Engineering properties of acha (*Digitaria exilis*) grains in relation to the design of grain processing machines

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Abstract: Engineering properties are very important in the design and manufacturing of processing machines. In this research work, the engineering (physical, aerodynamic and mechanical) properties of acha (*Digitaria exilis*) grains were determined as design parameters for the development of grain processing machines for the crop. The physical properties determined were length, width, thickness, arithmetic mean diameter, geometric mean diameter, roundness, sphericity, aspect ratio, surface area, projected area, volume, moisture content, one thousand seed weight, bulk density, true density and porosity. The average seed length, width and thickness were found to be 1.84±0.055mm, 0.85±0.023mm and 0.75±0.042mm respectively. The average arithmetic and geometric mean diameters were 1.15±0.014 mm and 1.05±0.018mm respectively. The average roundness, sphericity and aspect ratio were 0.5840±0.011, 0.5732±0.013 and 0.4678±0.012 respectively. The mean surface area, projected area and volume were 3.49±0.25mm^2, 1.23±0.033mm^2 and 0.61±0.029mm^3 respectively. The average moisture content was 14.73±2.14% dry basis and the thousand kernel weight was 0.827±0.053g. The average bulk and true densities were 1092.86±24.13kg m^{-3} and 1626.15±62.91kg m^{-3} respectively and the porosity was 32.52±1.34%. The aerodynamic properties determined in this study were terminal velocity, drag coefficient and Reynold's number. The average terminal velocity, drag coefficient and Reynold's number of the seeds were found to be 3.97±0.015 ms^{-1}, 0.684±0.062 and 311.37±13.47 respectively. The mechanical properties determined in this study were angle of repose, coefficient of static friction, shear strength and compressive strength. The mean angle of repose was 32.50±1.36^o while the mean coefficient of static friction on mild steel surface was 0.82±0.043. The mean shear strength and compressive strength of the seeds were 3840±72.32Nm^{-2} and 7615±90.28Nm^{-2} respectively. These parameters would provide important and essential data for the efficient design of acha processing machines.

Keywords: acha, physical, aerodynamic, mechanical, processing machines

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1 Introduction

Acha is a cereal crop of West African origin belonging to the family *graminaea* (Gibon and Pain, 1985). The plant is an important crop in Southern Mali, Western Burkina Faso, Eastern Senegal, Northern Guinea, North-eastern Nigeria, and Southern Niger (Chukwu and Abdul-Kadir, 2008). There are many varieties of acha, but the most prominent two are the white acha (*Digitaria exilis*) and black acha (*Digitaria iburua*). In Nigeria, the white acha is grown more widely (Chukwu and Abdul-Kadir, 2008). Acha contains about 85% dry matter, of which about 10% is starch (Morales-Payan et al. 2002), 5% is mineral and 7% is crude protein (Temple and Bassa, 1991). The protein of acha is higher compared with that of other grains (Chukwu

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and Abdul-Kadir, 2008), and is reputed to contain almost twice as much methionine as egg protein does (Temple and Bassa, 1991).

Acha is easily digested, and it is traditionally recommended for children, old people that cannot digest other cereals, sick people, diabetic patients and patients with stomach diseases (Cruz, 2004). The diets from acha have relatively low free sugar and low glycemic content, which makes it adequate as a suggested diet for diabetic patients (Obizoba and Anyika, 1994). Acha has high water absorption capacity that gives it ability to be utilized in baked foods. Its amino acid profile was compared to that of whole-egg protein, and showed that acha was rich in essential amino acids except for the low score of 46% in lysine. It also contains pentosans (Lasekan, 1994) which gives it the ability to form a gel in the presence of oxidizing agents at room temperature. The high levels of sulphur containing and hydrophobic amino acids in acha grains make it a useful crop for bakery products (Obizoba and Anyika, 1994).

Acha is used in the production of food and beverages, and manufacture of medicines. Acha grain is consumed in a variety of ways such as porridge and couscous. Balami et al. (2009) studied the suitability of acha as a substitute malt grain, and concluded that acha grains can be modified and used in the production of malt drink comparable to drinks produced from conventional brewing grains. Also, Ayo and Nkama (2004) mixed different inclusion levels of acha grain flour in replacement with wheat flour to produce bread, and found that inclusion level of acha grain flour not exceeding 30% generally produced bread of acceptable quality. In spite of the nutritional and economic importance of acha, there is dearth of the scientific knowledge needed for the mechanization of acha production, processing, handling, storage and distribution. In general, engineering properties of grains are essential to the design of equipment, especially for their handling, processing, and storage.

The engineering properties of grains could affect its threshing and milling quality parameters. The faulty designed machines and operations may result in the production of low-quality grain by cracking and breakage of the grain kernel and proper knowledge of their engineering properties can be used to overcome the mentioned fault. The dimensions of grains are used in selecting sieve separators for grading, calculating the power requirement during threshing process, calculating kernel volume and surface area, and determining quantities like, aspect ratio, surface area, sphericity, and geometric mean diameter that are necessary for the modeling of grain during drying, heating, cooling, and aeration (Varnamkhasti et al., 2007). Thousand grain weight is used to determine the expected milling output at the laboratory, by taking weights of 1,000 milled grains, corresponding them to 1,000 grain weight, and is expressed as percent weight of milled whole grains. Milling loss is quite evident when there is any shortfall in actual milling output due to breakage of grain (Sarker and Farouk, 1989), relative amount of dockage (foreign material) within a given grain lot and presence of shriveled immature kernels (Luh, 1980).

Bulk density, true density and porosity are major considerations in designing the drying, aeration and storage systems, as these properties affect the resistance to air flow through the grain mass. The ratio of the inter-granular void space volume and bulk volume of grain is porosity (Mohsenin, 1986) and includes the voids within and among the particles. Drying of a grain bed with low porosity increases the water vapor escape resistance that can be overcome using higher power to drive the aeration fans (Jouki and Khazaei, 2012). The differences between specific gravity and bulk density of the grain is the principle used for gravity cleaning of paddy separators to separate materials that have little difference in size and total mass (De-Datta, 1993). The volume, specific gravity, moisture content, and porosity of agricultural products are the basic parameters required for their drying, storage, and previewing quality loss of material until its marketing time (Correa et al., 2007).

Designing of the air conveying systems and the equipment for cleaning, handling, aeration, storing, and processing requires the knowledge of terminal velocity (Guner, 2007), which is equal to the air velocity at which particle remains in suspended state in vertical pipe. The role of terminal velocity is important in grain cleaning by removing impurities like chaff, dockage, immature, and hollow grains. The separation process by an air stream in grain mix depends on the ratio between terminal and air velocity of particles, and their entrained particle quantity in unit volume of air flow (Varnamkhasti et al., 2008). The knowledge of the aerodynamic characteristics of grains (terminal velocity, drag coefficient) is significant for the design and operation of machines which treat substances with air flow and in all cases when substances are moved in the air (Shahbazi et al., 2014). The behaviour of particles in an air stream during pneumatic conveying and separation greatly depends on their aerodynamic properties. The aerodynamic forces which exist during relative motion between the air and the materials act differently on different particles. Separation of a mixture of particles in a vertical air stream is only possible when the aerodynamic characteristics of the particles are so different that the light particles are entrained in the air stream and the heavy particles fall through it. When an air stream is used for separating a product such as acha seed from its associated foreign materials, such as straw and chaff, knowledge of aerodynamic characteristics of all the particles involved is necessary. This helps to define the range of air velocities for effective separation of the grain from the foreign materials. For this reason, the terminal velocity has been used as an important aerodynamic characteristic of materials in such applications as pneumatic conveying and their separation from foreign materials (Shahbazi et al., 2014).

The static coefficient of friction, the ratio of frictional force (force due to the resistance of movement) to normal force on surface wall, is employed for determining the positional angle of chutes in order to maintain a consistent flow of materials through the chute. The static coefficient of friction finds its application in sizing motor requirements for grain transportation, handling, and designing conveying equipment (Varnamkhasti et al., 2008). The coefficient of friction is also necessary for safe designing of equipment and silo wall surfaces to facilitate grain handling equipment, their processing, and storage (Suthar and Das, 1996). The angle between the base and slope of cone formed by free vertical fall of granular material is the angle of repose that finds use in designing packages and storage structures, mainly for calculating hopper sidewall slop angle (Razavi and Farahmandfar, 2008). The flowability of agricultural grains is usually measured using angle of repose that is a measure of grain internal friction between them and hence finds its use in hopper design, whose wall inclination angle must always be greater than angle of repose in order to maintain continuous material flow by gravity (Zareiforoush et al., 2010). Mechanical properties such as compressive strength provide information on the resistance of produce to cracking under harvesting and handing conditions and energy required in size reduction (Deshpande et al., 1993). Compressive strength is relevant in the choice of stack height to avoid produce damage in storage.

The threshing and processing of grains involves a large number of unitary operations. During these operations the grains are exposed to various forces as impact, shearing and friction mainly during threshing and milling. The magnitude of the damage caused during the processing depends on the physical and mechanical properties of the grains. The knowledge of the grain mechanical properties, mainly of the grain resistance to the compression is important for an analysis and breakage determination or its cracking during the processing (Ozumba and Obiakor, 2011). However, not much scientific data are available on the engineering properties of acha to aid the design of equipment for its harvesting, threshing, cleaning, dehulling, milling, packaging, handling, storage, and aeration. As a biological material, the properties of acha are influenced by many factors such as its moisture content and bulk density. Due to lack of knowledge of the interplay between its properties and these factors, design and fabrication of machines for acha have been fortuitous. These engineering properties are not only useful to the engineers but also to food scientists, processors, plant and animal breeders, and other scientists who may exploit them in their various disciplines. This study is an effort towards generating scientific data that could be valuable for accurate design of efficient machines for postharvest processing operations of acha. Therefore, this study was undertaken to determine the engineering properties of acha grains in relation to the design of grain processing machines.

1.1 Objectives of the study

1.1.1 Main objective

The main objective of the study is to determine the engineering properties of acha grains in relation to the design of grain processing machines.

1.1.2 Specific objectives

The specific objectives of the study are:

i. To determine the physical properties of acha grains,

ii. To determine the aerodynamic properties of acha grains,

iii. To determine the mechanical properties of acha grains.

1.2 Justification of the study

Information on engineering properties of grains could help food industries obtain products with better functional, nutritional and sensory qualities with greater cost benefits. To make superior nutritional value and yield products particularly rely on the in-depth knowledge of the engineering properties. Engineering properties of biological materials such as acha grain have unique characteristics which set them apart from other engineering materials. The irregular shape of most agricultural materials complicates the analysis of their behaviour. Also due to the increasing importance of agricultural products together with the complexity of modern technology for their production, processing and storage, a better knowledge of their engineering properties is necessary. The engineering properties of acha grains are pre-requisites in the designing of equipment for threshing, handling, storage and other processes. It is therefore essential to determine the relevant characteristics of acha grains which appears to be lacking in literature. Therefore, this work will reveal the engineering properties of acha grains which will aid anyone with the knowledge of acha grains and its engineering properties.

2 Materials and Methods

Physical properties of acha grains were grouped into two namely: dimensional properties (length, width, thickness, arithmetic mean diameter, geometrical mean diameter, roundness, sphericity, aspect ratio, surface area, projected area and volume) and gravimetric properties (moisture content, one thousand seed weight, bulk density, true density and porosity). The aerodynamic properties of acha grains include terminal velocity, drag coefficient and Reynold's number. Mechanical properties of acha grains were also grouped into two namely: frictional properties (angle of repose and coefficient of static friction) and strength properties (shear strength and compressive strength). These were evaluated as design parameters for the development of acha processing machines. They were determined following standard procedures.

2.1 Determination of physical properties of acha grains

2.1.1 Dimensional properties

In order to determine dimensions, one hundred acha grains were randomly selected. For each acha grain, the three principle dimensions, namely length, width and thickness were measured using a digital vernier caliper with accuracy of 0.001 mm. The length (*L*) was defined as the distance from the tip cap to kernel crown. Width (*W*) was defined as the widest point to point measurement taken parallel to the face of the kernel. Thickness (*T*) was defined as the measured distance between the two kernels faces as described by Pordesimo et al. (1990). Measurements were taken and the shape parameters were calculated.

2.1.1.1 Arithmetic mean diameter

The arithmetic mean diameter (*Da*) of the seed was calculated using Equation 1 given by Baryeh (2002).

$$\mathrm{Da} = \frac{\mathrm{L+W+T}}{3} \quad \text{(mm)} \qquad (1)$$

2.1.1.2 Geometric mean diameter

The geometric mean diameter (*Dg*) was determined from Equation 2 given by Baryeh (2002).

$$Dg = (\mathrm{LWT})^{\frac{1}{3}} \quad \text{(mm)} \qquad (2)$$

2.1.1.3 Roundness

The roundness (R) was determined from Equation 3 given by Baryeh (2002).

$$R = \frac{\left(\frac{W}{L}+\frac{T}{L}+\frac{T}{W}\right)}{3} \qquad (3)$$

2.1.1.4 Sphericity

The sphericity (ϕ) was determined from Equation 4 given by Baryeh (2002).

$$\phi = \frac{Dg}{L} \qquad (4)$$

2.1.1.5 Aspect ratio of seeds

The aspect ratio (Ra) was calculated from Equation 5 given by Omobuwajo et al. (1999).

$$R_a = \frac{W}{L} \qquad (5)$$

2.1.1.6 Surface area of seeds

The surface area (Sa) was obtained from Equation 6 given by Baryeh (2002).

$$S_a = \pi D_g^2 \quad (\mathrm{mm}^2) \qquad (6)$$

2.1.1.7 Projected area

The projected area (A_P) was determined using Equation 7 given by Mirzabe et al. (2013).

$$A_P = \frac{\pi WL}{4} \quad (\mathrm{mm}^2) \qquad (7)$$

2.1.1.8 Volume of seeds

The volume (V) of seeds was determined using Equation 8 given by Mohsenin (1986).

$$V = \frac{\pi}{6} D_g^3 = \frac{\pi}{6}\mathrm{LWT} \quad (\mathrm{mm}^3) \qquad (8)$$

2.1.2 Gravimetric properties

2.1.2.1 Seed moisture content

A known weight of acha seeds was manually cleaned to remove foreign matter, dust, dirt, broken and immature seeds. The initial moisture content of the samples was determined before processing by oven drying at 105°C for 72 h (Baryeh, 2002).

$$MC_{db} = \frac{w_1 - w_2}{w_2 - w_o} \times 100 \quad (\%) \qquad (9)$$

Where MC_{db} = moisture content (% dry basis), W_o = weight of container (g), W_1 = Weight of fresh sample and container (g) and W_2 = Weight of dry sample and container (g).

Equation 9 was used to calculate the moisture content.

2.1.2.2 Thousand-grain weight

The 1000 unit mass (M1000) was determined using mettle electronic balance of accuracy of 0.001g. One thousand unit grains were carefully counted out from a cleaned sample of acha grains and weighed in the balance. The measurements were replicated ten times (Sirisomboon et al., 2007).

2.1.2.3 Bulk density

The bulk density of the seeds was determined by filling a test tube of 20mL volume with the seeds and the content weighed using an electronic balance of 0.001g sensitivity. The measurements were replicated ten times (Garnayak et al., 2008). The bulk density was calculated from the mass of the kernels and the volume of the container from Equation 10 given by Garnayak et al. (2008).

$$\rho_b = \frac{M_1 - M_2}{V} \quad (\mathrm{Kg\ m^{-3}}) \qquad (10)$$

Where; ρ_b= bulk density (Kg m^{-3}), M_1 = mass of filled container (Kg), M_2 = mass of empty container (Kg) and V = Volume of container (m^3).

2.1.2.4 True density

The true density of the seeds was determined by water displacement method as described by Mohsenin (1986). 50mL of distilled water was taken in a 100mL measuring jar and pre-weighed acha grains was filled inside the jar and the change in the level of water in the measuring jar was recorded. The experiment was done as snappy as possible to minimize the absorption of water by the seeds. The measurements were replicated ten times. The true density was calculated as the ratio of the mass of seeds to the volume of water displaced as in Equation 11 (Pradhan et al., 2013).

$$\rho_t = \frac{M}{V} \quad (\mathrm{Kg\ m^{-3}}) \qquad (11)$$

Where; ρ_t= true density (Kg m^{-3}), M = mass of seeds (Kg) and V = volume of water displaced (m^3).

2.1.2.5 Porosity

Porosity (ρ_o) is defined as the fraction of space in the bulk grain, which is not occupied by grain. Equation 12 was used to obtain the porosity (Mohsenin, 1986).

$$\rho_o = (1 - \frac{\rho_b}{\rho_t}) \times 100 \qquad (\%) \qquad (12)$$

2.2 Determination of aerodynamic properties of acha grains

2.2.1 Terminal velocity

The terminal velocity (V_t) was measured using an air column apparatus. A cylindrical glass pipe posed vertically with a fitted air blower from the bottom side and an arrangement for controlling the air velocity. The sample grains were dropped into the pipe and the air velocity was adjusted so that the grains remain in a suspended position. The air velocity (terminal velocity) was measured with an anemometer (Mohsenin, 1986).

2.2.2 Drag coefficient

The drag coefficient (C_d) was calculated using Equation 13 given by Mohsenin (1986).

$$C_d = \frac{2Mg}{\rho_a A_p V_t^2} \qquad (13)$$

Where; C_d = drag coefficient, M = mass of the grain (kg), A_p = projected (frontal) area of the grain (m^2), g = acceleration due to gravity (9.81 ms^{-2}), V_t = terminal velocity (ms^{-1}), ρ_a = density of air (1.28 kg m^{-3}).

2.2.3 Reynold's number

The Reynold's number (N_{Re}) was calculated using Equation 14 given by Hexing (1989).

$$N_{Re} = \frac{\rho_a V_t \sqrt{A_p}}{\mu} \qquad (14)$$

Where; μ = dynamic viscosity of the air (1.81×10^{-5} Pa.s or 1.81×10^{-5} kg ms^{-1}).

2.3 Determination of mechanical properties of acha grains

2.3.1 Frictional properties

2.3.1.1 Angle of repose

This was determined by using an open-ended cylinder of 15 cm diameter and 30 cm height. The cylinder was placed at the centre of circular plate having a diameter of 70 cm and was filled with acha grains, tapping during filling were done to obtain uniform packing. The cylinder was raised slowly until it formed a cone on the circular plate. The height H of the cone was recorded. The angle of repose (θ) was calculated using Equation 15 (Umogbai, 2009; Davies, 2009).

$$\theta = Tan^{-1}\left(\frac{2H}{D}\right) \qquad \text{(Degrees)} \qquad (15)$$

Where; θ = angle of repose (^{o}), H = vertical height of conical heap of grains (mm) and D = the diameter of base of cone formed (mm).

2.3.1.2 Coefficient of static friction

The coefficient of static friction for seed was determined against mild steel surface using the inclined plane method. This involves placing the acha seeds on adjustable tilting surface equipment with the surface formed using a mild steel sheet. Manually, the inclination of the plate was increased gradually until the specimen starts to slide down and at that point, the angle of tilt α in degree was read on a graduated scale (protractor). The angle of inclination with the horizontal was measured by a scale provided and was taken as an angle of internal friction and tangent of the angle was taken as co-efficient of friction between surface and acha grains as in Equation 16 (Umogbai, 2009).

$$\mu = tan\,\alpha \qquad (16)$$

Where; μ = coefficient of static friction (dimensionless) and α = angle of inclination of material surface (^{o}).

2.3.2 Strength properties

2.3.2.1 Shear strength

The shear strength was measured in double shear using a shear box consisting essentially of two fixed parallel hardened steel plates 6 mm apart, between which a third plate can slide freely in a close sliding fit. A series of holes with diameters ranging from 0.5 to 2 mm was drilled through the plates to accommodate grains of differing diameters. Shear force was applied to the grain specimens by mounting the shear box in the tension/compression testing machine. The sliding plate was loaded at a rate of 10mm min^{-1} and, as for the shear test; the applied force was measured by a strain-gauge load cell and a force -time record obtained up to the specimen failure. The shear failure stress (or ultimate shear strength), τ_s, of the specimen was calculated using Equation 17 (Zareiforoush et al., 2010).

$$\tau_s = \frac{F_s}{2A} \qquad (\text{N mm}^{-2}) \qquad (17)$$

Where; τ_s = shear strength (N mm^{-2}), F_s = shear force at failure (N) and A = wall area of the specimen at the failure cross-section (mm^2).

2.3.2.2 Compressive strength

Compressive strength of the grain is considered as an important mechanical property in relation to the grain breakage. A universal testing machine (Testometric M500-100AT) was used to obtain the fracture force of the grain. The slots were screwed to compress the grain placed between them. The counter reading was taken immediately the first cracking sound was heard. Compressive strength was calculated by dividing the fracture force with the area in contact with the grain using Equation 18 (Craig et al., 2008).

$$\tau_c = \frac{F_c}{A} \qquad (\text{N mm}^{-2}) \qquad (18)$$

Where; τ_c = compressive strength (N mm^{-2}), F_c = compressive force at failure (N) and A = cross-sectional area defined by the length and width dimensions of the specimen (mm^2).

2.4 Statistical analysis

In the present study, the results are expressed as mean and standard deviation (S.D.) of various determinations.

3 Results and Discussions

3.1 Physical properties of acha grains

A summary of the results for the physical properties measured and determined is shown in Table 1.

The average moisture content was calculated as 14.73±2.14% dry basis and all the other experiments were conducted at this moisture content. The moisture content is very important as it influences the size, shape and angle of repose of the seeds; which in turn determine the hopper capacity and the free flow of the seeds. It was observed that the longitudinal dimension or Length (L) of the seeds ranged from 1.72 mm to 1.98 mm with the mean value as 1.84 ± 0.055 mm, the width (W) varied from 0.80 mm to 0.93 mm with the mean value as 0.85 ± 0.023 mm and the seed thickness (T) varied from 0.66 mm to 0.84 mm with the mean value as 0.75 ± 0.042 mm. Although, Mohsenin (1986) had effectively highlighted the imperativeness of the axial dimensions in machine design, the comparison of the data with existing work on the other seeds can be sufficient in making symmetrical projections towards process equipment adaptation. It is seen from Table 1 that the arithmetic mean diameter (Da) and geometrical mean diameter (Dg) of the kernels varied from 1.06 mm to 1.25 mm with the mean value of 1.15±0.014 mm and 0.97 mm to 1.16 mm with the mean value of 1.05±0.018 mm, respectively. Dimensions are important to design the cleaning, sizing and grading machines.

Table 1 Physical properties of acha grains

Physical Properties	Unit	Min	Max	Mean	Standard eviation
Dimensional Properties					
Length (L)	mm	1.72	1.98	1.84	0.055
Width (W)	mm	0.80	0.93	0.85	0.023
Thickness (T)	mm	0.66	0.84	0.75	0.042
Arithmetic mean diameter (Da)	mm	1.06	1.25	1.15	0.014
Geometrical mean diameter (Dg)	mm	0.97	1.16	1.05	0.018
Roundness (R)	-	0.5579	0.5991	0.5840	0.011
Sphericity (ϕ)	-	0.5630	0.5841	0.5732	0.013
Aspect ratio (Ra)	-	0.4651	0.4697	0.4678	0.012
Surface area (Sa)	mm^2	2.95	4.20	3.49	0.25
Projected area (A_P)	mm^2	1.08	1.45	1.23	0.033
Volume (V)	mm^3	0.48	0.81	0.61	0.029
Gravimetric Properties					
Moisture content (Mc)	%	10.86	19.94	14.73	2.14
One thousand grain mass ($M1000$)	g	0.594	1.364	0.827	0.053
Bulk density (ρ_b)	Kg m^{-3}	1065.72	1145.35	1092.86	24.13
True density (ρ_t)	Kg m^{-3}	1536.50	1733.67	1626.15	62.91
Porosity (ρ_o)	%	30.64	33.93	32.52	1.34

The results showed that roundness (R) of the seeds ranged from 0.5579 to 0.5991 with the mean value of 0.5840±0.011, sphericity (ϕ) varied from 0.5630 to 0.5841 with the mean value of 0.5732±0.013 and aspect ratio (Ra) ranged from 0.4651 to 0.4697 with the mean value of 0.4678±0.012. Garnayak et al. (2008) considered any grain, fruit and seed as spherical when the sphericity value is above 70%, thus, the high sphericity of the soya bean seeds is indicative of the shape towards being a sphere. The lower sphericity values thus suggest that the kernels tend towards a cylindrical shape (Omobuwajo et al., 2000). The aspect ratio is an indicator of a tendency toward an oblong shape (Heidarbeigi et al., 2009). Thus, the lower values of the aspect ratio and sphericity generally indicate a likely difficulty in getting the kernels to roll than that of peas like spheroid grains. They can, however, slide on their flat surfaces. This tendency to either roll or slide should be necessary in the design of hoppers for milling process. However, the surface area (*Sa*) ranged from 2.95 mm^2 to 4.20 mm^2 with the mean value of 3.49±0.25 mm^2, the projected area (A_P) ranged from 1.08 mm^2 to 1.45 mm^2 with the mean value of 1.23±0.033 mm^2 and the seed volume (*V*) varied from 0.48 mm^3 to 0.81 mm^3 with the mean value of 0.61±0.029 mm^3. The surface area is a relevant tool in determining the shape of the seeds. This will actually be an indication of the way the kernels will behave on oscillating surfaces during processing. The projected area of the particle is generally indicative of its pattern of behaviour in a flowing fluid such as air, as well as the ease of separating extraneous materials from the particle during cleaning by pneumatic means (Omobuwajo et al., 1999). The values of the dimensions of the acha seeds are useful in the calculation of the amount of seeds that will be crushed at the feed end portion of the machine. It also assists in determining the total force that will be required to grind the material based on the number of seeds to be processed per batch.

The average moisture content (*Mc*) was 14.73±2.14%, although the moisture content varied between 10.86% and 19.94%. The thousand kernel weight (*M1000*) ranged from 0.594 g to 1.364 g with the mean value of 0.827±0.053 g. One point worthy of note however that is the one thousand seed weight is a function of the individual mass (weight) of the seed/kernel/grain of the crops. Weight is an important parameter to be used in the design of cleaning grains using aerodynamic forces (Oje and Ugbor, 1991). The bulk density (ρ_b) of kernels ranged from 1065.72 kg m^{-3} to 1145.35 kg m^{-3} with mean value of 1092.86 ± 24.13 kg m^{-3}, the true density (ρ_t) value varied from 1536.50 kg m^{-3} to 1733.67 kg m^{-3} with mean value of 1626.15 ± 62.91 kg m^{-3} and the porosity (ρ_o) of the kernels varied from 30.64% to 33.93% with the mean value as 32.52 ±1.34%. The value of true density indicates that the kernel density is higher than water, which is the important property in case of food grains during wet cleaning, as the kernels do not float on water. The densities are useful in the theoretical calculation of the capacity of the processing machine.

3.2 Aerodynamic properties of acha grains

A summary of the results for the aerodynamic properties determined is shown in Table 2.

The aerodynamic properties examined for the seeds are the terminal velocity (V_t), drag coefficient (C_d) and the Reynold's number (N_{Re}).

Table 2 Aerodynamic properties of acha grains

Aerodynamic Properties	Unit	Min	Max	Mean	Standard Deviation
Terminal velocity (V_t)	ms^{-1}	3.94	3.99	3.97	0.015
Drag coefficient (C_d)	-	0.543	0.906	0.684	0.062
Reynold's number (N_{Re})	-	289.56	339.77	311.37	13.47

It was observed that the terminal velocity (V_t) of the seeds ranged from 3.94 ms^{-1} to 3.99 ms^{-1} with the mean value as 3.97 ± 0.015 ms^{-1}, the drag coefficient (C_d) varied from 0.543 to 0.906 with the mean value as 0.684 ± 0.062 and the Reynold's number (N_{Re}) varied from 289.56 to 339.77 with the mean value as 311.37 ± 13.47. Zewdu (2007) measured the terminal velocity of Tef grains. The researcher reported that it increased linearly from 3.08 ms^{-1} to 3.96 ms^{-1} with increasing moisture content from 6.5% to 30.1% w.b. The increase in terminal velocity with an increase in moisture content may be attributed to the increase in mass of an individual seed per unit frontal area presented to the air stream. The other reason is probably that the drag force is affected by the moisture content of particle. The implication of the variation of the terminal velocity with moisture content (increase in terminal velocity of material with moisture content) is the need to define the range of air velocities for effective separation of the grain from foreign materials and in the material handling process at various moisture contents (Zewdu, 2007). Afonso et al. (2007) reported that the drag coefficient of coffee cherries decreased from 0.05 to 0.03 as moisture content increased from 10.7% to 53.9% w.b. This was due to the fact that the terminal velocity, true density and the two principal dimensions (length and width) increased along with each other as moisture content increased. Therefore, the drag coefficient of seed decreased as moisture content increased. In common separation systems, the particles are separated when one particle moves in a different direction than other particles, due to the difference between their drag forces. Therefore the implication of the variation of the drag coefficient with moisture content is the need to design separation systems that will be effective at different moisture contents (Afonso et al., 2007).

Undesirable materials such as light grains, weed seeds, chaff, plant leaves and stalks can be removed with air flow and equipment of separation, when grains, fruits and vegetables are mechanically harvested (Kaleemullah and Gunasekar, 2002). In order to harvest sunflower seeds with combine harvester, or perhaps a stationary thresher and cleaning unit, it is important to know the physical and aerodynamic properties (engineering properties) of grain and material other grain of sunflower. The aerodynamic properties such as terminal velocity, drag coefficient and Reynold's number are needed for determination of the proper air speed in air conveyor and pneumatic separator (Sahay and Singh, 1994). These parameters are affected by the density, shape, size and moisture content of samples (Kashaninejad et al., 2006). By defining the terminal velocity of different threshed materials, it is possible to determine and set the maximum possible air velocity in which material out of grain (*MOG*) can be removed without loss of grain or the principle can be applied to classify grain into different size groups (Zewdu, 2007). The difference in terminal velocity between damaged and undamaged grains is used to separate them in a vertical wind tunnel. In addition, agricultural materials and food products are routinely conveyed using air. For such operations, the interaction between the solid particles and the moving fluids determine the forces applied to the particles (Zewdu, 2007). So, it is necessary to determine the aerodynamic properties as a function of numerous factors such as moisture content, size and variety. With this information, the separation and cleaning of acha grains can be better understood for and the potential for developing separation machinery evaluated.

3.3 Mechanical Properties of acha grains

A summary of the results for the mechanical properties determined is shown in Table 3.

Table 3 Mechanical properties of acha grains

Mechanical Properties	Unit	Min	Max	Mean	Standard Deviation
Frictional Properties					
Angle of repose (θ)	Degrees	30.80	35.10	32.50	1.36
Coefficient of static friction (μ)	-	0.72	1.11	0.82	0.043
Strength Properties					
Shear strength (τ_s)	Nm^{-2}	3659	3989	3840	72.32
Compressive strength (τ_c)	Nm^{-2}	7278	7782	7615	90.28

The mechanical properties include the frictional and strength properties. The frictional properties examined for the kernels are the angle of repose (θ) and the coefficient of static friction (μ). Essentially, the mean angle of repose was 32.50±1.36o, although the angle of repose varied from 30.80^{o} to 35.10^{o}. Angle of repose and coefficient of friction are important in designing equipment for solid flow and storage structures. The coefficient of friction between seed and wall is an important parameter in the prediction of seed pressure on wall (Ayman, 2009). This phenomenon is imperative in food grain processing, particularly in the designing of hopper for milling equipment. The angle of repose will determine the angle at which chutes must be positioned in order to achieve consistent flow of materials through the chute. To ensure free flow, an angle of repose which is modestly higher than the average angle of repose (32.50±1.36o) obtained for the acha seeds would be used. The co-efficient of static friction on mild steel surface found ranged from 0.72 to 1.11 with the mean value of 0.82±0.043. The knowledge of the coefficient of friction will be useful during the calculations of the various forces required to translate, compress and crush the seeds as well as the frictional force resulting from the motion of the screw and grinding discs.

The strength properties examined for the kernels are the shear strength (τ_s) and the compressive strength (τ_c). The shear strength and compressive strength of the kernels varied from 3659 Nm^{-2} to 3989 Nm^{-2} with the mean value of 3840±72.32 Nm^{-2} and 7278 Nm^{-2} to 7782 Nm^{-2} with the mean value of 7615±90.28 Nm^{-2}, respectively. In designing food processing machines, the knowledge of these properties has been emphasized by Adebayo (2004) when he carried out carried a compression test on Dura varieties of the palm nut in order to determine the force required for cracking the palm nut. The compressive strengths for minor, major and intermediate axis are 396.20 ± 49.40 Nm^{-2}, 216.30 ± 23.92 Nm^{-2} and 262.4 ± 174.80 Nm^{-2} respectively for the white almond. These parameters are important in designing of machines for processing biomaterials, particularly in the design of a cracking machine for extraction of nut from the kernel. These parameters also give the energy requirement and consideration governing equipment selection in size reduction operation (Orhevba et al., 2013).

4 Conclusions

The engineering properties of acha seeds in relation to the design of grain processing machines for the crop have been determined. The average seed length, width and thickness were found to be 1.84 ± 0.055 mm, 0.85 ± 0.023 mm and 0.75 ± 0.042 mm respectively. The average arithmetic and geometric mean diameters were 1.15±0.014 mm and 1.05±0.018 mm respectively. The average roundness, sphericity and aspect ratio were 0.5840±0.011, 0.5732±0.013 and 0.4678±0.012 respectively. The mean surface area, projected area and volume were 3.49±0.25 mm^2, 1.23±0.033 mm^2 and 0.61±0.029 mm^3 respectively. The average moisture content was 14.73±2.14% dry basis and the thousand kernel weight was 0.827±0.053 g. The average bulk and true densities were 1092.86 ± 24.13 kg m^{-3} and 1626.15 ± 62.91 kg m^{-3} respectively and the porosity was 32.52 ±1.34%. The average terminal velocity, drag coefficient and Reynold's number of the seeds were found to be 3.97 ± 0.015 ms^{-1}, 0.684 ± 0.062 and 311.37 ± 13.47 respectively. The mean angle of repose was 32.50±1.36^o while the mean coefficient of static friction on mild steel surface was 0.82±0.043. The mean shear strength and compressive strength of the seeds were 3840±72.32 Nm^{-2} and 7615±90.28 Nm^{-2} respectively. These parameters will serve as inputs for the efficient design of processing machines for acha seeds.

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