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Comparative Study of Physical Properties of Whole and Hulled Minor Millets for Equipment Designing

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The present research was done for the selected minor millets viz. barnyard (*Echinola esculenta*), Kodo (*Paspalum scrobiculatum*), and little millets (*Panicum sumatrense*). The physical and engineering properties were evaluated at a moisture content of 10–11%, (dry basis) for whole and hulled millets. Significant improvement in the physical properties of the millets was observed for the hulled millets. The hulled millets showed higher sphericity (0.68–0.86) and exhibited a decrease in whole grains' spatial dimensions. The analysis (Gravimetric properties, frictional properties, Aerodynamic properties) was conducted for both whole and hulled millets. In frictional properties, mild steel surface showed the highest angle of static friction (9.78–17.96°) with smooth-rolling. The hulling has shown an improvement in all the physical and engineering properties of millets. In the color values, the whiteness index was improved for hulled millets. In the mechanical property of grains, resistance to crushing was expressed in terms of hardness.

Keywords: Engineering properties, Gravimetric properties, Mechanical property, Minor millets, Whiteness index

Introduction

India's engagement in minor millets contributes 0.40 million tonnes annually, as reported in the year 2020-2021.[(1)] They are nutritious, resilient to biotic and abiotic factors; thus, it constitutes a traditional staple food of people living in semi-arid tropics and is called as 'food of the poor'.[2] Minor millets are nutrient-rich and inhabited utmost spot in regionally varied peoples' meal, accomplishing almost all nutritional and essential health demands for future buildout.[3] By the merit of their nutritional composition, minor millets possess high levels of proteins, minerals, vitamins, and antioxidants, over non-millet cereals, and hence they are called as 'nutritious millets'.[4]

India's native barnyard millet (*Echinola esculenta*) resembles an oval-shaped, grey-straw white colored with a coarser-papery hull. It contains low carbohydrate content of 58.56 g/100g with the digestibility of 25.88% and highly digestible protein (11.0 g/100 g) containing prolamin as a major fraction.[5] Crude fiber content (13.6 g/100 g) comprising insoluble (8.4 g/100 g) and soluble (4.2 g/100g) dietary fiber of the barnyard millet is effective in diminishing glucose in blood and lipid levels over other millet and staple crops.[6] Barnyard millet possesses higher levels of iron (18.6 mg/100 g) followed by little millet (9.3 mg/100 g), Kodo millet (1.7 mg/100 g).[5]

Kodo millet (*Paspalum scrobiculatum*), a monocot, resembles a spheroid shaped, possessing brick red colored seed coat, flourishes well in post-Kharif fallows, survives in the warm and dry climate of peninsular India. Its nutritional profile possesses protein (8%) with glutelins (40.4–52.1%), which form the largest protein fraction, carbohydrate, crude fiber, and fat are 66.6, 9, and 1.4 g/100 g, respectively.[7] Magnesium (166 mg/100 g) and copper (5.5 mg/100 g) contents are higher in Kodo millet, assists as co-factor in vital enzymatic reactions, and aids in iron absorption, forming red blood cells, respectively.[8] It exhibits a highest amount of 2,2-diphenyl-1-picryl-hydrazyl (DPPH) chelating capability. It also inhibits hydroxyl radicle and prevents lipid peroxidation similar to 200 ppm butylated hydroxyanisole.[8]

Little millets (*Panicum sumatrense*), a monocot, resembles oval-shaped, grey to straw white-colored, glossy appearance with cellulosic husk.[9] It has a high amount of sulfur-containing amino acids such as cysteine and methionine. It possesses nutritional components as protein (9.7 g/100 g), carbohydrate (60.9 g/100 g), crude fiber (7.6 g/100 g), and fat (5.2 g/100 g), respectively.[10] Zinc (3.70 mg/100 g),

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chromium (0.24 mg/100 g), and carotenoid (78 μg/100 g) contents are higher in little millet, which aids to immune function, stimulates cholesterol synthesis, intensifies vision, and proclaims antioxidant characteristics, respectively.[10]

Though these minor millets are full of nutritional composition, they are not utilized to their maximum limits. Since no machinery or equipment is available on the commercial and domestic scale to perform post-harvest operations.[11] To design and fabricate the post-harvest equipment, it is necessary to know about these minor millets' physical and engineering properties. Engineering properties for distinct millets at varied and initial moisture content (IMC) have been investigated by many researchers[12–15] but no data is available for the physical and engineering properties of the minor millets (Barnyard, Kodo, and Little millet) from the point of machine and equipment designing.

The research was conducted to investigate the physical and engineering properties for whole and hulled Barnyard, Kodo, and Little millet at the initial moisture content (10–11%, dry basis). The obtained results of the physical and engineering properties will be helpful for scientists, designers, and fabricators engaged in the post-harvest equipment designing of millet processing.

Fig. 1— (a) Whole Barnyard Millet (WBM), (b) Whole Kodo Millet (WKM), (c) Whole Little Millet (WLM), (d) Hulled Barnyard Millet (HBM), (e) Hulled Kodo Millet (HKM), and (f) Hulled Little Millet (HLM), respectively.

Materials and Methods

Materials

The selected whole and hulled minor millets (Fig. 1(A-F)) *viz.*, Barnyard, Kodo, and Little millet were procured during the month of December, from the Indian Institute of Millet Research (IIMR), Hyderabad, India and stored in an airtight metal bin at room temperature till further experiments are conducted. Both whole and hulled grains were dried to 10-11% (dry basis) using hot air oven method at 105°C ± 1°C for 24 h.[16] The confirmation of moisture content was done by using an infrared moisture meter (AXIS ATS-120; Khera instruments, India). The physical and engineering properties *viz*., grain spatial dimensions, sphericity, surface area, volume, thousand (M_{1000}) grain mass, densities, porosity, frictional properties, terminal velocity, color properties (L^* a^* b^*, whiteness index), and mechanical properties (hardness) were investigated as per the standard protocol mentioned as follows:

Determination of Spatial Dimensions

Grain cell structure deciphers three principal mutually perpendicular dimensions: largest dimension (L, mm), intermediate dimension (W, mm), and smallest dimension (T, mm) of 100 randomly selected minor millets were measured with the help of a digital Vernier caliper (CD-6AXS-Mitutoyo Corporation, Japan) with least count of ±0.01 mm.[17] Geometric mean diameter (D_g) defines the size of a minor millet, helpful in designing graders. Spatial dimensions were used to calculate the arithmetic mean diameter, D_a (mm); equivalent mean diameter, D_e (mm), projected area perpendicular to largest, intermediate, and smallest dimensions (P_L, P_I, P_S), respectively, and Criteria projected area (CPA), surface area and volume as per following, Eqs (1–9).[17,18]

$$D_a = (L + W + T)/3 \quad \ldots (1)$$

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

$$D_e = \left[\frac{L\times(W+T)^2}{4}\right]^{\frac{1}{3}} \quad \ldots (3)$$

$$P_L = \frac{\pi\times L\times W}{4} \quad \ldots (4)$$

$$P_I = \frac{\pi \times W}{4} \quad \ldots (5)$$

$$P_S = \pi \times T \times W \quad \ldots (6)$$

$$CPA = \frac{P_L + P_I + P_S}{3} \quad \ldots (7)$$

$$S = \frac{\pi \times B \times L^2}{2L - B}\text{; where } B = (W \times T)^{0.5} \quad \ldots (8)$$

$$V = \frac{\pi \times B^2 \times L^2}{6(2L - B)}\text{; where } B = (W \times T)^{0.5} \quad \ldots (9)$$

The shape is useful in screening solids to separate foreign impurities, heat and mass transfer calculations. It can be expressed with regard to sphericity (roundness index) and aspect ratio, governing grain flowability traits, obtained from Eqs (10, 11).[19,20]

$$\theta = \frac{(LWT)^{\frac{1}{3}}}{L} \quad \ldots (10)$$

$$R_a = \frac{W}{L} \quad \ldots (11)$$

where θ = sphericity and R_a = aspect ratio, respectively.

Radii of curvature are practical in designing conveyors for particulate grains, regulating how well the object will roll. Sharply rounded grain contact surface develops greater stresses and vice versa, obtained from Eqs (12, 13).[19]

$$R_{min} = \frac{W}{2} \quad \ldots (12)$$

$$R_{max} = \frac{W^2 + \frac{L^2}{4}}{2W} \quad \ldots (13)$$

where R_{min} = minimum radius of curvature and R_{max} = maximum radius of curvature

Gravimetric, Aerodynamic, and Frictional Properties

The bulk (ρ_b) and tapped (ρ_{tap}) density for whole and hulled minor millets were determined as per the method followed by other researchers.[21,22] True density (ρ_t) for particulate minor millets was precisely obtained for grains including internal pores by toluene (C_7H_8) displacement method using Eq. (14).[17] Interparticle bulk porosity (ε_{bulk}, %) was calculated from measured densities using Eq.(15).[19]

$$\rho_t = \frac{M_S}{V_S} \quad \ldots (14)$$

where M_S = Sample mass & V_s = Solid volume (liquid displacement method)

$$\varepsilon_{bulk}, \% = \left(\frac{\rho_t - \rho_b}{\rho_t}\right) \times 100 \quad \ldots (15)$$

One thousand grain mass (M_{1000}, g) of selected minor millets were determined as per procedure cited by Tunde-Akintunde & Akintunde.[21] Aerodynamic property for whole and hulled minor millets were obtained by measuring terminal velocity in a fabricated transparent columnar hollow cylindrical setup (0.08 m internal diameter and 0.05 m tall). A hot-wire anemometer (AM4204, Lutron, accuracy ±0.1m/s) was used to measure regulated airflow for controlled up thrust, as suggested by Singh *et al*.[23] The static angle of friction ($\emptyset_s = \tan^{-1} \mu_s$) was determined using Eq. (16), from angle of incline against five surfaces *viz*., plywood, mild steel, aluminium, glass, and toughened fiber as described by Pathak *et al*.[17] The static angle of repose for piling was determined using Eq. (17), according to Pradhan *et al*.[20] The angle of internal friction, was obtained using Eq. (18), for minor millets according to experimental setup for minor millets.[24]

$$\emptyset_s = \tan^{-1} \mu_s \quad \ldots (16)$$

where μ_S = coefficient of static friction, $\emptyset_s$ = inclined angle of static friction.

$$\phi_s = \tan^{-1}\left(\frac{2h}{D}\right) \quad \ldots (17)$$

where h = height of piled material and D = diameter of fixed circular base .

$$\varphi_i = \tan^{-1} \mu_i \quad \ldots (18)$$

where φ_i = angle of internal friction and μ_i = coefficient of intenal friction

Mechanical and Color Properties

Mechanical properties (hardness, N) for 25 randomly selected grains were determined using a Texture analyzer (CT3 Brookfield, USA). Standardized compression test mode was followed with 10 kg load cell using clear acrylic cylindrical probe TA10 (12.7 mm diameter and 35 mm tall), target value 0.8 mm, pre- and post-test speed 1 mm/s, test speed 0.7 mm/s, respectively.[25]

The color values were evaluated using a lab-scale colorimeter (ColorFlex EZ, Hunter Associates Laboratory Inc., Reston VA, USA), having an aperture of 12 mm. Color units in Hunter values are given as, L^* = lightness, 0 (black) to 100 (white); $a^* = -a$ (greenness) to +a (redness); $b^* = -b$ (blueness) to +b (yellowness). The distinct quantity of whiteness index (WI) was obtained from Eq.19.[26]

$$WI = 100 - \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2} \quad \ldots (19)$$

Statistical Analysis

All experimental data, unless specified, were performed in triplicate and reported as mean ± standard deviation. Software package SPSS (version 16) was applied for statistical analysis, drawing multiple comparisons of mean within the sample set at 5% significance level. Statistical significance was considered for $p< 0.05$ using Duncan multiple range test (DMRT).

Results and Discussion

The moisture content (m.c) selected for the experiments was in the range of 10–11% dry basis, which possess negligible store pest damage and yield high hulled grain recovery.

Seed Dimensions

Three principal mutually perpendicular dimensions for selected whole and hulled minor millets showed significant ($P<0.05$) distinct grades, the smallest dimension for whole little millet (WLM) and hulled Kodo millet (HKM) was found to be non-significant ($P<0.05$) as given in Table 1. The grain is elongated about the largest dimension, L (1.71–2.62 mm), whereas the intermediate dimension, W (1.41–2.16 mm), and smallest dimension, T (0.98–1.50 mm) are close to each other depicting spherical bases. This exhibited that whole, and hulled minor millets may be separated about their length and width. The spatial dimensions of all principal axes are shortened on hulling and can be visualized (as shown in Fig. (2)). Data on Geometric Mean Diameter (GMD) is useful in designing graders.[15] The GMD was observed to be (1.33–2.03 mm), and this value is lower than the length and width, and higher than thickness, except for Whole Barnyard Millet (WBM) and Whole Little Millet (WLM), respectively (Table 1). Pradhan *et al.* (2012)[(20)] deduced similar readings for bottle guard seeds at the moisture of 10.04±0.08% (wet basis). The GMD value difference in both of HKM and WLM data were not significant at 5% probability level assessed through standard DMRT. The GMD has a practical application in estimating the minor millets' projected area, which indicates a behavioral shift in turbulent or adjacent turbulent regions along with a streamline fluid-like airstream. The data is applicable in the fabrication of indigenous aspirator-pneumatic means for distinguishing semi-identical particles, better segregation of grains, and excision of foreign impurities simultaneously.[27] The arithmetic mean diameter (AMD) was evaluated to differ significantly ($p<0.05$) among selected whole and hulled minor millets from 1.36 to 2.09 mm. The equivalent mean diameter (EMD) has a wide range from 1.34 to 2.06 mm and were found non-significant ($p<0.05$) for hulled Kodo millet (HKM) and hulled little millet (HLM), respectively. This whole Kodo millet (WKM) and hulled little millet (HLM) exhibited upper and lower GMD, AMD, and EMD mean values. Such

Table 1 — Spatial dimensions of whole and hulled minor millets grains

Parameters	WBM	HBM	WKM	HKM	WLM	HLM
L, mm	2.37 ± 0.28^{c}	1.76 ± 0.17^{a}	2.62 ± 0.25^{d}	1.84 ± 0.15^{b}	2.33 ± 0.17^{c}	1.71 ± 0.14^{a}
W, mm	1.76 ± 0.21^{d}	1.62 ± 0.13^{c}	2.16 ± 0.23^{f}	1.82 ± 0.15^{e}	1.50 ± 0.13^{b}	1.41 ± 0.10^{a}
T, mm	1.47 ± 0.18^{d}	1.11 ± 0.12^{b}	1.50 ± 0.19^{d}	1.18 ± 0.10^{c}	1.14 ± 0.08^{bc}	0.98 ± 0.07^{a}
D_g , mm	1.82 ± 0.17^{d}	1.47 ± 0.11^{b}	2.03 ± 0.16^{e}	1.58 ± 0.09^{c}	1.58 ± 0.08^{c}	1.33 ± 0.07^{a}
D_a , mm	1.87 ± 0.17^{e}	1.50 ± 0.11^{b}	2.09 ± 0.16^{f}	1.61 ± 0.09^{c}	1.66 ± 0.08^{d}	1.36 ± 0.07^{a}
D_e , mm	1.83 ± 0.17^{d}	1.49 ± 0.11^{b}	2.06 ± 0.16^{e}	1.61 ± 0.09^{c}	1.59 ± 0.08^{c}	1.34 ± 0.07^{a}
P_L , mm^2	3.30 ± 0.67^{d}	2.25 ± 0.34^{b}	4.46 ± 0.76^{e}	2.63 ± 0.31^{c}	2.74 ± 0.32^{c}	1.89 ± 0.21^{a}
P_I , mm^2	2.48 ± 0.61^{c}	2.09 ± 0.34^{b}	3.70 ± 0.77^{d}	2.64 ± 0.39^{c}	1.77 ± 0.30^{a}	1.57 ± 0.21^{a}
P_S , mm^2	2.05 ± 0.45^{d}	1.42 ± 0.24^{b}	2.54 ± 0.47^{e}	1.70 ± 0.22^{c}	1.34 ± 0.17^{b}	1.08 ± 0.13^{a}
CPA, mm^2	2.61 ± 0.54^{d}	1.92 ± 0.29^{b}	3.57 ± 0.62^{e}	2.32 ± 0.28^{c}	1.95 ± 0.24^{b}	1.51 ± 0.17^{a}
S, mm^2	9.16 ± 1.77^{d}	6.05 ± 0.93^{b}	11.32 ± 1.83^{e}	7.09 ± 0.79^{c}	6.65 ± 0.65^{c}	4.81 ± 0.50^{a}
V, mm^3	2.50 ± 0.76^{c}	1.37 ± 0.33^{ab}	3.43 ± 0.87^{d}	1.75 ± 0.29^{b}	1.45 ± 0.23^{ab}	0.95 ± 0.15^{a}
θ	0.78 ± 0.07^{b}	0.84 ± 0.06^{c}	0.78 ± 0.06^{b}	0.86 ± 0.06^{d}	0.68 ± 0.05^{a}	0.78 ± 0.05^{b}
R_a	0.75 ± 0.10^{b}	0.93 ± 0.09^{d}	0.83 ± 0.09^{c}	1.00 ± 0.13^{e}	0.65 ± 0.07^{a}	0.83 ± 0.08^{c}
R_{min}, mm	1.03 ± 0.10^{e}	0.85 ± 0.07^{b}	1.20 ± 0.10^{f}	0.92 ± 0.05^{c}	0.96 ± 0.05^{d}	0.78 ± 0.04^{a}
R_{max}, mm	1.37 ± 0.14^{e}	1.08 ± 0.09^{b}	1.56 ± 0.13^{f}	1.15 ± 0.07^{c}	1.31 ± 0.08^{d}	1.01 ± 0.07^{a}

Data presented are the mean value ± standard deviation (n=100). Means followed by same letters in each rows are not significantly different ($p<0.05$) using DMRT; whole barnyard millet (WBM), whole kodo millet (WKM), whole little millet (WLM), hulled barnyard millet (HBM), hulled kodo millet (HKM), and hulled little millet (HLM), respectively

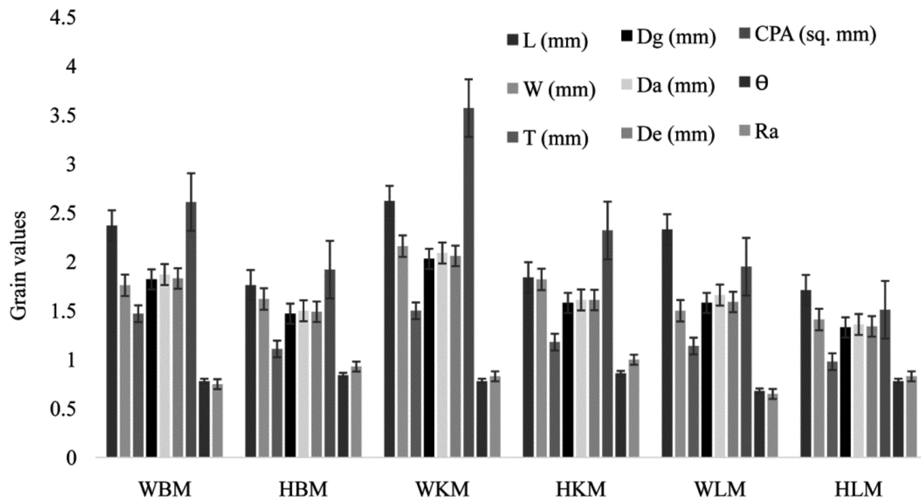

Fig. 2 — Effect of hulling on spatial dimensions of different minor millets: Whole barnyard millet (WBM), whole kodo millet (WKM), whole little millet (WLM), hulled barnyard millet (HBM), hulled kodo millet (HKM), and hulled little millet (HLM), respectively

variations in spatial dimensions may be the outcome of climate, habitat, and genetic inheritance of species and variety of the millets.

Surface Area, Volume, and Sphericity

Means of selected grain surface area and seed volume ranged between 4.81 to 11.32 mm^2 and 0.95 to 3.43 mm^3, respectively. A similar increasing inclination was deduced for HLM, HBM, WLM, HKM, WBM and WKM, in both these surface areas and volume. Frictional action during hulling removed intact cellulosic husk, diminishing overall spatial dimensions. The surface area difference in both these WLM and HKM data was not significant at a 5% probability level using DMRT. The surface area is instrumental in governing the outline of the seed, rendering behavioral drift in seeds on oscillating surfaces throughout cereal processing.[28] Also, seed volumes were evaluated to differ significantly ($p<0.05$) among WBM and WKM, respectively.

Information on sphericity (θ) and aspect ratio is applicable in shape expression.[19] Mean values for sphericity and aspect ratio ranged between 0.68 to 0.86 and 0.65 to 1.00, respectively. The grain sphericity was found to be the same at 0.78 for WBM, WKM, and HKM, respectively. Sphericity for WLM (0.68), HBM (0.84), and HKM (0.86) were evaluated to differ significantly ($p<0.05$), as established from Table 1. A significant increase in sphericity and aspect ratio of hulled grains can be seen from Table 1, which establishes that the hulling operation shortened the principal dimensions of whole grains. The hulling process has rendered an increase in sphericity and aspect ratio of whole millets. According to investigations by Garnayak *et al.*[29] and Pradhan *et al.*[20], desirable sphericity is above 0.70, perceives the spherical shape of the finite sample. Thus, WLM is considered equivalent to prolate spheroid shape due to its major dimension being depicted by a length and diameter. With the modest aspect ratio (correlates grain ratio of second dimension or W to largest dimension or L) and sphericity, deducing that WLM would rather slide steadily on flat smooth surfaces. This movement to either slide or roll is of prime importance in the fabrication of hoppers and decentralized hulling equipment.[20]

Investigation on the minimum and maximum radii of curvature (R_{min} and R_{max}) is convenient in designing conveyors and chutes for finite grains, governing how smoothly the object would roll.[19] Mean values for R_{min} and R_{max} ranged between 0.78 to 1.20 and 1.01 to 1.56, respectively. Radii of curvature (R_{min} and R_{max}) of whole and hulled minor millets were evaluated to differ significantly ($p<0.05$) can be observed in Table 1. Both of the WKM and HLM showed upper and lower radii of curvature (R_{min} and R_{max}) mean values, respectively. The hulled grains exhibited diminished radii of curvature in contrast to whole grains rendering a smooth surface of contact. Hence gain in sphericity and aspect ratio correlates to the low stresses developed during rolling.

Gravimetric and Terminal Velocity

Data on gravimetric properties, including densities (kg m^{-3}), porosity (%), M_{1000}, and terminal velocity, are displayed in Table 2. True density

Table 2 — Gravimetric, aerodynamic and frictional properties of whole and hulled minor millets

Parameters	WBM	HBM	WKM	HKM	WLM	HLM
ρ_t, kgm^{-3}	1335.09 ± 2.47^e	1250.87 ± 3.92^d	1250.79 ± 2.68^d	1145.34 ± 4.91^b	1163.37± 4.03^c	1114.66 ± 3.48^a
ρ_b, kgm^{-3}	527.34 ± 3.63^a	839.03 ± 2.82^d	672.96 ± 2.72^b	843.66 ± 3.58^d	738.20 ± 3.83^c	842.73 ± 5.90^d
ρ_{tap}, kgm^{-3}	549.48 ± 4.83^a	860.89 ± 1.07^d	690.55 ± 1.91^b	896.91 ± 8.15^f	779.97 ± 3.65^c	878.32 ± 11.60^e
ε_{bulk} (%)	60.50 ± 0.34^f	32.92 ± 0.44^c	46.20 ± 0.34^e	26.34 ± 0.33^b	36.55 ± 0.11^d	24.39 ± 0.56^a
M_{1000} (g)	3.08 ± 0.09^b	2.39 ± 0.08^{ab}	4.26 ± 0.15^c	3.03 ± 0.09^b	2.49 ±0.05^{ab}	2.04 ± 0.05^a
ν (ms^{-1})	5.40 ± 0.05^a	6.49 ± 0.07^c	5.48 ± 0.03^a	7.15 ± 0.07^e	5.59 ± 0.05^b	6.72 ± 0.06^d
Angle of static friction ($\emptyset_s$, degree)						
$\emptyset_s$ (Aluminum)	12.46 ± 0.36^c	11.72 ± 0.37^b	12.66 ± 0.70^c	11.76 ± 0.15^b	8.82 ± 0.16^a	12.32 ± 0.41^c
$\emptyset_s$ (Glass)	7.10 ± 0.25^a	9.76 ± 0.43^d	8.50 ± 0.37^b	8.58 ± 0.61^b	8.44 ± 0.30^b	9.22 ± 0.33^c
$\emptyset_s$ (Mild steel)	17.96 ± 0.54^f	13.10 ± 0.47^d	15.62 ± 0.45^e	11.84 ± 0.74^b	9.78 ± 0.23^a	12.48 ± 0.42^c
$\emptyset_s$ (Plywood)	12.16 ± 0.30^e	9.86 ± 0.18^b	12.68 ± 0.42^e	11.05 ± 0.35^d	8.56 ± 0.46^a	10.64 ± 0.40^{cd}
$\emptyset_s$ (Toughened fiber)	7.38 ± 0.48^b	9.46 ± 0.54^c	7.92 ± 0.19^b	9.90 ± 0.41^c	6.66 ± 0.44^a	11.06 ± 0.61^d
ϕ_s (angle of repose, degree)	28.07 ± 0.26^b	28.66 ± 0.25^c	30.40 ± 0.25^d	31.24 ± 0.24^e	25.02 ± 0.29^a	28.96 ± 0.25^c
φ_i (angle of internal friction, degree)	52.06 ± 0.02^e	53.20 ± 0.03^f	49.18 ± 0.11^b	51.43 ± 0.07^d	47.29 ± 0.09^a	50.78 ± 0.06^c

Data presented are the mean ± standard deviation (n=3); Means followed by different letters in each row are significantly different (p<0.05) using DMRT; whole barnyard millet (WBM), whole kodo millet (WKM), whole little millet (WLM), hulled barnyard millet (HBM), hulled kodo millet (HKM), and hulled little millet (HLM), respectively

(ρ_t) including internal pores for particulate minor millets ranged from 1114.66 to 1335.09 kg m^{-3}, and significant differences were assessed, according to $p < 0.05$, except for WKM and HBM. Both WKM (1250.79 kg m^{-3}) and HBM (1250.87 kg m^{-3}) exhibited higher grain density (ρ_t), kg m^{-3} as compared to rice and sorghum 1240 kg m^{-3}, respectively.[15] Whereas WBM (1335.09 kg m^{-3}) scored higher than pearl millet (1325 kg m^{-3}) and pigeon pea (1330 kg m^{-3}), respectively.[15] Cell structure plays a key role in deducing true density, an important quality attribute affecting grain hardness, respectively, on the breaking, grinding, and drying processes. During hulling, frictional exertion withdraws the intact cellulosic husk, reducing overall true density, while the inverse result was obtained for bulk and tapped density, respectively.

The bulk density of the grain varied between 527.34 and 843.66 kg m^{-3}, showing a non-significant difference ($p<0.05$) for HBM (839.03 kg m^{-3}), HKM (843.66 kg m^{-3}), and HLM (842.73 kg m^{-3}), respectively. The lower value of the bulk density for WBM was 527.34 kg m^{-3} as compared to others deducing strong grain to grain interaction due to coarse hulls, which attend higher inter-particle friction between WBM grains would withstand grain re-arrangement towards achieving high packing fraction, thus contributing to lower bulk density.[30] For finer grains, higher values of bulk density are attained since the particles attain a compact matrix, reducing interparticle voids, enhancing greater superficial contact with adjoining grains.[30] Hence, smaller size WLM can be compressed to a relatively larger tapped density than others. This parameter may be utilized for designing compaction tools and assess the magnitude of press movement required to compact and densify loose grains handy in the fabrication of storage and transit bins for particulate grains.[31]

Tapped density was obtained for an unsettled volume of particulate solids, vibrated under specific conditions. It is always higher than unsettled free-flow bulk density. The tapped density of the millets varied between 549.48 and 896.91 kg m^{-3} and were statistically significant at $p < 0.05$. Hulled grains of both the millets exhibited higher tapped density owing to more compactness attainment. Hence, HKM has the highest sphericity among all selected samples achieved the highest compaction of 6.31%. It may be concluded that particulate grains size, spatial dimensions, surface properties affect the density and porosity.

Bulk porosity (ε_{bulk}, %) can be defined as a void fraction of air in the unsettled free-flow particulate grains. Mean values for grain porosity varied significantly ($p < 0.05$), and ranged between 24.39% to 60.50%. Hulled grains of both the millets exhibited lower porosity due to more compact alignment than whole minor millets. Particulars on porosity are helpful in modeling heat and mass transfer processes, texture characterization, quality of drying, and predicting diffusional properties of cellular foods.[19] Due to the papery coarse hull and low bulk density, WBM (60.50%) exhibited more porous condition, while HLM (24.39%) scored the least due to higher bulk density and polished surface. Higher bulk porosity may result in losing internal temperature rapidly while storage or processing with ease in heat and mass transfer during drying and vice-versa in case of lower porosity.[32] Hence, upon conditioning of WLM may result in a damped mixture prolonging the soaking time by adding more water. Investigation on bulk porosity correlates resistance to airflow throughout the aeration and drying process. This parameter is a prerequisite in the fabrication of aeration and drying systems (mechanical and natural) to segregate the grains from extraneous matter.[20]

The M_{1000} of whole and hulled minor millets ranged between 2.04 to 4.06 g. They were evaluated to differ significantly ($p<0.05$) for WKM, while non-significance at $p<0.05$ was found between HBM-WLM and WBM-HKM, respectively. This parameter influences equivalent mean diameter (EMD), which is applicable in the theoretical calculation of minor millets volume and cleanse grain through pneumatic means.[23]

Terminal velocity was measured experimentally by suspension method in a vertical duct. Mean values for terminal velocity ranged between 0.68 to 0.86 ms^{-1} and significant differences were determined, according to $p < 0.05$, except for WBM (5.40 ms^{-1}) and WKM (5.48 ms^{-1}) owing to similar sphericity values (0.78), respectively. Hulled grains owing to diminished seed coat layers and lower M_{1000}, exhibited higher terminal velocity in contrast to whole grains. The results of aerodynamic property can be utilized for the fabrication and development of minor millets' combine harvester, or possibly a static thresher in conjugation with cleaning unit.

Frictional Properties

Data on frictional properties includes the angle of static friction ($\emptyset_S$) against varied surfaces *viz*., aluminium, glass, mild steel, plywood and toughened fiber, angle of repose for pilling (ϕ_s) and angle of internal friction (φ_i) expressed in degrees, respectively, are displayed in Table 2. Tangential force is required to initiate the motion, which is attained at the static angle of friction against varied surfaces. The least angle of friction investigated may be owing to the smooth texture of glass and toughened fiber sheet, exhibiting intermittent flow for selected whole and hulled minor millets. The rough surface of plywood offered resistive flow leaving stretches of particulate grains upon inclination. Investigation on the static angle of friction against mild steel and aluminium offered the least friction for experimental grains. Mean values for the static angle of friction against mild steel ranged between 9.78° to 17.96° with smooth-rolling, and significant ($p < 0.05$) differences were determined for varied grains of both the millets. Thus mild steel may be used for static threshers and hullers with higher hopper inclination, as seen in Table 2. Mean values for the static angle of friction against aluminium ranged between 8.82° to 12.66° and were obtained to differ significantly ($p<0.05$) for WLM due to lower sphericity indicated sliding movement, while non-significance at $p<0.05$ was found between WBM, WKM and WLM owing to similar sphericity values (0.78). HBM and HKM showed close sphericity values of 0.84 and 0.86, respectively. However, aluminium being lightweight is suitable for potable combined harvester-thresher and de-hulling equipment with lower hopper inclination. Both these material sheets are durable, robust, easy-to-clean, and render free-flow characteristics of whole and hulled minor millets in contrast to other surfaces. As seen from Table 2, upon hulling of WLM static angle of friction increased with an increase in sphericity depicting proportionate correlation against all surfaces. However, for the remaining particulate grains, an inverse relationship was established except against glass and toughened fiber sheets. This parameter is applicable in estimating inclination angle for chutes, hoppers, stem-harvester, and threshers.[17]

Mean values for the angle of repose for pilling (ϕ_s, Eq. 18) ranged between 25.02° to 31.24° and significant differences were determined, according to $p < 0.05$, except for HBM (28.66°) and HLM (28.96°), respectively. Chandan *et al.*[33] reported a similar trend for Kodo millet grain, hulled rice, and husk. The angle of repose depicts relative inter-particle cohesion applicable for the design of conveyors for handling particulate grains. Friction severity during the hulling process magnifies the sphericity of particulate grains, creating a higher number of superficial points for additional inter-particle associations.[31] Hence, reducing particulate grains' size upon de-hulling serves to increase cohesion behavior as the grain surface area per unit mass increases. Thus, the angle of repose (pilling) for

Table 3 — Mechanical and color properties of whole and hulled minor millets

Particulate grains	Mechanical Properties	Color properties			
	Hardness (N)	L*	a*	b*	Whiteness Index (WI)
WBM	38.71 ± 5.63[b]	55.86 ± 0.92[d]	4.50 ± 0.05[a]	22.18 ± 0.37[c]	50.40 ± 0.55[d]
HBM	25.85 ± 6.08[a]	61.29 ± 0.13[f]	4.81 ± 0.09[b]	21.70 ± 0.29[b]	55.49 ± 0.24[f]
WKM	51.21 ± 8.25[c]	38.04 ± 0.61[a]	9.46 ± 0.06[f]	18.33 ± 0.18[a]	35.05 ± 0.22[a]
HKM	43.34 ± 7.97[b]	44.33 ± 0.53[b]	9.12 ± 0.09[e]	25.74 ± 0.11[f]	38.01 ± 0.67[b]
WLM	23.63 ± 5.26[a]	45.76 ± 0.34[c]	6.37 ± 0.11[d]	23.56 ± 0.12[e]	40.63 ± 0.26[c]
HLM	22.02 ± 5.97[a]	57.51 ± 0.32[e]	5.29 ± 0.07[c]	22.66 ± 0.12[d]	51.63 ± 0.34[e]

Data presented are the mean ± standard deviation (n=25 for hardness and n=3 for color properties); Means followed by different letters in each column are significantly different (p<0.05) using DMRT; Whole barnyard millet (WBM), whole kodo millet (WKM), whole little millet (WLM), hulled barnyard millet (HBM), hulled kodo millet (HKM), and hulled little millet (HLM), respectively

hulled minor millets in contrast to whole ones are obtained higher, which depicts relatively higher inter-particle cohesion, applicable for the design of conveyors for handling particulate grains. The inter-particle cohesion force is furthermore influenced by the surface roughness of the grains.[30,31] It also governs mechanical interlocking forming stable bridges between particles on exertion of weak van der Waals forces of attraction.[31]

The particulate grains move in relation to each other; exerting resistance to relative motion is defined as the angle of internal friction. Experimental grains have shown that inter-particle locking demonstrated from geometric interaction contributes significantly ($p<0.05$) to the bulk internal friction, ranged from 47.29° to 53.20°. Hulled grains exhibited higher angle of internal friction exerting rise in cohesion behaviour, as grain surface area per unit mass increases. Among whole millets higher angle of internal friction was exhibited by WBM followed by WKM and WLM, due to inter-particle cohesion influenced by grain surface roughness among whole millets. Grain moisture content, spatial dimension and shape affects angle of internal friction.

Mechanical Properties

The mechanical properties of grains, i.e. resistance to crushing is a desirable milling factor measured in terms of hardness. The hardness values of WKM, WBM, and WLM were 51.21, 38.71, and 23.63 N, while their respective hulled grains HKM, HBM, and HLM were 43.34, 25.85, and 22.02 N, respectively as presented in Table 3. Hardness varies with the size of contact area between sample and probe, evident in case for hulled grains. However, cell structure plays a key role in deducing quality attribute affecting grain hardness, perceptivity to breaking, grinding and drying. Harder grains give higher milling yield and also influences water absorption.[34] The higher level of starch damage on milling occurs for higher hardness, which is desirable for bread making.[35] Grains with low starch damage are comparatively soft, desirable for cake and cookie products.

Color Properties

Mean values for the whiteness index (WI) ranged between 35.05 to 55.49, and significant differences were observed, according to $p < 0.05$. Among whole grains, WBM (55.86) displayed significantly ($P<0.05$) highest value, which suggests whiteness perceptibility, followed by WLM, and WKM respectively. +a (redness) value was observed highest for WKM (9.46), indicating dark brown to brick red color, and WLM (23.56) scored highest +b (yellowness) value indicating grey to straw white color with a glossy appearance. However, upon de-hulling whiteness index was improved for HBM (55.49), HLM (51.63), and HKM (38.01) owing to the absence of cellulosic husk. The differences in Hunter color values among the minor millets might be due to genetic traits and de-hulling operation. Recently, quick, accurate, and non-destructive techniques are involved in controlling food quality and safety. Machine vision technology (MVT) based on geometric factors and color processing may involve a whiteness index (WI) to quickly perform shape classification economically, hygienically, and consistently.

Conclusions

The conclusion drawn from the study are: Significant improvement in the physical properties such as color, hardness, static angle of repose, and sphericity was found. The hulling has intensified the whiteness index of millets. The hulling operation has increased cohesion behavior, thus obtaining a higher value for the angle of repose (pilling) in contrast to whole grains. The sphericity and aspect ratio of minor millets was raised as de-hulling shortened principal dimensional elements. The lower value of the bulk density deduced strong grain to grain interaction due to coarse hulls, withstanding the grains' collapsing. Hulled grains exhibited higher tapped density and lower porosity owing to more compact alignment. Investigation on the static angle of friction against mild steel and aluminium offered the least friction indicating higher and lower hopper angle, respectively, for all grains. The smooth texture of glass and toughened fiber sheets exhibited intermittent flow for selected whole and hulled minor millets. Upon de-hulling of WLM static angle of friction increased with an increase in sphericity depicting proportionate correlation, while an inverse relationship was established for other particulate grains. Henceforth, the investigated physical and engineering properties may be utilized for indigenous fabrication and development of easy-to-operate combined harvester-thresher, graders, dehullers, hoppers, conveyors, silos, machine vision technology (MVT) based grain sorter, milling components at commercial and decentralized domestic levels. More compact, portable, easy-to-clean, and easy to operate processing equipment designs can be manufactured to reduce human drudgery.

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References

1 First Advance Estimates of Production of Foodgrains (2020-21), Directorate of Economics & Statistics, DAC&FW (2020).
2 Malleshi N, Processing of small millets for food and industrial uses, *Small Millets in Global Agriculture*, (1989) 325‒339.
3 Jaybhaye R, Pardeshi I, Vengaiah P & Srivastav P, Processing and technology for millet based food products: a review, *J Ready Eat Food*, **1** (2014) 32‒48.
4 Saini S, Saxena S, Samtiya M, Puniya M & Dhewa T, Potential of underutilized millets as Nutri-cereal: an overview, *J Food Sci Technol*, (2021) 1‒13.
5 Veena B, *Nutritional, functional and utilization studies on barnyard millet*, M Sc Thesis, University of Agricultural Sciences, Dharwad (Karnataka), India, 2003.
6 Ugare R, Chimmad B, Naik R, Bharati P & Itagi S, Glycemic index and significance of barnyard millet (Echinochloa frumentacae) in type II diabetics, *J Food Sci Technol*, **51(2)** (2014) 392‒395.
7 Sudharshana L, Monteiro P V & Ramachandra G, Studies on the proteins of kodo millet (Paspalum scrobiculatum), *J Sci Food Agric*, **42(4)** (1988) 315‒323.
8 Hegde P S & Chandra T, ESR spectroscopic study reveals higher free radical quenching potential in kodo millet (Paspalum scrobiculatum) compared to other millets, *Food Chem*, **92(1)** (2005) 177‒182.
9 Food & Nations, Sorghum and Millets in Human Nutrition: Food and Agriculture Organization of the United Nations, 1995.
10 Girish C, Meena R K, Mahima D & Mamta K, Nutritional properties of minor millets: neglected cereals with potentials to combat malnutrition, *Curr Sci*, **107(7)** (2014) 1109‒1111.
11 Muniappan K, Raghavan V, Nachimuthu V, Raveendran M, Panaiyuran S, Vediyappan V & Nayak B K, CIFSRF final technical report: Scaling up small millet post-harvest and nutritious food products project (CIFSRF Phase 2), 2018.
12 Balasubramanian S & Viswanathan R, Influence of moisture content on physical properties of minor millets, . *Food Sci and Technol*, **47(3)** (2010) 279‒284.
13 Singh K P, Mishra H N & Saha S, Moisture-dependent properties of barnyard millet grain and kernel, *J Food Eng*, **96(4)** (2010) 598‒606.
14 Sunil C, Venkatachalapathy N, Shanmugasundaram S & Loganathan M, Engineering properties of foxtail millet (Setaria italic L): Variety-HMT 1001, *Int J Sci Environ Technol*, **5(2)** (2016) 632‒637.
15 Jain R & Bal S, Properties of pearl millet, *J Agric Eng Res*, **66(2)** (1997) 85‒91.
16 Chemists A A C C, Approved methods of the AACC, *The Association* (2000).
17 Pathak S S, Pradhan R C & Mishra S, Physical characterization and mass modeling of dried Terminalia chebula fruit, *J Food Process Eng*, **42(3)** (2019) e12992.
18 Mohsenin N, *Physical Properties of Plant and Animal Materials* (Gordon and Breach Science Publishers, New York) 1986.
19 Sahin S & Sumnu S G, *Physical Properties of Foods* (Springer Science & Business Media Verlag, New York) 2006.
20 Pradhan R C, Said P P & Singh S, Physical properties of bottle gourd seeds, *Agric Eng Int CIGR J*, **15(1)** (2012) 106‒113.
21 Tunde-Akintunde T Y & Akintunde B O, Some physical properties of sesame seed, *Biosyst Eng*, **88(1)** (2004) 127‒129.
22 Shirkole S & Sutar P, Modeling sorption phenomena and moisture migration rates in paprika (*Capsicum annuum* L.) using physicochemical characteristics, *J Food Sci Technol*, **55(2)** (2018) 678‒688.
23 Zewdu A, Aerodynamic properties of tef grain and straw material, *Biosyst Eng*, **98(3)** (2007) 304‒309.
24 Subramanium S & Viswanathan R, Bulk density and friction coefficient of selected minor millet grain and flour, *J Food Eng*, **81** (2007) 118‒126.
25 Vivek K, Mishra S & Pradhan R C, Physicochemical characterization and mass modelling of Sohiong (*Prunus nepalensis* L.) fruit, *J Food Meas Charact*, **12(2)** (2018) 923‒936.
26 Bruno L M, Lima J R, Wurlitzer N J & Rodrigues T C, Non-dairy cashew nut milk as a matrix to deliver probiotic bacteria, *Food Sci Technol*, **40(3)** (2020) 604‒607.

27 Shah A, Masoodi F A, Gani A & Ashwar B A, Geometrical, functional, thermal, and structural properties of oat varieties from temperate region of India, *J Food Sci Technol*, **53(4)** (2016) 1856–1866.

28 Alonge A F & Adigun Y J, Some physical and aerodynamic properties of sorghum as related to cleaning, *21st Annual Conf Nigerian Soc Agric Eng (NSAE)*, Federal Polytechnic Bauchi, Nigeria (1999).

29 Garnayak D K, Pradhan R C, Naik S N & Bhatnagar N, Moisture-dependent physical properties of jatropha seed (Jatropha curcas L.), *Ind Crops Prod*, **27(1)** (2008) 123–129.

30 Garg V, Mallick S S, Garcia-Trinanes P & Berry R J, An investigation into the flowability of fine powders used in pharmaceutical industries, *Powder Technol*, **336** (2018) 375–382.

31 Landillon V, Cassan D, Morel M H & Cuq B, Flowability, cohesive, and granulation properties of wheat powders, *J Food Eng*, **86(2)** (2008) 178–193.

32 Navarro S & Noyes R T, *The Mechanics and Physics of Modern Grain Aeration Management*, (CRC press) 2001.

33 Chandan Kumar V B, Palanimuthu V & Madhusudan Nayak C, Engineering properties of kodo millet (Paspalum scrobiculatum): CO (3) Variety, *Int J Agric Environ bio-res*, **3** (2018) 81–87.

34 Gomez M I, Obilana A B, Martin D, Madzvamuse M & Monyo E S, *Manual of Laboratory Procedures for Quality Evaluation of Sorghum and Pearl Millet* (International Crops Research Institute for the Semi-Arid Tropics) 1997.

35 Srilakshmi B, *Food science* (New Age International, New Delhi, India) 2003.