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Engineering properties of tender sorghum (*hurda*) panicles and grains for the design of mechanized processing equipment

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Abstract

Engineering properties of agricultural materials constitute fundamental design parameters for the development of efficient mechanized processing equipment. However, comprehensive information on the engineering properties of tender sorghum (*hurda*) grains harvested at the milk stage is scarce. Therefore, the present study was undertaken to determine the engineering properties of tender sorghum (Variety *Gulbhendi*) at an average moisture content of 66.52% (w.b.) to provide engineering design data for mechanized sorghum (*hurda*) grains processing equipment. Principal dimensions of panicles and grains, geometric characteristics, gravimetric properties, and flow properties were determined using standard experimental procedures. The average panicle length was 191.2 mm, while the average diameters at the top, middle, and bottom portions were 51.06 mm, 74.29 mm and 48.79 mm, respectively. Tender sorghum grains exhibited average major, medium and minor dimensions of 4.39 mm, 4.14 mm and 3.03 mm, respectively, with a geometric mean diameter of 3.69 mm and an average sphericity of 0.84. The average thousand-grain weight, bulk density, true density, porosity, angle of repose, terminal velocity, and coefficient of friction were 20.59 g, 625 kg/m³, 989 kg/m³, 36.39%, 33.23°, 4.64 m/s, and 0.632, respectively. The measured engineering properties provide essential design inputs for the development of feeding, conveying, hopper, extraction, separation, and cleaning systems of mechanized Sorghum *hurda* processing equipment. The engineering database generated in this investigation will facilitate the design optimization of specialized tender sorghum processing machinery and support future mechanization of sorghum *hurda* production.

Keywords: Tender sorghum (*hurda*) grains, engineering properties, panicle characteristics, grain geometry, physical properties, mechanised processing, agricultural machinery, machine design

1. Introduction

Sorghum (*Sorghum bicolor* L. Moench) is an important cereal crop widely cultivated in semi-arid and tropical regions because of its exceptional tolerance to drought, high temperature, and low-fertility soils. Besides its adaptability, sorghum has attracted considerable attention as a nutritious cereal owing to its high carbohydrate content, moderate protein level, dietary fiber, minerals, and diverse bioactive compounds, including phenolic and antioxidants. The crop is increasingly recognized as a sustainable food source and an important ingredient for developing functional and gluten-free food products (Xiong *et al.*, 2019; Abah *et al.*, 2020) ^[1, 2].

In India, tender sorghum grains, commonly known as *hurda*, are harvested at the milk to soft-dough stage and consumed as a traditional seasonal food, particularly in Maharashtra and adjoining regions. At this stage, the grains possess high moisture content, a soft endosperm, pleasant sweetness, and superior eating quality compared with mature sorghum grains. These unique characteristics make sorghum (*hurda*) grains an important value-added product with growing commercial potential. However, the high moisture content and immature cellular structure considerably alter the engineering behavior of the grains, influencing their dimensional, gravimetric, frictional, and flow properties during handling and processing (Mate *et al.*, 2021) ^[3]. Engineering properties of agricultural materials constitute the fundamental database required for the design, development, and optimization of post-harvest processing equipment. Parameters such as grain dimensions, geometric mean diameter, sphericity, thousand-grain weight, bulk density, true density, porosity, angle of repose, coefficient of static friction, and terminal velocity are

extensively used in the design of hoppers, conveyors, elevators, cleaning systems, grading equipment, storage bins, pneumatic separators, and other grain handling machinery. Furthermore, these properties facilitate mathematical modeling of grain behavior, optimization of machine components, and prediction of material flow characteristics, thereby improving processing efficiency while minimizing product losses and mechanical damage (Mohsenin, 1986; Gely and Pagano, 2017) [4, 5].

Numerous investigations have reported the engineering properties of mature sorghum grains over different moisture ranges and demonstrated that moisture content significantly influences grain size, shape, density, porosity, angle of repose, coefficient of friction, and thousand-grain weight (Mwithiga and Sifuna, 2006; Gely and Pagano, 2017) [6, 5]. These studies have primarily focused on dry sorghum intended for storage, transportation, milling, and conventional post-harvest operations. Since mature grains possess substantially lower moisture content and higher kernel hardness than tender grains, the engineering data generated for mature sorghum cannot be directly applied to the design of equipment intended for processing high-moisture tender sorghum (*hurda*) grains.

Although a few studies have reported selected physical properties of tender sorghum (*hurda*) grains, the available information remains limited and is largely restricted to basic characterization under varying moisture conditions. Comprehensive engineering data specifically intended to support the design and optimization of mechanized processing equipment for tender sorghum grains are still scarce. This lack of reliable engineering information limits the scientific design of feeding, conveying, extraction, cleaning, and handling systems for mechanized Sorghum *hurda* processing (Mate *et al.*, 2021) [3].

Therefore, the present investigation was undertaken to determine the engineering properties of tender sorghum (*hurda*) grains at the edible maturity stage. The generated engineering database is expected to provide scientifically validated design parameters for the development and optimization of mechanized processing equipment intended for handling, conveying, cleaning, and processing tender sorghum grains.

2. Materials and Methods

2.1 Sample Collection

The milky stage sorghum (*hurda*) grains of various locally grown variety *Gulbhendi* were procured from group of Sorghum growers, Mr. Kiran Narayan More, District Ch. Sambhaji Nagar for conducting the experiments on sorghum (*hurda*) grains extraction. The sophisticated equipment's and machineries viz: oven, moisture meter, tachometer, variable frequency drive etc. were used from AICRP on Post Harvest Engineering & Technology, Dr. PDKV, Akola. The average moisture content of the tender grains varied between 60 and 70% (w.b.), representing the edible maturity stage commonly used for sorghum (*hurda*) grains preparation.

2.2 Determination of Engineering Properties

The evaluated characteristics were classified as moisture, physical, gravimetric, frictional, and aerodynamic properties. All measurements were conducted in triplicate, and mean values were used for analysis and equipment design.

2.2.1 Moisture Content

Moisture content of tender sorghum (*hurda*) grain and sorghum (*hurda*) panicles was determined by the standard oven-drying method. A 20 g sample was dried at 103°C for 17 h, cooled in a desiccator, and weighed. Moisture content was calculated on a

wet basis (Mate *et al.*, 2021) [3].

$$\text{Moisture content(wb)} = \frac{(\text{Initial weight of sample}) - (\text{Final weight of sample})}{\text{Final weight of sample}} \times 100 \quad \dots\dots\dots (3.1)$$

2.2.2 Physical Properties

2.2.2.1 Panicle Dimensions and Weight

Panicle length and maximum width were measured using a digital vernier caliper with a least count of 0.01 mm. Individual sorghum (*hurda*) panicle weight and sorghum (*hurda*) grain weight per panicle were measured using a precision electronic balance with an accuracy of 0.01 g. Grain percentage was calculated as the ratio of grain weight to panicle weight, according to (Mate *et al.*, 2021) [3].

2.2.2.2 Grain Dimensions

Thirty randomly selected healthy and undamaged sorghum (*hurda*) grain were used for dimensional measurements. The major, medium, and minor axes were measured using a digital vernier caliper with a least count of 0.01 mm and calculate according to (Mate *et al.*, 2021) [3].

2.2.2.3 Geometric Mean Diameter

The geometric mean diameter of tender sorghum (*hurda*) grain was calculated from the three principal dimensions according to Mohsenin (1986) [4]:

$$D = (l \times b \times t)^{1/3} \quad \dots\dots\dots (3.2)$$

Where, l = length, mm

b = breadth, mm t = thickness, mm

2.2.2.4 Sphericity

Sphericity was calculated from the principal grain dimensions according to Mohsenin (1986) [4]:

$$\text{Sphericity} = \frac{(a \times b \times c)^{1/3}}{a} \quad \dots\dots\dots (3.3)$$

Where,

a = longest intercept, mm

b = Longest intercepts normal to a, mm

c = Longest intercept normal to a and b, mm

2.2.3 Gravimetric Properties

2.2.3.1 Thousand-Grain Weight

Thousand-grain weight was determined by weighing 1000 randomly selected tender sorghum (*hurda*) grain using a precision electronic balance and expressed in grams and calculate according to (Mate *et al.*, 2021) [3].

2.2.3.2 Bulk Density

Bulk density was calculated as the ratio of the mass of sorghum (*hurda*) grain to the volume occupied by the grains without compaction (Mohsenin, 1986) [4]:

$$\text{Bulk density (kg/m}^3\text{)} = \frac{\text{Weight of sample in container}}{\text{Volume of sample}} \quad \dots\dots\dots (3.4)$$

2.2.3.3 True Density

True density was determined using the liquid displacement method and calculated according to Mohsenin (1986) [4]:

$$\text{True density (kg/m}^3\text{)} = \frac{\text{Weight of sample}}{\text{True volume of sample}} \quad \dots\dots (3.5)$$

2.2.3.4 Porosity

Porosity represents the percentage of air spaces present within a bulk sorghum (*hurda*) grain mass and was calculated from bulk density and true density values using the following relationship (Mohsenin, 1986) ^[4]:

$$\text{Porosity, \%} = \frac{P_t - P_b}{P_t} \times 100 \quad \dots\dots\dots (3.6)$$

Where,

P_t = True density, kg/m³

P_b = Bulk density, kg/m³

2.2.4 Frictional Properties

2.2.4.1 Angle of Repose of Grains

The angle of repose of tender sorghum (*hurda*) grain was determined using the fixed-funnel method. The grains were allowed to discharge freely through the funnel to form a natural heap. The heap height and base diameter were measured, and the angle of repose was calculated using Eq. (3.7) according to (Mohsenin, 1986) ^[4]

$$\theta = \tan^{-1} 2H/D \quad \dots\dots\dots (3.7)$$

Where,

θ = Angle of repose, degree H = Height of pile, mm

D = Diameter of disc, mm

2.2.4.2 Coefficient of Static Friction

The coefficient of friction of tender sorghum (*hurda*) grain against a mild steel surface was determined using an inclined plane method. It was calculated using Eq. (3.8) according to (Mohsenin, 1986) ^[4]:

$$\mu = \tan \theta \quad \dots\dots\dots (3.8)$$

Where,

μ = coefficient of static friction

θ = angle of inclination at the initiation of grain movement, degree

2.2.5 Aerodynamic Properties

2.2.5.1 Terminal Velocity

Terminal velocity was determined using a vertical air column by gradually increasing the airflow until an individual tender sorghum grain attained a suspended state. The air velocity corresponding to the onset of suspension was recorded as terminal velocity and calculated according to (Mate *et al.*, 2021) ^[3], expressed in m/s.

3. Results and Discussion

The engineering properties of tender sorghum (*hurda*) panicles and sorghum (*hurda*) grains were determined at 66.52% moisture content (w.b.), corresponding to the milk stage commonly used for sorghum (*hurda*) grain preparation. The measured properties were grouped into physical, gravimetric, frictional, and aerodynamic characteristics. The consolidated results are presented in Table 1.

Table 1: Engineering properties of tender sorghum panicles and grains at 66.52% moisture content (w.b.)

Sr. No.	Measured engineering property	Mean $\pm$ SD	Unit
A Physical properties of panicles			
1	Panicle length	191.20 $\pm$ 8.30	mm
2	Maximum panicle width	74.29 $\pm$ 4.07	mm
3	Panicle weight	78.29 $\pm$ 15.90	g
4	Grain weight per panicle	51.19 $\pm$ 12.35	g
5	Grain proportion	65.40 $\pm$ 4.94	%
6	Straw proportion	35.16 $\pm$ 4.82	%
B Physical and geometric properties of grains			
7	Major axis	4.39 $\pm$ 0.29	mm
8	Medium axis	4.14 $\pm$ 0.14	mm
9	Minor axis	3.03 $\pm$ 0.13	mm
10	Geometric mean diameter	3.69 $\pm$ 0.18	mm
11	Sphericity	0.84 $\pm$ 0.03	–
C Gravimetric properties of grains			
12	Thousand-grain weight	20.59 $\pm$ 0.22	g
13	Bulk density	625.00 $\pm$ 8.68	Kg/m ³
14	True density	989.00 $\pm$ 3.59	Kg/m ³
15	Porosity	36.39 $\pm$ 0.17	%
D Frictional properties of grains			
16	Angle of repose	33.23 $\pm$ 0.21	°
17	Coefficient of static friction on mild steel	0.632	–
E Aerodynamic properties of grains			
18	Terminal velocity	4.64 $\pm$ 0.23	m/s

3.1 Moisture Content

The average moisture content of the tender sorghum (*hurda*) panicles and tender sorghum (*hurda*) grain was 66.52% (w.b.). This value represents the tender physiological condition at the milk stage used for sorghum (*hurda*) grain preparation. Moisture content influences the dimensional, gravimetric, frictional, and aerodynamic characteristics of cereal grains through changes in grain volume, mass, surface condition, and inter-particle interaction.

The observed moisture level was comparable with the range investigated for tender sorghum (*hurda*) grain by Mate *et al.* (2021) ^[3], who evaluated engineering properties of sorghum (*hurda*) var. *Gulbhendi* at approximately 62–70% moisture content (w.b.). Their results demonstrated that moisture variation significantly influenced grain dimensions, thousand-grain weight, density, porosity, angle of repose, and frictional behavior. Similar moisture-dependent changes in sorghum engineering properties have been reported by Gely and Pagano (2017) ^[5]. Thus, characterization at 66.52% moisture content provides representative engineering information for the tender sorghum *hurda* condition.

3.2 Physical Properties of Tender Sorghum Panicles

The mean panicle length was 191.20 $\pm$ 8.30 mm, ranging from 178 to 203 mm, while the maximum panicle width was 74.29 $\pm$ 4.07 mm, with values between 38.4 and 57.6 mm. The variation in panicle dimensions reflects natural biological variability among individual panicles arising from varietal characteristics, crop growth conditions, and differences in panicle development. The mean individual sorghum (*hurda*) panicle weight was 78.29 $\pm$ 15.90 g, whereas the grain weight per panicle was 51.19 $\pm$ 12.35 g. The grain and straw fractions constituted 65.40 $\pm$ 4.94% and 35.16 $\pm$ 4.82%, respectively. The higher grain *hurda* fraction indicates that grain constituted the major mass component of the tender panicles at the examined maturity stage. The observed

variation in panicle and grain weight is expected because whole panicles comprise grains and supporting structural tissues with different dimensions and moisture distribution.

3.3 Dimensional and Shape Characteristics of Tender Sorghum Grains

The mean major, medium, and minor axes of tender sorghum grains (*hurda*) were 4.39 ± 0.29 , 4.14 ± 0.14 , and 3.03 ± 0.13 mm, respectively. The corresponding geometric mean diameter was 3.69 ± 0.18 mm. The relatively low standard deviations indicate limited variation in grain dimensions within the sampled material. The measured dimensions were comparable with values reported for mature sorghum under lower moisture conditions. Surpam *et al.* (2019) ^[7] reported mean grain dimensions of 4.39, 4.20 and 2.64 mm for length, width, and thickness, respectively, with a geometric mean diameter of 3.64 mm at 9.15% moisture content. The close agreement in geometric diameter indicates that the present tender sorghum (*hurda*) grain fall within the dimensional range reported for sorghum despite the substantial difference in moisture condition.

Moisture-dependent dimensional changes have been reported in sorghum. Mwithiga and Sifuna (2006) ^[6] observed increases in principal grain dimensions and geometric mean diameter with increasing moisture content, while Sabar *et al.* (2020) ^[8] reported similar increases in grain length, width, thickness, and geometric mean diameter over a moisture range of 8.7–21.8% (w.b.). These changes are associated with moisture absorption and expansion of grain tissues.

The mean sphericity of the tender sorghum (*hurda*) grain was 0.84 ± 0.03 , indicating a relatively rounded grain shape. This value closely agrees with the value of approximately 0.834 reported by Surpam *et al.* (2019) ^[7]. Mate *et al.* (2021) ^[3] reported sphericity values of approximately 0.838–0.869 for tender sorghum over a comparable moisture range, placing the present observation within the reported range for sorghum (*hurda*) grain. The result therefore confirms that the tender sorghum (*hurda*) grain retain a comparatively rounded morphology at the examined moisture condition.

3.4 Gravimetric Properties of Tender Sorghum Grains

The thousand-grain weight was 20.59 ± 0.22 g, with values ranging from 20.22 to 21.06 g. The relatively low standard deviation indicates limited variation in grain mass within the sampled population. The observed value closely corresponds with the range of 20.41–21.14 g reported by Mate *et al.* (2021) ^[3] for tender sorghum over a comparable moisture range. Sabar *et al.* (2020) ^[8] also reported an increase in thousand-grain weight with increasing moisture content in sorghum. The relatively high mass observed in the present tender grains can therefore be associated partly with their high moisture content.

The mean bulk density was 625.00 ± 8.68 kg/m³, whereas the true density was 989.00 ± 3.59 kg /m³. The lower bulk density compared with true density reflects the presence of inter-granular void spaces within the grain mass. Mate *et al.* (2021) ^[3] reported bulk-density values ranging from approximately 662 to 610 kg/m³ and true-density values from 997 to 984 kg/m³ over increasing moisture contents in tender sorghum. The present values fall within this reported range and show comparable density characteristics.

The observed reduction in bulk density relative to true density is consistent with the moisture-dependent behaviour reported by Gely and Pagano (2017) ^[5]. Increasing moisture content causes grain expansion and modifies the packing arrangement, resulting in changes in the volume occupied by a given grain mass. The

measured porosity was $36.39 \pm 0.17\%$, indicating a substantial proportion of inter-granular void space. The value is also comparable with porosity values reported for sorghum (*hurda*) grain by Mate *et al.* (2021) ^[3].

3.5 Frictional Properties of Tender Sorghum

The angle of repose of tender sorghum (*hurda*) grains was $33.23 \pm 0.21^\circ$. The close numerical agreement indicates similar heap-forming behaviour under the respective experimental conditions, although the two materials differ considerably in their physical form and structure.

The grain angle of repose was comparable with values reported for sorghum under both tender and mature conditions. Surpam *et al.* (2019) ^[7] reported an angle of repose of approximately 35° at 9.15% moisture content, whereas Sabar *et al.* (2020) ^[8] observed values increasing from 39.84 to 43.19° over 8.7–21.8% moisture content. Mate *et al.* (2021) ^[3], however, reported values of approximately 33.14 – 33.77° for tender sorghum over a comparable high-moisture range. The present value of 33.23° therefore agrees particularly well with observations for tender sorghum (*hurda*) grain.

The coefficient of static friction of tender sorghum (*hurda*) grain against mild steel was 0.632. This value was considerably higher than the coefficient of approximately 0.20 reported by Surpam *et al.* (2019) ^[7] for mature sorghum at 9.15% moisture content. Gely and Pagano (2017) ^[5] reported an increase in the coefficient of friction with increasing moisture content, attributing the change to increased surface interaction and adhesion. Sabar *et al.* (2020) ^[8] similarly observed an increase in the coefficient of friction against mild steel with increasing moisture content.

3.6 Aerodynamic Properties of Tender Sorghum Grains

The mean terminal velocity of tender sorghum (*hurda*) grain was 4.64 ± 0.23 m/s. This represents the air velocity at which individual grains attained a suspended condition under the experimental setup.

The observed value was lower than the terminal velocity reported for mature sorghum at considerably lower moisture contents. Sabar *et al.* (2020) ^[8] reported terminal velocities ranging from 7.06 to 7.99 m/s as moisture content increased from 8.7 to 21.8% (w.b.). The lower value obtained in the present study can be associated with the substantially higher moisture content and tender physiological condition of the grains. Moisture alters grain mass, dimensions, density, and projected area, thereby influencing aerodynamic behaviour.

Overall, the measured properties were consistent with the established moisture-dependent behaviour of sorghum and showed close agreement with published observations for sorghum (*hurda*) grain. The present dataset therefore provides a comprehensive characterization of tender sorghum panicles and grains under a moisture condition representative of the commercial sorghum (*hurda*) grain harvesting stage.

4. Conclusion

The engineering properties of tender sorghum (*Sorghum bicolor* L.) (*hurda*) panicles and (*hurda*) grains (var. *Gulbhendi*) were characterized at 66.52% moisture content (w.b.). The mean sorghum (*hurda*) panicle length, maximum width, panicle weight and grain weight per panicle were 191.20 mm, 74.29 mm, 78.29 g and 51.19 g, respectively, with grain and straw proportions of 65.40 and 35.16%. The tender sorghum grains (*hurda*) exhibited mean major, medium, and minor axes of 4.39, 4.14, and 3.03 mm, respectively, with a geometric mean diameter of 3.69 mm and sphericity of 0.84.

The mean thousand-grain weight, bulk density, true density, porosity, angle of repose, coefficient of static friction against mild steel and terminal velocity were 20.59 g, 625 kg/m³, 989 kg/m³, 36.39%, 33.23°, 0.632, and 4.64 m/s, respectively. The measured properties were consistent with the characteristic moisture-dependent behaviour of tender sorghum (*hurda*) reported in the literature and provide a consolidated engineering-property dataset for tender sorghum at the commercial sorghum (*hurda*) grain harvesting stage.

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Author Contributions

P.P. Thakur: Conceptualization, Experimental trials, Data analysis, Writing – original draft; V. N. Mate: Methodology, Design Optimization, Testing, Writing – review & editing; P. H. Bakane: Trial support, Data recording, Literature review; M.M. Dange & V.V. Kalpande: Literature survey, Data collection, Writing – review & editing.

Conflict of Interest

The authors declare that there is no conflict of interest in any from that could have influenced the research work reported in this paper.

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