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Review Article

Evaluation of the Engineering Properties of Two Varieties of African Yam Bean (*Sphenostylis stenocarpa*) Seeds

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Abstract

The aim of this work was to evaluate the engineering properties of two selected varieties of African yam bean (*Sphenostylis stenocarpa*) seeds – The brown-coated and white testa seed varieties. Physical dimensions (length, width, thickness, weight, volume, amongst other parameters) of the selected test seeds were measured using appropriate devices. Established mathematical formulae were used in the computation of the data generated to deduce several relevant engineering properties of the seeds. The values derived for all parameters are presented in this work. From the results obtained, the mean values for length, width and thickness (all in mm) were generally lower for the white variety than for the brown variety. The average arithmetic and geometric mean diameter values further confirmed this, as was evident from the bigger sizes of the brown seeds compared to the white species. The mean sphericity values for both seeds implied that both seeds were closer to a sphere in shape, though the white seed type had a higher tendency to roll when placed at a particular orientation to improve emptying (as in hopper or conveyor belt/inclined plane platforms). The specific surface and mean surface areas suggested that both seed varieties would fall through a stream of air at the right velocity while lighter/irregularly-shaped chaff/extraneous matter are blown away during pneumatic separation (such as aspiration/winnowing processes) or remain on the belt during pneumatic conveyance. The mean values for volume, bulk density solid density, 1,000-seed mass, unit mass and porosity values indicated that the seeds will not float in water and these values would help to separate unwanted particles from the seeds during wet cleaning on the basis of buoyancy differences. Though, more seeds of the white variety would occupy the same space than the seeds with brown seed coat. The values of angle of repose suggested that the seeds would readily form heaps during collection/packaging and flow out readily during emptying of the holding vessel. The coefficient of static friction on various surfaces (plywood, glass, stainless steel, aluminium, planed wood surface and formica) was indicative of the trend of increased resistance to sliding of the bulk seeds when placed on the respective surfaces. This would be useful in the design of conveying devices like raw materials' reception plane, processing machine hoppers or agricultural machine (planter) hoppers. All the values generated may be exploited in the design and fabrication of equipment to manage, convey, process, contain or preserve African Yam bean seeds.

INTRODUCTION

African yam bean (*Sphenostylis stenocarpa*) is an herbaceous leguminous plant occurring throughout tropical Africa, which is often cited among the lesser-known and under-exploited species [1]. It is a grain legume which is a good source of protein and energy cultivated in South-Eastern Nigeria for its edible seeds, but cultivated in Central African Republic, Zaire, East Africa and Ethiopia for its tubers. In areas where it is grown for its seeds, African yam bean has become an important substitute for the more widely-eaten cowpea [2]. Like cowpea, the seeds are contained in a pod, with each pod containing between ten and thirty seeds. The seeds of the African yam bean have brown, black, white, grey or speckled bean-shaped appearance [3].

Being cheaper in cost than animal products such as meat, fish, poultry and egg; legumes (of which African yam bean is a part) are eaten especially in the developing or poor countries where the consumption of animal protein may be limited as a result of social, economic, cultural or religious factors [4].

There is a general tendency to effect the mechanization of agricultural and food production operations because of steadily rising labor costs (due to the aging population of rural farmers, rural-urban migration, etc), shortage in hand labor and to save time and efforts [5]. However, the knowledge of various physical, mechanical, engineering and chemical properties (as the case may be) of agricultural products are very essential to the design of suitable machines and equipment for the handling, processing and storage of these products. For instance, size and shape of the materials are essential in sizing, sorting and other separation processes. Bulk and true densities of the materials are important in order to design equipment for its processing, sorting, grading, transporting and storage. Its angle of repose is important for designing packages or storage structures and the coefficient of friction plays an essential role for transportation, handling and storage structures [6].

The knowledge of these physical and mechanical properties constitutes vital and essential engineering data in the design of machines, storage structures, processing and for the purpose of quality control. This basic information is not only important to food engineers, but it is also useful to those who may exploit these properties and find new uses for the plant material [7].

In South-Eastern Nigeria, the consumption of African yam bean seeds is restricted to the harvesting period, after which their availability in the rural market becomes scarce, as they are not cultivated in large quantities and their uses are limited [8]. This trend is not unconnected with the fact that there is hardly any food processor of African yam bean that possesses mechanized equipment for its harvesting, handling or processing. Most subsistence/small-scale producers perform the key operations manually which yields a product with poor quality and low nutrient. The design and fabrication of mechanical systems and associated equipment for handling, harvesting, processing, moving and storing the African yam bean seeds would be predicated on the determination of the engineering properties of the seeds. The data so generated there from, considering the fact that few researchers have worked on this study area, would be handy to overcome some of the handicaps which may be faced in the fabrication process of processing equipment.

MATERIALS AND METHODS

Material selection

Source of materials: The mature seeds of the white- and brown-colored African yam bean were sourced from Isiukwuato in Abia State, Nigeria.

Preparation of sample: The samples were prepared using the modified methods described by [9] and [3]. The African yam bean seeds were cleaned manually to remove all foreign matters such as dust, dirt, stones and chaff, as well as immature and broken seeds, after which they were kept in covered containers for subsequent analysis.

Determination of moisture content: The method adopted by [3] was used. Samples were randomly selected to determine the moisture content by oven-drying 100g of each sample at 130°C for 6h. The samples were then cooled in desiccators and weighed using an electronic top-loading weighing balance (Atom Model-110°C) reading to 0.01g in order to determine the moisture loss. The measurement on each sample was triplicate and the average moisture content was obtained. The moisture content of the seed in % (dry basis) was calculated using the formula:

$$Ms = \frac{100(M_{si} - M_{sf})}{M_{sf}} \quad (1)$$

Where Ms = Moisture content in % dry basis, M = Mass (g), and Subscripts *s*, *i* and *f* represent seeds, initial and final respectively.

The following methods were used in the determination of some selected engineering properties of the African yam bean seeds (Figure 1 & 2).

Size and shape analyses

(i) Geometric mean diameter (Dg)

The method of [9] was used. A vernier caliper was used to measure the axial dimensions of 100 randomly-selected seeds; length, width and thickness. From the average of axial dimensions, the geometric mean diameter (Dg) in mm was determined using the formula below:

$$D_g = (abc)^{1/3} \quad (2)$$

Where a = Length dimension along the longest axis (mm)

b = Width dimension along the longest axis perpendicular to a (mm),

c = Thickness dimension along the longest axis perpendicular to a and b (mm).

(ii) Arithmetic Mean diameter (Da)

This was determined mathematically using the formula as described by Adebowale et al. (2012):

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

Where L = length, W = width and T = thickness

(iii) Volume (V)

This was calculated using the mathematical relationship of [10].

$$V = \frac{\pi BL^2}{6\,(2L - B)} \quad (4)$$

Where π =3.142, L = Length (mm), T = Thickness (mm), B = $(WT)^{0.5}$, W = Width (mm)

Figure 1 White and brown seeds of African yam bean (AYB).

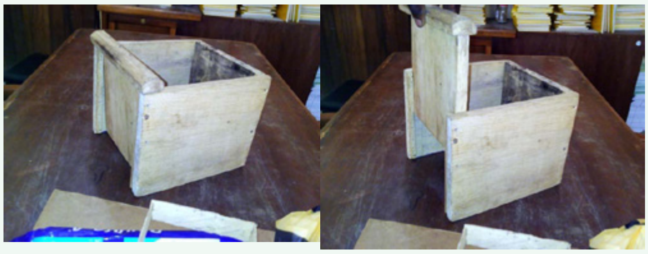

Figure 2 Demonstrating Θe with the fabricated box apparatus..

(iv) Sphericity (φ)

This was determined mathematically based on the mathematical relationship used by [11].

$$\varphi = \frac{D_g}{L} \qquad q = \frac{(LWT)^{1/3}}{L} \tag{5}$$

Where φ = Degree of sphericity, Dg = Geometric mean diameter, L = Length (mm), W = Width (mm), T = Thickness (mm).

Thousand-seed weight: The method by [9] was adopted. Thousand-seed weight (TSW) was measured by counting 100 seeds and weighing them with the aid of an electronic top-loading weighing balance to an accuracy of 0.01g. The resulting value was multiplied by 10 to give the mass of 1,000 seeds.

Surface Area (S): This was determined mathematically according to the formula used by [6].

$$S = \pi(Dg)^2 \tag{6}$$

Where π = 3.142, Dg = Geometric mean diameter

Specific Surface area (Ss): This was calculated using the mathematical relationship by [3].

$$Ss = \frac{Sl_b}{Ms} \tag{7}$$

Where Ss = Specific surface area of seed (mm^2/cm^3), S = Surface area (mm^2), l_b = Bulk density (g/cm^3), M_s = Mass of unit seed (g)

Bulk Density and Solid Density: The value of Bulk density was obtained according to the method described by [9], while the Solid density was determined according to the method described by [3].

(i) Bulk Density (ρ_b)

A weighed empty 250mL graduated cylinder was filled with the seeds and weighed. The weight of the seeds was obtained by subtracting the weight of the cylinder from the weight of the cylinder and seeds. To achieve uniformity in bulk density values, the graduated cylinder was tapped 10 times on the workbench for the seeds to consolidate. The volume occupied was then noted. The process was replicated three (3) times and the bulk density for each replication was calculated from the following relationship:

$$\rho b = \frac{Ws}{Vs} \tag{8}$$

Where ρ_b = Bulk density (Kg/m^3), Ws = Weight of the sample (Kg), Vs = Volume occupied by the sample (m^3).

(ii) Solid Density (ρ_s)

The Solid density was calculated by dividing the mass of the individual seed by its volume. The mass of the individual seed was measured and recorded. The volume of the individual seeds was determined by water displacement method as follows:

$$V = \frac{Ms}{\rho w} \tag{9}$$

Where Ms = Mass of seed weighed in water (g), ρ_w = Density of water ($1.0g/cm^3$)

Porosity (P): The Porosity of the bulk seed was computed from the values of the true density and bulk density of the seeds by using the relationship adopted by [3].

$$P = \frac{(1-\rho_b)}{\rho_s} \times 100 \tag{10}$$

Where P = Porosity, ρ_b = Bulk density, ρ_s = Solid density.

Angle of Repose: The filling and emptying angles of repose were determined according to the method described by [12].

(i) Filling angle of repose (Θ_f)

The beans were allowed to fall onto a circular plate of 200mm diameter mounted on a laboratory stand from a height of 150mm to form a natural heap. The height of the heap (h) was measured and the angle of repose (Θ_f) was calculated as:

$$\theta_f = \tan^{-1}\frac{h}{100} \tag{11}$$

Where h = height of the heap (cm)

(ii) Emptying angle of repose (Θ_e)

This was obtained using a plywood box of dimensions 200mm x 200mm x 200mm which had a front sliding panel. The box was filled with the seeds and the front sliding panel was quickly slid upward allowing the bean seeds to flow out and form a natural heap. The angle of repose was determined from measured height of beans at two points (h_1 and h_2) in the sloping bean heap and the horizontal distance between the two points (x_1 and x_2) using the relation:

$$\theta_e = \tan^{-1}\left[\frac{h_2 - h_1}{x_2 - x_1}\right] \tag{12}$$

Where h_1 and h_2 are the least and highest heights (mm) of the heap respectively chosen, and x_1 and x_2 are the respective horizontal distance (mm) between the two points.

Static coefficient of friction (μ): The method of [11] was adopted. The Static coefficient of friction of the seeds was determined with respect to each of the following six structural materials namely plywood, glass, aluminium, wood, stainless steel and formica. A four-sided plywood container with dimensions of 150mm x 100mm x 40mm open at both the top and bottom was filled with the seeds after placing on an adjustable tilting surface. The structural surface with the box on its top was gradually raised until the box just started to slide down. The angle of inclination was read from a graduated scale and the coefficient of friction was taken as the tangent of this angle. This procedure was repeated using the other structural materials.

$$\mu = \tan \beta \quad (13)$$

Where μ = Static coefficient of friction for the structural material, β = Angle of inclination

NOTE: $\beta = \tan^{-1}$ Vertical height of inclined plane

Base length of the platform

RESULTS AND DISCUSSION

The results of the engineering properties of white-coated seed variety of the African yam bean and the brown-coated variety are shown in Tables 1 and 2 respectively. The numeric values of the properties and their implications are jointly presented as follows:

Moisture content

The value of moisture content (on wet weight basis) was 2.820% for the brown variety and 4.056% for the white variety. The value obtained for the brown variety was close to the range (2.840% - 3.130%) stated by [3]. It can be seen that the brown-coated AYB seed is of lower moisture content than the white variety. In addition, the value of moisture content on dry weight basis was 2.904% for the brown variety and 4.230% for the white variety. Nonetheless, the seeds can be said to be of generally low moisture content.

Size and shape of seeds

The length of the white-coated AYB seed cultivar ranged from 5.40mm to 7.50mm, with a mean value of 6.52mm, while the value of the width was between 3.70mm and 5.90mm with a mean value of 4.84mm. The thickness was spread between 3.80mm and 5.70mm with an average value of 4.88mm. The arithmetic mean diameter ranged from 4.30mm to 6.23mm with a mean value of 5.42mm, while the geometric mean diameter was in the range of 4.17mm to 6.07mm with an average of 5.35mm.

In contrast, the brown-coated variety had a length of 6.22-7.90mm (mean, 7.402mm), width, 4.2-6.2mm (mean, 5.344mm) and thickness of 4.9-5.8mm (average, 5.4mm). The arithmetic mean diameter of the brown variety was in the range of 5.37mm to 6.37mm (average, 6.0409mm) and the geometric mean diameter values ranged from 5.183mm to 6.183mm (mean, 5.872mm). These values indicated that the brown-coated variety was larger than the white variety, probably as a function of species diversity, and this size disparity could be utilized in the design of aperture sizes of size-sorting equipment [10] in cases where mixed seed sizes occur.

The shape of the seeds, on the basis of sphericity Φ, implied that the white variety is closer to a sphere (mean value, 0.821) than the brown-coated variety (average, 0.793). This property is relevant in the conceptualization of hoppers where decision is premised/based on rolling or sliding characteristics of agricultural produce and handling machineries [13]. This suggested that, seed for seed, the white variety of AYB seed would have an increased tendency to roll on a surface than the brown variety, as a lower sphericity is an indication that the seed cannot roll on its side, but slide when suitably inclined. This has been stated by [6] in their work on the measurement of some engineering properties of sandbox seeds.

Surface area and specific surface area

The value of surface area of the seeds ranged from 54.741mm^2 to 115.767mm^2 (mean, 90.053mm^2) for the white variety, and 84.395mm^2 to 120.121mm^2 (Average, 108.328mm^2) for the brown-coated specie. The surface area of food materials is important in handling and processing operations, especially in calculating the terminal velocity of the material which is utilized in aero- and hydrodynamic activities such as in pneumatic conveying and separation processes where the material is lifted only when the air velocity is greater than its terminal velocity [14], thus affecting the air stream that can be used in order to separate the seed from unwanted materials as in pneumatic separators, or to move the seed as in pneumatic conveyors.

The specific surface area values for the seeds (218.158mm^2/cm^3 for the white cultivar and 211.583mm^2/cm^3 for the brown-coated specie) are quite high. This indicated that the brown-coated AYB seeds would exhibit less mass or energy transfer rate through its surface than the white variety, as explained by [3] in their work on the determination of some physical properties of African yam beans.

Seed volume and thousand-seed mass

The values for the volume of the seeds were 13.238mm^3 and 16.341mm^3 for the white and brown-coated cultivars respectively. This suggested that the brown variety would occupy more space than the white variety, albeit with fewer number of seeds i.e the bulk of the seeds of the white variety would be contained by the same vessel that would enclose (being filled with) a lower quantity of brown seeds.

The thousand seed mass of the white variety ranged from 261.80g to 275.90g with a mean value of 267.167g compared to the brown variety which had a range of 322.70g to 342.40g with a mean value of 334.267g. This wide disparity was expected, as the variations in surface area, bulk density and volume imply the possibility of the brown AYB seed containing more matter within it than the white variety. Also, mathematically, the mean unit mass of the seeds would be 0.267g and 0.334g for the white and brown-coloured varieties respectively which was within the range of values (0.129g to 0.384g) obtained by [3] for African yam bean seeds.

Bulk density, solid density and porosity

The tapped bulk density of the white variety had a mean value of 0.805g/cm^3 (min. 0.797g/cm^3, max. 0.814g/cm^3) while the brown variety had an average value of 0.801g/cm^3 (min. 0.799g/cm^3, max, 0.802g/cm^3). The smaller sizes, as well as the variation in shape of the white-coated cultivar, may have accounted for the higher bulk density values [12] as they would be more aggregated than the brown varieties in the same volume. Nonetheless, it must be well understood that bulk density is not an intrinsic property of a material, as it can change depending on how the material is handled, the interaction between the surfaces of the materials in contact and the degree of intensity of the compaction process [15].

The solid density values were in the range of 1.364g/cm^3 – 1.371g/cm^3 (mean, 1.368g/cm^3) for the white AYB seeds and

Table 1: Engineering properties of white-coated African yam bean seeds..

Properties	N	Mean	S.D	Min Value	Max. value
Length (mm)	20	6.524	±0.05421	5.4	7.5
Width (mm)	20	4.843	±0.05241	3.7	5.94
Thickness (mm)	20	4.881	±0.05195	3.8	5.7
A.M.D, Da (mm)	20	5.416	±0.5125	4.3	6.23
G.M.D, Dg (mm)	20	5.3536	±0.98129	4.174	6.07
Sphericity,Φ	20	0.8206	±0.0954	0.6944	0.823
Surface area (mm^2)	3	90.053	±31.0764	54.7408	115.7667
M**1, 000** (g)	3	267.167	±7.6291	261.8	275.9
Bulk density, ρ_b (g/cm^3)	3	0.8055	±0.0081	0.7974	0.8136
Solid density, ρ_s (g/cm^3)	3	1.3679	±0.0035	1.364	1.3707
Porosity, P (%)		41.11			
Volume, V (mm^3)		13.238			
Specific surface		218.1584			
Area (mm^2/cm^3)					
		Angle of repose (Θ)			
Filling method, θ_f (°)	3	5.597	±0.2601 5	5.3132	5.824
Emptying method, θ_e (°)	3	22.132	±4.5565	18.835	25.277
		Coefficient of static friction (µ) on various surfaces			
Plywood	3	0.2918	±0.000999	0.2907	0.2924
Glass	3	0.35	±0.007216	0.3426	0.3564
Stainless steel	3	0.25	±0.003797	0.2469	0.2531
Aluminum	3	0.298	±0.00644	0.2903	0.3021
Wood	3	0.2476	±0.001145	0.2362	0.2591
Formica	3	0.37	±0.00663	0.364	0.376
		Moisture content (%)			
Wet basis		4.056			
Dry basis		4.23			

Keys: A.M.D = Arithmetic mean diameter G.M.D = Geometric mean diameter; $M_{1,000}$ = One thousand seed mass N = Number of replications; S.D = Standard deviation

Table 2: Engineering properties of brown speckled African Yam bean seeds.

Properties	N	Mean	S.D	Min Value	Max. value
Length (mm)	11	7.4018	±0.0491	6.22	7.9
Width (mm)	11	5.344	±0.0487	4.2	6.2
Thickness (mm)	11	5.4	±0.0252	4.9	5.8
A.M.D, Da (mm)	11	6.0486	±0.53595	5.1827	6.1831
G.M.D, Dg (mm)	11	5.8718	±0.01661	0.7835	0.7986
Sphericity,Φ	3	0.7933	±0.01661	0.7835	0.7986
Surface area (mm^2)	3	108.328	±18.9151	84.3953	120.1209
M**1, 000** (g)	3	334.267	±10.289	322.7	342.4
Bulk density, ρ_b (g/cm^3)	3	0.8008	±0.00193	0.7987	0.8025
Solid density, ρ_s (g/cm^3)	3	1.2216	±0.00238	1.2189	1.2232
Porosity, P (%)		65.55			
Volume, V (mm^3)		16.3406			
Specific surface		211.583			
Area (mm^2/cm^3)					
		Angle of repose (θ)			
Filling method, θf (°)	3	5.73	±0.0866	5.6539	5.824
Emptying method, θe (°)	3	22.073	±5.3912	18.1595	25.781
		Coefficient of static friction (µ) on various surfaces			
Plywood	3	0.258	±0.00406	0.256	0.263

Glass	3	0.297	±0.00265	0.2941	0.2993
Stainless steel	3	0.225	±0.00	0.225	0.225
Aluminum	3	0.2668	±0.01465	0.2522	0.2815
Wood	3	0.2451	±0.00975	0.2343	0.2533
Formica	3	0.334	±0.00589	0.328	0.34
		Moisture content (%)			
Wet basis		2.82			
Dry basis		2.904			

Keys: A.M.D = Arithmetic mean diameter; G.M.D = Geometric mean diameter; M1,000 = One thousand seed mass
N = Number of replications; S.D= Standard deviation

1.219g/cm^3 – 1.223g/cm^3 (average, 1.222g/cm^3) for the brown type. It indicated that the seeds would sink in water, being denser than water (ρ = 1.0g/cm^3), as was evident during the analytical process. This property could be optimized when separating the African yam bean seeds from less dense contaminants (e.g husks, chaff, spoilt seeds, etc) during wet cleaning operations, especially via soaking.

The porosity values of the seeds were 41.11% for the white-coated variety and 65.55% for the brown variety, and it was indicative of the volume fraction of void space or air inside a material, which accounts for the interaction of components and formation/collapse of air or void phase during processing [16]. The porous properties of food materials determine key macroscopic parameters such as water-holding capacity and texture [17]. Diffusion coefficient is enhanced by increases in porosity which, in turn, is affected by the water content of foods. An increase in the moisture content of foods leads to a swelling of the components and a subsequent decrease in porosity of the material [18]. This implied that while the seeds do not hydrate easily, the brown seeds would hydrate more readily than the white variety when the threshold was attained.

Angles of repose

The mean filling angle of repose (Θ_f) of the white AYB seeds (5.597°) is less than that of the brown seeds (5.730°). This contradicts the true assertion of [12] that smaller sizes can interlock more to cause a higher heap formation than relatively bigger sizes. Still, the angular variation may not be critical enough to result in any wide disparity, and may be a function of the shape/size of the seed and surface conditions of the seeds which influences their cohesion/adhesion characteristics [5].

The mean emptying angle of repose (Θ_e) obtained for the white and brown seed varieties were very close at 22.132° and 22.073° respectively. It must be stated that the mean emptying angle of repose (Θ_e) obtained for sandbox seeds was in the range (19.2 – 26.2°) [6] while 23.78° was obtained by [3] for African yam bean. This implied that the brown varieties seemed to have a somewhat slightly smoother surface than the white variety. Though, both would readily flow out of self-emptying bins or hoppers during raw material reception or processing when the vessel bearing them was tipped at an angle.

Coefficient of static friction (μ) on various surfaces

For the white variety, the mean values of the coefficient of static friction were found to increase progressively from planed wood surface (0.248) to stainless steel (0.250), plywood (0.292), aluminium (0.298), and glass (0.350) and to formica (0.370). These values differed from the mean values obtained for the brown-coated AYB seed cultivar, with the structural surfaces progressively exhibiting the following values: Stainless steel (0.225), planed wood surface (0.245), plywood (0.258), aluminium (0.267), glass (0.297) and Formica (0.334).

Generally, aluminium, glass and Formica were surprisingly observed to offer some resistance to sliding to the box of seeds in either variety of African yam beans. Though the size and weight of seeds, as well as the packing differences of seeds in the box, and surface characteristics of each of the structural surfaces used (even at the microscopic level) may have resulted in the degrees of disparities observed in the values of the coefficient of static friction. This observation may make a case for using less expensive, natural sources of contact surfaces when selecting and determining the slopes of the feed hopper of AYB seed processing equipment, or in the design of seed hopper in mechanized planters.

CONCLUSION

This work has successfully investigated the engineering properties of two varieties of African yam bean seeds, the white-coated and brown-coated varieties.

The mean values for length, width and thickness (all in mm) were generally lower for the white variety than for the brown variety. The average arithmetic and geometric mean diameter values further confirmed this, as was evident from the bigger sizes of the brown seeds compared to the white species.

The mean sphericity values for both seeds implied that both seeds were closer to a sphere in shape, though the white seed type had a higher tendency to roll when placed at a particular orientation to improve emptying (as in hopper or conveyor belt/inclined plane platforms).

The specific surface and mean surface areas suggested that both seed varieties would fall through a stream of air at the right velocity while lighter/irregularly-shaped chaff/extraneous matter are blown away during pneumatic separation (such as aspiration/winnowing processes) or remain on the belt during pneumatic conveyance.

The mean values for volume, bulk density solid density, 1,000-seed mass, unit mass and porosity values indicated that the seeds will not float in water and these values would help to separate unwanted particles from the seeds during wet cleaning on the basis of buoyancy differences. Though, more seeds of the white variety would occupy the same space than the seeds with brown seed coat.

The values of angle of repose suggested that they would readily form heaps during collection/packaging and flow out readily during emptying of the holding vessel.

The coefficient of static friction on various surfaces was indicative of the trend of increased resistance to sliding of the bulk seeds when placed on the respective surfaces. This would be useful in the design of conveying devices like raw materials' reception plane, processing machine hoppers or agricultural machine (planter) hoppers.

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