Journal of Applied Horticulture, 26(1): 73-77, 2024

https://doi.org/10.37855/jah.2024.v26i01.14

Journal of Applied Horticulture

ISSN: 0972-1045

Engineering properties of colored capsicum crop for innovative robotic harvesting solutions in protected agriculture

R. Sai Prasanth[1]*, A. Surendrakumar[1], R. Kavitha[1], K. Nagarajan[2], K. Venkatesan[3], and R. Ravikumar[4]

*[1]Department of Farm Machinery and Power Engineering, Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore, India. [2]Department of Soil and Water Conservation Engineering, Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Kumulur, India. [3] Department of Spices and plantation crops, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore, India.[4]Mathematics, Department of Agricultural Meteorology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore, India.*E-mail: saiprasanthravuri@gmail.com*

Abstract

Capsicum annuum L., also known as bell or sweet pepper, is a globally significant horticultural crop in the Solanaceae family. India's red and yellow colored capsicum holds 13th rank in export. In India, color capsicum is a valuable crop, yielding 2.34 times more per square meter in protected cultivation comparing open field. Tamil Nadu contributes 16,689 tonnes on 284 hectares, comprising 5.13% of India's total. Modern agriculture benefits from automation and robotics, especially in protected cultivation for selective, high-quality capsicum harvesting, reducing labor fatigue. In consideration to the issues like timely and repetitive harvestings and shortage of labour a study was focused to develop a robotic harvester. The study evaluated the engineering attributes of red and yellow capsicum during protected cultivation, classified into size categories A, B and C. Moisture content ranged from 83.6% to 87.12%. Capsicum dimensions spanned 57 mm to 110 mm in length, 52 mm to 98 mm in width, and 51 mm to 96 mm in thickness. Red capsicum had slightly larger arithmetic, geometric, square mean, and equivalent diameters, with sphericity ranging from 0.89 to 0.93. Surface area varied from 87 cm^2 to 316 cm^2, volume from 108 cm^3 to 363 cm^3, and mass from 67 g to 226 g, with red capsicum slightly larger. The highest static friction coefficient was with aluminum, at 0.61 to 0.66. Using the CIELAB model for color estimation, the significant color difference for red and yellow capsicum were 79.26 and 70.28 respectively. Moisture content was negatively correlated with aspect ratio and sphericity, and other attributes had positive correlations. This data is valuable for potential capsicum harvesting mechanization in robotics and protected cultivation.

Key words: *Capsicum annuum* L., robotics, harvester, protected cultivation, engineering properties, precision agriculture

Introduction

Capsicum annuum L., also referred to as bell pepper, sweet pepper, or simply capsicum, is a widely grown and economically important plant variety that is extensively cultivated within the Solanaceae plant family (Srivastava and Mangal, 2019) As per FAO statistics, 2022, the global production of fresh bell pepper reached 36.00 million metric tons with China as the leading producer contributing to 53% of the world's production. As per Horticultural Statistics 2021-22 estimates, India cultivated capsicum across 38,000 hectares, resulting in a total yield of 563,000 metric tons, with a productivity rate of 14.8 metric tons per hectare. Indian capsicum varieties are in high demand for export, ranking 13th in terms of exports to countries such as Qatar, Oman, the UAE, the UK, and Bangladesh. Colored capsicum, is a valuable vegetable crop of significant importance, grown both in open fields and under protected cultivation in India. The yield of capsicum in a protected cultivation, when compared to open field conditions, was determined to be 2.34 times higher per square meter of cultivated area (Ghosal and Das, 2012). Therefore, considering both the higher yield and export demand, farmers prefer cultivating capsicum in protected environments, over open field conditions. In India the states of Karnataka, Himachal Pradesh, Haryana, Jharkhand, Madhya Pradesh, Maharasthra, Tamil Nadu, Utharakhand, Jammu & Kashmir and Odisha are considered as top 10 producing states of capsicum. During the 2017-2018 period, Capsicum production in Tamil Nadu amounted to approximately 16,689 tonnes, cultivated across 284 hectares, representing 5.13 percent share of the total capsicum production in India.

Cultivating high-value vegetables in protected environments such as greenhouses has shown promise in benefiting farmers' well-being. Technological advancements in this area not only create new opportunities at an advanced level but also help smaller-scale growers by increasing productivity, which remains economically relevant to agriculture (Bala, 2013).

The progress of technology has led to the adoption of various automation and robotics applications in modern agriculture. Robotic manipulators and robots are increasingly being used, particularly in protected cultivation. The utilization of emerging technology in developing robotic arms is crucial for harvesting fruits and vegetables in protected environments (Ringdahl *et al.*, 2019). Robotic harvesting facilitates extended selective harvesting, enhancing quality and reducing labor fatigue from repetitive tasks, such as harvesting capsicum vegetables from the first picking (Moghimi *et al.*, 2015). To address issues like timely harvesting and labor shortages, research has focused on developing robotic harvesters for mature capsicum. These units typically include an image recognition system to identify ripe capsicum, a robotic arm with an end-effector comprising a holding unit for the capsicum and a cutting unit for removing it from the plant, and a mobility unit to navigate between plants and collect harvested capsicum.

The design of robotic harvesters relies heavily on the physical properties of the crops to determine the size of the unit and the robotic arm (Al-Maiman and Ahmad, 2002; Bachche and Oka, 2013; Lehnert *et al.*, 2017). Engineering properties of capsicum, especially regarding the development of the end-effector for the robotic arm, are crucial. The end-effector typically includes an image sensor to identify ripe capsicum, a gripper to hold the capsicum, and a cutting tool to detach it from the plant. Understanding these parameters involves studying both the physical properties of the crop and its engineering properties (Celik and Ercisli, 2009; Bac *et al.*, 2016).

This objective of the study encapsulates the research focus on understanding the physical and mechanical characteristics of capsicum varieties relevant to robotic harvesting technologies, emphasizing their application in modern agricultural practices.

Materials and methods

The capsicum crop physical properties data was collected from farmers' fields at Hosur district of Tamil Nadu. The Rizwan variety of capsicum was mostly cultivated in that region, which includes both Red and Yellow color variations, widely recognized and popular across India. The crop physical properties such as soil type, type of cultivation, bed spacing, row to row and plant to plant spacing, crop height, crop canopy area, number of fruits per plant and average yield were recorded. The capsicum was classified into three classes such as class A, B and C based on its size (Fig.1) and demand in export market. The engineering properties of capsicum vegetable for 50 numbers were tested in the laboratory of Department of Farm Machinery and Power Engineering at Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore.

Fig. 1. Different classes of capsicum

The moisture content of both vegetable and peduncle ($M.C_V$ and $M.C_f$,% w.b) was determined using oven dry method (Rokayya and Khojah, 2016). The physical dimensions of individual capsicum vegetable, including length (L, mm), width (W, mm), and thickness (T, mm), were measured using vernier calipers with a sensitivity of 0.01 mm. Peduncle dimensions were also recorded with standard one inch micrometer with a sensitivity of 0.01 mm. The morphological characteristics of the capsicum such as Aspect ratio (A_r), Geometric mean diameter (D_g), Arithmetic mean diameter (Da), square mean diameter (D_{sqm}) and equivalent diameter (D_e) were computed according to the mathematical expressions of ellipsoidal bodies (Maduka and Faborode, 1990; Mohsenin, 1986; Rokayya and Khojah, 2016; Carvalho *et al.*,2021).

$$\mathrm{Ar} = \frac{W}{L}$$

$$Da = \frac{L + W + T}{3}$$

$$Dg = (LWT)^{0.333}$$

$$Dsqm = (\frac{LW + WT + TL}{3})^{0.333}$$

$$De = \frac{Da + Dg + Dsqm}{3}$$

Where L: length (mm), W: Width (mm) and T: thickness (mm)

The sphericity (ϕ) is determined by using following equation by Fathollahzadeh *et. al.* (2008). The volume of the capsicum was calculated by three different mathematical relations such as actual volume (V_a, cm^3) the amount of water displaced by one vegetable, prolate spheroid volume (V_s, cm^3) which is essential for elongated or stretched sphere and ellipsoidal volume (V_{el}, cm^3). These volume values were determined by the following mathematical relationships (Taheri-Garavand *et al.,* 2011; Rokayya and Khojah, 2016).

$$\varphi = \frac{Dg}{L}$$

$$Vm = \frac{w}{\gamma}$$

$$Vs = \frac{4\pi}{3} \times \frac{L}{2} \times (\frac{W}{2})^2$$

$$Vel = \frac{4\pi}{3} \times \frac{L}{2} \times \frac{W}{2} \times \frac{T}{2}$$

Where, D_g - geometric mean diameter, *w* (kg) - the weight of the displaced water and ($kg.cm^{-3}$) - the weight density of water.

The individual mass of capsicum for all the variety was determined using electronic balance with an accuracy of 0.01 g. The co-efficient of static friction on different surfaces with stainless steel, galvanized iron, aluminum and wood materials was measured by sliding apparatus with loading pan. The experiment was replicated 10 times for each variety.

$$\mu_s = \frac{F}{N}$$

Where, μ_s = Co-efficient of static friction. F= Frictional force, N (weight of the load added in the loading pan). N = Normal Force, N (weight of capsicum)

The L*, a* and b* color values were observed by a Hand-Held Imaging Spectrocolorimeter (Lovibond® LC100). Considering the red and yellow varieties of capsicum a total of five different classes were considered. The spectrometer was calibrated using the manufacturer's standard white plate. The vegetable was captured with the optics of spectrometer keeping on the surface of the capsicum at minimum of 5 different places. All changes of color were quantified in the CIELAB color space model (CIE stands for Commission Internationale de l´Eclairage (The International Commission on Illumination)). The color values were determined by using following mathematical equation (Rossi *et al.,* 2021; Sharangi *et al.,* 2022)

$$DE^*ab = [(DL)^2 + (Da)^2 + (Db)^2]^{1/2}$$

The data collected from replications of both red and yellow color capsicum were subjected to analysis of variance (ANOVA) using SPSS statistical package. Significant difference between the means was determined by Duncan's New Multiple Range Test (*P* < 0.05). The correlation between the properties was determined by using R statistical package.

Results and discussion

An overview of physical characteristics of Rizwan variety capsicum crop is displayed in Table 1. The capsicum crop was preferred to be cultivated in raised bed as the crop exhibits indeterminent growth pattern under protected cultivation. The bed width of 45 cm for single row and 90 cm for paired row cultivation was observed. The row to row and plant to plant spacing was 0.45 m and 0.40 m respectively. The spacing between the beds was 1 m. These dimensions were used as the basis for determining the harvester unit size.

The summary of the engineering properties of capsicum for all red and yellow colored capsicum of class A, B and C are provided in Table 2. The average moisture content during harvesting time was calculated by hot oven dry method which falls within the range of 87.46 to 91.12% with specific values being 91.12, 86.12, 88.60, 88.04, 90.67 and 87.46% for red and yellow capsicum in classes A, B and C respectively. The moisture content relates to weight of capsicum for designing the end effector which holds the capsicum after the detachment from the plant. Additionally, it serves as an indicator of capsicum quality and contributes to the overall weight of the capsicum, making it a significant factor in these aspects. The fundamental physical attributes of capsicum which includes length, width, thickness and aspect ratio were measured for all the categories of colored capsicums. The values were different and the significant difference is indicated in the Table 2. The overall ranges of length, width and thickness for red colored capsicum was 108.14mm to 59.33mm, 98.78mm to 51.87mm and 96.19mm to 52.01 mm respectively. Similarly for yellow variety the values fall between the range of 110.50 mm to 57.80 mm, 93.24 mm to 52.63 mm and 94.62 mm to 49.04 mm respectively. These values have significant effect in defining the size of the capsicum. The results closely aligned with the findings of Bachche and Oka (2013) and Lehnert *et al.* (2017).

Table 1. Data collected from the farmers' fields in Satyamangalam, Hosur (Dist.), Tamil Nadu

Characteristics		Specification
Variety	:	Rizwan
Color of capsicum	:	Red, Yellow
Type of sowing	:	Seedlings growing in portrays up to 45 days and then transplanting on the raised beds
Sowing pattern	:	Single row or paired Row
Row to row spacing	:	0.45 m (Paired row)
Plant to Plant	:	0.40 m
Bed Dimensions	:	0.9*0.15 m
Spacing between beds	:	1 m
Type of soil	:	Red soil
Average plant height	:	1.8 to 2.2 m
No. of vegetables per plant per whole season	:	24 to 30
Yield per acre	:	60 tonnes per acre
Average no. of harvestings	:	55 to 60
Yield per harvesting	:	0.8 to 1 ton
Harvesting stage	:	80 DAT
Duration of crop	:	10 months

The morphological attributes such as aspect ratio (A_r), Geometric mean diameter (D_g), Arithmetic mean diameter (D_a), Square mean diameter (D_{sqm}) and Equivalent diameter (D_e) were determined for all the classes of both color capsicum and the mean values are provided in the Table 1. The aspect ratio for Red color capsicum ranged from 0.88 to 0.92 and for yellow variety it varies from 0.85 to 0.91. The average geometric diameter measurements for red capsicum in groups A, B and C were 100.31 mm, 73.77 mm, and 54.01 mm respectively. Similarly, for yellow capsicum in the same groups, the average geometric diameters were 98.60 mm, 74.58 mm and 52.78 mm, respectively.

The observation showed that as the size of the capsicum increased, the geometric mean diameter of that capsicum also increased. Consequently, the capsicum with the smallest minor diameter or thickness had the smallest geometric mean diameter. This geometric mean of the axial dimension serves as a valuable way to define the characteristic dimension for irregularly shaped vegetables (Rokayyaand Khojah, 2016). Additionally,

Table 3. Engineering attributes of capsicum varieties

Type of capsicum	Red_A	Red _B	Red_C	Yellow_A	Yellow_B	Yellow_C
Moisture content (%)	85.46±3.07b	87.12±2.31c	83.6±2.93a	86.04±2.07b	85.67±2.20b	83.46±3.13a
Length (mm)	108.14±8.49d	88.87±5.97c	59.33±3.36a	110.5±6.0e	82.57±4.94b	57.8±3.30a
Width (mm)	98.78±4.81e	67.03±4.07b	51.87±3.83a	93.24±4.22d	71.39±3.00c	52.63±2.17a
Thickness (mm)	96.19±5.36d	68.54±3.42c	52.01±2.38b	94.62±6.27d	69.74±3.90c	49.04±2.72a
Aspect Ratio	0.92±0.09d	0.76±0.07a	0.88±0.08c	0.85±0.06b	0.87±0.06b	0.91±0.07d
Arithmetic diameter (mm)	101.04±3.42e	74.81±2.46c	54.4±1.70b	99.45±3.14d	75.12±2.67c	53.16±1.57a
Geometric diameter (mm)	100.31±3.31e	73.77±2.32c	54.01±1.70d	98.6±3.15d	74.58±2.64c	52.78±1.55a
Square mean diameter (mm)	28.59±0.62f	23.17±0.50c	18.88±0.44b	28.17±0.59e	23.41±0.55d	18.67±0.35a
Equivalent diameter (mm)	76.65±2.45e	57.25±1.75c	42.43±1.28b	75.41±2.29d	57.7±1.95c	41.53±1.15a
Surface area (cm^2)	316.28±20.94e	171.05±10.71c	91.68±5.80b	305.56±19.66d	174.85±12.34c	87.54±5.17a
Sphericity	0.93±0.06d	0.83±0.04a	0.91±0.04bc	0.89±0.04b	0.91±0.04bc	0.92±0.04cd
Prolate spheroid volume (cm^3)	552.45±68.9d	209.12±27.01b	83.82±13.13a	503.02±53.28c	220.35±23.28b	83.73±7.88a
Ellipsoid volume (cm^3)	536.43±53.50d	213.12±19.92b	83.55±7.98a	509.32±49.45c	214.79±20.03b	77.93±6.94a
Actual volume (cm^3)	363.8±16.10e	268.24±9.76c	108.62±9.92a	356.6±16.96d	254.42±15.16b	113.8±10.09a
Mass (g)	226.27±9.46f	152.19±6.52c	62.95±0.48b	217.12±8.44e	155.27±8.1d	57.95±5.48a

The values in the table are represented as mean ± standard deviation (n=50). Significant differences (P<0.05) within the same column of each class of both red and yellow capsicum are indicated by different letters.

the average values of arithmetic mean diameter (D_a), square mean diameter (D_{sqm}) and equivalent diameter (D_e) shown significant difference with each class among A, B and C classes of Red and Yellow capsicum varieties.

The average values of the surface areas fall within the range of 316.28 cm^2 to 87.54 cm^2 with specific values being 316.28 cm^2, 171.05 cm^2, 91.68 cm^2, 305.56 cm^2, 174.85 cm^2 and 87.54 cm^2 for red and yellow capsicum in classes A, B and C, respectively (Rokayya and Khojah, 2016 and Rossi *et al.,* 2016)

The mean values of sphericity were reported as 0.93, 0.83, 0.91, 0.95, 0.87 and 0.92 for red and yellow capsicum in classes A, B, and C respectively. The sphericity of the vegetable signifies gripping area and also for the design of the hopper for collecting harvested capsicum. The findings were found nearer to the results of Lehnert *et al.* (2017).

The volume of capsicum were determined in three different forms such as prolate spheroid volume, ellipsoid volume and actual volume since the capsicum have ellipsoid shape. The volume of the capsicum was 552.45 (V_s, cm^3), 536.43 (V_{el}, cm^3) and 363.80 (V_a, cm^3) for Red (A), 209.12 (V_s, cm^3), 213.12 (V_{el}, cm^3) and 268.24 (V_a, cm^3) for red (B) and 83.82 (V_s, cm^3), 83.55 (V_{el}, cm^3) and 108.62 (V_a, cm^3) for red (C), 503.02 (V_s, cm^3), 509.32 (V_{el}, cm^3) and 356.60 (V_a, cm^3) for yellow(A), 220.35 (V_s, cm^3), 214.79 (V_{el}, cm^3) and 254.42 (V_a, cm^3) for yellow (B), 83.73 (V_s, cm^3), 77.93 (V_{el}, cm^3) and 113.80 (V_a, cm^3) for yellow (C) varieties. The trend in the values follows with the results of Rokayya and Khojah (2016) and the values were closely aligned with the values of Bachche and Oka (2013) and Lehnert *et al.* (2017).

The average mass values for the red capsicum variety with A, B and C values were 212.6 g, 151.5 g and 53.6 g respectively, followed by yellow colored capsicum with the values as 206.4 g, 155.7 g, and 48.9 g for A, B and C classes respectively. The coefficient of static friction was determined and the results of the experiment depicts that the values for aluminum surface gives high coefficient of static friction (0.61 to 0.66) followed by galvanized sheet (0.41to 0.45) and stainless steel (0.53 to 0.59).

The color characteristics of capsicum play a crucial role for the image sensor for identifying matured capsicum based on their color changes. Table 3 provides the average color values using the CIELAB model, which are used is several fascinating insights. The correlation coefficients between various engineering attributes of colored capsicum are dipected in Table 4.

Table 3. CIELAB values of different classes of colors in both red and yellow colored capsicums

Colour class	L*	a*	b*	E*
Green	-69.00±2.40c	-3.94±3.45a	15.12±4.34a	71.40±4.5b
Brown	-69.50±3.22c	19.34±5.21d	18.60±3.54b	75.54±4.45c
Red	-73.22±3.54d	23.08±1.54e	17.98±5.46b	79.26±6.55d
Greenish yellow	-60.98±4.38b	10.04±2.34b	28.30±4.33c	70.30±4.52a
Yellow	-51.74±30.67a	13.42±3.56c	43.80±6.5d	70.28±3.44a

The values in the table are represented as mean ± standard deviation (n=10). Significant differences (P<0.05) within the same column of each class of both red and yellow capsicum are indicated by different letters

Firstly, it is evident that moisture content is positively correlated with length, width, and thickness with correlation coefficients of 0.319, 0.242, and 0.276 respectively at 0.01 significant levels. This suggests that as moisture content increases, these physical dimensions tend to increase as well. Conversely, moisture content exhibits a strong negative correlation with Aspect Ratio (-0.205) indicating that higher moisture content tends to result in a more spherical shape. Secondly, the attributes related to diameter (arithmetic diameter, geometric diameter, square mean diameter, and equivalent diameter) are highly positively correlated with each other, with correlation coefficients close to or exceeding 0.99. This indicates a strong linear relationship between these dimensions, implying that they tend to change proportionally. These dimensions also have a strong positive correlation with surface area, suggesting that larger diameters result in greater surface areas.

Additionally, the aspect ratio of capsicum is negatively correlated slightly with most physical properties, particularly with moisture content (-0.205), length (-0.267), volume (-0.105) and mass (-0.079) indicating that more spherical higher aspect ratios are associated with lower moisture content, length, volume and mass values.

Table 4. Values indicating correlation coefficients of different engineering attributes of capsicum

	MC	L	W	T	A.R	A.D	G.D	S.M.D	E.D	S.A	S	PSV	EV	AV
M.C	1	0.319**	0.242**	0.276**	-0.205**	0.287**	0.284**	0.288**	0.286**	0.260**	-0.174**	0.225**	0.237**	0.335**
L	0.319**	1	0.911**	0.919**	-0.267**	0.970**	0.967**	0.966**	0.968**	0.955**	-0.233**	0.928**	0.936**	0.951**
W	0.242**	0.911**	1	0.951**	0.143*	0.977**	0.979**	0.982**	0.979**	0.981**	0.158**	0.983**	0.973**	0.935**
T	0.276**	0.919**	0.951**	1	0.001	0.977**	0.978**	0.974**	0.977**	0.978**	0.114*	0.943**	0.972**	0.944**
A.R	-0.205**	-0.267**	0.143*	0.001	1	-0.051	-0.038	-0.03	-0.043	-0.003	0.928**	0.067	0.024	-0.105
A.D	0.287**	0.970**	0.977**	0.977**	-0.051	1	1.000**	0.999**	1.000**	0.995**	0.005	0.974**	0.982**	0.969**
G.D	0.284**	0.967**	0.979**	0.978**	-0.038	1.00**	1	0.999**	1.000**	0.996**	0.019	0.974**	0.983**	0.968**
S.M.D	0.288**	0.966**	0.982**	0.974**	-0.03	0.99**	.999**	1	.999**	0.993**	0.021	0.972**	0.978**	0.971**
E.D	0.286**	0.968**	0.979**	0.977**	-0.043	1.00**	1.00**	0.999**	1	0.995**	0.013	0.974**	0.982**	0.968**
S.A	0.260**	0.955**	0.981**	0.978**	-0.003	0.995**	0.996**	0.993**	0.995**	1	0.052	0.987**	0.995**	0.947**
S	-0.174**	-0.233**	0.158**	0.114*	0.928**	0.005	0.019	0.021	0.013	0.052	1	0.081	0.076	-0.046
PSV	0.225**	0.928**	0.983**	0.943**	0.067	0.974**	0.974**	0.972**	0.974**	0.987**	0.081	1	0.991**	0.909**
EV	0.237**	0.936**	0.973**	0.972**	0.024	0.982**	0.983**	0.978**	0.982**	0.995**	0.076	0.991**	1	0.920**
AV	0.335**	0.951**	0.935**	0.944**	-0.105	0.969**	0.968**	0.971**	0.968**	0.947**	-0.046	0.909**	0.920**	1
M	0.325**	0.950**	0.947**	0.951**	-0.079	0.974**	0.974**	0.977**	0.974**	0.955**	-0.019	0.921**	0.929**	0.982**

The sphericity of capsicum is positively correlated with aspect ratio (0.928) and negatively correlated with most physical properties, particularly with moisture content (-0.174), length (-0.233), volume (-0.046) and mass (-0.019) indicating that more spherical shapes are associated with high aspect ratio and low moisture content, length, volume and mass values.

In conclusion, the correlation analysis of capsicum physical properties provides valuable insights into the relationships between various attributes. These insights can be used to better understand the characteristics of capsicum and potentially inform agricultural practices or product quality control processes.

The study assessed engineering attributes of red and yellow capsicum during harvest for developing a robotic harvester in protected cultivation. The protected cultivation capsicum was categorized into size classes as A, B and C. The findings revealed that the moisture content across all classes fell within the range of 83.6 to 87.12%. The physical attributes of capsicum length varied from 57 mm to 110 mm, width ranged from 52 mm to 98 mm, and the thickness spanned from 51 mm to 96 mm. The calculated arithmetic, geometric, square mean, and equivalent diameters were slightly higher in red capsicum than yellow. The sphericity varied from 0.89 to 0.93, surface area ranged 87 cm^2 to 316 cm^2, volume ranged 108 cm^3 to 363 cm^3 and the mass varied from 67 g to 226 g. Notably, the linear dimensions of red bell peppers were slightly larger than those of yellow ones. The highest coefficient of friction was observed with aluminum material, ranging from 0.61 to 0.66. the color difference values accessed with CIELAB model indicated a greater distinction for red bell capsicum at 79.26, compared to 70.28 for yellow colored capsicum. The major finding in the correlation among the engineering attributes was the moisture content which was negatively correlated with aspect ratio and sphericity and all the remaining values were positively correlated. The data gathered from this study provides valuable insights for the potential mechanization of capsicum harvesting, particularly in the realm of robotics and protected cultivation.

Acknowledgement

The authors of this article acknowledge the departments of Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore for providing access to conduct the laboratory experiments related to this research.

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Received: September, 2024; Revised: December, 2023; Accepted: January, 2024