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Determination of engineering properties of Chinese potato tubers (*Plectranthus rotundifolius*): Implications for designing a grading equipment

Chinese potato (*Plectranthus rotundifolius)* is a starchy root crop native to Asia and Africa. Chinese potato is rich in carbohydrates, fiber, and essential minerals, making it a nutritious addition to various diets. It is a valuable food source, particularly in tropical regions, due to its adaptability, nutritional value, and versatility in culinary preparations. Chinese potato is a minor tropical tuber crop in India, cultivated primarily for its edible tubers (Reddy, 2015). In India, its cultivation is concentrated in Thrissur, Palakkad, Kasaragod and Kannur districts of Kerala as well as Tirunelveli, Tenkasi, Tuticorin, Virudhunagar and Kanyakumari districts of Tamil Nadu (Krishnakumar et al. 2023). It is an aromatic tuber crop with approximately 18-20% starch on fresh weight basis. The tubers have medicinal properties due to their high phenolic and flavonoid contents. Chinese potato can be cultivated in both upland and lowland conditions, but it thrives best in well-drained, loamy soils with good rainfall or irrigation. Upland cultivation generally involves preparing ridges or mounds, while lowland cultivation can utilize raised beds to prevent waterlogging. The shape and size of Chinese potato tubers exhibit great variability, largely due to differences in cultivation conditions, specifically upland and lowland areas. At present, the mechanization of this crop is very low in India. Knowledge of the engineering properties of agricultural produce is essential for effective mechanization in agriculture and food processing. The physical properties such as moisture content, length, width, thickness, geometric mean diameter, arithmetic mean diameter, surface area, sphericity, roundness ratio, bulk density and true density are important for designing of processing, transportation, sorting, and separating equipment. By understanding these properties, engineers can develop and fine-tune equipment for various operations, such as harvesting, sorting, processing, and packaging, resulting in improved efficiency and minimized losses. Presently, there is an apparent lack of information on engineering properties of Chinese potato tubers. Keeping all these in view and importance in the design of size based grading equipment, a study was undertaken to estimate the engineering properties of Chinese potato tubers. The resulting data will serve as critical design parameters for developing size based grading equipment for Chinese potato tubers.

Chinese potato tubers of Sree Dhara variety were harvested and collected from the farmer's field in Kuthapanjan Village located in Alangulam Taluk, Thirunelveli district, Tamil Nadu. The harvested tubes were categorized into four commercial grades *viz*., small (up to 20 mm diameter), medium (20.1-30 mm), large (30.1-40 mm) and very large (>40 mm) as shown in Figure 1.

Small (0-20 mm)
Grade IV

Medum (20.1-30 mm)
Grade III

Large (30.1-40 mm)
Grade II

Very large (>40 mm)
Grade I

Fig. 1. Commercial grades of Chinese potato

The procedures for determining the physical properties of Chinese potato tubers are outlined below. Moisture content of fresh Chinese potato tubers was determined using the oven drying method (AOAC, 1995). A 50 g of sample was dried in the oven at 105°C until it reached a constant mass (bone dry condition) and the moisture content was expressed on a wet basis (% w.b). The dimensions of Chinese potato tubers, specifically length (L), width (W), and thickness (T) were measured using a digital vernier calliper with a precision of 0.01 mm. A random sample of 25 tubers was selected for the measurement, and the values were accurately recorded in millimetre. The geometric mean diameter (D_g) in mm was calculated with the help of the following expression (Mohsenin, 1986).

$$D_g = LWT\frac{1}{3} \quad \ldots \text{Equation 1}$$

Where L, W and T were the length, width and thickness of Chinese potato tuber in mm.

The arithmetic mean diameter (D_a) in mm was determined using the formula proposed by Mohsenin (1986).

$$D_g = \frac{L+W+T}{3} \quad \ldots \text{Equation 2}$$

Where L, W and T were the length, width and thickness of Chinese potato tuber in mm.

The surface area (S) of Chinese potato tubers in mm^2 was calculated by the following expression (Baryeh, 2001).

$$S = \pi D_g^2 \quad \ldots \text{Equation 3}$$

Where D_g was geometric mean diameter (mm)

The volume (V) of Chinese potato tubers in m^3 was calculated using the following formula (mohsenin, 1986).

$$V = \left(\frac{\pi}{6}\right)(LWT) \quad \ldots \text{Equation 4}$$

Where L, W and T were the length, width and thickness of Chinese potato tuber in mm.

The mass (M) of each Chinese potato tuber in kg was measured by using a digital balance (Shimadzu, Kyoto, Japan, model BL-220 H) with an accuracy of 0.001 g. The true density (ρ_t) of Chinese potato tubers was determined using the following expression (Mohsenin, 1986).

$$\rho_t = \frac{M}{V} \quad \ldots \text{Equation 5}$$

Where M was the mass of Chinese potato tuber (kg) and V was the volume (m^3) of Chinese potato tuber.

The bulk density (ρ_b) of Chinese potato tubers was measured using the following expression (Mohsenin, 1986).

$$\rho_b = \frac{M}{V_{measured}} \quad \ldots \text{Equation 6}$$

Where M was the mass (kg) and $V_{measured}$ was the measured volume (m^3) of Chinese potato tuber. The volume of Chinese potato tubers was measured using the water displacement method, where the tubers were submerged in a cylindrical flask of known volume filled with water, and the resulting volume was measured.

The porosity of Chinese potato tubers was calculated using the following formula (Mohsenin, 1986).

$$\in = \frac{\rho_t - \rho_b}{\rho_t} \quad \ldots \text{Equation 7}$$

Sphericity (ϕ) is defined as the ratio of the surface area of a sphere with a same volume as the tuber to the surface area of the tuber and was calculated using the following mathematical expression (Mohsenin, 1986). This parameter shows the shape character of the Chinese potato tubers relative to the sphere having same volume.

$$\phi = \frac{Da}{L} \quad \ldots \text{Equation 8}$$

Where, D was the arithmetic mean diameter and L was the length of Chinese potato tuber.

A simple technique based on geometrical attribute analysis can be used to determine the shape of Chinese potato tubers. Roundness ratio was used to classify the shape of Chinese potato tubers as oblate, regular, circular, elliptical and oblong. The roundness ratio of Chinese potato tubers was calculated using the following formula (Sahay and Singh, 1996).

$$\text{Roundness ratio} = \frac{\text{Radius of curvature (r) of the sharpest corner}}{\text{Mean radius of the particle (R)}} \quad \ldots \text{Equation 9}$$

The procedures for determining frictional properties of tubers are detailed below. The rolling angle of Chinese potato tubers was determined by placing individual tubers on a horizontal mild steel surface and incrementally tilting the surface until the tuber began to roll. This process was repeated with 25 randomly selected tubers, and the average rolling angle was calculated to estimate the angle of maximum stability. To determine the angle of friction of Chinese potato tubers, groups of 10 randomly selected tubers were bound together and placed on a horizontal mild steel surface. The surface was incrementally tilted until the tubers began to slide without rolling. This test was repeated 5 times, and the average angle of friction was calculated.

The coefficient of friction (μ) is defined as the tangent of the angle of friction. The coefficient of friction of Chinese potato tubers is calculated using the formula.

$$\mu = \tan\theta \quad \ldots \text{Equation 10}$$

Where μ was the coefficient of friction and θ was the angle of friction (°).

The mean and standard deviation were calculated for triplicate determinations. To determine the significance of the treatments, a one-way analysis of variance (ANOVA) was conducted. Tukey's HSD mean comparison test was performed in SPSS software (Ver. 20.0) to assess significant differences between the variables, with a significance level set at $p < 0.05$.

The physical properties of different commercial grades of Chinese potatoes such as moisture content, length, width, thickness, geometric mean diameter, arithmetic mean diameter, surface area, true density, bulk density, porosity, sphericity and roundness ratio are presented in Table 1. The results showed that length, width and thickness of Chinese potato tubers were 19.22-64.12 mm, 15.34-51.34 mm and 14.25-48.12 mm, respectively. The length and thickness of the tubers were statistically different for different commercial grades studied ($p<0.05$). The moisture content of the tubers varied between 74.41% and 75.35% (w.b) across Grade I, II, III, and IV tubers. The highest moisture content of 75.32 % w.b was noticed in Grade I tubers. The geometric mean diameter and arithmetic mean diameter showed an increasing trend with an increase in length, width and thickness of Chinese potato tubers. Statistically significant differences ($p<0.05$) were observed in the geometric mean diameter and arithmetic mean diameter among the different grades of tubers. The volume and surface area of tubers showed a liner relationship with grade size. The true density of Chinese potato tubers varies from 918 to 1218 kgm^{-3}. An inverse relationship was observed between moisture content and true density in Chinese potato tubers across different grades. Conversely, bulk density increased with increasing moisture content, regardless of the commercial grade. There was an inverse relationship between moisture content and porosity in different commercial grades of Chinese potato.

The shape of food materials is determined in terms of sphericity and roundness ratio (Dash et al. 2008). The surface area, sphericity, and roundness ratio of the different commercial grades of Chinese potato tubers increased with an increase in dimensions such as length, breadth and thickness. This could be due to regular spherical shape of the tubers. A similar trend in turmeric was reported by Dhineshkumar and Anandakumar (2016). From the present study it was found that the Chinese potato tuber shape was correlated with sphericity and roundness ratio, which are important parameters for characterizing tuber geometry. The sphericity values of the tubers were found to vary significantly across different grades. The minimum sphericity value of 0.49 was recorded for Grade IV tubers, while the maximum value of 0.69 was observed for Grade I tubers. The sphericity value of 0.69 for Grade I tubers indicates that these tubers have a shape that approximates a sphere, with some deviation from perfect sphericity. A similar trend was observed for the roundness ratio of different commercial grades. The roundness ratio of Chinese potato tubers ranged from 0.40 (Grade IV) to 0.69 (Grade I), representing the minimum and maximum values, respectively. A significant ($p<0.05$) variation in sphericity and roundness of different commercial grades of Chinese potato tubers was noticed.

Frictional properties, including rolling angle, angle of friction, and coefficient of friction, play a vital role in the design and operation of various equipment and systems used in handling and processing agricultural materials. These properties are particularly important in the design of storage bins, hoppers, pneumatic conveying systems, screw conveyors, and other machinery. In mechanical and pneumatic conveying systems, agricultural materials often move or slide in direct contact with the trough, casing, and other components of the machine. This interaction between the material and the machine surfaces generates frictional forces that can significantly impact the performance and efficiency of the system. The frictional losses that occur due to these interactions must be overcome by providing additional power to the machine, which can increase energy consumption and operating costs. Therefore, having a thorough understanding of the frictional properties of Chinese potato tubers is essential for designing and optimizing equipment and systems that handle the tubers.

The frictional properties of different commercial grades of Chinese potato tubers are presented in Table 2. In grading equipment design, the rolling angle plays a critical

Table 1. Physical properties of different commercial grades of Chinese potato tubers

Physical properties	Commercial grades of Chinese potato tubers			
	Small (Grade IV)	Medium (Grade III)	Large (Grade II)	Very large (Grade I)
Moisture content (%)	74.41±2.62^{a}	74.63±3.51^{a}	75.06±3.11^{a}	75.32±2.58^{a}
Length (mm)	19.22±3.24^{d}	27.58±2.64^{c}	34.07±3.28^{b}	64.12±2.83^{a}
Width (mm)	15.34±1.98^{d}	21.34±1.56^{c}	32.95±2.06^{b}	51.34±2.76^{a}
Thickness (mm)	14.25±2.28^{d}	20.98±2.37^{c}	30.55±3.05^{b}	48.12±3.62^{a}
Geometric mean diameter (mm)	15.69±2.97^{d}	23.09±3.11^{c}	31.37±2.29^{b}	51.99±2.54^{a}
Arithmetic mean diameter (mm)	16.27±3.11^{d}	23.28±2.39^{c}	32.52±2.47^{b}	54.52±3.09^{a}
Surface area (mm^{2})	20.18±1.15^{b}	21.13±2.23^{b}	25.72±1.94^{a}	28.57±2.28^{a}
True density (kg m^{-3})	1218.16±123.55^{a}	1164.60±112.62^{b}	1029.04±95.32^{c}	918.0±63.48^{d}
Bulk density (kg m^{-3})	514.22±78.66^{c}	535.12±81.47^{b}	538.25±79.24^{b}	627.70±72.35^{a}
Porosity (%)	57.79±1.23^{c}	54.03±0.94^{c}	47.71±2.42^{b}	31.69±1.65^{a}
Sphericity	0.49±0.04^{d}	0.53±0.08^{c}	0.59±0.05^{b}	0.69±0.02^{a}
Roundness ratio	0.40±0.09^{d}	0.42±0.05^{c}	0.63±0.02^{b}	0.69±0.05^{a}

role in determining the curvature and shape of bent metal components, directly affecting the equipment's functionality and precision. The rolling angle of Chinese potato tubers decreased with respect to grades i.e. 17°, 20°, 21° and 23° for Grade I, Grade II, Grade III and Grade IV. The rolling angle of Chinese potato tubers was increased as the moisture content increased. The similar trend was reported by Balakrishnan et al. (2020) and Parveen et al. (2013) in turmeric rhizomes. The size of food produce has a direct impact on its physical behaviour, with larger products typically exhibiting higher rolling angles and angles of friction. The angle of friction plays a critical role in determining the flowability of granular materials, such as grains, powders, or tubers. A higher angle of friction can indicate poorer flowability, which can lead to issues during handling and storage, such as clogging, bridging, or segregation. The angle of friction for Chinese potato tubers varied between 11° and 17° across different grades. Notably, the smallest tubers exhibited the lowest angle of friction (11°), while the largest tubers had the highest angle of friction (17°). The coefficient of friction of Grade I, II, III and IV of Chinese potato tubers were 0.30, 0.24, 0.21 and 0.19, respectively. The coefficient of friction of Chinese potato tubers decreased as the moisture content decreased. The same trend was reported by Balakrishnan et al. (2020). Statistically significant differences ($p<0.05$) were observed in the coefficient of friction among the different grades of Chinese potato tubers.

Table 2. Frictional properties of different commercial grades of Chinese potato tubers

Frictional properties	Commercial grades of Chinese potato tubers			
	Small (Grade IV)	Medium (Grade III)	Large (Grade II)	Very large (Grade I)
Rolling angle (°)	17 ± 0.05^{c}	20 ± 0.03^{b}	21 ± 0.06^{ab}	23 ± 0.02^{a}
Angle of friction (°)	11 ± 0.02^{c}	12 ± 0.05^{bc}	14 ± 0.03^{b}	17 ± 0.04^{a}
Coefficient of friction	0.19 ± 0.04^{c}	0.21 ± 0.07^{c}	0.24 ± 0.04^{b}	0.30 ± 0.03^{a}

A decreasing trend was observed in length, width, thickness, bulk density, true density, and coefficient of friction for different grades of Chinese potato tubers. The tubers approximated a spherical shape, with sphericity values ranging from 0.69 (Grade I) to 0.49 (Grade IV) and roundness values ranging from 0.69 (Grade I) to 0.40 (Grade IV) among the different commercial grades studied. Notably, the bulk density decreased from 627 kg m^{-3} (Grade I) to 514 kg m^{-3} (Grade IV). The arithmetic mean diameter values exceeded the geometric mean diameter values across different commercial grades of Chinese potato. Chinese potato tubers larger than 40 mm in size (Grade I) exhibited higher angles of friction and coefficients of friction.

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