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INTERRELATIONSHIP OF GRADING AND SORTING PARAMETERS OF INDIAN JUJUBE (*Ziziphus mauritiana* L.) USING COMPUTATIONAL SIMULATION

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ABSTRACT

Various physical attributes of jujube fruits, including axial dimensions, geometric and arithmetic mean diameters, sphericity, weight, volume, and projected areas, were analyzed to estimate their relationship with fruit mass. This analysis utilized five different models—S-curve, linear, power, quadratic, and logarithmic—for both ungraded and three size-graded categories of jujube fruits. Among the models, the power model ($M = 0.984V^{1.014}$) demonstrated the best fit for ungraded fruits, exhibiting the highest R^2 value (0.999) and the lowest standard error of estimate (SEE = 0.012) for mass prediction. For the graded fruits, the power model ($M = 1.012V^{1.005}$) based on the actual volume of small jujube fruits proved to be the most efficient, with an R^2 value of 0.996. These findings suggest that mass modelling using actual volume for ungraded Indian jujube fruits yields the most accurate predictions compared to graded fruits, which is critical for the design and development of effective and precise grading mechanisms.

Keywords: Grading, Indian jujube, Mass, Modelling, Physical properties

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Accurately determining the physical attributes of agricultural produce is essential for the development and design of grading and sorting equipment, material handling systems, processing machinery, and packaging solutions. Grading, which frequently involves assessing physical characteristics such as size, shape, mass, colour, appearance, and texture, is a critical process in this regard (Banga *et al.*, 2019). Proper grading facilitates the achievement of uniform physical qualities, thereby optimizing packaging configurations and minimizing both packaging and transportation costs (Sadrnia *et al.*, 2007). However, grading becomes more complex when fruits appear similar but differ in mass. Therefore, mass-based grading is crucial for the design of effective grading machinery and equipment. Grading by mass is often more cost-effective compared to grading by size, as highlighted by Birania *et al.* (2022). Among the most significant physical properties for designing grading systems are mass, volume, dimensions, and projected area (Shahbazi & Rahmati, 2014). These properties are also critical for food processing systems (Birania *et al*., 2022b; Mandale *et al*., 2023; Ghanghas *et al*., 2024) and food packaging (Kargwal *et al.*, 2021). Additionally, understanding these fundamental physical attributes is valuable for pharmacists, researchers, scientists, engineers, crop breeders, and industrial processors, as they explore advanced applications of biomaterials (Pathak *et al.*, 2019).

Numerous studies have demonstrated that fruit mass can be predicted using various physical properties. For example, research has been conducted on apples (Tabatabaeefar *et al.*, 2005), bananas (A'Bidin *et al.*, 2020), dates (Khodabakhshian *et al.*, 2016), Indian coffee plums (Barbhuiya *et al.*, 2020), onions (Ghaben *et al.*, 2010), and pomegranates (Khosnam *et al.*, 2007). However, there is a notable gap in the literature regarding mass modelling for Indian jujube. This study aims to address this gap by evaluating the physical attributes of Indian jujube, including dimensions, mass, volume, arithmetic mean diameter, geometric mean diameter, aspect ratio, sphericity, and projected area. These attributes were assessed across three size grades as well as for ungraded fruits, drawing parallels with studies on *kinnow* mandarin (Mahawar *et al.*, 2019), strawberries (Birania *et al.*, 2022), and wood apples (Grover *et al.*, 2024).

The study seeks to identify the most appropriate model for predicting fruit mass based on the diverse physical properties of both graded and ungraded jujube fruits. The outcomes of this research are expected to significantly contribute to the development of an effective grading system for Indian jujube cv. Apple, based on their physical characteristics.

MATERIALS AND METHODS

Freshly harvested Indian jujube fruits, cv. Apple, were procured from the university orchard at CCS Haryana Agricultural University, Hisar, India. For this study, a total of 90 mature fruits, representing a range of sizes, were classified into three grades based on visual observation: small, medium, and large. Each grade

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consisted of 30 representative fruits (Table 1).

Evaluation of physical attributes

The jujube fruit exhibits a tri-axial ellipsoid shape, characterized by three linear dimensions: major intercept (length, LLL), intermediate intercept (width, WWW), and minor intercept (thickness, TTT). These dimensions were measured in triplicate using a Vernier caliper (CD-6" CSX, Mitutoyo Corp., Japan, accuracy ±0.001 mm), following the methodology outlined by Birania *et al.* (2022). The mass of the jujube fruits was determined using an electronic balance (BT 423S; Sartorius, Germany, accuracy ±0.001 g). Fruit volume (VVV), expressed in cubic centimeters (cc), was measured using the water displacement method as described by Abdel-Sattar et al. (2021). The following physical attributes were calculated using the methods and formulas provided by Abdel-Sattar *et al.* (2021) and Birania *et al.* (2022):

$$Da = \frac{L + W + T}{3} \quad (1)$$

$$Dg = (L \times W \times T)^{1/3} \quad (2)$$

$$AR = \frac{L}{W} \quad (3)$$

$$\emptyset = \frac{(LWT)^{1/3}}{L} \quad (4)$$

$$\varepsilon = \left(1 - \frac{P_b}{P_t}\right) \times 100 \quad (5)$$

$$Sa = \pi \times D_g^2 \quad (6)$$

In addition to the aforementioned dimensional attributes, the projected area of a fruit serves as a valuable indicator of mass for individual fruits. This information is particularly useful in the design of grading systems that utilize machine vision technology (Ghanghas *et al.*, 2024). Such technology enhances grading accuracy and efficiency and supports improved drying and cooling processes by providing precise modelling of heat and mass transfer phenomena (Manju *et al.*, 2021). The three projected areas of Indian jujube in three perpendicular dimensions *viz*., PA_L, PA_W, PA_T, projected area (mm^2) perpendicular to the length, width, and thickness respectively, were observed by using a camera and Fiji ImageJ software. The average/criteria projected area (CPA) was calculated using the three perpendicular projected areas, as described in equation (7) proposed by Birania *et al.* (2022) and Pathak *et al.* (2019).

$$CPA = \frac{PA_L + PA_W + PA_T}{3} \quad (7)$$

Mass modelling of fruits

Based on the measured physical attributes (dimensional, projected area, and volume), the mass prediction of the Indian jujube was analyzed under three categories of the models suggested below:

- Jujube fruit mass dependent on dimensional attributes *viz*. L, W, T, AMD, GMD, and sphericity in a single variable regression analysis.
- Jujube fruit mass dependent on the observed volume (V) in a single variable regression analysis.
- Jujube fruit mass dependent on the projected areas *viz*. PA_L, PA_W, PA_T, and CPA in a multiple variable regression analysis.

For mass prediction of ungraded and graded jujube fruits, five regression models were used: Linear (M=a+bX), Logarithmic (M=a+b ln(X)), Power (M= aX^b), Quadratic (M=a+bX+cX^2), and S-curve (M=a+(b/X)).

where. M stands for the jujube fruit's mass in gram (g), and X is the average of the physical attributes that were taken into consideration (dimension, volume, or predicted area) to determine how mass relates to those attributes. Where, for each equation, a, b, and c are various curve fitting constants.

Statistical analysis and validation of the model

Statistical data analysis and model applicability were evaluated using SPSS version 26.0, with significance set at the 5% level. The suitability of the models for predicting fruit mass was assessed based on the coefficient of determination (R^2) and the standard error of estimation (SEE). For all three grades of jujube fruits, both graded and ungraded, the regression model with the highest R^2 value and the lowest SEE value was deemed the most suitable. This approach aligns with the criteria set forth by Birania *et al.* (2022), where a higher R^2 and a lower SEE indicate a better model fit.

RESULTS AND DISCUSSION

Physical properties of Indian jujube fruits

Indian jujube fruits exhibit significant variation across different grades. For instance, the length (L) ranges from 34.5 to 56.49 mm, thickness (T) from 22.11 to 39.1 mm, and width (W) from 23.16 to 42.21 mm. The aspect ratio (AR) varies between 1.10 and 1.64, while the arithmetic mean diameter (Da) ranges from 26.59 to 45.29 mm and the geometric mean diameter (Dg) spans from 26.04 to 44.75 mm. Additionally, the surface area (Sa) ranges from 2131.6 to 6292.22 mm^2, and the volume (V) varies from 11.21 to 48.45 mm^3. These attributes are essential for the design and optimization of mechanical components in grading machinery. Detailed data on these physical attributes, including

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Table 1. Physical attributes of Indian jujube (mean ± standard deviation)

Properties	Small	Medium	Large
L (mm)	40.10 ± 2.27	43.48 ± 2	48.83 ± 3.47
W (mm)	29.13 ± 2.6	34.39 ± 1.58	38.18 ± 1.84
T (mm)	27.78 ± 2.64	32.35 ± 1.57	35.92 ± 1.53
Aspect Ratio	1.38 ± 0.11	1.27 ± 0.08	1.28 ± 0.1
AMD (mm)	32.33 ± 2.14	36.75 ± 1.13	40.98 ± 1.76
GMD (mm)	31.87 ± 2.24	36.42 ± 1.13	40.58 ± 1.67
Sphericity	0.80 ± 0.04	0.84 ± 0.03	0.83 ± 0.04
Weight (g)	18.06 ± 2.99	25.98 ± 2.37	35.54 ± 4.17
Volume (cc)	18.54 ± 3.11	26.72 ± 2.41	36.9 ± 4.46
Density (g/cc)	0.97 ± 0.01	0.97 ± 0.01	0.96 ± 0.01
Porosity	38.1 ± 0.72	49.29 ± 0.58	67.51 ± 0.42
Surface area (mm^2)	3205.15 ± 434.75	4169.88 ± 258.81	5182.29 ± 431.66
PA_L (mm^2)	689.94 ± 118.02	943.77 ± 74.68	1161.96 ± 89.68
PA_W (mm^2)	918.39 ± 115.37	1158.87 ± 85.03	1444.81 ± 143.79
PA_T (mm^2)	1005.01 ± 126.16	1284.52 ± 81.72	1601.52 ± 157.21
CPA (mm^2)	871.11 ± 115.9	1129.05 ± 70.38	1402.76 ± 120.65

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statistical implications for both ungraded and graded jujube fruits, are presented in Table 1. For the three axial dimensions—length, width, and thickness—the mean ± standard deviation (SD) values are provided for small, medium, and large jujube fruits. Notably, across all three grades, the length (L) consistently exhibits the highest average value compared to width (W) and thickness (T). These results align with the findings of Mathangi and Maran (2020) and Pareek *et al.* (2009), demonstrating consistency with previous research on similar attributes.

For all three grades of jujube fruits, the mean ± standard deviation (SD) values for the aspect ratio (AR), arithmetic mean diameter (AMD), and geometric mean diameter (GMD) are detailed in Table 1. Comparable results for these attributes have also been reported for blood fruit and strawberries, as documented by Sasikumar *et al.* (2021) and Birania *et al.* (2022), respectively.

An ideal sphere has a sphericity value of one (Birania *et al.*, 2022). For the jujube fruits, the mean ± standard deviation (SD) values of sphericity across different grades were as follows: small jujube fruits had a sphericity of 0.80 ± 0.04, medium jujube fruits had a sphericity of 0.84 ± 0.03, and large jujube fruits had a sphericity of 0.83 ± 0.04. These values indicate that all three grades of jujube fruits exhibit approximately equal sphericity. Regarding weight, the average values were 18.06 ± 2.99 g for small jujube fruits, 25.98 ± 2.37 g for medium jujube fruits, and 35.54 ± 4.17 g for large jujube fruits.

The average volume of small jujube fruits was 18.54 ± 3.11 cc, while medium jujube fruits had an average volume of 26.72 ± 2.41 cc, and large jujube fruits had an average volume of 36.9 ± 4.46 cc. The average fruit density was 0.97 ± 0.01 for small and medium jujube fruits and 0.96 ± 0.01 for large jujube fruits, indicating that all three grades of jujube fruits have similar fruit densities. The mean ± standard deviation (SD) values of porosity were 38.1 ± 0.72 for small, 49.29 ± 0.58 for medium, and 67.51 ± 0.42 for large jujube fruits, as detailed in Table 1. These results are consistent with those reported by Pareek *et al.* (2009) and Mathangi & Maran (2020) for Indian jujube fruits.

The mean ± standard deviation (SD) values for the surface area of small, medium, and large jujube fruits were 3205.15 ± 434.75 mm^2, 4169.88 ± 258.81 mm^2, and 5182.29 ± 431.66 mm^2, respectively. The surface area and mean projected areas perpendicular to the three axial dimensions—length (PAL), width (PAW), and thickness (PAT)—are presented in Table 1. Using these dimensions, the criteria projected area was calculated, with mean values of 871.11 ± 115.9 mm^2 for small, 1129.05 ± 70.38 mm^2 for medium, and 1402.76 ± 120.65 mm^2 for large jujube fruits. These physical attributes are fundamental for the design and development of vision-based grading systems.

Mass modelling of Indian jujube

Mass modelling for both ungraded and all three grades of jujube fruits was conducted using dimension-based, volume-based, and projected area-

Table 2. Mass modelling results for small-sized Indian jujube fruits

Models	Parameters	Constants			R^2	SSE
		a	b	c		
Dimension Based Models						
Linear	Length	31.675	0.466	-	0.378	1.819
Quadratic		26.869	1.048	-0.017	0.384	1.843
Power		22.417	0.201	-	0.405	0.045
S-Curve		3.874	-3.230	-	0.417	0.045
Logarithmic		17.583	7.821	-	0.390	1.802
Linear	Width	14.319.	0.820	-	0.887	0.891
Quadratic		12.460	1.045	-0.007	0.887	0.904
Power		7.202	0.484	-	0.901	0.030
S-Curve		3.802	-7.589	-	0.887	0.032
Logarithmic		-9.747	13.505	-	0.883	0.907
Linear	Thickness	12.913	0.823	-	0.865	0.988
Quadratic		7.782	1.445	-0.018	0.870	0.986
Power		6.298	0.514	-	0.872	0.036
S-Curve		3.779	-8.037	-	0.854	0.039
Logarithmic		-11.333	13.585	-	0.865	0.988
Linear	AMD	19.636	0.703	-	0.963	0.421
Quadratic		15.704	1.179	-0.014	0.965	0.400
Power		11.006	0.374	-	0.971	0.012
S-Curve		3.810	-5.882	-	0.963	0.013
Logarithmic		-1.166	11.637	-	0.968	0.391
Linear	GMD	18.485	0.741	-	0.976	0.346
Quadratic		14.511	1.222	-0.014	0.981	0.316
Power		10.055	0.400	-	0.983	0.010
S-Curve		3.818	-6.285	-	0.973	0.012
Logarithmic		-3.400	12.250	-	0.980	0.319
Linear	Sphericity	0.625	0.009	-	0.424	0.033
Quadratic		0.582	0.015	0.000	0.425	0.034
Power		0.449	0.198	-	0.422	0.043
S-Curve		-0.056	-3.055	-	0.401	0.044
Logarithmic		0.350	0.155	-	0.419	0.034
Volume Based Models						
Linear	Volume	-0.204	1.038	-	0.995	0.215
Quadratic		1.842	0.790	0.007	0.996	0.204
Power		1.012	1.005	-	0.996	0.012
S-Curve		3.805	-15.752	-	0.979	0.027
Logarithmic		-30.355	16.985	-	0.978	0.465
Area Based Models						
Linear	Surface Area	603.078	144.095	-	0.980	62.853
Quadratic		355.495	174.081	-0.878	0.980	63.271
Power		317.643	0.800	-	0.983	0.019
S-Curve		-12.571	8.781	-	0.973	0.025
Logarithmic		-3618.443	2370.338	-	0.973	72.245
Linear	PA_L	-1.711	38.302	-	0.939	29.577
Quadratic		-8.014	39.065	-0.022	0.939	30.118
Power		38.261	0.999	-	0.942	0.045
S-Curve		7.414	-15.630	-	0.923	0.053
Logarithmic		-1117.164	627.741	-	0.926	32.606
Linear	PA_W	244.606	37.312	-	0.933	30.421
Quadratic		122.547	52.095	-0.433	0.934	30.610
Power		115.099	0.719	-	0.947	0.031
S-Curve		7.460	-11.302	-	0.937	0.034
Logarithmic		-851.923	614.960	-	0.930	31.004
Linear	PA_T	295.641	39.283	-	0.865	47.219
Quadratic		294.338	39.440	-0.005	0.865	48.085
Power		137.794	0.687	-	0.886	0.045
S-Curve		7.524	-10.834	-	0.881	0.046
Logarithmic		-854.900	646.083	-	0.859	48.256
Linear	CPA	179.512	38.299	-	0.974	19.032
Quadratic		136.290	43.534	-0.153	0.974	19.308
Power		91.697	0.779	-	0978	0.021
S-Curve		7.460	-12.236	-	0.967	0.026
Logarithmic		-941.329	629.595	-	0.966	21.668

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based attributes. The results of the regression model equations for each approach are detailed in tables 2-5 which present the regression model equations for each model.

Dimensional properties-based models

From all the dimension based characterized models, the selected models are described by the following equations:

$$M = 10.055 \times GMD^{0.4} \quad (8)$$

$$M = 3.928 + \left(\frac{-8.6}{GMD}\right) \quad (9)$$

$$M = 23.225 + 0.576GMD - 0.002GMD^2 \quad (10)$$

$$M = 11.285 \times GMD^{0.359} \quad (11)$$

The Power model based on GMD as equation (8) for small jujube fruits has resulted in higher R^2 and lower SEE that are 0.983 and 0.010, respectively (Table 2), the S-curve model based on GMD as equation (9) for medium-size jujube fruits has resulted with the higher R^2 and lower SEE that are 0.934 and 0.008 respectively (Table 3), and Quadratic model based on GMD as equation (10) for large size jujube fruits has resulted in the best-fitted model with higher R^2 (0.967) and lower SEE (0.315) as compared to other models for large size fruits (Table 4). In comparison to the large jujube fruits, the results of the entire dimension-based models for the small and medium jujube fruits exhibit lower R^2 values; this may indicate that the large jujube fruits have uniform mass corresponding to their size or dimensions. The Power model from equation (11) based on GMD was the best-suited model for the ungraded jujube fruits, with the highest R^2 (0.993) and lowest SEE (0.010), as shown in Table 5.

Miraei-Ashtiani *et al.* (2014) found that for lime cultivars, the minor diameter-based linear model was the most suitable for mass prediction, achieving an R^2 value of 0.97. Similarly, Mahawar *et al.* (2019) recommended the power model based on the geometric mean diameter (GMD) for predicting the mass of *kinnow* mandarin. For *Terminalia chebula* fruits, Pathak *et al*. (2019) demonstrated that the quadratic model, utilizing the equivalent mean diameter, provided the highest R^2 value of 0.96. Sasikumar *et al.* (2021) reported that the quadratic model was also the most effective for predicting the mass of blood fruit, with the highest R^2 values of 0.954 for arithmetic mean diameter (AMD) and 0.943 for GMD. Additionally, Birania *et al.* (2022) identified the S-curve and power models as suitable for predicting the mass of ungraded strawberries based on GMD, with an R^2 value of 0.949.

Volume-based models

The selected models of volume-based models for all grades are described as the following equations:

$$M = 1.012 \times V^{1.005} \quad (12)$$

$$M = 1.842 + 0.79V + 0.007V^2 \quad (13)$$

$$M = 0.46 + 1.011V \quad (14)$$

$$M = 0.347 + 1.019V + 0.000V^2 \quad (15)$$

$$M = -0.997 + 1.066V \quad (16)$$

$$M = -1.838 + 1.112V - 0.001V^2 \quad (17)$$

$$M = 0.984 \times V^{1.014} \quad (18)$$

Based on the actual volume, for small-sized jujube fruits, the Power and Quadratic models as equations (12) & (13) based on volume were the best-fitted models with a higher R^2 value of 0.996 for both models and a lower SEE value of 0.012 and 0.204 respectively (Table 2). For medium-size jujube fruits, the linear and quadratic models as equations (14) & (15) based on the volume were the best-suited models for the mass prediction with a higher R^2 value of 0.985 for both models and a lower SEE value of 0.299 and 0.304, respectively (Table 3). The linear and quadratic models as equations (16) & (17) based on the volume were the best-suited models for large-sized jujube fruits prediction of mass with a higher R^2 value of 0.990 for both models and lower SEE value of 0.451 and 0.459, respectively (Table 4). For ungraded jujube fruits, the higher R^2 (0.999) and lower SEE (0.012) have resulted in the Power model as equation (18) based on the actual volume (Table 5).

Miraei Ashtiani *et al*. (2014) reported a good relationship between the measured volume and mass of lime cultivars with the higher R^2 value but the best-fit model to predict the mass of lime was based on the estimated volume (prolate spheroid shape) with an R^2 value of 0.99 for sorting systems. Mass prediction of *Terminalia chebula* fruits has depicted the highest R^2 value of 0.97 for quadratic and linear models based on the true and ellipsoid volume as suggested by Pathak *et al*. (2019). The power model was the best for mass prediction based on the true volume of blood fruit with the highest R^2 value of 0.917 as reported by Sasikumar *et al*. (2021). Birania *et al*. (2022) reported the quadratic and linear models for mass prediction of ungraded strawberries based on actual volume, having an R^2 value of 0.996.

Area-based models

The selected models of surface area and projected areas based models for all grades are described as the

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following equations:

$$M = 317.643 \times S_a^{0.8} \quad (19)$$

$$M = 129.422 \times CPA^{0.665} \quad (20)$$

$$M = 7.701 + \left(\frac{-17.360}{CPA}\right) \quad (21)$$

$$M = 1557.71 + 101.986 S_a \quad (22)$$

$$M = 1354.29 + 113.019 S_a - 0.147 S_a^2 \quad (23)$$

$$M = 110.917 \times CPA^{0.712} \quad (24)$$

$$M = 400.078 \times S_a^{0.719} \quad (25)$$

$$M = 591.247 + 160.012 S_a - 0.850 S_a^2 \quad (26)$$

Amongst all the models based on surface area and projected areas, for small-sized jujube fruits, the higher R^2 (0.983) and lower SEE (0.019) resulted in the Power model based on the surface area (S_a) as equation (19) (Table 2), for medium-size jujube fruits, the highest R^2 value was 0.942 and lower SEE (0.015) were obtained in Power and S-curve models based on the CPA as equation (20) & (21), respectively (Table 3). For large-sized jujube fruits, the linear and Quadratic models based on the surface area as equations (22) & (23) indicated a higher R^2 value of 0.968 for both models and a lower SEE value of 78.039 and 79.406, respectively (Table 4). For ungraded jujube fruits three models have resulted, the Power model based on the CPA as equation (24) indicated the higher R^2 and lower SEE value as 0.993 and 0.019 respectively, and the Power and Quadraticmodel based on the surface area as equation (25) & (26) indicated higher R^2 (0.993) and lower SEE value of 0.019 and 76.365, respectively (Table 5). Therefore, it can be concluded that,when compared to all the three sizes of graded fruits, the model based on ungraded jujube fruits is the best.

Miraei Ashtiani *et al*. (2014) reported that the projected area-based power model for mass prediction of the lime cultivars was the best-suited model as $M = 0.001\ PA_1^{1.552}$, having an R^2 value of 0.98. Mass prediction of *Terminalia chebula* fruits in a quadratic model based on the PA_L depicts the highest R^2 value (0.94) as suggested by Pathak *et al*. (2019). The power model ($M=129.3SA^{-0.36}$) was the best-fitted model for the prediction of mass based on the surface area of blood fruit with the highest R^2 value of 0.845 as reported by Sasikumar *et al*. (2021). Birania *et al*. (2022) reported the power model equation with an R^2 value of 0.942 for area-based mass prediction of ungraded strawberries.

This study determined some of the physical attributes of the three grades and an ungraded fruits grade of Indian jujube cv. Apple, based on physical dimensions, volume, and area, and their correlation was established and analyzed with the mass. The Power model for dimension-based models was suggested for the ungraded fruits based on GMD in the non-linear equation of $M=11.285GMD^{0.359}$ having an R^2 value of 0.993. The Power model for volume-based models was the best-fitted model for ungraded jujube fruits in a non-linear equation of $M=0.984V^{1.014}$ having an R^2 value of 0.999. The Power and Quadratic model equation based on the surface area, and the Power model equation based on the CPA of the jujube fruits for ungraded Indian jujube fruits were suggested in form of $M=400.078S_a^{0.719}$, $M=591.247+160.012S_a-0.850S_a^2$, and $M=110.9178CPA^{0.712}$ respectively, with an R^2 value of 0.993.

This study aimed to develop a mass modelling framework for Indian jujube cv. Apple based on selected physical attributes. The goal was to utilize these results in the design and development of an automated, precise grading unit. This unit is intended to grade and segregate large quantities of Indian jujube with high accuracy and minimal labour. The ultimate objective is to facilitate the efficient handling of Indian jujube for various processing operations, enhancing both operational efficiency and overall effectiveness.

Practical applications

Consumers generally prefer fruits that display uniformity in shape, size, and weight. Consequently, grading fruits based on these attributes—size, weight, and appearance—is vital. In automated grading systems, fruit mass is a crucial physical attribute due to its effectiveness and accuracy in operational processes, as well as in the design of storage units and processing machinery. Mass-based grading is fundamental for optimizing packaging configurations, reducing transport resources, minimizing handling waste, and enhancing product marketability. Recent research has increasingly focused on mass modelling using physical attributes for various fruits, such as apples, pomegranates, dates, oranges, lemons, blood fruit, strawberries, and *kinnow* mandarin. This study aims to investigate the relevance, effectiveness, and impact of mass modelling specifically for Indian jujube cv. Apple. The goal is to develop mass models based on selected physical attributes to guide the design and development of an automated, precise grading system. Furthermore, the study seeks to improve drying and cooling operations through accurate modeling of heat and mass transfer phenomena. This paper provides a comprehensive analysis of the relationship between fruit mass and its axial dimensions, volume, and projected area.

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Table 3. Mass modelling results for medium-sized Indian jujube fruits

Models	Parameters	Constants			R^2	SSE
		a	b	c		
Dimension Based Models						
Linear	Length	30.684	0.493	-	0.342	1.650
Quadratic		25.649	0.877	-0.007	0.342	1.680
Power		16.746	0.293	-	0.340	0.038
S-Curve		4.068	-7.641	-	0.339	0.038
Logarithmic		1.364	12.945	-	0.342	1.650
Linear	Width	24.429	0.383	-	0.333	1.311
Quadratic		36.016	-0.501	0.017	0.336	1.332
Power		13.579	0.285	-	0.332	0.037
S-Curve		3.824	-7.407	-	0.328	0.037
Logarithmic		1.772	10.026	-	0.330	1.314
Linear	Thickness	19.415	0.498	-	0.563	1.060
Quadratic		-19.351	3.456	-0.056	0.596	1.037
Power		8.534	0.409	-	0.568	0.033
S-Curve		3.893	-10.752	-	0.576	0.032
Logarithmic		-10.579	13.197	-	0.572	1.048
Linear	AMD	24.843	0.458	-	0.921	0.325
Quadratic		14.105	1.277	-0.016	0.926	0.320
Power		12.674	0.327	-	0.926	0.009
S-Curve		3.935	-8.541	-	0.927	0.008
Logarithmic		-2.481	12.056	-	0.924	0.317
Linear	GMD	24.550	0.457	-	0.926	0.312
Quadratic		12.441	1.381	-0.017	0.933	0.303
Power		12.473	0.329	-	0.932	0.008
S-Curve		3.928	-8.600	-	0.934	0.008
Logarithmic		-2.715	12.028	-	0.931	0.302
Linear	Sphericity	0.805	0.001	-	0.009	0.032
Quadratic		0.606	0.016	0.000	0.011	0.033
Power		-0.140	-0.959	-	0.008	0.038
S-Curve		2.398	0.063	-	0.008	0.038
Logarithmic		0.727	0.034	-	0.010	0.032
Volume Based Models						
Linear	Volume	0.460	1.011	-	0.985	0.299
Quadratic		0.347	1.019	0.000	0.985	0.304
Power		1.086	0.983	-	0.984	0.011
S-Curve		4.276	-25.635	-	0.982	0.012
Logarithmic		-59.589	26.530	-	0.984	0.315
Area Based Models						
Linear	Surface Area	1442.899	104.973	-	0.925	72.111
Quadratic		-948.505	287.470	-3.454	0.930	71.056
Power		488.778	0.658	-	0.932	0.016
S-Curve		9.001	-17.200	-	0.934	0.016
Logarithmic		-4818.508	2762.869	-	0.929	70.341
Linear	PA_L	276.198	25.698	-	0.666	43.936
Quadratic		-300.050	69.673	-0.832	0.669	44.518
Power		94.857	0.705	-	0.685	0.044
S-Curve		7.562	-18.422	-	0.686	0.044
Logarithmic		-1256.203	676.231	-	0.668	43.779
Linear	PA_W	342.765	31.415	-	0.768	41.710
Quadratic		-913.626	127.295	-1.814	0.780	41.344
Power		114.058	0.712	-	0.775	0.035
S-Curve		7.775	-18.632	-	0.779	0.035
Logarithmic		-1536.743	828.582	-	0.774	41.145
Linear	PA_T	526.299	29.187	-	0.717	44.209
Quadratic		1134.603	-17.235	0.879	0.720	44.773
Power		188.576	0.589	-	0.712	0.034
S-Curve		7.750	-15.315	-	0.706	0.035
Logarithmic		-1201.129	764.045	-	0.712	44.595
Linear	CPA	381.754	28.767	-	0.939	17.648
Quadratic		-26.358	59.911	-0.589	0.941	17.691
Power		129.422	0.665	-	0.942	0.015
S-Curve		7.701	-17.360	-	0.942	0.015
Logarithmic		-1331.358	756.286	-	0.941	17.417

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Table 4. Mass modelling results for large-sized Indian jujube fruits

Models	Parameters	Constants			R^2	SSE
		a	b	c		
Dimension Based Models						
Linear	Length	25.347	0.661	-	0.628	2.154
Quadratic		23.307	0.771	-0.001	0.628	2.193
Power		8.516	0.489	-	0.620	0.044
S-Curve		4.391	-17.732	-	0.614	0.044
Logarithmic		-38.004	24.361	-	0.626	2.160
Linear	Width	27.285	0.307	-	0.484	1.343
Quadratic		22.490	0.567	-0.003	0.447	1.365
Power		13.399	0.293	-	0.480	0.035
S-Curve		3.946	-10.680	-	0.479	0.035
Logarithmic		-2.274	11.351	-	0.486	1.340
Linear	Thickness	26.274	0.271	-	0.545	1.052
Quadratic		22.852	0.457	-0.002	0.546	1.069
Power		13.359	0.277	-	0.538	0.030
S-Curve		3.867	-10.080	-	0.536	0.030
Logarithmic		0.147	10.036	-	0.546	1.050
Linear	AMD	26.302	0.413	-	0.952	0.391
Quadratic		22.883	0.598	-0.002	0.953	0.395
Power		11.070	0.367	-	0.951	0.010
S-Curve		4.092	-13.323	-	0.946	0.010
Logarithmic		-13.377	15.249	-	0.952	0.392
Linear	GMD	26.598	0.393	-	0.966	0314
Quadratic		23.225	0.576	-0.002	0.967	0.315
Power		11.509	0.353	-	0.965	0.008
S-Curve		4.068	-12.831	-	0.960	0.008
Logarithmic		-11.220	14.533	-	0.966	0.314
Linear	Sphericity	0.942	-0.003	-	0.126	0.034
Quadratic		0.932	-0.003	-7.2E-6	0.126	0.035
Power		1.351	-0.136	-	0.124	0.041
S-Curve		-0.323	4.902	-	0.122	0.041
Logarithmic		1.235	-0.113	-	0.125	0.034
Volume Based Models						
Linear	Volume	-0.997	1.066	-	0.990	0.451
Quadratic		-1.838	1.112	-0.001	0.990	0.459
Power		0.941	1.027	-	0.989	0.013
S-Curve		4.666	-37.350	-	0.986	0.014
Logarithmic		-103.230	39.316	-	0.986	0.532
Area Based Models						
Linear	Surface Area	1557.710	101.986	-	0.968	78.039
Quadratic		1354.290	113.019	-0.147	0.968	79.406
Power		416.098	0.707	-	0.965	0.015
S-Curve		9.281	-25.662	-	0.960	0.016
Logarithmic		-8223.374	3761.030	-	0.965	81.815
Linear	PA_L	502.476	18.556	-	0.743	46.287
Quadratic		284.910	30.357	-0.158	0.744	47.011
Power		146.729	0.580	-	0.732	0.040
S-Curve		7.656	-21.094	-	0.731	0.040
Logarithmic		-1283.157	685.991	-	0.744	46.176
Linear	PA_W	329.311	31.387	-	0.827	60.925
Quadratic		256.834	35.318	-0.053	0.827	62.032
Power		90.840	0.775	-	0.827	0.041
S-Curve		8.072	-28.121	-	0.822	0.041
Logarithmic		-2680.097	1157.264	-	0.824	61.449
Linear	PA_T	343.966	35.384	-	0.879	55.696
Quadratic		237.052	41.183	-0.077	0.879	56.692
Power		94.617	0.792	-	0.864	0.036
S-Curve		8.194	-28.766	-	0.859	0.037
Logarithmic		-3049.549	1304.880	-	0.876	56.347
Linear	CPA	391.918	28.442	-	0.964	23.258
Quadratic		259.599	35.619	-0.096	0.964	23.592
Power		104.353	0.728	-	0.962	0.017
S-Curve		7.996	-26.440	-	0.957	0.018
Logarithmic		-2337.601	1049.378	-	0.962	23.971

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Table 5. Mass modelling results for ungraded Indian jujube fruits

Models	Parameters	Constants			R^2	SSE
		a	b	c		
Dimension Based Models						
Linear	Length	30.500	0.514	-	0.821	1.900
Quadratic		34.453	0.202	0.006	0.830	1.865
Power		17.551	0.284	-	0.789	0.046
S-Curve		4.032	-6.023	-	0.704	0.054
Logarithmic		3.433	12.593	-	0.770	2.155
Linear	Width	20.496	0.505	-	0.878	1.492
Quadratic		12.041	1.172	-0.012	0.920	1.213
Power		9.165	0.402	-	0.921	0.037
S-Curve		3.891	-9.052	-	0.924	0.036
Logarithmic		-8.424	13.095	-	0.921	1.203
Linear	Thickness	19.733	0.463	-	0.882	1.339
Quadratic		11.517	1.111	-0.012	0.930	1.037
Power		8.934	0.393	-	0.921	0.036
S-Curve		3.826	-8.858	-	0.929	0.034
Logarithmic		-6.869	12.031	-	0.930	1.031
Linear	AMD	23.576	0.494	-	0.977	0.602
Quadratic		19.337	0.829	-0.006	0.989	0.412
Power		11.746	0.351	-	0.991	0.010
S-Curve		3.918	-7.745	-	0.958	0.022
Logarithmic		-3.954	12.573	-	0.988	0.438
Linear	GMD	23.095	0.497	-	0.974	0.649
Quadratic		17.960	0.902	-0.007	0.991	0.372
Power		11.285	0.359	-	0.993	0.010
S-Curve		3.916	-7.978	-	0.968	0.020
Logarithmic		-4.780	12.706	-	0.992	0.347
Linear	Sphericity	0.771	0.002	-	0.134	0.039
Quadratic		0.569	0.018	0.000	0.385	0.033
Power		0.643	0.076	-	0.210	0.046
S-Curve		-0.116	-1.955	-	0.277	0.044
Logarithmic		0.627	0.060	-	0.203	0.037
Volume Based Models						
Linear	Volume	-0.480	1.051	-	0.998	0.342
Quadratic		0.253	0.993	0.001	0.998	0.336
Power		0.984	1.014	-	0.999	0.012
S-Curve		4.188	-22.310	-	0.957	0.066
Logarithmic		-56.968	26.099	-	0.962	1.618
Area Based Models						
Linear	Surface Area	1186.010	113.091	-	0.988	97.899
Quadratic		591.247	160.012	-0.850	0.993	76.365
Power		400.078	0.719	-	0.993	0.019
S-Curve		8.977	-15.955	-	0.968	0.040
Logarithmic		-5035.274	2852.934	-	0.982	120.016
Linear	PA_L	226.238	26.603	-	0.942	52.095
Quadratic		-93.143	51.799	-0.456	0.966	40.389
Power		69.191	0.795	-	0.958	0.052
S-Curve		7.551	-17.923	-	0.963	0.049
Logarithmic		-1269.312	681.038	-	0.865	40.805
Linear	PA_W	362.398	30.598	-	0.964	46.690
Quadratic		311.342	34.626	-0.073	0.965	46.653
Power		128.713	0.677	-	0.971	0.037
S-Curve		7.664	-14.898	-	0.931	0.056
Logarithmic		-1301.241	765.831	-	0.943	58.713
Linear	PA_T	387.069	34.305	-	0.968	49.682
Quadratic		343.089	37.774	-0.063	0.968	49.755
Power		137.735	0.687	-	0.968	0.039
S-Curve		7.771	-15.091	-	0.926	0.060
Logarithmic		-1475.041	857.656	-	0.945	64.967
Linear	CPA	325.235	30.502	-	0.989	25.736
Quadratic		187.096	41.400	-0.197	0.992	21.484
Power		110.917	0.712	-	0.993	0.019
S-Curve		7.664	-15.770	-	0.964	0.042
Logarithmic		-1348.531	768.175	-	0.980	34.762

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CONCLUSION

In conclusion, this study has successfully developed and analyzed mass models for Indian jujube cv. Apple based on selected physical attributes. The investigation revealed significant variations in physical properties such as axial dimensions, volume, surface area, and sphericity across different fruit grades. By examining these attributes, the study provides valuable insights into the effectiveness of various mass modelling approaches for jujube fruits. The findings demonstrate that mass-based grading is essential for optimizing fruit packaging, minimizing transport resources, and enhancing marketability. The results support the development of an automated, precise grading system tailored to jujube fruits, which can improve operational efficiency, reduce labour requirements, and facilitate accurate handling for processing operations. Additionally, the study's insights into the relationships between fruit mass and its physical attributes can enhance drying and cooling processes through precise modelling of heat and mass transfer phenomena.

Overall, this research contributes to the broader understanding of fruit mass modelling and its practical applications in the design and development of grading systems. The detailed analysis of jujube fruit attributes provides a foundation for future studies and technological advancements aimed at improving fruit grading and processing efficiency.

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Authors' contribution

Conceptualization and designing of the research work (AK, NK); Execution of field/lab experiments and data collection (AK, SB); Data analysis and interpretation (AK, AKA, SK); Preparation of manuscript (AK, NK, SK).

Conflict of interest: The authors declare that they have no conflict of interests.

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