaf seeds.

The results provided a detailed understanding of the effects of kenaf variety and strength parameters on the mechanical properties of kenaf seeds. The P-value associated with the kenaf variety as a source of variation stands at 0.8483. This high P-value suggested that the kenaf variety alone was not significantly affected the mechanical properties being measured. In essence, when considering the variety of kenaf seeds in isolation, there was no substantial difference in their mechanical behavior. In contrast, the strength parameter was significant ($p < 0.0001$), which indicated a highly significant affected. The result suggested that the mechanical properties of kenaf seeds are considerably influenced by the measured strength parameters. It included aspects such as compressive stress, rupture load, and other factors determining the mechanical resilience of the seeds. The interaction between kenaf variety and strength parameters revealed no significant interaction effect between the kenaf variety and the strength parameters. The way in which different varieties of kenaf seeds responded to mechanical stresses was not significantly varied which depending on the specific strength parameters.

Kenaf seeds showed a lower compressive stress and rupture load, with the highest compressive stress reported at 1.1106 MPa for Cuba 108 seeds. However, kenaf stems exhibited significantly higher values, indicating robustness, particularly in Tianung 1 variety with compressive stress reaching 8.70 MPa and rupture load at 191.51 N (Dauda *et al.,* 2014). Moisture content plays a pivotal role, affected mechanical properties such as Young's modulus and toughness, which increased with plant maturity while moisture decreased (Nazari *et al.,* 2008, Dauda *et al.,* 2014; Falana *et al.* 2019a and Falana *et al.,* 2019b).

The correlation matrix provided significant insights into the relationships between the physical and mechanical properties of kenaf seeds. A strong positive correlation between length and thickness (0.979) suggested that as the length of the seed increased, its thickness tended to increase proportionally. Similarly, the width of the seed showed a moderate positive correlation with its length (0.608), indicating that longer seeds were also wider to some extent. The mechanical properties, particularly compressive stress, demonstrated a strong correlation with the physical dimensions of the seeds. For instance, compressive stress is highly correlated with length (0.957) and width (0.783), indicating that larger seeds in terms of length and width can typically withstand more compressive stress. This might be attributed to a larger surface area distributing the force more effectively. The correlation between compressive stress and thickness was also significantly (0.893), reinforced the idea that larger seeds were mechanically stronger. Rupture loaded which measured the force required to break the seed, showed a strong correlation with length (0.863) and thickness (0.873), but an interestingly low correlation with width (0.126). This could imply that the rupture load is more dependent on the overall size rather than the width of the seed.

Rupture energy and toughness, which are indicators of the energy required to break the seed and its resistance to stress, respectively, both showed very strong correlations with compressive stress (0.963). It suggested that seeds capable of withstanding higher compressive stress required more energy to rupture and are tougher. The high correlation of rupture energy and toughness with width (0.829) and length (0.851) also highlighted the importance of the physical size of the seeds in determining their mechanical resilience. The result corroborated the findings of Ghahraei *et al.* (2011), Dauda *et al*. (2014), Falana *et al.* (2019a), and Falana *et al.* (2019b).

The overall analysis suggested that while the geometry of the kenaf seed samples appeared similar, indicating uniformity in physical dimensions, their behavior under mechanical loading conditions differed. The slight dispersion in the values of the properties implies that there are subtle but significant differences in how these varieties respond to mechanical forces. Consequently, although the kenaf seeds may deform in a similar trend under the same loading conditions, the specific mechanical properties, such as load-bearing capacity, vary among the different kenaf seed varieties. This variation is critical for understanding the resilience and suitability of these seeds for different applications, particularly in the context of agricultural handling and processing.

In conclusion, the research findings provided a detailed examination of the physical and mechanical properties of various kenaf seed varieties, offering essential insights for agricultural and engineering applications. The analysis revealed that while the geometry of the kenaf seeds may vary, there were definitive maximum dimensions and characteristics observed: length up to 5.25 mm, width up to 4.18 mm, thickness up to 2.96 mm, and mass up to 0.03 g. Additional physical properties were revealed that the thousand seed mass up to 27.50 g, bulk density up to 642.00 kg/m³, true density up to 1021.74 kg/m³, and porosity up to 38.60%. The study further highlighted the coefficient of static friction on various structural surfaces (glass, stainless steel, mild steel, and plywood) and the maximum angle of repose (27.74°), which are crucial for understanding the handling and processing dynamics of these seeds.

Moreover, the research shed light on the strength characteristics of kenaf seeds. It was observed that the maximum compressive stress reached 1.106 MPa, rupture load at 49.835 N, rupture energy at 0.063 J, and toughness at 0.272 N/mm. These mechanical properties are concerned particularly relevant to engineers and researchers developing machinery and devices for handling and processing kenaf seeds. The results emphasized that the strength parameters significantly affected the mechanical properties of the seeds, more than the variety itself. This knowledge is vital for tailoring agricultural processes and equipment design to optimize the handling of kenaf seeds, thus enhancing efficiency and effectiveness in their utilization. The study's findings offered valuable contributions to the field of agricultural engineering, paving the way for further research and innovation in seed processing technologies.

Based on the detailed examination of the physical and mechanical properties of various kenaf seed varieties, it is recommended that designers of agricultural machinery and processing equipment consider the notable variation in moisture content and the geometric characteristics of the seeds. The findings underscored the importance of tailoring equipment to accommodate the specific properties of kenaf seeds, such as their sphericity and the coefficient of static friction on different surfaces, to enhance handling efficiency. Furthermore, given the significant impact of strength parameters over variety on the mechanical properties of seeds, it is crucial to develop processing techniques that apply a precise force level to avoid damage, particularly in varieties with lower compressive stress and rupture load.

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