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Physical, thermal, mechanical, and nutritional properties of bitter apple (*Citrullus colocynthis* L.)

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The physical, mechanical, thermal, and nutritional properties of bitter apple and their significance in processing, machine designing, and product development are discussed in the present study. Physical parameters of average length, width, and thickness of small, medium, and large fruit were 47.53, 59.08, and 70.63 mm; 46.62, 58.25, and 70.77 mm; and 46.00, 58.25, and 70.49 mm, respectively. The true and bulk density and porosity of bitter apple were measured as 1005 kg m^{-3}, 465 kg m^{-3}, and 53.69%, respectively. In this study, specific heat, thermal conductivity, and thermal diffusivity of bitter apple were found to be 3.866 $\pm$ 0.053 kJ per kg per °K, 0.58 $\pm$ 0.010 W per m °C, and 0.147 $\pm$ 0.001 $\times$ (10^{-7}) m^2 s^{-1}, respectively. The fruit was a good source of protein (8–9%), fat (6.5–7.5%), crude fiber (7–8%), carbohydrates (58%), and energy (339.69 kcal/100 g), respectively. The results found in this study could be useful in the design and development of processing machinery for the commercial production of bitter apples. Despite having significant nutritional and medicinal value, the bitter apple is an underutilized fruit. By understanding the physical and mechanical properties of bitter apple and the development of processing machinery and post-harvest handling equipment accordingly, we can improve efficiency, reduce waste, and promote sustainability. Additionally, knowledge of the nutritional and thermal properties of bitter apples would provide for preserving the nutrients of bitter apple that may require special processing techniques.

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1. Introduction

Citrullus colocynthis L. is an annual or perennial wild creeping herb grown in arid and sandy soil. *C. colocynthis* is broadly grown across the world, throughout India, west Asia, Arabia, tropical Africa, and the Mediterranean region.[1] The Cucurbitaceae family includes the prostrate annual herb known as bitter apple or tumba (*Citrullus colocynthis* L.). It can easily grow on very marginal soil, even on sand dunes in hot, arid climates, and is particularly resilient to a variety of abiotic stresses like drought, heat, and soil salt.[1] Bitter apple is a trailing annual scabrid herb and is known by different names in various regions, like Hadla in Jordan, Abujahl watermelon or Kadu Hanzal in Persia, and bitter apple in Europe.[2] In India, it is known by various names like Indark in Gujarat, Ghudmba in Punjab, Makal in Bengal, and Kartama in southern India. The bitter apple fruit is a fleshy berry with a pale yellow color at the ripening stage. Bitter apple has medicinal properties and is used in traditional medicine as a laxative agent. In India, the seed oil of bitter apples is utilized in industry for preparing candles and soaps. Additionally, it can be used for oilseed feedstock to replace lubricants to some extent.[3] The nutritional composition of bitter apple seeds and its other parts in various regions across the world was found as protein (13–26%), fat (14–24%), carbohydrate (20–30%), and ash (2–4%).[4,5] According to its geographic distribution in different parts of the world, the fatty acid composition of seed oil of bitter apple varies significantly: linoleic acid (55–74%), oleic acid (9–17%), palmitic acid (8.35–11.70%), and stearic acid (5.36–9.84%).[5–8]

The usefulness of bitter apple is similar to that of other vegetable oils, its seed oil being primarily composed of unsaturated fatty acids (approximately 70%). Polyunsaturated fatty acids make up the majority of it, along with certain significant odd-chain fatty acids that have lately been proposed as being crucial for the health of humans.[9] There is wide use of bitter apples in food (soups) as a thickening and gelling agent.[10] Additionally, it has a sizable amount of naturally occurring bioactive substances with potent antioxidant properties (phenolics, oryzanols, flavonoids, carotenoids, lignin, *etc.*), which makes it highly stable against oxidative degradation at the time of frying and a good source of antioxidants with pharmaceutical and nutraceutical uses.[11]

Researchers have always tried to find the physical and mechanical properties of agricultural produce to design and develop machines and equipment. Designed and developed machines can be used in sorting, processing, transportation,

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and storage of agricultural products to obtain good-quality products. Various important physical properties of agricultural products include mass, characteristics of dimensions, surface area, volume, image surface, coefficient of sphericity, aspect ratio, porosity, and static friction coefficient. Mechanical properties include deformation, yield force, firmness, hardness, and breakdown energy.[12–16] Directly or indirectly, mechanical damage is a cause of agricultural produce wastage and lower quality of fresh produce. During harvesting and post-harvesting different operations including transportation, storage, and processing of agricultural products mean that they are exposed to numerous mechanical forces and physical damage. In most cases, mechanical damage is due to the forces that tear the cell wall of products. Therefore, this topic is the most important problem for experimental analysis and modeling in the biosystems engineering field.[17–22]

As yet, many types of research have been carried out worldwide in finding out the physical, mechanical, nutritional, and hydrodynamic properties of agricultural produce. Some relevant studies are the following.

Moghadam and Kheiralipour[23] studied the physical and nutritional properties of hawthorn fruit. They found that some physical properties like surface area, sphericity, and slenderness ratio were 1.69 mm, 1.13%, and 1.26, respectively. In nutritional properties, they found that TSS and TA were 18.7% and 1.71%, respectively. Jahanbakhshi[24] determined the physical and mechanical properties of snake melon. He found that length, width, thickness, surface area, and density play an important role in many cases related to designing special machines or assessing materials' behavior at the time of transferring. The maximum force at the time of pressure, shearing, and bending tests on the snake melon were found to be 309.66, 33.66, and 44.4 N, respectively. For the physical, hydrodynamic, and mechanical properties of scolymus, Jahanbakhshi *et al.*[25] noticed that density is less than that of water, and thus it could be hydraulically sorted and transferred without any damage. The maximum bending and shearing force for the scolymus were 41.5 and 82.9 N, respectively. Similarly, study was carried out[29,32] on bael fruit and cashew apple fruit. The average length, width, and thickness of bael and cashew apple were measured at 89.2, 82.2, 79.5 (mm), and 50.34, 42.78, 36.08 (mm), respectively.

Appropriate knowledge of the physical, thermal, nutritional, and mechanical properties of bitter apple would aid in the design and modification of equipment which is required for various post-harvest operations like washing, sorting, grading, peeling, cutting, drying, storage, *etc.*[26,27] These above-mentioned properties may also aid in grading up the design perspective such as simulation and modeling during heat transfer characteristics of cold storage, the cooling system of the grinder at the time of spices grinding in cryogenic conditions, and so on.

By understanding the physical, mechanical, thermal, and nutritional properties of bitter apple and developing processing machinery and post-harvest handling equipment and storage systems, value can be added to it and its by-products accordingly. Additionally, by knowing these properties it is easy to clean and maintain the machines and equipment. These kinds of study on different properties such as mechanical, physical, thermal, textural, and nutritional properties of bitter apple are not abundant. Therefore, the present study aimed to explore the properties of bitter apple for the effective designing of processing machinery and the development of products from bitter apple. By designing machines and equipment with keeping sustainability in mind, we can reduce the negative impact of food production and processing on the environment and promote food sustainability.

2. Materials and methods

2.1 Material selection

Bitter apples were collected during the period June 2022 from the dryland university farm, CCS HAU, Hisar (India), and fruits were properly washed and cleaned. Fresh and healthy fruits were randomly selected for further measurements and determination of the engineering properties.

2.2 Physical properties

2.2.1 Length (L), width (W), and thickness (T). The bitter apple length, width, and thickness were measured with the help of a digital vernier caliper (D-12 PSX, Japan) (Fig. 1) with the least count of 0.001 mm. The value of length, width, and thickness was measured along the longitudinal (x-axis), intermediate (y-axis), and transverse (z-axis) directions (Fig. 2). The mass of bitter apples was measured by using a weighing balance (Sartorius, BT 423S) with the least count of 0.001 g.

2.2.2 Mean diameter (D). The geometric mean diameter (D_g), arithmetic mean diameter (D_a), and equivalent mean diameter (D_e) of fruit were determined by using eqn (1)–(3):[28,29]

$$D_g\ (\text{cm}) = (L \times W \times T)^{1/3} \tag{1}$$

$$D_a\ (\text{cm}) = \frac{L + W + T}{3} \tag{2}$$

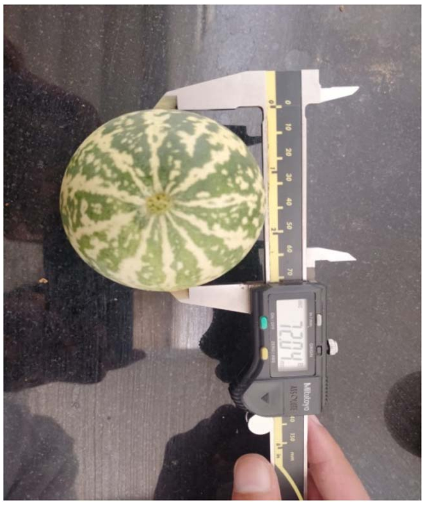

Fig. 1 Measurement of dimensions with vernier caliper.

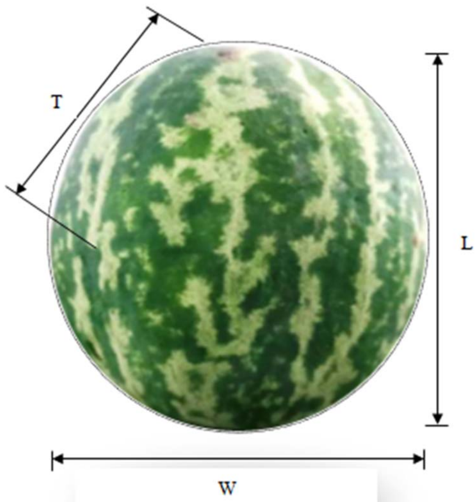

Fig. 2 Dimensions of bitter apple.

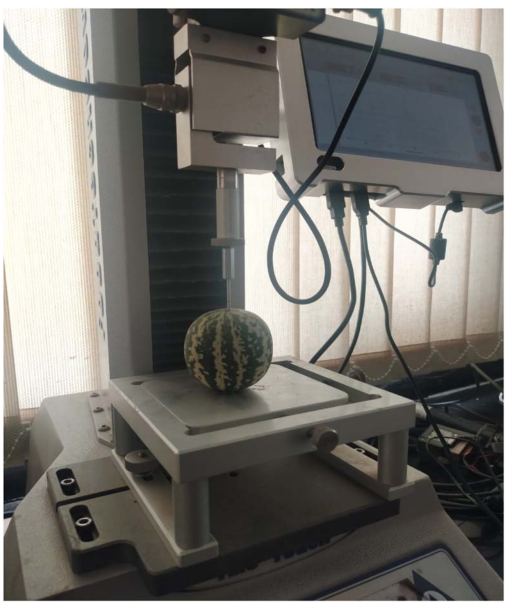

Fig. 3 Analyzing the textural properties of bitter apple.

$$D_e \text{ (cm)} = \left[\frac{\left\{L(W+T)^2\right\}}{4}\right]^{1/3} \quad (3)$$

2.2.3 Shape. Sphericity (Φ) showed the roundness of fruits, aspect ratio (R_a) showed the width and height relation, and flakiness ratio (F_r) showed the degree of packing where elongation ratio (E_r) indicated the dilation and curvature, and were determined by using eqn (4)–(7):[30]

$$\varphi = \frac{(L \times W \times T)^{1/3}}{L} \quad (4)$$

$$R_a = \frac{W}{L} \quad (5)$$

$$F_r = \frac{T}{W} \quad (6)$$

$$E_r = \frac{L}{W} \quad (7)$$

2.2.4 Surface area (S_A). The surface area (S_A) of the bitter apple was determined by using eqn (8).[31] The projected area (P) of fruits was measured with projections perpendicular to length (P_W), width (P_W), and thickness (P_T) using eqn (9)–(11) (ref. 32) and criteria projected area (CPA) was calculated based on eqn (12):[33]

$$S_A \text{ (cm}^2) = \pi (D_g)^2 \quad (8)$$

$$P_W \text{ (cm}^2) = \frac{\pi W^2}{4} \quad (9)$$

$$P_T \text{ (cm}^2) = \frac{\pi T W}{4} \quad (10)$$

$$P_L \text{ (cm}^2) = \frac{\pi L W}{4} \quad (11)$$

$$\text{CPA (cm}^2) = \frac{PL + PW + PT}{3} \quad (12)$$

2.2.5 Volume (V). The prolate volume (V_{pro}), ellipsoidal volume (V_{ellip}), and oblate spheroid volume (V_{osp}) of bitter apples were calculated by using eqn (13)–(15):[29,33]

$$V_{pro} \text{ (cm}^3) = \frac{4\pi}{3} \times \frac{L^2}{2} \times \frac{W}{2} \quad (13)$$

$$V_{ellip} \text{ (cm}^3) = \frac{4\pi}{3} \times \frac{L}{2} \times \frac{W}{2} \times \frac{T}{2} \quad (14)$$

$$V_{osp} \text{ (cm}^3) = \frac{4\pi}{3} \times \frac{L}{2} \times \frac{W^2}{2} \quad (15)$$

2.2.6 Gravimetric properties. Bitter apple of known mass was filled in a container of known volume for the measurement of bulk density (ρ_b). A bitter apple was submerged in water and the rise in the volume of water in the container was used to calculate the true density (ρ_t). Porosity (ε) was measured in the void space between the fruits kept in the container. Eqn (16)–(18) were used to find out the true density, bulk density, and porosity of fruits:[34,35]

$$\rho_b = \frac{\text{weight of bitter apple fruit in container (g)}}{\text{volume of container(cm}^3)} \quad (16)$$

$$\rho_t = \frac{\text{weight of bitter apple fruit dipped in water (g)}}{\text{volume of water displaced (cm}^3)} \quad (17)$$

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \quad (18)$$

Table 1 Physical properties of bitter apple

	Grades								
	Small			Medium			Large		
Physical property	Mean ± SD	Max	Min	Mean ± SD	Max	Min	Mean ± SD	Max	Min
Mass of bitter apple, g	52.95 ± 8.47	62.5	37.5	111.16 ± 33.85	173.00	66.50	202.14 ± 20.71	249.00	178.00
Length, mm	47.53 ± 2.81	51.39	43	59.08 ± 5.77	71.04	50.90	70.63 ± 5.60	76.83	53.28
Width, mm	46.62 ± 2.45	50	41.14	59.25 ± 6.41	71.18	49.46	70.77 ± 5.72	77.40	52.70
Thickness, mm	46.00 ± 2.30	48.17	40.25	58.25 ± 6.04	71.65	49.41	70.49 ± 5.64	76.71	52.50
Arithmetic mean diameter (D_a), mm	46.72 ± 2.37	49.85	41.46	58.86 ± 5.92	69.09	49.92	70.63 ± 5.60	76.98	52.83
Geometric mean diameter (D_g), mm	44.94 ± 2.26	47.92	39.93	56.49 ± 5.62	66.16	48.00	67.68 ± 5.32	73.71	50.77
Equivalent mean diameter (D_e), mm	44.95 ± 2.26	47.93	39.93	56.50 ± 5.63	66.21	48.00	67.68 ± 5.32	73.71	50.77
Sphericity (F), %	94.62 ± 2.34	100.95	92.09	95.62 ± 2.25	102.19	91.95	95.84 ± 1.42	99.33	93.77
Aspect ratio (R_a)	0.98 ± 0.03	1.06	0.95	1.00 ± 0.04	1.14	0.94	1.00 ± 0.02	1.06	0.97
Flakiness ratio (F_r)	0.99 ± 0.02	1.03	0.96	0.98 ± 0.03	1.04	0.81	1.00 ± 0.01	1.01	0.98
Elongation ratio (E_r)	1.02 ± 0.03	1.05	0.95	1.00 ± 0.04	1.06	0.87	1.00 ± 0.02	1.03	0.94
Surface area, mm^2	6358.29 ± 625.42	7212.11	5007.01	10117.84 ± 2009.88	13746.02	7235.84	14465.32 ± 2057.78	17058.91	8093.98
Projected area perpendicular to length (P_L), mm^2	1744.09 ± 185.55	2017.06	1388.68	2774.40 ± 1976.25	3969.45	1976.25	3945.91 ± 565.68	4668.11	2204.17
Projected area perpendicular to width (P_w), mm^2	1710.52 ± 175.79	1962.50	1328.61	2787.08 ± 602.40	3977.28	1920.34	3955.76 ± 578.80	4702.75	2180.17
Projected area perpendicular to thickness (P_t), mm^2	1687.41 ± 164.45	1890.67	1299.87	2736.99 ± 568.67	3886.55	1918.40	3939.65 ± 571.76	4660.82	2171.90
Critical projected area, mm^2	1714.01 ± 172.48	1956.74	1339.05	2766.16 ± 573.34	3860.31	1938.33	3947.11 ± 570.30	4677.23	2185.41
Ellipsoid volume (V_{ellip}), mm^3	53706.89 ± 7829.42	64764.13	37257.00	109792.15 ± 32892.98	172088.05	65087.26	187358.28 ± 36801.97	238689.33	77133.56
Prolate spheroid volume (V_{pro}), mm^3	55589.62 ± 8956.24	69093.39	39802.51	111329.57 ± 33121.29	187963.33	67050.02	187692.30 ± 36988.55	239062.72	78279.54
Oblate spheroid volume (V_{osp}), mm^3	54476.92 ± 8379.59	67224.54	38080.82	111870.69 ± 34436.66	188333.75	65153.12	188119.27 ± 37091.00	240836.33	77427.40

2.3 Thermal properties

The thermal properties, namely thermal conductivity (W per m °C), specific heat (kJ per kg per °K), and thermal diffusivity (m^2 s^{-1}), were determined by using eqn (19)–(21) based on the moisture content of agricultural products. The moisture content of bitter apples was determined at 105 ± 2 °C for 24 h in a hot air oven:[29,32]

$$k \text{ (W per m per °C)} = 0.148 + 0.00493 M_c \tag{19}$$

$$C_p \text{ (kJ per kg per °K)} = 1.675 + 0.025 M_c \tag{20}$$

$$\alpha \ \left(m^2 \ s^{-1}\right) = \frac{k}{\rho C_p} \tag{21}$$

where: M_c = moisture content (wet basis, %).

2.4 Mechanical properties

A texture analyzer (TA.HD plus C, 7.5 kN, UK) with a cylindrical probe was used to determine the toughness (T) and firmness (F_m) (Fig. 3). The compression load was applied with the different adjustments of bitter apple based on length, width, and thickness. The toughness and firmness of the bitter apple were calculated by using eqn (22) and (23), respectively:[36,37]

$$\text{Toughness } (T) = \frac{\text{rupture force } (F) \times \text{deformation } (D)}{2 \times \text{ellipsoid volume } \left(V_{ellip}\right)} \tag{22}$$

$$\text{Firmness } (F_m) = \frac{\text{rupture force } (F)}{\text{projected area perpendicular to } L \text{ or } W \text{ or } T} \tag{23}$$

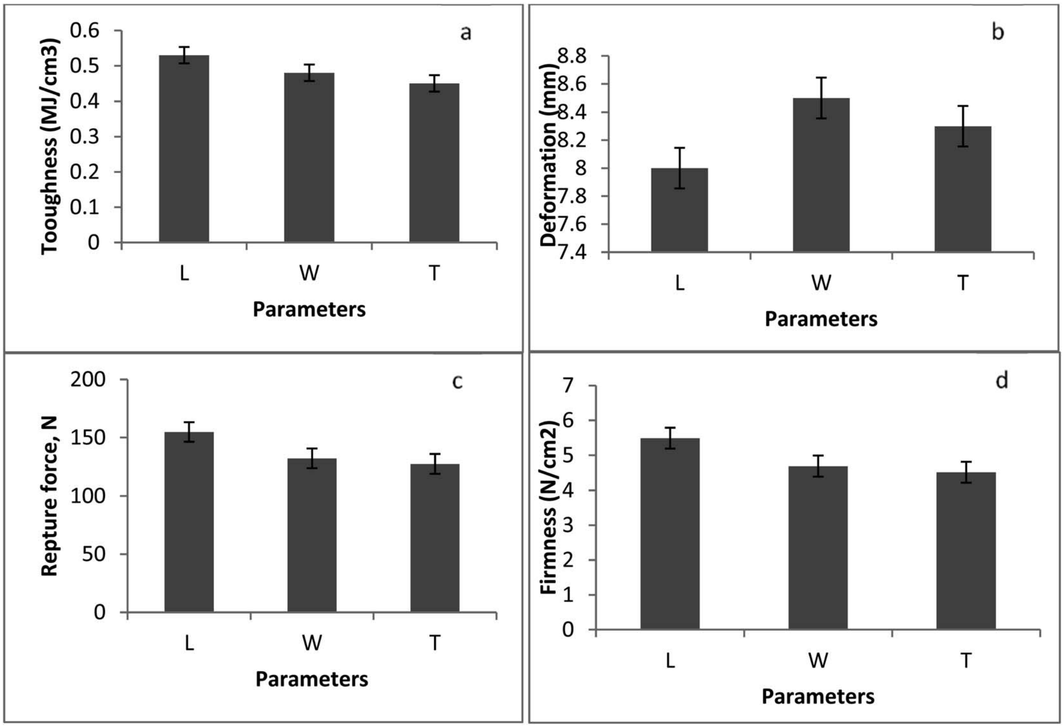

Fig. 4 (a) Toughness, (b) deformation, (c) rupture, and (d) firmness of bitter apple along length (*L*), width (*W*), and thickness (*T*).

2.5 Nutritional properties

2.5.1 Moisture. Moisture content was estimated by employing standard methods of analysis:[38]

$$\text{Moisture content }(\%) = \frac{\text{loss in weight (g)}}{\text{weight of sample (g)}} \times 100 \quad (24)$$

2.5.2 Crude protein. Crude protein was calculated by the standard micro-Kjeldahl method of analysis using Kel plus KES04ER equipment manufactured by Pelican, Chennai, India.[39] One gram of sample (finely ground) was kept in a digestion tube to which were added 12 ml of H_2SO_4 and 3 g of catalyst. After that, the mixed sample was heated at 420 °C until the completion of the digestion process in the digestion unit. The sample was changed from black charred material to blue-green solution. Samples were kept for cooling, then diluted with 50 ml of water to avoid solidification. Tubes with digested samples were loaded in the distillation unit and mixed with 50 ml of NaOH. The distillation process was scratched and liberated ammonia was collected in 30 ml of 4% boric acid solution containing a few drops of mixed indicator. More than 150 ml of distillate was collected during the distillation process. Finally, the distillate was titrated with 0.1 N hydrochloric acid to determine the ammonia absorbed in boric acid.

$$\text{Nitrogen }(\%) = \frac{\text{titre volume }(S-B)\times\text{normality}\times 14}{1000\times W} \times 100 \quad (25)$$

$$\text{Crude protein }(\%) = \text{nitrogen }(\%) \times \text{conversion factor} \quad (26)$$

where: W = weight of sample taken (g); S = volume (ml) of HCl (N/10) used in titration for sample; B = volume (ml) of HCl (N/10) used in titration for blank.

2.5.3 Crude fiber. The crude fiber was estimated by the standard method of analysis. Crude fiber apparatus Fibraplus (FES 08 R, manufactured by Pelican, India) was used for determination.[40] This involved weighing 1 g of fat-free and moisture sample and shifting to a weighed and pre-dried crucible. Boiling acid was poured from the top of the crucible up to the manufacturer's mark while the crucible was attached to the Fibraplus device. Using the heating unit, the acid was brought to the boil for 30 minutes, and then filtered through the crucibles. The alkali underwent the same procedure and was

Table 2 Nutritional properties of bitter apple

Moisture content (wb)	Crude protein (%)	Crude fat (%)	Crude fiber (%)	Ash (%)	Carbohydrates (%)	Energy (kcal/100 g)
84.8 ± 1.13	9.2 ± 0.35	6.9 ± 0.30	7.3 ± 0.55	18.6 ± 0.31	58.0	339.69

ultimately rinsed with water. Crucibles were dried in an oven and weighed after cooling in a desiccator. Finally, after ashing in a muffle furnace at 560 °C for one hour, crucibles were weighed and the percentage fiber content was determined by the following equation:

$$\text{Crude fibre }(\%) = \frac{W_1 - W_2}{\text{Weight of sample (g)}} \times 100 \tag{27}$$

where W_1 = weight of crucible + weight of the treated sample after oven drying; W_2 = weight (g) of crucible + weight of sample after ashing.

2.5.4 Crude fat. An automatic Soxhlet fat extraction apparatus Socs Plus (SCS 08 AS, manufactured by Pelican, India) based on the method of AOAC[40] was used for the determination of fat content. Clean, empty beakers were dried in a hot air oven at 100 °C before being weighed and labeled. A 5 g moisture-free sample was collected in dry, empty thimbles, and thimble holders were used to attach the thimbles to the beakers. Each beaker received 100 ml of petroleum ether. Beakers were connected to the Socs Plus device and heated continuously for four hours at 80 °C. After the initial two hours, 30 ml of ether was once again poured into each beaker, and the procedure was continued for the remaining period. By increasing the temperature of the heating apparatus to 120 °C, the solvent was finally totally evaporated. Without thimbles, beakers were placed in a hot air furnace for an hour to burn out any remaining solvent.

$$\text{Fat }(\%) = \frac{W_2 - W_1 \text{ (g)}}{\text{Weight of sample (g)}} \times 100 \tag{28}$$

where: W_1 = weight of empty beaker; W_2 = weight of beaker after extraction; W = weight of sample.

2.5.5 Ash. Ash content in the samples was estimated by employing the standard method of analysis with a muffle furnace.[40] Ash content was measured using a muffle furnace and the AOAC (2005) technique. Five grams of sample were placed in each of the necessary numbers of clean, dry, preweighed silica crucibles, and each was placed on a hot plate until smoking stopped and the samples were properly charred. After moving the charred samples into crucibles, the muffle furnace was used to ash the samples at 560 °C for five hours. Crucibles were taken out of the furnace after they reached a safe temperature below 100 °C, cooled in a desiccator, and then weighed. The difference in weight obtained was used to determine the ash content, by using the following equation:

$$\text{Ash }(\%) = \frac{W_2 - W_1 \text{ (g)}}{\text{Weight of sample (g)}} \times 100 \tag{29}$$

where W = weight of sample (g); W_1 = weight of crucible (g); W_2 = weight of the crucible (g) + ash.

2.5.6 Nitrogen-free extract. Carbohydrate content was calculated by different methods[40] on dry basis using the following formula:

$$\text{Total carbohydrates }(\%) = 100 - (\text{crude fat }(\%) + \text{crude protein }(\%) + \text{ash }(\%) + \text{crude fiber }(\%)) \tag{30}$$

2.5.7 Energy. The energy was calculated by the factorial method on a dry basis using the following formula:

$$\text{Energy (kcal)} = 4.0 \times \text{protein (g)} + 4.0 \times \text{carbohydrate (g)} + 9.0 \times \text{fat (g)} \tag{31}$$

2.6 Mass distribution of fruits

The mass of bitter apple fruits was not uniform, with very large differences in the mass, so the samples of fruits were categorized into three groups, small, medium, and large, by considering the average mass (X_m) and its standard deviation (σ_x):[41]

$$\text{Small} = X < X_m - \sigma_x \tag{32}$$

$$\text{Medium} = X_m - \sigma_x < X < X_m + \sigma_x \tag{33}$$

$$\text{Large} = X > X_m + \sigma_x \tag{34}$$

2.7 Statistical analysis

Statistical indices for physical, thermal, mechanical, and nutritional properties were calculated using Microsoft Office Excel 2016. The data are represented as mean ± SD.

3. Results and discussion

3.1 Physical properties

The physical properties of bitter apples are the fundamental and basic parameters required during the designing of processing machines. The physical properties of bitter apples were calculated and are indicated in Table 1. The average mass of bitter apple in small to large groups varied from 52.95 g to 202.14 g, respectively. Similarly, Sonawane *et al.*[29] found that the average mass of bael fruit was 310.60 g. The design of processing machineries like graders, sorters, and cleaners heavily relies on the three basic dimensions of length (L), width (W), and thickness (T). The average length, width, and thickness of bitter apples were from 47.53 mm to 70.53 mm, 46.62 mm to 70.77 mm, and 46.00 mm to 70.49 mm, respectively, based on small to large size. The volume of the whole fruit is an important parameter to consider while designing containers and spaces for transportation, conveying, and storage of the fruits and measuring density and heat transfer rates for the design of suitable cold room, cooling chamber, or dryer unit. In a similar study carried out by Sonawane *et al.*[29] on bael fruit, the average values of length (L), width (W), and thickness (T) were 89.2 ± 8.1, 82.2 ± 5.5, and 79.5 ± 4.8 mm, respectively. Different-sized fruits were measured, where their mean volume varied from 51.23 ml to 197 ml. The average mean diameters are useful for predicting the size of an aperture for developing separation equipment and for finding out how a particle moves in a turbulent or nearby turbulent air stream area.[30] The geometric mean diameter (D_g), arithmetic mean diameter (D_a) and equivalent mean diameter (D_e) of bitter apple varied from 46.72

to 70.63 mm, 44.94 to 67.68 mm, and 44.95 to 67.68 mm, respectively. Similarly, Singh *et al.*[32] found that the arithmetic mean diameter, geometric mean diameter, and equivalent diameter of cashew apple fruit were 43.07, 42.6, and 40.48 mm, respectively. The aspect ratio of an object is calculated as the ratio of its width to its length/height and provides information about the shape of the fruit. It shows how oblong a bitter apple is, and the sphericity values help to design separators and sizing machines. The fruit will have a greater tendency to roll over a surface rather than slide if the sphericity value is higher. Different sizes of bitter apples had average values of aspect ratio, sphericity, elongation ratio, and flakiness ratio varying from 0.98 to 1.00, 94.62 to 95.84%, 1.02 to 1.00, and 0.99 to 1.00, respectively. In a similar study carried out by Singh *et al.*,[32] average values of aspect ratio, sphericity, flakiness ratio, and elongation ratio of cashew apple fruit were found to be 84.98, 0.85, 0.84, and 1.18, respectively. The size-based bitter apple had average surface area, critical projected area, projected area perpendicular to L, projected area perpendicular to T, and projected area perpendicular to W varying from 6358.29 to 14465.32 mm^2, 1714.01 to 3947.11 mm^2, 1744.09 to 3945.91 mm^2, 1687.41 to 3939.65 mm^2, and 1710.52 to 3955.76 mm^2, respectively. A similar finding was observed by Mahawar *et al.*,[33] where the projected area perpendicular to length was 5644–4172 mm^2, the projected area perpendicular to width was 4348–3490 mm^2, and the projected area perpendicular to thickness was 4370–3584 mm^2, respectively. In addition to their usage in developing sizing systems, the above-mentioned areas are used in the modeling of heat and mass transfer studies to calculate water loss, respiration rate, ripening index, and gas permeability.[32,42] Density has a significant impact on various machine designs used for fruit processing, packaging, and transportation. The porosity value shows the total area occupied by the intergranular space of fruit. The average true density (kg m^{-3}) and bulk density (kg m^{-3}) for bitter apples were 1005 $\pm$ 10 and 465 $\pm$ 10, respectively, while the average value of porosity was 53.69 $\pm$ 1.30%. Similarly, Sonawane *et al.*[29] observed that the bulk density, true density, and porosity of bael fruits were 0.470 $\pm$ 0.144 g cm^{-3}, 1.067 $\pm$ 0.243 g cm^{-3}, and 55.96 $\pm$ 1.50%, respectively. The average ellipsoid volume, prolate volume, and oblate volume of bitter apples were from 53706.89 $\pm$ 7829.42 to 187358.28 $\pm$ 36801.97 mm^3, 55589.62 $\pm$ 8956.24 to 187692.30 $\pm$ 36988.55 mm^3, and 54476.92 $\pm$ 8379.59 to 188119.27 $\pm$ 37091.00 mm^3, respectively, based on small to large size. Similarly, Singh *et al.*[32] found that the mean values of ellipsoid volume and spheroid volume of cashew fruit were 50176.93 mm^3 and 67267.16 mm^3, respectively.

3.2 Thermal properties

Thermal properties are essential for the design and development of various refrigeration and storage equipment based on the process parameters such as drying, heating, cooling, or freezing of produce. The fruit maintains its temperature for a long period; hence the specific heat with high value shows that a considerable amount of energy is needed for cooling and heating of fruits. The specific heat of the bitter apple was calculated to be 3.866 $\pm$ 0.053 kJ per kg per °K. Similarly, Sonawane *et al.*[29] found that the specific heat of bael fruit pulp was 3.2512 kJ per kg per °K. This can be due to the high amount of moisture content, but other food components (protein, fat, and others) also may have an impact. The average thermal conductivity and thermal diffusivity of bitter apple were measured as 0.58 $\pm$ 0.010 W per m per °C and 0.147 $\pm$ 0.001 m^2 s^{-1} (10^{-7}), respectively. Similar findings were reported by Vivek *et al.*[30] for sohiong fruit. The thermal conductivity and thermal diffusivity of sohiong fruits were measured as 0.548 J ms^{-1} and 1.37 $\times$ 10^{-4}, respectively. Thermal conductivity is mostly used to control or measure the heat flux of food throughout processing. The porosity and moisture content of fruits may have an impact on their thermal conductivity because an increase in water content enhances the thermal conductivity of products. Due to their lower water content, fruits often have a lower thermal conductivity than juice.[30]

3.3 Mechanical properties

Fig. 4(a) indicates the average toughness of bitter apple with the orientation of length (L), width (W), and thickness (T) measured as 0.53, 0.48 and 0.45 mJ cm^{-3}, respectively. The highest toughness was observed along the length whereas the toughness at width and thickness was the same. The average deformation of bitter apple along the length, width, and thickness was measured as 8, 8.5, and 8.3 mm (Fig. 4(b)) respectively. The highest deformation was observed for width whereas the lowest was for length. The toughness and firmness along the length were observed maximum as compared to width and thickness. A similar study found that the deformation at the flat top position (10.09–35.47 mm) recorded higher values than the ridge top position (6.34–34.92 mm) for different varieties as reported by Pandiselvam *et al.*[43] Fig. 4(c) shows that the average rupture force (F) along with the length (L), width (W), and thickness (T) was measured as 154.8 N, 132.3 N, and 127.5 N respectively. The rupture force is highest for length and lowest for thickness. Fig. 4(d) shows the average firmness (N cm^{-2}) along the orientation of length, followed by that along the width and thickness, was 5.49, 4.69, and 4.52, respectively. Similar findings were reported by Goyal *et al.*[44] in that Aonla's surface hardness varied from 12 to 17 N for different cultivars. The mechanical properties of fruit showed that the different varieties of fruits are heterogeneous and their behavior under load conditions also differs. Knowledge of these mechanical properties is useful for the design of size reduction or cutting machines.

3.4 Nutritional properties

Table 2 indicates the nutritional properties of bitter apple. Moisture content in fresh samples of bitter apple was found to be 84.8%. High moisture content is essential to maintain the turgidity of the vegetable cells and keep them fresh;[45] it also affects the storage stability of fruit. Ash content ranging from 18 to 19% shows that bitter apples are rich in minerals. The whole fruit is also a good source of fat, protein, crude fiber, carbohydrates, and energy which is shown in Table 2. Wild fruits in whole form are considered low in fat and protein;[46] while some other researchers suggested that the biochemical composition of wild fruits depends on various factors such as the type of soil, climatic factors, harvest conditions, genetic factors of plant, and storage conditions, which significantly affect the supply of energy in fruits.[47] These fruits grow in summer and are harvested from May to October while in some areas these are perennial so this may also affect the amount of carbohydrates, protein, fats, and fiber. Similar results for nutritional values were obtained for other varieties of bitter apples.[45,47]

4. Conclusion

In the present study, some engineering properties of bitter apple like physical, thermal, mechanical, and nutritional properties were calculated.

(1) For physical properties, the average lengths (mm) of small-, medium-, and large-size fruits were 47.53 ± 2.81, 59.08 ± 5.77, and 70.63 ± 5.60, respectively. For the different categories of bitter apple, sphericities were 94.62 ± 2.34 (small), 95.62 ± 2.25 (medium), and 95.84 ± 1.42 (large). These features could be of help in the design of transfer, displacement, and grading systems.

(2) The average true density (kg m^{-3}) and bulk density (kg m^{-3}) for bitter apple were 1005 ± 10 and 465 ± 10, respectively, while the average value of porosity was 53.69 ± 1.30%. These are important in various processing procedures as well as evaluation of product quality.

(3) Thermal diffusivity, thermal conductivity, and specific heat capacity of bitter apple were 0.147 ± 0.001 $m^2\ s^{-1}$ (10^{-7}), 0.58 ± 0.010 W per m per °C, and 3.866 ± 0.053 kJ per kg per °K, respectively.

(4) The average toughness of bitter apple varied with the orientation of thickness, width, and length and was found to be 0.45, 0.48, and 0.53 mJ cm^{-3}, while average firmness was found to be 4.52, 4.69, and 5.49 N cm^{-2}, respectively. These mechanical properties can be used for the design of size reduction or cutting machines, separating, and packaging.

(5) In addition, the nutritional properties of bitter apple can be used to develop mineral- and fiber-rich food and formulations.

(6) The measured physical, mechanical, thermal, and nutritional properties of bitter apple would be beneficial to researchers, machine designers for food processing, food technologists, and scientists in designing, developing, and fabrication of postharvest handling equipment. These will also be useful for product and by-product development. Besides, design and development can improve efficiency, reduce waste, and promote food sustainability.

Author contributions

Rinku Grover: conceptualization; writing – original draft preparation, methodology, formal analysis; Raveena Kargwal: conceptualization, writing – review and editing, formal analysis, resources; Punit Singh: software: resources, data curation, writing – review and editing, formal analysis; Ravi Pandiselvam: conceptualization; methodology, formal analysis, writing – review and editing.

Conflicts of interest

The authors declare no conflict of interest.

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