



SOME PHYSICAL PROPERTIES OF ACHA (*DIGITARIA EXILIS*) RELEVANT IN MECHANICAL DEHULLING AND CLEANING

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ABSTRACT

The properties of acha (*Digitaria exilis*) are important in the development of effective machines for dehulling and cleaning of the paddy. In this study, some of the relevant crop properties were determined, such as; moisture content, length, width, thickness, size and shape, arithmetic, geometric and equivalent mean diameters, surface area, volume and a thousand weight. Others includes; bulk and solid densities, porosity, angle of repose and coefficient of static friction. The fineness modulus, uniformity coefficient, particle size distribution and terminal velocity were determined for both paddy acha and grains. The properties were determined using standard methods at the moisture content of 10.3% (db) in replicates. The results showed that the length, width, thickness, size of grain, flatness index, thousand grain weight, angle of repose, angle of internal friction, bulk and solid densities were 1.58 mm, 0.90 mm, 0.76 mm, 1.58 mm, 1.65, 0.53g, 24.7°, 0.46°, 608.01 kg m⁻³ and 1131.0 kg m⁻³ respectively. The terminal velocity, porosity, coefficient of static friction, arithmetic and geometrical mean, equivalent diameters, surface area, volume, fineness modulus (paddy), fineness modulus (grain), particle size distribution (grain), particle size distribution (paddy), uniformity coefficient (grain), uniformity coefficient (paddy) was 3.96 m s⁻¹, 46.24, 0.459, 1.127 mm, 1.859 mm, 1.059 mm, 3.36 mm², 3.00 mm³, 3.17, 3.00, 0.34, 0.36, 0.63 and 0.60 respectively. Thus, the acha (paddy and grains) can be classified as medium size and spherical in shape. In the sieve analysis of the paddy acha, 99.57 % of the paddy was retained on 0.351 mm mesh while 27.27 % and 61.72 % of the grains were retained on the 0.894 and 0.351 mm meshes. This is indicative of more variability in the grains than in the paddy. The properties show that the paddy separates easily and the grains are easily cleaned from contaminants.

1.0 Introduction

Acha is a typical West African cereal crop cultivated in large quantity in Nigeria. Other large acha cropping and producing Countries in West Africa Guinea are: Mali and Burkina Faso. It was reported that about 587,270 tons of acha were produced on 566,047 hectares in these regions in 2012 (Wilma *et al.*, 2018). Acha produces rough pods also known as raw or paddy acha (Figure 1a), which still have their glume and lemmas after threshing (Cruz *et al.*, 2016). The paddy has an oval seed coating with slightly flattened side. The paddy is very small (Figure 1a), measuring 1.5 mm in length, 0.9 mm in width and a 1000 weight of 0.5g (Satimehin and Philip, 2012). Hulled acha grains (Figure 1b) have a shiny shin pericarp whose colours vary from white through yellow to purple depending on the variety (Rose, 2017).



Figure 1: Acha, a. Greatly magnified 1 mm acha paddy b. Grains
(Source: Koréissi, 2015; Cruz *et al.*, 2016)

Chakraverty *et al.* (2003) identified seed and system parameters as the two broad factors that affect the cleaning of agricultural grains and seeds. The accurate estimation of seed shape is fundamental in the design of pneumatic technology for grain cleaning because it is important for the determination of terminal velocity and drag coefficient used for estimating the Reynolds number (Cervantes *et al.*, 2016). The seed sizes are classified into three categories namely small, medium and large based on their length (Philip, 2011). Komar and Reimers (1978) stated that the departure of a grain from a spherical shape causes a decrease in its settling or terminal velocity within a fluid; the more non-spherical the particle, the greater the departure from the terminal velocity of a grain of the same weight in a stream of air (Carventes *et al.*, 2016). The moisture content of grains is known to alter the shape of the grain. El - Fawal (2009) reported an increase in seed sphericity with increased moisture content.

The 1000-kernel weight is a good indicator of the grain size, which can vary relative to growing conditions and maturity even for the same variety of a given crop when compared with other crops at the same moisture level. The 1000 - kernel weight also provide an idea of relative size of the kernel for handling purposes (Sablani and Ramawamy, 2003). The bulk density gives a good idea of the storage space required for a known quantity of particular grain. Bulk density also influences the effective conductivity and other transport properties (Philip, 2011). Satimehin and Philip (2012) recorded a bulk density of 0.607 g m^{-3} at 10.31% moisture content (db) for acha grains (*Digitaria exilis*) in Nigeria. Bulk densities of some biomaterials increase linearly with increase in moisture content between 12 and 18% while some decrease linearly with increase in moisture content (Sokhansanj and Lang, 1996; Fraser *et al.*, 1978; Irvine *et al.*, 1992; Dutta *et al.*, 1988; Carman, 1996; Bala and Woods, 1991; Deshpande *et al.*, 1993). Satimehin and Philip (2012) found the mean kernel density of acha grain to be 1.13 g cm^{-3} at 10.31% moisture content (db). The porosity of grain is an important parameter that affects the kernel hardness, breakage susceptibility, milling, drying rate, and resistance to fungal development (Chang, 1988).

Stroescu *et al.* (2019) identified terminal velocity, angle of friction, angle of repose and the coefficient of internal resistance of seeds as properties that enable their separation from a matrix of other materials by pneumatic segregation. The ease with which the particles fall along the tray depends on the tilt or repose angle that is used in designing adjustable inclined cleaning trays in dehulling and cleaning. Terminal velocity is an important aerodynamic property of seeds that is necessary for designing pneumatic conveying systems, fluidized bed dryers and cleaning of seeds from foreign materials (Ghamari *et al.*, 2011). Experimental results have shown that the value of terminal velocity even for the same species of grains fluctuates in a very vast range (Kaankuka, 2015 and Stroescu *et al.*, 2019). This is because the motion of a grain particle falling freely through air during the separation of undesirable chaff from the grain, is guided by the shape and weight of the grain and the density of the media (air) through which it is falling as well as gravitational pull on the grain (Sümer and Helvacı, 2008). The greater the difference between values of critical velocities of individual components in a mixture, the better and more efficient its pneumatic separation (Panasiewicz *et al.*, 2012). According to

Panasiewicz et al. (2012) the lower the critical velocity is, the lower the density and drag of a particle, which in turn depend on the shape and properties of its surface (such as smooth, coarse, ribbed, mesh, covered with trichomes). Khoshtaghaza and Mehdizadeh (2006) and Refit et al. (2006) found that increasing the mass and moisture content of the kernel results in a linear increase in the terminal velocity. Kaankuka et al. (2015) reported terminal velocities of acha, the acha chaff and the velocity of the air required for the cleaning the hulls as 3.96 ms^{-1} , 1.9 ms^{-1} and 2.5 ms^{-1} respectively.

There are no technologies for the processing of acha because of the dearth of literature on its properties relevant to designing them such as the dehulling and cleaning machine. The properties of acha will help make the design of processing machines easier and more efficient. This study is geared towards generating some engineering data of acha, relevant for designing efficient machines for its postharvest processing operations. Thus, the objective of this study is to determine some physical properties of acha relevant to mechanical its dehulling and cleaning. The objective of this study is to determine the properties of acha relevant to mechanical dehulling and cleaning.

2. Materials and Methods

Acha (*Digitaria exilis*) paddy and grains that were used in determining some selected physical properties were bought from Jos South Local Government Area of Plateau State, Nigeria. The properties of paddy acha and grains relevant to mechanical dehulling and cleaning were determined. The properties of paddy acha determined were the moisture content, size, shape, 1000-paddy weight, bulk and solid densities, porosity, angle of repose and coefficient of static friction. The properties of paddy acha and grains determined were fineness modulus, particle size distribution, uniformity coefficient and terminal velocity.

2.1 Determination of moisture content

The moisture content of paddy acha was determined by the oven-dry method. 10 to 15 g of paddy acha was taken from the paddy lot, put into a container and weighed using an electronic digital weighing machine (Metler Toledo balance) having a sensitivity of 0.01 g. The known weight was oven dried at a temperature of 110°C for 18 hours. The weight of the dried sample was taken and the moisture content was obtained using equation 1.

$$MC_{(d.b)}\% = \frac{W_w - W_d}{W_d} \times 100. \quad (1)$$

Where:

W_w is weight of wet paddy acha (g)

W_d is weight of dry paddy acha (g)

2.2 Determination of size

The size of paddy acha can be subdivided into length, width and thickness (Figure 2). These dimensions were measured using a digital vernier caliper with 0.01mm accuracy and used to determine the size of paddy. Some paddy acha were pinched between the thumb and the index finger from the lot onto a plane white surface from which ten (10) samples were randomly selected, measured and the sizes calculated using equations 2, 3, 4 and equation 5 (Maduako and Hannan, 2004).

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

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

$$d_s = \left[\frac{LW + WT + TL}{3} \right]^{1/2} \quad (4)$$

$$d_e = \frac{d_a + d_g + d_s}{3} \quad (5)$$

Where:

d_g is the geometric mean diameter (mm)

d_a is the arithmetic mean diameter (mm)

d_s is the square mean diameter (mm)

d_e is the equivalent diameter (mm)

L is the mean length of the seeds (mm)

W is the mean width of the seeds (mm)

T is the mean thickness of the seeds (mm)

The surface area (S_a) was determined using equation 6 (Malik *et al.*, 2016)

$$S_a = \pi \times d_g^2 \quad (6)$$

The sphericity (ϕ) of particle was determined using equation 7.

$$\phi = \frac{d_g}{L} \quad (7)$$

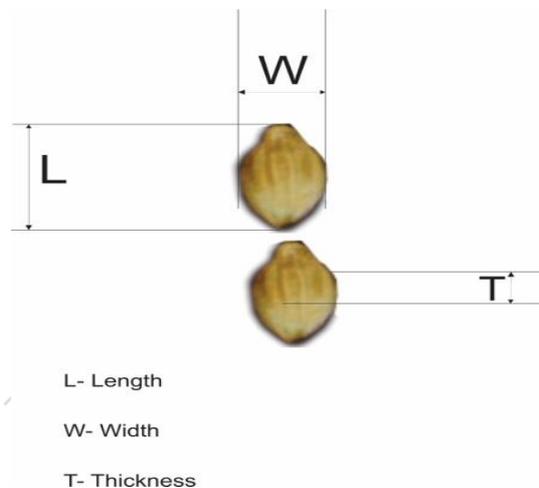


Figure 2: Dimensional Axes of the Acha Paddy

2.3 Determination of seed shape

The seed shape was determined from the flatness index (FI) which measures the relationship between the seed's dimensions along the three principal axes (Cervantes *et al.*, 2016; Cerda and Garcia-Fayos, 2002) to characterize seed shape. The index was determined from equation 8. It ranges from a value of 1 for spheres to values greater than 2 for spindly seeds (Cervantes *et al.*, 2016).

$$FI = \frac{(L+W)}{2H} \quad (8)$$

Where L is the length and W is the width and H is the height of the seed (mm)

2.4 Determination of one thousand weight

1000 grain weight of paddy acha was measured using a Mettler XSR electronic balance with accuracy of 0.001g. Cleaned paddy acha were carefully counted to 1000 kernel and placed on the weighing pan of the electronic balance and weighed. The procedure was carried out in 5 replicates and the results recorded.

2.5 Determination of bulk and solid density

A plexi-glass cylindrical container (63.00 mm in height and 64.03 mm in diameter) was filled with paddy acha and weighed on a Mettler XSR electronic balance with accuracy of 0.01g. The procedure was repeated five times and the bulk density was calculated from equation 9.

$$\rho_{ab} = \frac{W_2 - W_1}{V} \quad (9)$$

Where:

ρ_{ab} is paddy acha bulk density (kg m^{-3})

W_1 is weight of empty cylindrical container (kg)

W_2 is weight of the paddy acha and cylindrical container (kg)

V is volume of the container (m^3)

The solid or kernel (true) density refers to the density of an individual unit and is another way of describing density. This may or may not contain internal pores. The solid density was calculated using equation 10 as described by Ozturk et al. (2009).

$$\rho_{at} = \rho_w \times GSP \quad (10)$$

Where:

ρ_{at} is the true density (kg m^{-3})

ρ_w is the density of water (kg m^{-3})

GSP is the specific gravity of the paddy acha (g/g)

2.6 Determination of porosity

The porosity of seeds depends on bulk density and the true density, and is usually affected by the moisture content of a crop material. The porosity value (ϵ) which is defined as the fraction of space in the bulk grain not occupied by the grains was calculated from the average values of bulk density and true density using equation 11 (Mohsenin, 1986).

$$\epsilon(\%) = \left(1 - \frac{\rho_{ab}}{\rho_{at}}\right) \times 100 \quad (11)$$

Where:

ϵ – porosity

ρ_{ab} -bulk density of paddy acha (kg m^{-3})

ρ_{at} - true (kernel) density of paddy acha (kg m^{-3})

2.7 Determination of angle of repose

A double-ended open cylindrical container of 20 cm diameter and 40 cm height was placed on a 100 cm circular plastic plate and filled with acha grains. The cylinder was tapped until a uniform packing was attained and then gently lifted up 20 mm above the surface where the bottom of the container was uncovered. The lifting of the container continued gradually until all the paddy acha formed a conical heap on the plate. The procedure was replicated 5 times

while measuring the heights each time and the angle of repose calculated using equation 12 (Waziri and Mittal, 1983).

$$R_a = \tan^{-1} \left(\frac{2H_h}{H_d} \right) \quad (12)$$

Where:

R_a is the angle of repose of the acha paddy (°)

H_h is the height of the heap of paddy (mm)

H_d is diameter of the plastic plate (mm)

2.8 Determination of fineness modulus

The fineness modulus of Paddy acha and grains was determined in the laboratory according to ASTM E11(2001) using a Gilson shaker (serial no.064438) and Golden Mettler electronic weighing balance of 0.001g accuracy. One hundred grams (100 g) of paddy acha was weighed in a pan of known weight (24.4g) and placed on 5 sieves stacked sifter with an empty bottom pan. The sieves stack was arranged from the biggest to the smallest from top to bottom: 2.818, 1.201, 0.894, 0.351 and 0.186 mm with a bottom pan that has no mesh/covering and designated as 0. The shaker was manually agitated vigorously for 10 min in three replications. The paddy acha retained after the sifting on each screen was weighed and the percentage paddy retained on each designated sieve was calculated. The percentage of paddy acha retained on each screen and the bottom pan was determined from equation 13. The fineness modulus, which is the cumulative percentage of the paddy retained on each sieve and the pan added up and divided by 100 was obtained using equation 14 (Karaj and Muller, 2010). The procedure was also undertaken for acha grains.

$$R (\%) = \left(\frac{M_1 - M_2}{M} \right) \times 100 \quad (13)$$

$$FM = \frac{R}{100} \quad (14)$$

Where:

FM is the fineness modulus

R is the percentage grains retained on each sieve (%)

M_1 is mass of each sieve (g)

M_2 is mass of each sieve + mass of paddy acha or grains retained on the sieve (g)

M is the total mass of the paddy acha or grains (g)

2.9 Determination of particle size distribution

The particle size distribution for the paddy acha and grains were determined. The particle size distribution was calculated using equation 15 (Boloni, 1994).

$$PSD = 0.135 \times (1.366)^{FM} \quad (15)$$

Where PSD is the particle size distribution and FM is the fineness modulus

2.10 Determination of uniformity coefficient

The uniformity coefficient (C_u) expresses the dispersion in particle sizes of paddy acha and grains. It is defined as the ratio of D_{60} to D_{10} determined from the gradation curve, which is a logarithm plot (Figure 3) of the cumulative percent passing of paddy acha or grains on the y-axis and the sieve size opening on the x-axis (Keaton, 2018). The C_u for paddy and grains were computed using equation 16.

$$C_u = \frac{D_{60}}{D_{10}} \quad (16)$$

Where:

D_{60} is paddy acha or grain diameter at which 60% of particles that is finer and 40% of particles that are coarser (mm).

D_{10} is paddy acha or grain diameter at which 10% of particles are finer and 90% of the particles are coarser (mm).

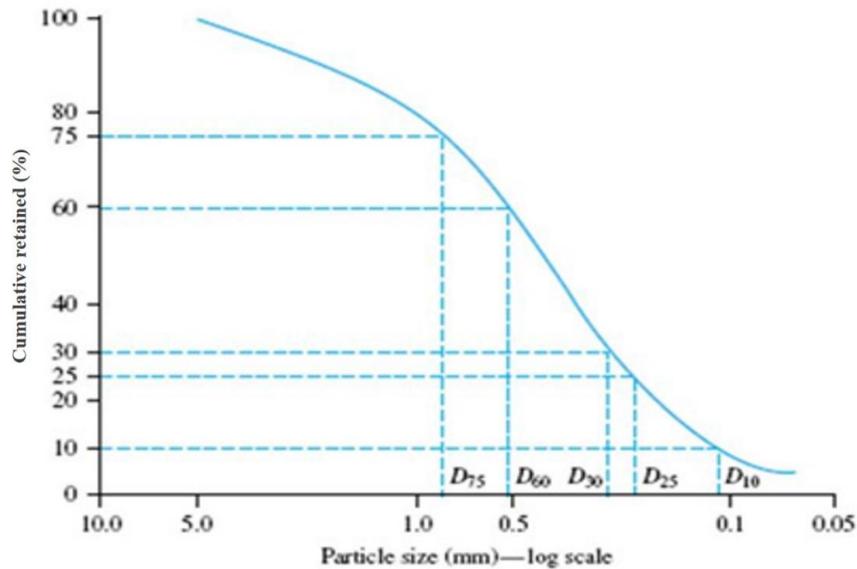


Figure 3: Grain size Distribution Curve

2.11 Determination of terminal velocity

The terminal velocity of the paddy acha and grains were calculated from equation 17.

$$V_t = \sqrt{\frac{2W(\rho_p - \rho_f)}{C_d A_p \rho_p \rho_f}} \quad (17)$$

Where:

V_t - Terminal velocity (m s^{-1})

C_d - Drag coefficient

W - Weight of grains (kg)

ρ_p - Density of particle (kg m^{-3})

ρ_f - Density of air (kg m^{-3})

A_f - Frontal Area, which is equal to 1.088×10^{-6} for paddy acha and grains (m^2) (Kaankuka et al., 2015)

2.12 Determination of coefficient of static friction

The coefficient of static friction of paddy acha was determined on a galvanized steel surface using a tilting table. The angle of inclination of the table to the horizontal at which samples started sliding were measured with a protractor attached beside the inclined plane apparatus (Maduako and Hannan, 2004). Measurements were replicated five times and the coefficient of static friction was determined using Equation 18.

$$\mu = \tan \alpha \quad (18)$$

Where:

μ = Coefficient of static friction

α = Angle of inclination of the table to the horizontal ($^{\circ}$)

3. Results and Discussion

The summary of some properties of paddy acha and grain is presented in Table 1. The coefficient of static friction was determined to be 0.46 and is similar to the value of 0.456 obtained by Philip (2011) but lower than the value of 0.82 reported by Bako and Bardey (2020). This variation may be due to the difference in the moisture contents of the acha grains used in the different studies as the coefficient of internal resistance of grain have been reported to increase with increases in moisture content (Aviara *et al.*, 2017). The terminal velocity was 3.96 m/s for paddy acha and 2.13 for grain. The result is consistent with the values of 3.96 m/s paddy acha and 1.9 m/s for grain reported by Kaankuka *et al.* (2015) and the value of 3.97 m/s for paddy acha reported by Bako and Bardey (2020). The difference in the terminal velocities of the paddy acha and grain lend them to separation by using appropriate air velocities in conveyor and pneumatic separation and can be applied to the separation of damaged grains from whole grains as well.

The length of the paddy acha was 1.58mm. This is consistent with the value of 1.604 mm reported by Philip (2011) and 1.84 mm reported by Bako and Bardey (2020). The width of the paddy acha was 0.9 mm, which is similar to the values of 0.864 and 0.85 reported by Philip (2011) and Bako and Bardey (2020) respectively. The thickness of the paddy acha was 0.76 mm, which compares to 0.796 mm and 0.75 mm reported by Philip (2011) and Bako and Bardey (2020) respectively. The knowledge of the axial dimension of seeds has been used in the determination of the clearance between dehulling cylinders and drums (Tokan *et al.*, 2012; Solanki *et al.*, 2018; Simonya and Yiljep, 2008) to minimize damage to grains. The knowledge of the axial dimension of the grain can also be used in the design of indented cylinders for acha grain cleaning.

The one thousand grain weight of the paddy acha was 0.53 g. The value is the same as 0.529 g established by Philip (2011) but differs from the 0.83 g reported by Bako and Bardey (2020). The bulk and solid densities were 608.01 kg m⁻³ and 1131.00 kg m⁻³ respectively. These values are similar to 606.6 kg/m³ and 1130 kg/m³ for solid and bulk densities respectively reported by Philip (2011). Bako and Bardey (2020) reported solid and bulk densities of 1626.15 kg/m³ and 1092.86 kg/m³ respectively which are different from the results obtained in this study. The porosity was determined to be 46.24 % which is similar to the value of 46.25% reported by Philip (2011) but different from 32.52 % reported by Bako and Bardey (2020). Although porosity is reported to have a linear relationship with moisture content (Karimi *et al.*, 2009), it is known to decrease with increase in bulk density and this may explain the variation in the porosities reported in these studies. The knowledge of the weight and densities of seed is important in the design of feed hoppers and the size of hopper throats. The ratio of the inter-granular void space volume and bulk volume of seeds is the porosity and it is important in pneumatic cleaning as less hulls attached to the kernel are cleaned and can be easily blown off by the impeller air velocity.

The angle of repose of the paddy acha was 24.70° which corroborate the value of 24.50° reported by Kaankuka *et al.* (2014). Bako and Bardey (2020) reported a value of 32.50°. The different values in the different studies may still be due to variation in moisture content as the angle of repose increases linearly with increasing moisture content (Bako and Bardey, 2020; Aviara *et al.*, 2017). The angle of repose is an important determinant in the estimation of forces acting on structures and the design of solid flow structures such as silos, storage bins and the design of free fall devices such as hoppers. It is vital in determining the angles at which chutes are inclined for consistent flow of granular materials.

Table I. Properties of Paddy Acha and Grains

Properties	Value
Length (mm)	1.58
Width (mm)	0.90
Thickness (mm)	0.76
Size of grain (mm)	1.58
Arithmetic mean diameter (mm)	1.13
Geometric mean diameter (mm)	1.86
Square mean diameter (mm)	1.58
Equivalent diameter (mm)	1.06
Surface area (mm ²)	3.36
Volume (mm ³)	3.36
Flatness index	1.63
1000-wieght (g)	0.53
Angle of repose (deg)	24.7
Bulk Density (kg/m ³)	608.01
Solid density (kg/m ³)	1131.00
Porosity	46.24
Fineness modulus (grain)	3.00
Fineness modulus (paddy)	3.17
Particle size distribution (grain)	0.35
Particle size distribution (paddy)	0.36
Uniformity coefficient (grain)	0.63
Uniformity coefficient (paddy)	0.60
Terminal velocity, paddy (m/s)	3.96
Terminal velocity, grain (m/s)	2.13
Coefficient of static friction	0.46

Table 2 is the sieve analysis for fineness modulus and particle size analysis for paddy acha and grain. The fineness modulus of the grain and paddy were 3.00 and 3.17 respectively while the particle size distribution of the paddy and grain were 0.35 mm and 0.36 mm respectively. In the sieve analysis of the paddy acha, 99.57% of the paddy was retained on 0.351 mm mesh while 27.27% and 61.72% of the grains were retained on the 0.894 and 0.351 mm meshes. This is indicative of more variability in the grains than in the paddy. Aviara et al. (2017) investigated the effect of moisture content (5 - 30% d.b.) on the particle size distribution of two acha varieties (*Digitaria exilis* and *iburau*) using sieve analysis method and reported that only a little fraction (less than 1.5%) of the grains passed through the 0.425mm mesh. The results of this study agree with that of Aviara et al. (2017). Particle size distributions of grains have been used in the determination of the grain weight for bins and hopper designs (Belay et al., 2009) and is an important factor in feed rate calibration (Khurmi and Gupta, 2007).

Table 2. Sieve Analysis for Fineness Modulus and Particle Size of Acha Paddy and Grain

Sieve No (Size BSS, mm)	Acha type	Mass of acha retained (g)	Percentage retained per sieve (%)	Cumulative Percentage retained per sieve (%)	Percentage Finer (%)
6 (2.818)	Paddy	0	0	0	100
	Grain	0	0	0	100
14 (1.201)	Paddy	0.03	0.06	0.06	99.94
	Grain	0.07	0.96	0.96	99.04
20 (0.894)	Paddy	0.20	0.37	0.43	99.57
	Grain	1.9	27.27	28.23	71.77
44 (0.351)	Paddy	53.73	99.57	100.00	0
	Grain	4.3	61.72	89.95	10.05
80 (0.186)	Paddy	0	0	100.00	0
	Grain	0.6	8.61	98.57	1.44
Pan (0)	Paddy	0	0	100	0
	Grain	0.1	1.44	100	0
Total	Paddy	53.97		300.49	
	Grain	6.97		317.70	

Figure 4 is the grain size distribution curve for the paddy acha and grain. The D_{10} , D_{30} and D_{60} for paddy acha were 1.0 mm, 0.9 mm and 0.6 mm respectively. The figure also shows that the D_{10} , D_{30} and D_{60} for grain were 0.8 mm, 0.7 mm and 0.5 mm respectively. The uniformity coefficient for paddy acha and grain was 0.60 and 0.63 respectively (Table I). The uniformity coefficient expresses the proportion of coarse to fine particles of the acha. A uniformity coefficient greater than 6.0 indicates a densely graded (well graded) material with a considerable range of particle size. A uniformity coefficient of less than 4.0 indicates a uniformly graded (open graded) material with a narrow range of particle size. The uniformity coefficient is useful in designing the clearance between the dehulling cylinder and concave in the dehulling unit of machines.

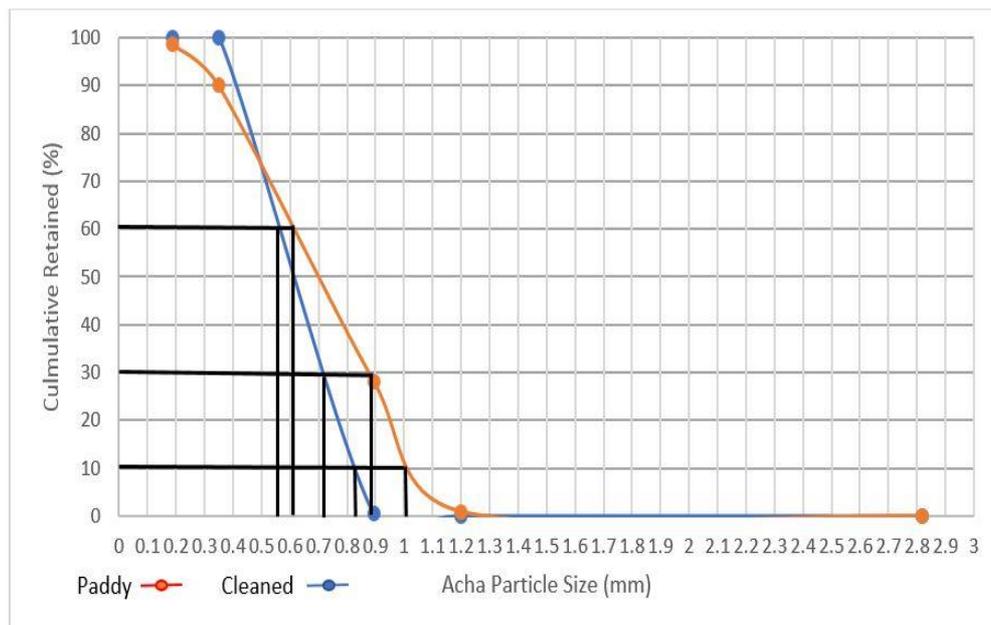


Figure 4: Grain Size Distribution Curve for Paddy and Hulled Acha

4. Conclusions

Acha (paddy and grains) can be classified as medium size and spherical in shape. The paddy was more uniformly graded and of finer aggregates than the grains that were of more variability of considerable range between fine and coarse. The gravimetric properties of the paddy acha shows that it separates easily according to its weight and the grains can be easily cleaned from contaminants.

The determined properties are recommended for use in designing the size of hopper, diameter of the hopper throat, clearance between the dehulling cylinder and concave, size of openings on the screen in the cleaning unit of dehulling machines and the appropriate velocity of air required for effective cleaning of the grains.

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