



A Study on Moisture Dependent Properties of Barnyard Millet (*Echinochloa frumentacea*) Grains

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

A vital component in the design of threshers, dehuskers, shellers, and winnowers is the combination of geometrical, frictional, gravimetric, and aerodynamic characteristics. Consequently, to assess these qualities of barnyard millet grain, experiments were conducted. samples within a suitable moisture content range of 6.21 to 22.57% (db). were used in the experiments. Based on the moisture content appropriate for the majority of post-harvest operations, a range of 6 to 24% was selected. The geometrical mean diameter, equivalent mean diameter, arithmetic mean diameter, and square mean diameter increased from 2.05 to 2.24 mm, 2.63 to 2.87 mm, 2.18 to

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2.38 mm, and 3.67 to 4.00 mm, respectively, with an increase in moisture content. Similarly, the coefficient of static friction with mild steel, GI sheets, plywood, and glass increased linearly from 0.369 to 0.533, 0.342 to 0.492, 0.288 to 0.301, and 0.314 to 0.363, respectively. Comparing the other three surfaces, it was found that mild steel had the highest coefficient of static friction while plywood had the lowest. Porosity, bulk density, and true density decreased from 0.572 to 0.429, 682.92 to 563.72 kg m⁻³, and 1318.95 to 1196.81 kg m⁻³ within the moisture content range, while angle of repose, aspect ratio, sphericity, surface area, volume, 1000 grain weight, coefficient of internal friction, and terminal velocity increased from 23.62° to 40.82°, 65.53 to 66.77, 0.6492 to 0.6569, 13.20 to 15.76 mm², 4.35 to 6.22 mm³, 3.97 to 5.07 g, 0.556 to 0.863, and 4.42 to 5.23 ms⁻¹.

Keywords: Barnyard millet; engineering properties; millet processing.

1. INTRODUCTION

“Barnyard millet (*Echinochloa frumentacea*), is the oldest millet crop grown in warm regions of the globe, notably in India, Japan, China, and Korea. Globally, it is the fourth most-produced minor millet. In terms of area (0.146 Mha) and production (0.147 MT), India is the world's top producer of barnyard millet, with an average productivity of 1034 kg/ha during the previous three years” [1]. It is mainly cultivated in the Indian states of Odisha, Gujarat, Madhya Pradesh, Maharashtra, Bihar, Tamil Nadu, Punjab, and the hills of Uttarakhand [2]. “It contains 10.1% protein, 3.9% fat, 8.7% moisture, 2.0% total fat, 68.8% carbohydrate, 6.7% crude fiber, and 398 kcal/100 g. High dietary fibre content (12.5%) including insoluble (8.4%) and soluble (4.2%) fractions was reported for barnyard millet” [3]. Mechanization of post-harvest activities of barnyard millet, such as threshing, grading, and cleaning can minimize operating costs and labor requirements. This helps in increasing the net benefit to small and marginal farmers. Subramaniam and Viswanathan [4] evaluated “some physical properties like friction coefficient and bulk density of barnyard millet grain within the moisture content range of 11.1 to 25 % (db)”. Similarly, Singh et al. [5] studied “the physical, mechanical and engineering properties of barnyard millet grains and kernels within the moisture content range of 6.5 to 26.5 % (db)”. However, properties of barnyard millet grain of a local variety (*Echinochloa frumentacea*) grown in the state of Odisha are not studied. Barnyard millet is generally harvested at a moisture content of 16 to 18% [6] and stored at 11 to 12% [7]. The threshing cylinder, threshing element, hopper, sieve size, sieve slope, and concave clearance of a thresher are all designed with consideration to engineering characteristics of barnyard millet grain, including size, weight, shape, surface

area, diameter, and bulk density [8–12]. Additional machine parameters, like the threshing cylinder's length, sieve size, speed, air flow velocity and discharge capacity, angle of inclination, etc., are decided as per engineering properties. This includes, physical characteristics like sphericity and equivalent diameter, frictional characteristics like the angle of repose and internal friction [13-20] and aerodynamic properties like terminal velocity. The present experiment was conducted to study the effect of moisture content on the engineering properties of barnyard millet grain within the suitable moisture content range of 6.21 to 22.57% (db).

2. MATERIALS AND METHODS

The local variety of barnyard millet, named Gajapati local, were collected in adequate quantity from the Centre for Pulse Research (OUAT), Ratanpur, Ganjam, Odisha, India (20.264512°N 85.81202°E). After precisely cleaning the grain samples to get rid of any extraneous materials such as dust, dirt, stones, broken grains, immature grain, and chaffs, they were sorted. The standard hot-air oven procedure was utilized to ascertain the initial moisture levels of these samples [19]. The moisture content range was chosen by the fact that the crop is harvested in October and November at a dry basis (db.) moisture content of 24–26% and is thereafter maintained in the sun to dry until the moisture content falls to 12–14% (db). Samples with five levels of moisture content within the range of 6.21 to 22.57% (db) were prepared by adding the appropriate quantity of distilled water, following the procedure by Coşkun et al. [20] and Jambamma et al. [21]. The sample's moisture content was calculated and presented as the average of the four replications. Fig. 1 shows the oven drying of samples to determine moisture content. “The design of the experiment for the study was



Fig. 1. Measurement of moisture content through oven drying

Randomized Block Design (RBD) with five treatments (levels of moisture contents) and four replications (values of properties). There were five treatments (levels of moisture content) and four replications (values of properties). Statistical analysis of the results was conducted using Microsoft Excel. The association between moisture content and different parameters were modelled using linear, logarithmic, polynomial, and exponential models. The models with the best coefficient of determination (R^2) have resulted as the most suitable model to predict" [22].

2.1 Geometrical Properties

"Using an electron microscope with an accuracy of ± 0.01 mm, barnyard millet grains were randomly selected and measured along the three principal axes (major (L), medium (W), and minor (T)). For every moisture content level, all engineering parameters were measured" [14,23].

"The geometric mean of the three axial dimensions and the arithmetic mean were used to determine the grain's average diameter. The following relationships were used to compute the grains' arithmetic mean diameter (AMD), geometric mean diameter (GMD), square mean diameter (SMD), and equivalent diameter (EMD)" [18,24].

$$\text{AMD} = \frac{(L+W+T)}{3} \quad \text{Equation 1}$$

$$\text{GMD} = \sqrt[3]{(LWT)} \quad \text{Equation 2}$$

$$\text{SMD} = \sqrt{((LW + WT + TL))} \quad \text{Equation 3}$$

$$\text{EMD} = ((AMD+GMD+SMD))/3 \quad \text{Equation 4}$$

By using the expression given by Singh et al., 2010, surface area (S) was calculated [5].

$$S = \pi \times \text{GMD}^2 \quad \text{Equation 5}$$

The aspect ratio (R_a), which is the ratio of longer diameter to shorter diameter, was determined using the relationship provided by Maduako and Faborode [25]:

$$R_a = W/L \times 100 \quad \text{Equation 6}$$

Sphericity (ϕ) is defined as the ratio of the surface area of a sphere with the same volume as the grain to the surface area of the grain, and was found using the following formula: [18,24].

$$\phi = \sqrt[3]{LWT/L} \quad \text{Equation 7}$$

Where,

L= length of grain, mm

W= width of grain, mm

T= thickness of grain, mm

The volume of the grain was determined by taking the dimensions of the grains in three axes of length, width, and thickness in 4 replications at different moisture contents and then the volume was estimated using the relationship as described by Mohsenin [26].

2.2 Gravimetric Properties

Using an electronic top pan balance (Contech, India) with a minimum count of 0.01 g, one thousand randomly chosen test sample grains at different moisture levels were gathered and weighed (Fig. 2). This magnitude obtained is called a thousand-grain weight. The procedure mentioned in IS: 4333 (Part IV)-1968 [27] was followed. The weight of one thousand grains for the sample was recorded based on the average data of ten replications.



Fig. 2. Measurement of 1000 grain weight

The bulk density of grains is the ratio of its mass to bulk volume. It was measured using the IS: 4333 (Part III)-1967 [28]. A 500 ml cylinder was filled with grains from a height of 15 cm. Without crushing the grains, the excess grains were taken out by scraping the cylinder's surface. The ratio of the kernel weight to the cylinder's volume was then used to calculate the bulk density. True density (ρ_t) was determined using the toluene displacement method [26,28]. Toluene (40 ml) was filled in a 100 ml graduated measuring cylinder and 50 g of grains were poured into it. The volume of displaced toluene was measured, and the ratio of sample mass to toluene displacement volume was used to determine the true density.

Density ratio is the ratio of bulk density to true density, which was calculated by the formula

$$\text{Density ratio} = \text{BD/TD} \quad \text{Equation 8}$$

The percentage of void volume in the test sample at a given moisture content is called porosity (ϵ). It is computed as the following formula, which expresses the true density value in percentage terms, divided by the difference between the true

and bulk densities. The average of ten replications was considered as a percent porosity value of the sample.

$$\epsilon = 1 - \text{BD/TD} \quad \text{Equation 9}$$

2.3 Frictional Properties

The angle at which a material will stand when poured and the horizontal is known as the angle of repose. This was ascertained with the apparatus, which was as shown in Fig. 3 and comprised a 140 x 160 x 35 mm wooden box with fixed and adjustable plates. The sample was placed within the box at a fixed height of 15 cm, and the plate was adjusted to tilt the sample at a progressive inclination. This allowed the grains to fall freely and develop a natural slope, or angle of repose.



Fig. 3. Measurement of angle of repose

The coefficient of static friction (μ_s) of the prepared samples of barnyard millet grain was determined in a set-up that consists of a hollow wooden box connected to a weighing pan through a thread passing on a pulley. The coefficient of static friction was measured with respect to four surface materials such as plywood, glass, galvanized iron and mild steel (Fig. 4). As stated by Shashikumar et al. [29], and Obi et al. [30], this work investigates the flowability of grains by the hopper. The coefficient of friction was calculated using the equation presented below.

$$\mu_s = \tan\theta \quad \text{Equation 10}$$

Where,

μ_s = coefficient of friction; and

θ = angle of inclination of the material surface



Fig. 4. Measurement of coefficient of friction w.r.t. different materials

The coefficient of internal friction of samples of barnyard millet grains was determined with two hollow wooden boxes of different dimensions, placed one over the other and filled with barnyard millet grains. Then the smaller wooden box was hooked with the weighing pan through a thread. The coefficient of internal friction was calculated using the equation given below.

$$\mu_i = (F_1 - F_2) / N \quad \text{Equation 11}$$

F_1 = Force required to displace filled wooden box
 F_2 = Force required to displace empty wooden box

N = Weight of the barnyard millet grains

2.4 Aerodynamic Properties

The terminal velocity is the air velocity which cancels the effect of gravity; generating suspended state for the grains. It was measured by using an air column apparatus [31]. The measuring process is shown in Fig. 5.



Fig. 5. Measurement of terminal velocity

3. RESULTS AND DISCUSSION

3.1 Effect of Moisture Content on Linear Dimensions and Average Diameters

The linear dimensions i.e. length, width and thickness of barnyard millet grain were reported

to increase from 3.13 to 3.41, 2.09 to 2.27 and 1.33 to 1.46 mm respectively with increased moisture content. This is due to the absorption of moisture by barnyard millet grain, increasing its size. A strong relation between moisture content and grain dimensions was found. Similarly, the average diameters i.e., AMD, GMD, SMD, and EMD were observed to increase linearly with an increase in moisture content (Fig. 6). It was observed that the AMD, GMD, SMD, and EMD increased significantly from 2.18 to 2.38, 2.05 to 2.24, 3.67 to 4.00 and 2.63 to 2.87 mm respectively with the corresponding moisture content from 6.21 to 22.57%. A similar relationship was reported by Singh et al. [5], Balasubramanian and Viswanathan [4], Sial et al. [32], Panda et al. [33], Sabar et al. [34].

The following relations were established between moisture content and linear as well as average diameters.

$$\text{Length} = 0.2216 \ln(x) + 2.7301 \quad (R^2 = 0.99)$$

$$\text{Width} = 0.0111x + 2.0199 \quad (R^2 = 0.99)$$

$$\text{Thickness} = 0.0079x + 1.2856 \quad (R^2 = 0.99)$$

$$\text{AMD} = -0.0003x^2 + 0.0221x + 2.0575 \quad (R^2 = 0.99)$$

$$\text{GMD} = -0.0003x^2 + 0.0191x + 1.9415 \quad (R^2 = 0.99)$$

$$\text{SMD} = -0.0005x^2 + 0.0334x + 3.4823 \quad (R^2 = 0.99)$$

$$\text{EMD} = -0.0004x^2 + 0.0248x + 2.4904 \quad (R^2 = 0.99)$$

3.2 Effect of Moisture Content on Shape

The physical properties i.e. aspect ratio, sphericity, surface area and volume of barnyard millet grain are shown in Fig. 7 which were found to increase significantly within the test moisture content from 65.53 to 66.77, 64.92 to 65.69%, 13.20 to 15.76 mm², 4.35 to 6.22 mm³, respectively, which may be due to absorption of moisture by the barnyard millet grain. It was observed that physical properties were increased linearly with an increase in moisture content from 6.21 to 22.57% (db). Similar trends have been reported by Sial et al. [32] for finger millet, Panda et al. [33] for pearl millet and Sabar et al. [34] for sorghum seed. However, Singh et al. [5] found the relationship between moisture content and shape parameters for barnyard millet grain as well as kernel.

The following relations were established between moisture content and shape parameters.

$$\text{Aspect ratio} = 0.0037x^2 - 0.0243x + 65.502 \quad (R^2 = 0.90)$$

$$\text{Sphericity} = 2E-05x^2 - 1E-05x + 0.6486 \quad (R^2 = 0.96)$$

$$\text{Surface Area} = 0.1561x + 12.333 \quad (R^2 = 0.99)$$

$$\text{Volume} = 0.1157x + 3.6088 \quad (R^2 = 0.97)$$

3.3 Effect of Moisture Content on Gravimetric Properties

While the density ratio increased, the characteristics of barnyard millet grain, such as bulk density, true density, and porosity, decreased as moisture content increased. With moisture content varying from 6.21 to 22.57% (db), the bulk density, true density, and porosity dropped from 682.92 to 563.72 kg m⁻³, 1318.95 to 1196.81 kg m⁻³, and 0.572 to 0.429, respectively. Between the test moisture content range, the density ratio dramatically increased from 0.43 to 0.57. The result is presented in Fig. 8.

Similar trend was found by Baryeh [35] for millet, Singh et al. [5] for barnyard millet grains and kernel, Balasubramanian and Viswanathan [4] for barnyard millet, kodo millet, foxtail millet and little millet. Sial et al. [32], Panda et al. [33] and Sabar et al. [34] established similar relationship between moisture content and millet grains like finger millet, pearl millet and sorghum. However, Al-Mahasneh and Rababah [36] found porosity to be decreased with the increase moisture content for green wheat and similar trend was reported by Dursun and Dursun [37] and Karababa [38] for caper seed and popcorn, respectively. Such deviations may have happened due to difference in shape and size of different grains.

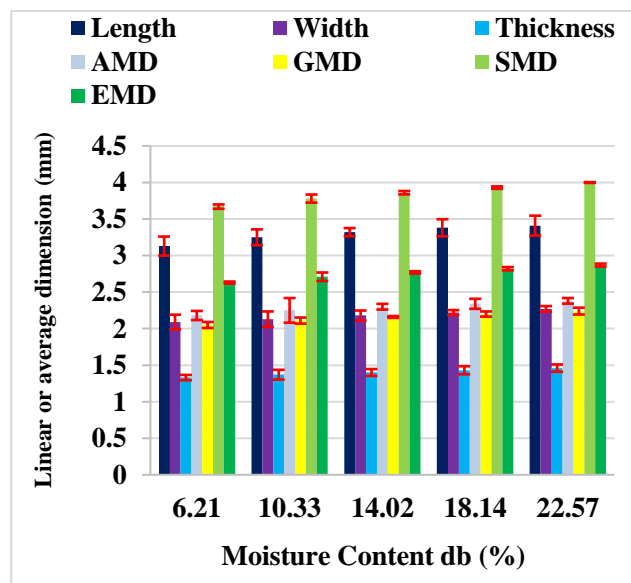


Fig. 6. Effect of moisture content on linear dimensions and average diameters of Barnyard Millet grain

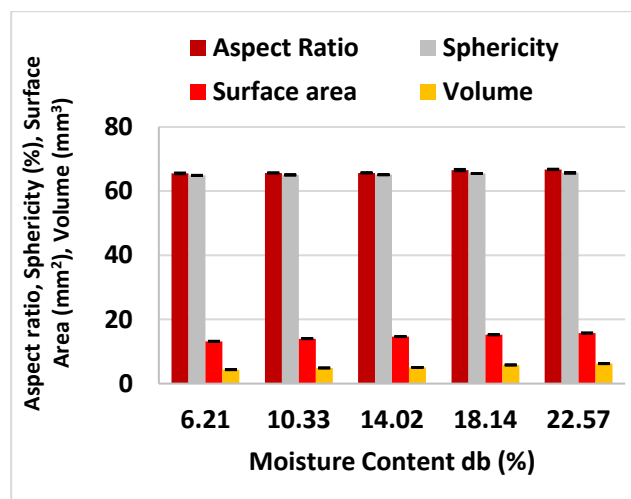


Fig. 7. Effect of moisture content on aspect ratio, 1000 grain weight, surface area, volume, and sphericity of Barnyard Millet grain

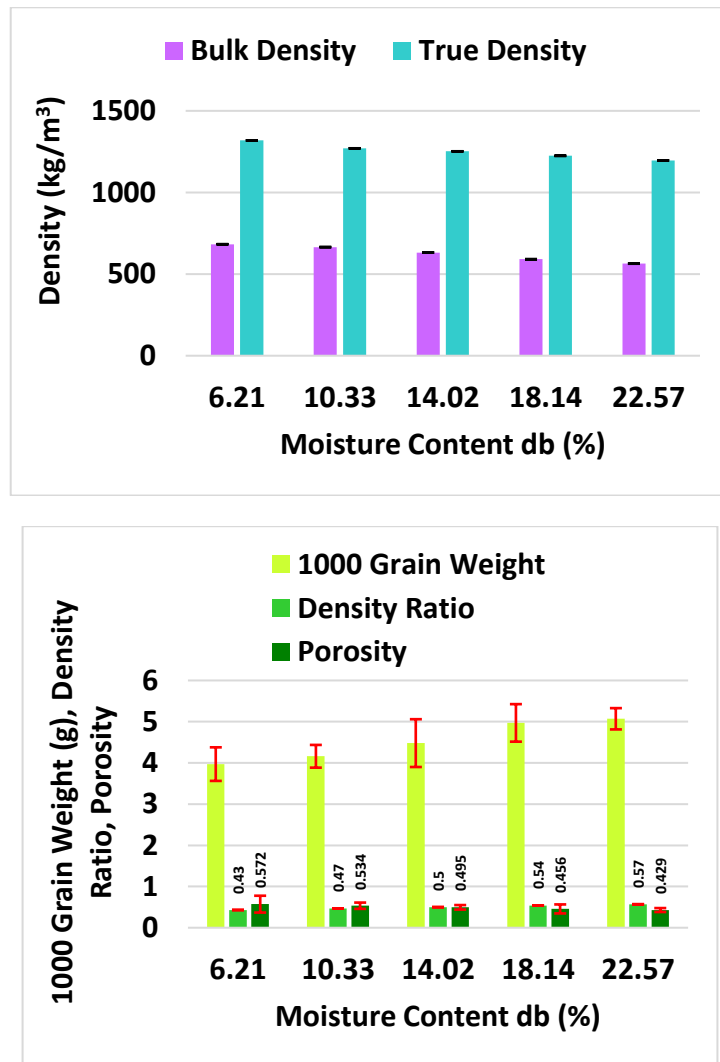
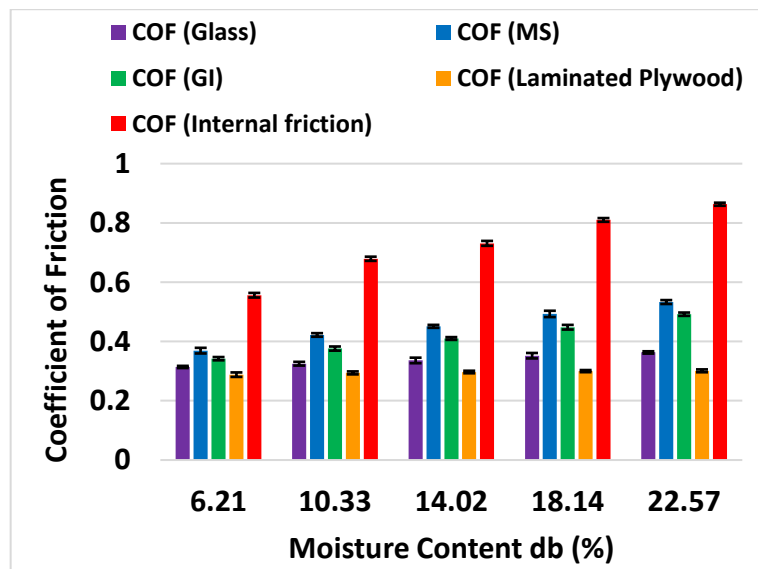


Fig. 8. Effect of moisture content on bulk density, true density, density ratio and porosity of Barnyard millet grain



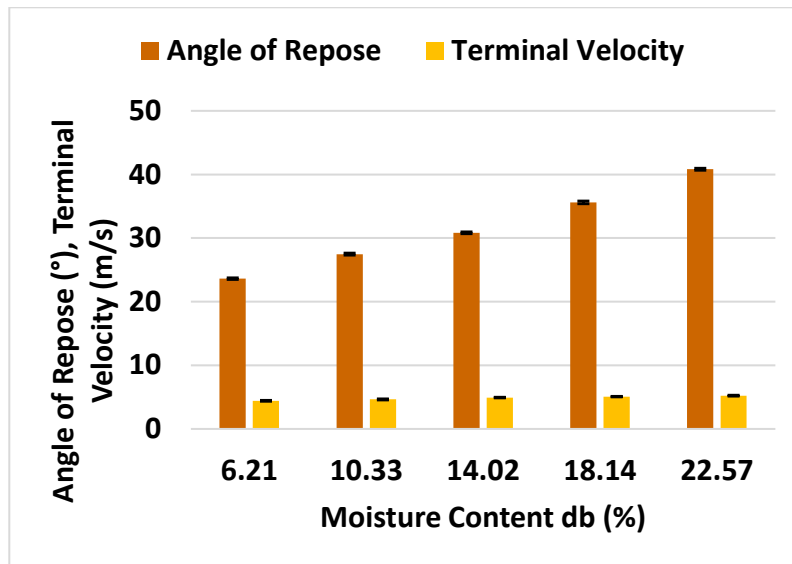


Fig. 9. Effect of moisture content on the coefficient of static friction, coefficient of internal friction, terminal velocity and angle of repose of barnyard millet grain

The following relations were established between moisture content and gravimetric properties.

$$1000 \text{ Grain Weight} = 0.074x + 3.475 \quad (R^2 = 0.96)$$

$$\text{Bulk Density} = -7.7039x + 736.92 \quad (R^2 = 0.98)$$

$$\text{True Density} = 0.1688x^2 - 12.026x + 1384.1 \quad (R^2 = 0.99)$$

$$\text{Porosity} = -0.009x + 0.6249 \quad (R^2 = 0.99)$$

3.4 Effect of Moisture Content on Frictional and Aerodynamic Properties

The result of the effect of moisture content on frictional and aerodynamic properties of barnyard millet grain within the moisture content range of 6.21 to 22.57% (db) is presented in Fig. 9. Moisture content has a statistically significant effect on both the angle of repose and terminal velocity. The angle of repose obtained was 23.62° and 40.82° at a moisture content of 6.21 and 22.57%, respectively. These findings are in agreement with Singh et al. [5]. The result showed that the terminal velocity increased linearly with an increase in test moisture content range from 4.42 to 5.23 ms⁻¹.

The coefficient of static friction of barnyard millet grain was calculated for four distinct surfaces within the test moisture range from 6.21 to 22.57% (db). The coefficient of static friction for all contact surfaces increased linearly with moisture content. The data revealed that the lowest value to highest value of glass, GI sheet,

mild steel sheet and laminated plywood were found to be 0.314 to 0.363, 0.369 to 0.533, 0.342 to 0.492, and 0.288 to 0.301 respectively at 6.21 to 22.57% (db) moisture content.

When compared with different surfaces, laminated plywood had the lowest coefficient of static friction, while mild steel had the highest coefficient of static friction. These findings are in agreement with the earlier findings of Subramaniam and Viswanathan [4]; and Singh et al. [5].

The coefficient of internal friction of barnyard millet grain was determined at moisture range from 6.21 to 22.57% (db). A higher value for the coefficient of internal friction was obtained with higher moisture levels. The data revealed that the lowest value to highest values were 0.556 to 0.863 respectively at 6.21 to 22.57% (db) moisture content. The obtained result is presented through Fig. 9.

The following relations were established between frictional and aerodynamic properties.

$$\text{Angle of repose (°)} = 1.051x + 16.692 \quad (R^2 = 0.99)$$

$$\text{Coefficient of static friction (Glass)} = 0.0031x + 0.2941 \quad (R^2 = 0.99)$$

$$\text{Coefficient of static friction (MS)} = 0.0098x + 0.3133 \quad (R^2 = 0.99)$$

$$\text{Coefficient of static friction (GI)} = 0.0092x + 0.2827 \quad (R^2 = 0.99)$$

$$\text{Coefficient of static friction (Plywood)} = 0.0092x + 0.2827 \quad (R^2 = 0.99)$$

Coefficient of static friction (Internal)=
 $0.3025x^{0.3381}$ ($R^2 = 0.99$)

Terminal velocity (ms^{-1}) = $-0.0014x^2 + 0.091x + 3.8939$ ($R^2 = 0.99$)

The trend of increase or decrease of the magnitudes of these engineering properties were found to be similar to the results of Singh et al. [5]; Panda et al. [33]; Sabar et al. [34]; Kenghe et al. [39], Singh et al. [37] and Powar et al. [22]

4. CONCLUSION

The seed dimensions, shape properties, density ratio, angle of repose, coefficient of friction, and terminal velocity increases with moisture content while true density, bulk density, porosity decreases. The current study provides a comprehensive understanding of the geometrical, gravimetric, frictional, and aerodynamic features of barnyard millet grain, which is useful in designing small-scale post-harvest machinery, especially a thresher for barnyard millet for small and marginal farmers. The size of holes and concave clearance, the coefficient of friction for designing sieve slopes, the angle of repose for designing hopper and feeding chutes, grain size (GMD, SMD, AMD, and EMD) for designing sieve openings, and terminal velocity for designing blower and aspirator are all included in this. The assessed qualities and their relationship to moisture content can also be applied in the design of post-harvest machinery and processing equipment.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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