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Studies on evaluation of physical properties of turmeric (*Curcuma longa* L.) rhizomes (Var. Kesar)]

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Abstract
Turmeric (*Curcuma longa* L.) (var. Kesar) rhizome sample was divided into three grades (I: 25-45 mm, II: 46-66 mm, and III: 67-87 mm on the according to its major dimension for the study of physical properties. The average length, breadth and thickness of the samples ranged from 26.50 - 45.00 mm, 44.44 - 64.25mm and 40.20 - 84.99 mm for Grade I, Grade II and Grade III respectively. The geometric mean diameter, arithmetic mean diameter, square mean diameter, equivalent mean diameter, sphericity, aspect ratio, surface area, unit volume and shape factor ranged from 13.43 - 33.51mm, 20.97 -38.82 mm and 28.21 - 47.68 mm, 15.72 -34.61 mm, 27.65 - 41.15 mm, 30.19 - 52.23 mm, 24.81 =59.11 mm, 40.79 = 68.53 mm, 51.57 - 85.85 mm, 17.99 - 42.41mm, 29.80 - 49.24 mm, 37.06 - 61.92 mm, 43.22% - 87.57%, 37.26% - 79.91%, 41.30% - 73.57%, 0.29 - 0.96, 0.29 - 0.83, 0.27 - 0.72, 492.81 mm^2 - 3090.12 mm^2, 1276.59 mm^2 - 3997.86 mm^2, 2229.47 mm^2 - 6033.42 mm^2, 755.98 mm^3 - 15582.37 mm^3, 2723.92 mm^3 - 21630.35 mm^3, 6795.96 mm^3 - 35926.89 mm^3 and 0.03 - 0.11, 0.03 - 0.08, 0.03 - 0.05 for Grade I, II and III respectively. Among the gravimetric properties, thousand-rhizome weight averaged 14.043 kg. The bulk density decreased from 457.2 kg m^{-3} (Grade I) to 432.6 kg m^{-3} (Grade II) and 395.4 kg m^{-3} (Grade III). True density ranged from 1060 to 1102 kg m^{-3} with mean values of 1079, 1060 and 1102 kg m^{-3} for Grades I, II and III, respectively. Porosity increased with rhizome size, recording mean values of 57.6%, 59.2% and 64.1% for Grades I, II and III, respectively. The results of the study will be helpful in designing cleaners, sorters, graders, packaging and storage systems or equipment.

Keywords: Turmeric Rhizome, Physical property, gravimetric property

Introduction
Mother earth has been nourishing all living beings since their evolution. Man has been using various natural plant products for various purposes since the time immemorial. A large number of products are produced as secondary metabolites by plants as a natural defence mechanism against disease and infection. Many of these natural products have pharmacological or biological activity that can be exploited in the area of pharmaceutical drug discovery as well as drug design. Natural medicines derived from plants have played a pivotal role in the health care of many cultures, both ancient and modern. Our ancient Indian system of holistic medicine widely known as "*Ayurveda*" uses mainly plant-based medicines or formulations to treat various ailments. Turmeric (*Curcuma longa* L.) is one of the holy plants that have a very ancient and long history of medicinal use, dating back nearly 4000 years. In Southeast Asia, turmeric is used not only as a principal spice but also as a component in religious ceremonies. Because of its brilliant yellow colour, turmeric is also known as "Indian saffron." Turmeric (*Curcuma longa* L.) is one of the world's most important spices. It is used to flavour and to colour foodstuffs. It is a principal ingredient in curry powder. Turmeric oleoresin is used in brine pickles and to some extent in mayonnaise and relish formulations, non-alcoholic beverages, gelatins, butter and cheese etc. The colour curcumin extracted from turmeric is used as a colourant. It is also used as a dye in textile industry. It is mainly cultivated in Asian countries including India, Bangladesh, China, Thailand, Cambodia, Malaysia, Philippines, and Indonesia (Ravindran *et al*., 2007) [1]. India leads global production and export, with a cultivated area of 291,000 hectares and estimated output of 1.116 million tonnes in 2024-25. Maharashtra, Tamil Nadu, Telangana, Karnataka, Madhya Pradesh, Odisha, and West Bengal are the top turmeric-producing states. In the first half of 2024-25 alone, India exported 137,000 tonnes of turmeric (https://en.wikipedia.org).

The turmeric plant is an herbaceous perennial, 60-90 cm high, with a short stem and tufted leaf. There are 7 to 12 leaves, the leaf sheaths forms the pseudo stem. The lamina is green above, pale green below, and has a length of 30-40 cm and width 8-12 cm. Inflorescence is a central spike of 10-15 cm length. 1-4 flowers are born in axil of the bract opening one at a time. Turmeric is harvested when the plants are between 7 and 10 months of age, when the stems and leaves start to dry out and die back. The whole plant is removed from the ground, taking care not to cut or bruise the rhizomes. The side (lateral) branches (which are known as the fingers) of the rhizomes are removed from the main central bulb (known as the mother). The mothers and fingers are heaped separately, covered in leaves and left to sweat for one day. The finger rhizomes are used for further processing while the mother rhizomes are stored for sowing purpose. The rhizomes have different forms such as spherical, slightly conical, hemispherical and cylindrical. They have brown peel covering just above an orange yellow flesh.

As far as preservation, processing and storage are concerned, the information about the physical properties of an agricultural produce are very quiet important and necessary. These technical information are very crucial in design and development of different processing equipment such as cleaner, sorter, grader, dryer, grinder, conveyor and packaging machines for any specific crop. Besides, also very useful in their further processing. Nevertheless, there is limited published work on physical properties of turmeric rhizomes. Therefore, the present investigation was carried out to study the physical properties of turmeric rhizomes (*Curcuma longa* L.) (Var. Kesar).

The study was conducted at the Department of Post-Harvest Technology, College of Horticulture, SDAU, Jagudan. The turmeric rhizomes (var. Kesar) were procured from the farm of the College of Horticulture, SDAU, Jagudan.

Materials and Methods

Procurement of raw material and sample preparation

Turmeric rhizomes (var. Kesar) were procured from the farm at the College of Horticulture, S.D. Agricultural University, Jagudan, District Mehsana. After harvesting, turmeric rhizomes were collected and segregated into two categories: mother rhizomes and finger rhizomes (Plate 1). The mother rhizomes (Plate 2) were reserved for propagation purposes, while the finger rhizomes (Plate 3) were selected for the present experimental study. The fresh finger rhizomes were washed with water to remove adhering soil and extraneous materials (Plate 4). Any damaged or undesirable portions were manually discarded. Subsequently, the rhizomes were rewashed to ensure complete cleanliness prior to their use in the experiments.

Plate 1: Separation of mother and finger rhizomes

Plate 2: Mother rhizomes

Plate 3: Finger rhizomes

Plate 4: Washing of finger rhizomes

Determination of physical properties of turmeric rhizomes

The physical properties of turmeric rhizomes, such as axial dimensions, arithmetic mean diameter (AMD), geometric mean diameter (GMD), square mean diameter (SMD), equivalent diameter, sphericity, aspect ratio, unit volume, surface area, and shape factor, were determined using standard methods (Mohsenin, 1986) [3]. Gravimetric properties including bulk density, true density, and porosity were also measured. To reduce measurement error due to size variation, rhizomes were classified into three grades based (Plate 5) on major dimension: Grade I (25-45 mm), Grade II (46-66 mm), and Grade III (67-87 mm). Axial dimensions were measured with a digital Vernier caliper (Mitutoyo Corporation, Model CD-6" ASX) having a measuring range of 0-150 mm and minimum indication of ±0.01 mm.

Plate 5: Measurement of axial dimensions of turmeric rhizomes for grading

Geometric mean diameter (GMD)

The geometric mean diameter (GMD) is a key size parameter calculated as the cube root of the product of the three principal dimensions of a turmeric rhizome: the major dimension (a), the medium dimension (b), and the minor dimension (c). Mathematically, it is expressed as:

$$\text{Geometric mean diameter } (GMD) = \sqrt[3]{abc}$$

Where, a = Major dimension, mm
b = Medium dimension, mm
c = Minor dimension, mm

In this study, measurements of these three axes were taken for 100 turmeric rhizome samples to calculate the average GMD. This metric provides an accurate representation of rhizome size by combining length, width, and thickness, which is essential for characterizing physical properties and designing processing equipment.

Arithmetic mean diameter (AMD)

The arithmetic mean diameter (AMD) was calculated using the following formula (Mohsenin, 1986) [3]:

$$\text{Arithmetic mean diameter (AMD)} = \frac{a+b+c}{3}$$

Where, a = Major dimension, mm
b = Medium dimension, mm
c = Minor dimension, mm

This formula provides the average dimension used as a size parameter in physical characterization studies. This standard method is widely applied for calculating the arithmetic mean of irregular agricultural produce and is essential for engineering design and quality assessment.

Square mean diameter (SMD)

The square mean diameter (SMD) was calculated using the following formula (Mohsenin, 1986) [3]:

$$\text{Square mean diameter (SMD)} = \sqrt[2]{ab + bc + ca}$$

Where, a = Major dimension, mm
b = Medium dimension, mm
c = Minor dimension, mm

This formula computes the root mean square of the pairwise products of the dimensions, providing a representative mean diameter for the object, useful in characterizing the size for engineering and processing applications.

Equivalent diameter (EQD)

The equivalent diameter (ED) was calculated using the following formula (Mohsenin, 1986) [3]:

$$\text{Equivalent diameter (EQD)} = \frac{AMD+GMD+SMD}{3}$$

Where, AMD = Arithmetic mean diameter, mm
GMD = Geometric mean diameter, mm
SMD = Square mean diameter, mm

This formula calculates the average of the three mean diameters to represent an equivalent size parameter for the turmeric rhizome.

Sphericity (Ø)

The degree of sphericity (Φ) of turmeric rhizomes was calculated using the following equation described by Mohsenin (1986) [3]:

$$\text{Sphericity}(\emptyset) = \frac{\sqrt[3]{abc}}{a}$$

Where, a = Major dimension, mm
b = Medium dimension, mm
c = Minor dimension, mm

Here, the sphericity is defined as the ratio of the geometric mean diameter (cube root of the product of three dimensions) to the major dimension. This parameter expresses the shape of the rhizome relative to a perfect sphere and is an important property in fluid flow, heat, and mass transfer calculations related to the material.

Aspect ratio (AR)
The aspect ratio (AR) was calculated using the following formula given by Mohsenin (1986) [3]:

$$\text{Aspect ratio (AR)} = \frac{b}{a}$$

Where, a = Major dimension, mm
b = Medium dimension, mm
c = Minor dimension, mm

The aspect ratio expresses the ratio of width to length as a percentage and is used to describe the elongation or shape characteristics of the rhizome. This parameter is important for designing handling, processing, and sorting equipment based on the shape profile of the agricultural produce.

Unit volume (V) and surface area (S)
The unit volume and surface area of the samples were calculated using the standard geometric relationships proposed by Jain and Bal (1997) [4]. The mathematical expressions employed are as follows:

$$\text{Surface area (S)} = \frac{\pi B a^2}{2a - B}$$

$$\text{Unit volume (V)} = \frac{\pi B^2 a^2}{6(2a - B)}$$

Where, $B = \sqrt[2]{bc}$

b = Medium dimension, mm
c = Minor dimension, mm

These equations enable precise estimation of the surface area (S) and unit volume (V) of irregularly shaped biological materials, such as rhizomes or seeds, by approximating them to an ellipsoidal form.

Shape factor (λ)
The shape factor (λ), which characterizes the geometric configuration of a particle in relation to its surface area and volume, was determined following the method described by McCabe and Smith (1984) [5]. The shape factor was computed using the following relationship:

$$\text{Shape factor } (\lambda) = \frac{D}{C}$$

Where, $C = \frac{V}{b^2}$ and $D = \frac{S}{6b^2}$
The parameter λ provides a quantitative indication of the departure of the sample's geometry from a perfect sphere. A value of λ=1represents a spherical shape, whereas deviations from unity indicate elongation or flattening of the sample.

Thousand rhizomes mass
The mass of one hundred turmeric rhizomes was measured using a precision electronic balance (Labtroniks, India) having a resolution of 0.01 g. The recorded mass of 100 rhizomes was subsequently multiplied by a factor of 10 to estimate the corresponding weight of 1,000 rhizomes, in accordance with the standard procedure for bulk weight determination.

Bulk density (ρ_b)
The bulk density of turmeric rhizomes was determined as the ratio of the mass of the sample to the volume it occupied in a known container (Plate 7). For this purpose, rhizomes were carefully filled into a cylindrical container of 1,000 cm³ capacity without applying any compaction. The mass of the filled container was measured using an electronic balance, and the bulk density was computed using the following expression:

$$\text{Bulk density } (\rho b) = \frac{mass\ of\ turmeric\ rhizome(kg)}{Volume\ of\ container\ (m^3)}$$

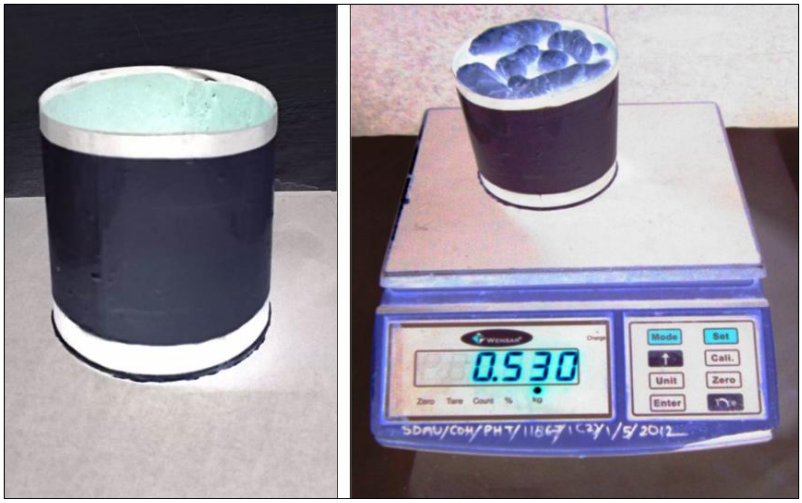

Plate 7: Cylindrical container used for determination of bulk density

True density (ρ_t)

The true density of turmeric rhizomes was determined following the procedure outlined by Mohsenin (1986) [3]. Fresh turmeric rhizomes were initially weighed using a precision electronic balance. The weighed samples were then carefully immersed in a graduated measuring cylinder containing toluene ($C_6H_5CH_3$), ensuring that the samples did not come into contact with the cylinder's walls or bottom (Plate 8). Toluene was selected as the displacement medium due to its favourable physicochemical properties, including a low tendency to penetrate the sample, low surface tension (allowing smooth flow over the material surface), minimal solvent action on organic constituents such as fats, a relatively high boiling point, and a low specific gravity. The true volume of the rhizome samples was determined based on the mass of toluene displaced, and the true density was calculated using the following relationship:

$$\text{True density } (\rho_t) = \frac{Weight\ of\ turmeric\ rhizome\ (kg)}{Volume\ of\ displaced\ toluene\ (m^3)}$$

This method provides an accurate estimation of the material's intrinsic density, excluding interstitial air spaces, and is essential for evaluating physical properties such as porosity and structural compactness.

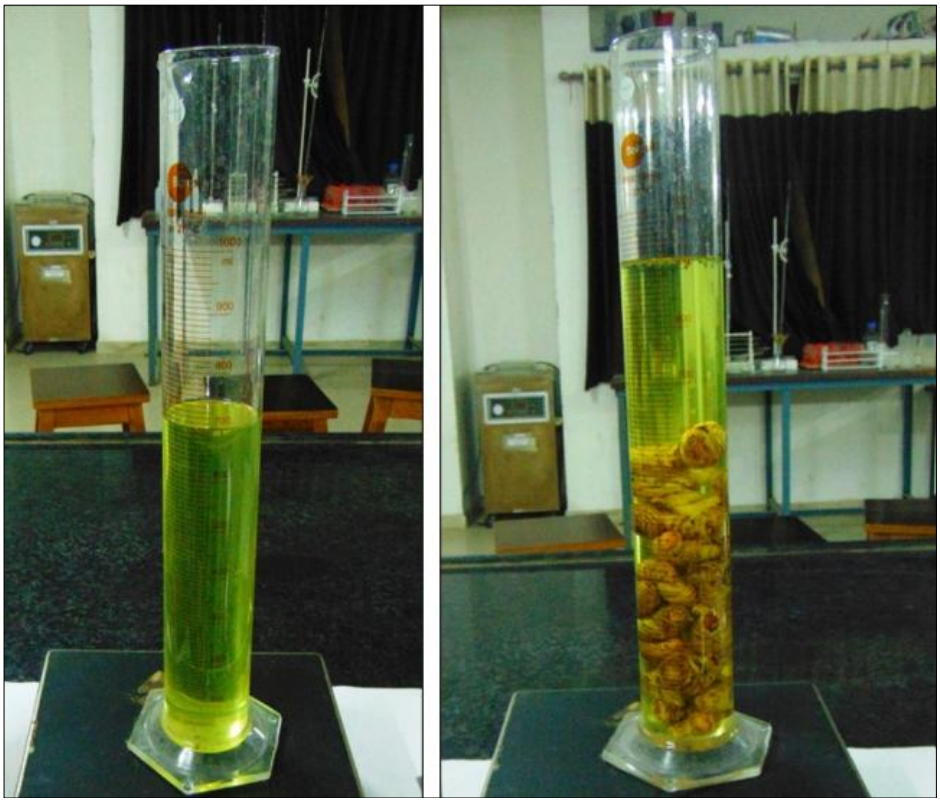

Plate 8: Determination of true density by toluene displacement method

Porosity (%)

The porosity of turmeric rhizomes represents the proportion of void spaces within the material structure at a given moisture content. It was determined as the ratio of the difference between the true density and bulk density to the true density, and expressed as follows:

$$\text{Porosity } (\%) = [1 - \frac{\rho_b}{\rho_t}] \times 100$$

Where, ρ_b = Bulk density, kg/m^3
ρ_t = True density, kg/m^3

Porosity is an important physical property that reflects the internal structural arrangement and compactness of the material. It influences various post-harvest and processing characteristics such as drying rate, rehydration capacity, and mechanical strength of the rhizomes.

Results

Axial dimensions

The axial dimensions of 100 samples from each of the three grades of turmeric rhizomes were measured. In grade I (length: 25-45 mm), length, breadth, and thickness varied from 26.50 mm to 45.00 mm, 9.30 mm to 39.56 mm, and 8.13 mm to 23.14 mm respectively (Fig 1). The Mean values of length, breadth, and thickness were 36.38 mm, 20.97 mm, and 17.04 mm, respectively. In grade II (length: 46-66 mm), length, breadth, and thickness ranged from 64.25 mm to 44.44 mm, 39.94 mm to 16.55 mm, and 28.58 mm to 9.63 mm, respectively. For grade III (length: 67-87 mm), length, breadth, and thickness ranged from 84.99mm to 40.20 mm, 47.55mm to 18.18 mm, and 33.40 mm to 14.60 mm, respectively. The Mean values for this grade were 71.84 mm, 31.29 mm, and 23.77 mm, respectively (Table 1). Similar results were reported by Ramos *et al*. (2021) [6] and Thul *et al*. (2022) [7].

Table 1: Axial dimensions of turmeric rhizomes

Parameter	Grade I (25-45 mm)			Grade II (46-66 mm)			Grade III (67-87mm)		
	Length (mm)	Breadth (mm)	Thickness (mm)	Length (mm)	Breadth (mm)	Thickness (mm)	Length (mm)	Breadth (mm)	Thickness (mm)
Mean	36.38	20.97	17.04	56.20	26.06	20.38	71.84	31.29	23.77
SD	6.10	5.69	3.81	5.26	6.05	4.30	7.01	7.52	4.56
CV	16.77	27.12	22.38	9.36	23.22	21.08	9.76	24.04	19.17
S.Em.	0.6101	0.5686	0.3814	0.5261	0.6052	0.4296	0.7010	0.7521	0.4556

Geometric Mean Diameter (GMD)

The results showed that the GMD ranged from 13.43 to 33.51mm, 20.97 to 38.82mm and 28.21 to 47.68mm in grade I, grade II and grade III respectively. The Mean values of geometric Mean diameter of rhizomes were found to be 23.29 mm, 30.74 mm and 37.38 mm for grade I, grade II and grade III respectively (Table 2, 4.3, 4.4). Balasubramanian *et al*. (2012) [8], Thul *et al*. (2022) [7] and Basha *et al*. (2024) [9] found similar results.

Arithmetic Mean Diameter (AMD)

The arithmetic Mean diameter (AMD) of fresh turmeric rhizomes ranged from 15.72 to 34.61 mm, 27.65 to 41.15 mm, and 30.19 to 52.23 mm in grade I, grade II, and grade III, respectively. The Mean AMD values were found to be 24.80 mm, 34.21 mm, and 42.30 mm for grade I, grade II, and grade III, respectively (Tables 4.2, 4.3, and 4.4). Similar results were reported by Nimbalkar *et al.* (2021) [10] and Basha *et al.* (2024) [9] in their studies on turmeric rhizomes.

Square Mean Diameter (SMD)

The results showed that the SMD of fresh turmeric rhizomes ranged from 24.81 to 59.11mm, 40.79 to 68.53mm and 51.57 to 85.85mm in grade I, grade II and grade III respectively. The Mean values of square Mean diameter of fresh rhizomes were 66.67 mm, 65.01 mm and 63.88 mm for grade I, grade II and grade III respectively (Table 4.2, 4.3, 4.4). Basha *et al*. (2024) [9] also found similar results in their experiment on turmeric rhizomes.

Equivalent Mean Diameter (EMD)

The EMD of fresh turmeric rhizomes ranged from 17.99 to 42.41mm, 29.80 to 49.24mm and 37.06 to 61.92mm in grade I, grade II and grade III respectively. The Mean values of equivalent Mean diameter of rhizomes were found to be 48.19 mm, 47.04 mm and 46.29 mm for grade I, grade II and grade III respectively (Table 4.2, 4.3, 4.4). Basha *et al.* (2024) [9] also found similar results in their experiment on turmeric rhizomes.

Sphericity

The sphericity of turmeric rhizomes ranged from 43.22% to 87.57%, 37.26% to 79.91% and 41.30% to 73.57% in grade I, grade II and grade III respectively. The Mean values of sphericity of rhizomes were 64.78%, 54.93% and 52.20% for grade I, grade II and grade III respectively (Table 4.2, 4.3, 4.4). Ramos *et al.* (2020), Thul *et al*. (2022) [7] also reported similar findings in their experiments.

Bulk density (ρ_b)

The bulk density of fresh turmeric rhizomes was observed to range from 438 kg/m^3 to 481 kg/m^3, 416 kg/m^3 to 445 kg/m^3 and 688 kg/m^3 to 406 kg/m^3 in grade I, grade II and grade III respectively. The Mean values of bulk density of rhizomes were found to be 457.2 kg/m^3, 432.6 kg/m^3 and 395.4 kg/m^3 for grade I, grade II and grade III respectively (Table 5). Similar results were found by Basha *et al.* (2024) [9] and Balasubramanian *et al*. (2012) [8].

True density (ρ_t)

The true density of fresh turmeric rhizomes ranged from 1062 kg/m^3 to 1108 kg/m^3, 1040 kg/m^3 to 1075 kg/m^3 and 1092 kg/m^3 to 1111 kg/m^3 in grade I, grade II and grade III respectively. The corresponding Mean values of true density of rhizomes were 1079 kg/m^3, 1060 kg/m^3 and 1102 kg/m^3 for grade I, grade II and grade III respectively (Table 5). Comparable findings were reported by Balasubramanian *et al*. (2012) [8], Shelake *et al.* (2018) and Basha *et al.* (2024) [9].

Porosity (ε)

The porosity of fresh turmeric rhizomes was observed in the range of 55 to 60, 58 - 60 and 63 - 65% in grade I, grade II and grade III respectively. The Mean values of true density of rhizomes were 57.6%, 59.2% and 64.1% for grade I, grade II and grade III respectively (Table 4.5). Similar results were found by Shelake *et al.* (2018) Basha *et al.* (2024) [9], Balasubramanian *et al*. (2012) [8] and Parmar and Dabhi (2022).

Table 2: Geometric properties of Grade I fresh turmeric rhizomes

Geometric properties									
Parameter	GMD (mm)	AMD (mm)	SMD (mm)	EQD (mm)	Sphericity (%)	Aspect ratio (AR)	Surface area(S) (mm^2)	Unit Volume (V) (mm^3)	Shape Factor (ë)
Max.	33.51	34.61	59.11	42.41	87.57	0.96	3090.12	15582.37	0.11
Mini.	13.43	15.72	24.81	17.99	43.22	0.29	492.81	755.98	0.03
Mean	23.29	24.80	41.47	29.85	64.78	0.59	1498.19	5051.06	0.06
SD	4.2	4.01	7.11	5.08	10.97	0.16	520.84	2868.34	0.02
CV%	17.84	16.18	17.15	17.01	16.93	27.88	34.76	56.79	27.27
S.Em.	0.4153	0.4011	0.7114	0.5079	1.0966	0.0163	52.0841	286.8345	0.0015

Table 3: Geometric properties of Grade II fresh turmeric rhizomes

Geometric properties									
Parameter	**GMD (mm)**	**AMD (mm)**	**SMD (mm)**	**EQD (mm)**	**Sphericity (%)**	**Aspect ratio (AR)**	**Surface area(S) (mm^2)**	**Unit Volume (V) (mm^3)**	**Shape Factor (ë)**
Max.	38.82	41.15	68.53	49.24	79.19	0.83	3997.86	21630.35	0.08
Min.	20.97	27.65	40.79	29.80	37.26	0.29	1276.59	2723.92	0.03
Mean	30.74	34.21	55.79	40.25	54.93	0.47	2569.49	10236.39	0.05
SD	4.05	3.59	6.75	4.77	7.43	0.12	2569.49	10236.39	0.01
CV%	13.18	10.51	12.10	11.86	13.52	25.25	645.57	4394.18	19.70
S.Em.	0.4053	0.3594	0.6750	0.4773	0.7427	0.0118	64.5566	439.4182	0.0009

Table 4: Geometric properties of Grade III fresh turmeric rhizomes

Geometric properties									
Parameter	**GMD (mm)**	**AMD (mm)**	**SMD (mm)**	**EQD (mm)**	**Sphericity (%)**	**Aspect ratio (AR)**	**Surface area(S) (mm^2)**	**Unit Volume (V) (mm^3)**	**Shape Factor (ë)**
Max.	47.68	52.23	85.85	61.92	73.57	0.72	6033.42	35926.89	0.05
Min.	28.21	30.19	51.57	37.06	41.30	0.27	2229.47	6795.96	0.03
Mean	37.38	42.30	68.27	49.32	52.20	0.44	3825.05	18096.81	0.04
SD	5.26	4.84	8.94	6.32	6.57	0.11	1019.37	8002.85	0.01
CV%	14.07	11.43	13.10	12.82	12.58	25.05	26.65	44.22	19.18
S.Em.	0.5260	0.4837	0.8944	0.6324	0.6568	0.0110	101.9365	800.2848	0.0007

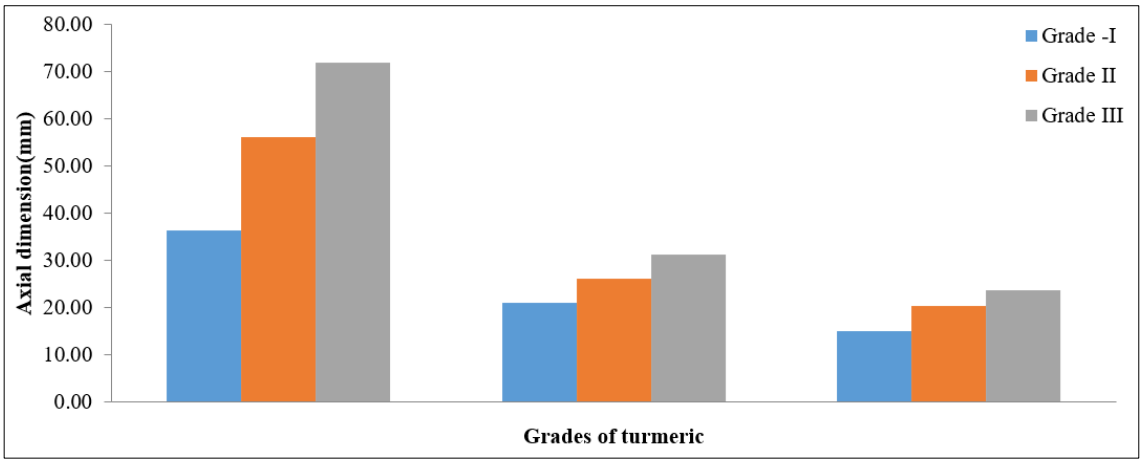

Fig 1: Axial dimensions of turmeric rhizomes of different

Table 5: Gravimetric properties of fresh turmeric rhizomes

	Grade I			Grade II			Grade III		
Parameters	**Bulk density (kg/m^3)**	**True density (kg/m^3)**	**Porosity (%)**	**Bulk density (kg/m^3)**	**True density (kg/m^3)**	**Porosity (%)**	**Bulk density (kg/m^3)**	**True density (kg/m^3)**	**Porosity (%)**
Max	481	1108	60	445	1075	60	406	1111	65
Min	438	1062	55	416	1040	58	388	1092	63
Mean	457.2	1079	57.6	432.6	1060	59.2	395.4	1102	64.1
SD	20.58	20.88	2.51	12.12	13.54	1.10	8.82	8.17	1.02
CV%	4.50	1.94	4.36	2.80	1.28	1.85	2.23	0.74	1.60
S.Em.	9.2054	9.3386	1.1225	5.4185	6.0532	0.4899	3.9446	3.6538	0.4583

Conclusion

The physical properties of fresh turmeric rhizomes were evaluated to generate engineering data required for grading, handling, drying and processing equipment design. The geometric characteristics increased with increase in rhizome grade. The average length increased from 36.38 mm (Grade I) to 71.84 mm (Grade III), whereas breadth and thickness also increased accordingly. The geometric mean diameter (23.29 mm, 30.74 mm and 37.38 mm for grade I, grade II and grade III respectively), arithmetic mean diameter (24.80 mm, 34.21 mm, and 42.30 mm for grade I, grade II, and grade III, respectively), surface area(1498.19 mm^2, 2569.49 mm^2 and 3825.05 mm^2 for grade I, grade II and grade III respectively) and unit volume(5051.06 mm^3, 10236.39 mm^3 and 18096.81 mm^3 for grade I, grade II and grade III respectively) increased with rhizome size, while sphericity(64.78%, 54.93% and 52.20% for grade I, grade II and grade III respectively) and aspect ratio(0.59, 0.47 and 0.44 for grade I, grade II and III respectively) decreased. Among the gravimetric properties, the thousand rhizome weight averaged 14.043 kg. The bulk density decreased from 457.2 kg m^{-3} (Grade I) to 432.6 kg m^{-3} (Grade II) and

395.4 kg m^{-3} (Grade III). True density ranged from 1060 to 1102 kg m^{-3} with mean values of 1079, 1060 and 1102 kg m^{-3} for Grades I, II and III, respectively. Porosity increased with rhizome size, recording mean values of 57.6%, 59.2% and 64.1% for Grades I, II and III, respectively. These engineering properties provide useful information for designing grading, conveying, storage and drying systems.

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