Structural Characterization of Kodo Millet (*Paspalum scrobiculatum* L.)

ABSTRACT

Structural characteristics of kodo millet (*Paspalum scrobiculatum* L.) are vital for designing equipment used in handling, transporting, processing, and storing this crop. A study was conducted to determine these characteristics for the DSLM-36-3 variety at a moisture content of 10.99±0.20% (wet basis). The research was carried out at the Department of Processing and Food Engineering, College of Agricultural Engineering, UAS, Raichur, Karnataka, India, during 2022–23 and 2023–24. Key structural characteristics were measured using standard procedures and instruments. The mean size of kodo millet grains was 2.25±0.05 mm, and the grains were obovate in shape. The bulk density, true density, porosity, and thousand-grain weight were found to be 734.90±1.57 kg/m³, 1138.88±2.44 kg/m³, 35.47±0.12%, and 6.14±0.06 g, respectively. The colour values of kodo millet in terms of *L**, *a** and *b** values were found to be 38.08±0.27, 7.87±0.13 and 16.74±0.10, respectively. The angle of repose was measured at 34.75±0.08°. The coefficient of internal friction was 1.26±0.05, and the coefficient of external friction on a mild steel sheet was 0.37±0.04. These findings provide critical data for developing post-harvest machinery such as threshers, de-stoners, graders, de-hullers, and storage systems tailored to kodo millet.

Keywords: Kodo millet, equipment design, structural characteristics, colour values, coefficient of friction

1. INTRODUCTION

"Millet is a robust and quick growing cereal which is more efficient in its utilization of moisture and has a high level of heat tolerance compared to sorghum or maize. Its great merit is that it can be grown on poor sandy soil in low rainfall areas and give economic yields, although light loams and well drained soils are preferred" (Balasubramanian et al., 2014). "They are broadly classified into major and minor millets based on the area cultivated and grain size. Major millets include sorghum (*Sorghum vulgare*), finger millet (*Eleusine coracana*), and pearl millet (*Pennisetum glaucum*). Minor millets comprise little millet (*Panicum miliare*), proso millet (*Panicum miliaceum*), kodo millet (*Paspalum scrobiculatum*), browntop millet (*Brachiaria ramose*), foxtail millet (*Setaria italica*), and barnyard millet (*Echinochloa frumantacea*)" (Khatoniar and Das, 2020).

"Millets originated in Asia and Africa and are important crops in the semi-arid regions of these continents. Notably, 97% of millet production occurs in developing nations. The global millet production was 90.65 million MT in 2022, cultivated across an area of 71.70 million ha, with India having the largest market share of 19.00% and 17.60 million MT production from an area of 14.00 million ha. Within India, Rajasthan is the largest producer of millets with a production of 5.15 million MT in 2020-21, contributing to 28.61% to the national production.

Karnataka is the second largest contributor, producing 2.56 million MT and contributing to 14.26% of national production" (APEDA, 2022).

In 2021-22, India produced 0.37 million metric tonnes (MT) of minor millets, cultivated over 0.44 million hectares, with an average yield of 789 kg/ha. "Among the top five states, Uttarakhand led with a production of 0.07 million MT, closely followed by Madhya Pradesh, also producing 0.07 million MT. Other major contributors included Arunachal Pradesh, Karnataka, and Andhra Pradesh, with Karnataka producing 0.020 million MT and recording a productivity of 778 kg/ha from 0.03 million hectares" (DA and FW, 2024).

"Araka, or Kodo millet (*Paspalum scrobiculatum L.*), was domesticated in India nearly 3000 years ago. It thrives in humid regions across the tropics and subtropics and remains a minor grain crop in India, particularly significant in the Deccan plateau. The primary areas of cultivation include Gujarat, Karnataka, Chhattisgarh, eastern Madhya Pradesh, and parts of Tamil Nadu. In recent years, millets have gained recognition as vital alternatives to major cereals, helping to address global food shortages and meet the rising demand from the growing populations in both developing and developed nations" (Kumar et al., 2016).

"Kodo millet grains are known for their ability to be easily stored, making them a reliable food reserve during famines. It is rich in vitamins, minerals, and phytochemicals containing sulfur, so it is called "nutria-cereals. It is also rich in essential amino acids, like lysine, threonine, valine, sulphur containing amino acids and the ratio of leucine to isoleucine is about 2.0" (Ravindran, 1992; Antony et al., 1996). "Kodo millets are rich in vitamin B3, vitamin B6 and folic acid as well as minerals such as calcium, potassium, magnesium and zinc. Kodo millet grain contains 8.3 per cent protein in which major protein is glutelin (Sudharshana et al., 1988). It contains high amount of crude fiber (9%) as compared to wheat (1.2%). It provides 353 Kcal energy per for 100 gm of grain. Kodo millet contains 66.6% carbohydrate, 2.4% minerals, 1.4% fat and 2% ash. The range of iron content in kodo millet is 25.86 ppm to 39.60 ppm (Chandel et al., 2014). With their established nutritional benefits, they hold strong potential for large-scale production in baby foods, snacks, and dietary products" (Subramanian & Viswanathan, 2007).

"Understanding the structural characteristics of millet grains is crucial for designing equipment for handling, transportation, processing, and storage. Structural characteristics such as size, shape, geometric mean diameter, volume, sphericity, 1000-seed mass, true density, bulk density, porosity, angle of repose, coefficients of static and internal friction, and terminal velocity for various millets at different moisture levels have been extensively studied by many researchers" (Baryeh, 2002; Subramanian & Viswanathan, 2007; Singh et al., 2010; Kumar et al., 2016; Sunil et al., 2016; Rao et al., 2020; Gaurav et al., 2021). "These properties tend to vary depending on the millet variety, moisture content, and the agronomic conditions under which they are grown" (Konak et al., 2002), resulting in significant differences during processing. The objective of this study was to determine the structural characteristics of kodo millet (*Paspalum scrobiculatum* L.) of variety DSLM-36-3 at a moisture content of 10.99±0.20% (wet basis).

2. MATERIAL AND METHODS

Kodo millet (DSLM -36-3) was procured from the Millet Processing Unit at the University of Agricultural Sciences in Raichur, Karnataka. Randomly selected kodo millet from the whole mass was used for determination of structural characteristics. The structural characteristics such as size, shape, bulk density, true density, porosity, thousand grain weight, colour values, angle of repose, coefficient of internal friction and coefficient of external friction (mild steel sheet) of kodo millet were estimated by following the standard methods.

Moisture content

The moisture content of kodo millet was determined using hot air oven by following the method (925.10) given in AOAC (2016). Five grams of the sample was weighed on an electronic balance into a pre-weighed moisture box (W_1), then dried in a hot air oven at 105±2°C for 24 h. After drying, the sample was cooled in a desiccator and weighed again. Repeated the process of drying, cooling and weighing at 30 min. intervals until a constant weight was obtained. The final constant weight of the dried sample was recorded as W_2. The moisture content of the sample on% (w.b.) was calculated using the following formula.

$$\text{Moisture content (\%, w.b.)} = \frac{W_1 - W_2}{W_1} \times 100$$

Where,

W_1 = Initial weight of the kodo millet, g
W_2 = Final weight of the kodo millet, g

Size

A digital vernier caliper (Mitutoyo, 500-196-30, Illinois, USA) having the accuracy of ± 0.001 mm was used for measuring all linear dimensions, namely length, width and thickness of kodo millet. Ten randomly selected grains were measured for size and the average value was recorded for each sample. The geometric mean diameter was computed using the relationship mentioned below (Mohsenin, 1986).

$$D_g = \sqrt[3]{L \times W \times T}$$

Where,

D_g = Geometric mean diameter, mm
L = Length of the grain, mm
W = Width of the grain, mm
T = Thickness of the grain, mm

Shape

Shape of the kodo millet grains was determined by measuring the longitudinal and lateral diameters using the digital vernier caliper. Ten randomly selected grains were measured for size and the dimensions were compared with the shapes described in the standard chart (Mohsenin, 1986) and recorded.

Bulk density

“The bulk density is the ratio of weight of the grain sample to the total volume of the sample. The bulk density of kodo millet was determined using a 100 mL measuring jar. The measuring jar was weighed, then filled with sample and weighed. The experiment was carried out in triplicate and the average value was recorded. The bulk density was computed using the following expression” (Mohsenin, 1986).

$$\text{Bulk density (kg/m}^3\text{)} = \frac{\text{Weight of kodo millet filled in measuring jar, g}}{\text{Volume of measuring jar, mL}} \times 1000$$

True density

"The true density is the ratio of the mass of the grain sample to the solid volume occupied by the sample. Fifty mL of toluene was taken in a 100 mL measuring jar. Ten g of kodo millet were poured into the measuring jar and rise in the toluene level (mL) was recorded as the true volume of the sample. The experiment was carried out in triplicate and the average value was recorded. The true density of the sample was calculated by using the following equation and average value was recorded for each sample" (Mohsenin, 1986).

$$\text{True density (kg/m}^3\text{)} = \frac{\text{Weight of kodo millet, g}}{\text{Change in volume of toluene in measuring jar, mL}} \times 1000$$

Porosity

The porosity of kodo millet was calculated from bulk and true densities using the relationship given by Mohsenin (1986) as given below.

$$\text{Porosity (\%)} = \frac{\text{True density-Bulk density}}{\text{True density}} \times 100$$

Thousand grain weight

"A grain weight of 1 kg was roughly divided into 5 equal portions and then 1000 numbers of kodo millet were randomly selected from each portion and weighed on a digital electronic balance (Essae, PG/FB, Bengaluru, India). The measurements were carried out in triplicate and the mean values were recorded for each sample" (Balasubramanian and Viswanathan, 2010).

Colour values

The colour values (L^*, a^* and b^*) of kodo millet were determined by colourimeter (Hunterlab, CLFX-45, Reston, USA). The colour was measured by using CIELAB scale at 10° observer at D_{65} illuminant. It works on the principle of focusing the light and measures the energy reflected from the sample across the entire visible spectrum. It provides reading in terms of L^*, a^*, and b^* values. Where, luminance (L^*) forms the vertical axis, which indicates whiteness (100) to darkness (0), a^* indicates redness (+60) to greenness (-60) and b^* indicates yellowness (+60) to blueness (-60).

"The instrument was initially calibrated with black as well as standard white plate. After calibration, sample was taken in a cylindrical glass sample cup and placed at the light port to get the colour values in terms of L^*, a^*, and b^*. All the measurements were carried out in triplicate and the average values were recorded for each sample" (Balasubramanian *et al*., 2014).

Angle of repose

Angle of repose is the angle between base and slope of the cone formed on free vertical fall of material onto a horizontal plane. It was determined by following the method described by Sahay and Singh (2001). The apparatus consisted of a hopper filled with kodo millet and circular metal platform supported by three legs. The grains were allowed to flow freely from the hopper over the circular metal platform [25]. A heap of grains was formed on a circular iron plate. From the height and diameter of grains heap in natural pile, the angle of repose was calculated by using the following formula. All the measurements were replicated thrice and the average values were recorded for each sample.

$$\theta = \tan^{-1} \frac{H}{r}$$

Where,

θ = Angle of repose, °

H = Height of heap, mm

r = Radius of heap, mm

Co-efficient of internal friction

"The coefficient of internal friction is the friction between the grain mass of kernels against each other. A box of size 10×10×10 cm^3 tied by a cord passing over pulley was attached to a pan. The surface was filled with kodo millet to a depth of 1 cm. The weight (W_1) was put into pan until the empty box started to slide on kodo millet surface. Later, the empty box was filled with 200 g of kodo millet (W) and again the weights were put into pan and were allowed to slide. The weights (W_2) required to slide the filled box on the kodo millet surface was recorded" (Shivabasappa et al., 2012). The experiments were repeated thrice and the average value were recorded.

$$\text{Coefficient of internal friction } (\mu_i) = \frac{W_2 - W_1}{W}$$

Where,

W_1 = Weight to cause sliding of empty box, g
W_2 = Weight to cause sliding of kodo millet filled box, g
W = Weight of kodo millet inside box, g

Co-efficient of external friction

"Coefficient of external friction is the sliding friction between the grain and the horizontal plane against the wall. The coefficient of external friction was determined for kodo millet using test surface of mild steel. The box of the size 10×10×10 cm^3 was tied by cord passing over pulley and a pan was attached to the other end of the cord. The weights (W_1) were put into pan until the empty box started to slide. Later, the box was filled with 200 g of kodo millet (W) and again the weights were put into pan to cause it sliding. The weights (W_2) required to slide the filled box was recorded" (Shivabasappa et al., 2012). The experiments were repeated thrice and the average value were recorded.

$$\text{Coefficient of external friction } (\mu_e) = \frac{W_2 - W_1}{W}$$

Where,

W_1 = Weight to cause sliding of empty box, g
W_2 = Weight to cause sliding of kodo millet filled box, g
W = Weight of kodo millet inside box, g

3. RESULTS AND DISCUSSION

The structural characteristics such as size, shape, bulk density, true density, porosity, thousand grain weight, colour values, angle of repose, coefficient of internal friction and coefficient of external friction of kodo millet were estimated by the standard procedure and the obtained results are as shown in Table1 and discussed hereunder.

The dimensions of millet grains are crucial in determining parameters for sieves, such as the size, shape, and spacing of perforations (Datta, 2003). These dimensions also play an important role in determining terminal velocity and drag coefficient (Mohsenin, 1986). The mean size of kodo millet grains was 2.25±0.05 mm at a moisture content of 10.99±0.20% (w.b.). The kodo millet was found to be obovate in shape. According to Kumar et al. (2016), the size of Indira Kodo-I was 2.07 mm. Rao et al. (2020) reported that the size of kodo millet was 2.30 mm, while Gaurav et al. (2021) found that at a moisture content of 10 to 11% dry basis, the size of kodo millet was 2.03 mm. These discrepancies could be due to cell structure of the millet (Balasubramanian and Viswanathan, 2010).

“Bulk density, true density, porosity, and thousand grain weight are key parameters in food engineering and post-harvest processes. Bulk density determines storage, packaging, and transport requirements, while true density helps assess the solid mass of grains, crucial for processes like drying and milling. Porosity affects airflow during drying, aeration, and fumigation, and thousand grain weight is used to evaluate grain quality, yield, and sizing during processing” (Gaurav et al., 2021). The mean bulk density, true density, porosity, and thousand grain weight of kodo millet were 734.90±1.57 kg/m^3, 1138.88±2.44 kg/m^3, 35.47±0.12%, and 6.14±0.06 g, respectively. Subramanian and Viswanathan (2007) found that the bulk density of kodo millet grains decreased linearly from 810.10 to 681.30 kg/m^3 as the moisture content increased from 8% to 28% (d.b.). Similarly, Nayak et al. (2019) reported a decrease in bulk density from 957.23 kg/m^3 at 12% moisture to 954.81 kg/m^3 at 14%. Rao et al. (2020) reported that kodo millet had a bulk density of 0.78 g/mL, a true density of 1.10 g/mL, a porosity of 29.01%, and a thousand grain weight of 5.74 g. Gaurav et al. (2021) found that at a moisture content of 10 to 11% dry basis, kodo millet had a bulk density of 672.96 kg/m^3, a true density of 1250.79 kg/m^3, and a thousand grain weight of 4.26 g.

The colour values of kodo millet in terms of *L**, *a** and *b** values were found to be 38.08±0.27, 7.87±0.13 and 16.74±0.10, respectively. These measurements are used to assess grain quality and appearance, both of which are critical for consumer acceptance. Color measurements, in particular, help monitor the effects of processing methods such as roasting or drying, ensuring control over the final product quality. Gaurav et al. (2021) reported an *L** value of 38.04, an *a** value of 9.46, and a *b** value of 18.33 for kodo millet.

The angle of repose was found to be 34.75±0.08° for the kodo millet. This affects the design of storage hoppers, silos, and conveyors, as it indicates how the grains will flow and settle during handling and storage. Nayak et al. (2019) reported that the average angle of repose for kodo millet increased from 26.23° to 26.50° as the moisture content (w.b.) rose from 12% to 14%. Gaurav et al. (2021) found the angle of repose for kodo millet to be 30.04°. The mean coefficient of internal friction of kodo millet was 1.26±0.05. This property is crucial in determining how grains interact with each other during storage and transportation. It influences the design of equipment for mixing, handling, and storage to avoid clogging or bridging. Whereas, the mean coefficient of external friction of kodo millet was found to be 0.37±0.04 on mild steel sheet. This helps in designing contact surfaces for grain handling equipment, such as chutes, hoppers, and conveyors, ensuring smooth movement without excessive resistance or grain damage.

It was clear that the values of structural characteristics obtained for kodo millet in this study have similar trend as that of reported values in the literature perhaps for different varieties and grain moisture.

Table 1. Structural characteristics of kodo millet

Characteristics		**Value (s)**
Size, mm		2.25±0.05
Shape		Obovate
Bulk density, kg/m^3		734.90±1.57
True density, kg/m^3		1138.88±2.44
Porosity, %		35.47± 0.12
Thousand grains weight, g		6.14±0.06
Colour values	*L**	38.08±0.27
	*a**	7.87±0.13
	*b**	16.74±0.10
Angle of repose, °		34.75±0.08
Co-efficient of internal friction		1.26±0.05
Co-efficient of external friction (mild steel)		0.37±0.04

Data represent the mean ± standard deviation

4. CONCLUSION

Various structural characteristics such as size, shape, bulk density, true density, porosity, thousand grain weight, color values, angle of repose, and coefficients of internal and external friction were determined for the kodo millet of variety DSLM-36-3. These characteristics are essential for the design of post-harvest machinery and equipment, including threshers, de-stoners, graders, de-hullers, and storage structures.

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DISCLAIMER

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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