Received: 17 October 2019 | Revised: 30 November 2019 | Accepted: 5 December 2019
DOI: 10.1111/jfpe.13349

ORIGINAL ARTICLE

Journal of Food Process Engineering
WILEY

Mechanical properties of tender coconut (*Cocos nucifera* L.): Implications for the design of processing machineries

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Funding information
AICRP on Post-Harvest Engineering and Technology, Ludhiana, Grant/Award Number: 1000767021

Abstract

The mechanical properties such as punching force, cutting force, punching energy, and cutting energy of tender coconut at its different orientations are pertinent for the design and development of efficient and ergonomic tender coconut processing machineries viz., punch and cutter, trimming machine, and snowball machine. However, the mechanical properties of tender coconut have not been investigated scientifically yet. Hence, the mechanical properties of tender coconut at six different positions were determined. Four genotypes of tender coconut were used in this study, such as Andaman Giant Tall (AGT), Chowghat Orange Dwarf (COD), Kulasekaran Green Dwarf (KGD), and Ganga Bondam Green Dwarf (GBGD). A laboratory-scale texture analyzer with a customized probe for cutting and punching was developed and used for the measurements. The highest punching and cutting force was observed at the bottom section (near fruit base) of the tender coconuts followed by the middle and top section. The maximum punching energy (2.23 J) in fruit top loading position was recorded for GBGD, whereas the minimum punching energy (0.82 J) was observed for the genotype AGT. The highest cutting energy of 11.79, 15.53, and 16.59 J recorded for AGT at flat loading position (top, middle, and bottom, respectively). Statistical analysis indicates that genotypes and loading positions of tender coconut significantly ($p \le .01$) affected the punching and cutting force.

Practical applications

The basic information of tender coconuts including physical and mechanical properties is crucial for the design and development of tender coconut processing machinery. Earlier, we have reported the physical properties of tender coconuts necessary for the development of a trimming machine. As a follow-up, herein we present the mechanical properties of tender coconut that are essential for the design of components such as punching and cutting tool, knife settings in trimming machine and the rotor design in snowball machine. This is the first scientific report highlighting the mechanical properties of the tender coconuts.

1 | INTRODUCTION

Tender coconut (*Cocos nucifera* L.) water is a natural health drink loaded with many nutrients. It is one of the most popular drinks among the consumers because of its tremendous health benefits including antiaging, antioxidant, antithrombotic, and anticarcinogenic properties (Jean, Yong, Yan, & Swee, 2009). The major coconut growing countries are India, Indonesia, Malaysia, Philippines, Sri Lanka, and

Mexico. At present, more than 90% of the global supply originates from Asia where it is a prominent source of income for many countries (Kalina & Navaratne, 2019).

Indian coconut water market has been pegged at $9.2 million in 2017 and is projected to grow $25.4 million by 2023 due to the rising health awareness among the consumers regarding the deleterious health effects of carbonated drinks (Mahnot, Mahanta, Keener, & Misra, 2019; Techsci Research, 2018). Also, there is a huge demand for preservation and processing of tender coconut due to its unique flavor and natural rehydrating properties (Mahnot et al., 2019).

The major tender coconut products are snowball, a pentagonal shape trimmed tender coconut, coconut water, and coconut pulp/flesh-based frozen delicacy and/or ice cream, tender coconut water-based beverages, Jam, Jelly, and tender coconut chips (Manikantan, Pandiselvam, Beegum, & Mathew, 2018). For the preparation of the aforementioned products, tender coconut husk has to be removed by manual or mechanical means. Researchers have reported that tender coconut husk weight constitutes about 85% of the fruit weight (Ishizaki, Visconte, Furtado, de Oliveira, & Leblanc, 2008). To the best of our knowledge, limited numbers of commercial machines are available for mechanical chopping and/or trimming of tender coconut because of its hard nature.

Street vendors in south India (Tamil Nadu, Kerala, Andhra Pradesh, and Karnataka) who sell the tender coconuts along the roadside generally use a lengthy knife for partial dehusking of tender coconut. While chopping and/or cutting the tender coconut husk, two major unit operations are followed by the vendors: Cutting and punching. Two main forces encountered during chopping and punching the tender coconut are cutting strength and punching strength. The cutting strength is experienced by the exocarp (outer skin) and part of the mesocarp section and the puncture strength is experienced by the mesocarp and endocarp section. An automatic punching and cutting machine are required for hygienic handling of tender coconut. Hence, the food engineers and manufacturers of coconut processing machinery have attempted to develop automatic or continuous type machinery for processing of tender coconuts.

The engineering properties of coconuts are crucial for the design and development of energy-efficient processing machines. The knowledge of mechanical properties of matured coconut husk, shell and endosperm are invaluable to design of dehusking, deshelling, and coconut meat grating/pulverizing/slicing machine, respectively (Pandiselvam et al., 2018). Terdwongworakul, Chaiyapong, Jarimopas, and Meeklangsaen (2009) and Terdwongworakul, Jarimopas, Chaiyapong, Singh, and Singh (2009) studied the physical and acoustic properties of Thai tender coconuts (variety: Nam Hom and Nahm Wahn) for maturity separation. Similarly, mechanical properties of tender coconuts are useful for the design and development of tender coconut punching tools, cutting knife, trimming machine knife, and snowball tender coconut processing machine. Hence, the present research work aims to investigate the mechanical properties of four tender coconut genotypes.

2 | MATERIALS AND METHODS

2.1 | Coconut samples

The nuts of Andaman Giant Tall (AGT), Chowghat Orange Dwarf (COD), Kulasekaran Green Dwarf (KGD), and Ganga Bondam Green Dwarf (GBGD) are commonly preferred by Indian consumers because of its unique flavor, sweet aromatic juice, and soft flesh. Coconut growers have evinced more interest to cultivate dwarf varieties for the production of tender coconut. Further, the genotypes are preferred for their high yield potential and the high percentage of tender coconut water as compared to the traditional coconut varieties. Hence, the present study has focused on the determination of the mechanical properties of these genotypes. Twenty-five tender coconuts from each genotype were harvested from the orchard of ICAR-Central Plantation Crops Research Institute (CPCRI), Kasaragod, Kerala, India. While harvesting, care was taken to select the nuts of similar maturity (6 months maturity or 180th day after pollination). Tender coconuts were tied to a rope and brought down to avoid mechanical damage during harvesting. After transportation to the laboratory at Agro-Processing Complex, CPCRI, Kasaragod, the tender coconuts were subjected to preliminary inspection to ensure that they were not damaged.

2.2 | Laboratory-scale texture analyzer

The mechanical properties of tender coconuts were determined with a Stable Micro Systems Texture Analyzer (model TA. HD Plus). The regular probes (supplied along with the instrument) are used to find out the cutting and punching force of agro-products. However, the regular probes were not suitable for the present study because of the hard nature of tender coconut. Hence, a customized punching and cutting tool was fabricated using high carbon steel (Figure 1). The dimensions of the punching tool used in this study are 5 mm (diameter) × 68 mm (length) and that of the cutting tool is 70 mm (width) × 66 mm (length) × 3 mm (thickness). Bevel angle of cutting tool is 30°.

FIGURE 1 Punching and cutting probe used in this study

2.2.1 | Texture analyzer setup

Punching and cutting tests were performed at six loading positions as ridge top (near to perianth), ridge middle, ridge bottom (near to fruit base), flat-top (near to perianth), flat-middle, and the flat-bottom (near to fruit base) as shown in Figure 2. The texture analyzer parameters for test conditions were pretest speed—2 mm s^{-1}, test speed—1 mm s^{-1}, post-test speed—10 mm s^{-1}, test distance—40 mm, trigger type—auto, target mode—distance, trigger force—5 g, and load cell—750 kg. The accuracy of the instrument was ±0.001 mm in deformation and ±0.001 N in force. The punching probe used in this study was a flat-end. Exponent Lite software (supplied with instrument) was used to plot the graph between force offered by the tender coconut husk and penetration distance. The peak force obtained from the graph was considered as the maximum punching/cutting force and the area under this curve known as punching/cutting energy.

2.3 | Microscopic images

Understanding the tender coconut fiber structure in the mesocarp section of the husk is very important for this study. Hence, we have taken 20 × 20 mm specimens from three different locations (bottom, middle, and top) of the mesocarp section of the tender coconut. The microscopic images of the specimen were recorded at 10× by using a stereomicroscope (Nikon SMZ 800N).

2.4 | Statistical analysis

The experiments were conducted with 25 replications for each genotype. The mean and standard deviation values were calculated using Microsoft Excel-2003. The effect of genotype and loading position on punching and cutting force of tender coconut was analyzed using AGRES software (Ver. 7.01).

3 | RESULTS AND DISCUSSION

High carbon steel has been widely used for manufacturing tools for heavy-duty operations. In the coconut processing industry, product tools such as tender coconut cutter, deshelling machine rotor, tender coconut trimming knife, and snowball shell cutting disc were made from high carbon steel (Manikantan et al., 2018). The major advantage of using high carbon steel is its food-grade applicability and its high strength. Hence, the cutting and punching probes were fabricated using the high carbon steel.

3.1 | Punching force

Determination of punching force is essential to calculate the torque and horsepower required to punch the tender coconut. These calculations are very necessary to develop tender coconut punching machine. The effect of genotype and loading position on the punching force of tender coconut is shown in Table 1. The highest punching force of 402.93, 536.40, 255.95, and 339.51 N was recorded in AGT at four different loading positions (flat middle, flat bottom, ridge middle, and ridge bottom, respectively). COD required more punching force in the flat-top (126.97 N) and ridge-top (122.95 N) section. The lowest punching force at five different orientations (except ridge top) was observed in the genotype of KGD, whereas, the lowest punching force (102.80 N) at the ridge-top section was noted in GBGD. The

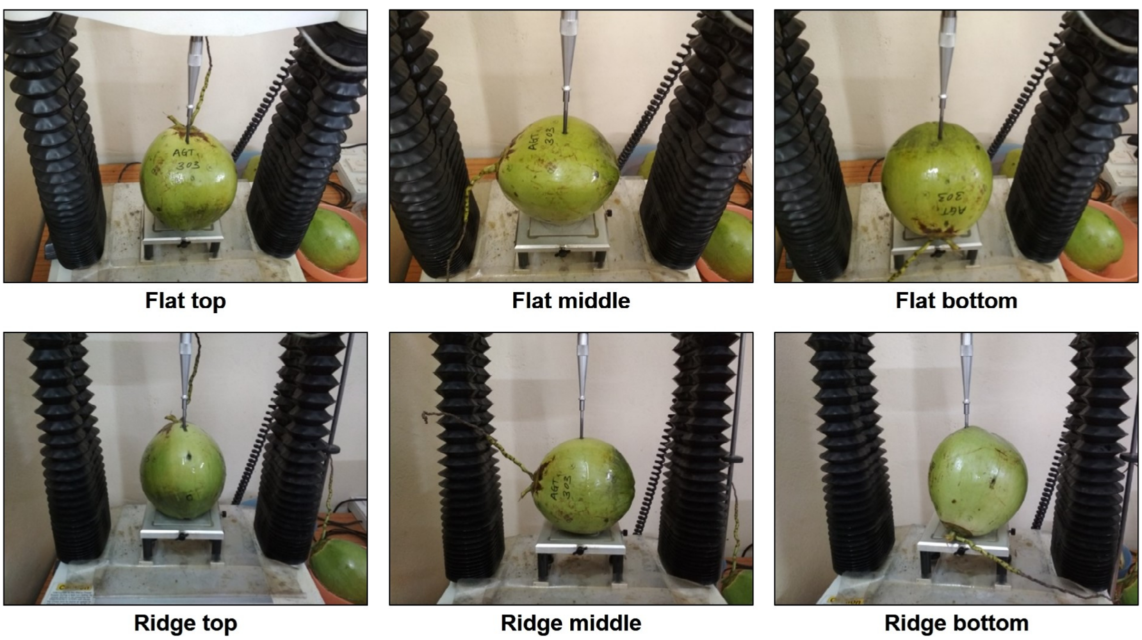

FIGURE 2 Six loading positions of tender coconut

punching force increased with the change of orientation from flat-top to flat-bottom by 353.46, 88.28, 72.75, and 116.06%, with the genotypes AGT, COD, KGD, and GBGD, respectively. Punching force in the ridges (102.80–272.77 N) is higher than the flat direction for the varieties COD, KGD, and GBGD. However, the nuts of AGT showed a reversal in this trend.

Biologically, the tender coconut husk is composed of three major tissues namely exocarp, mesocarp, and endocarp (Figure 3). Lignin and cellulose are the major components of the tender coconut husk (Lomelí-Ramírez, Anda, Satyanarayana, de Muniz, & Iwakiri, 2018), which contributes to the hardness of the exocarp and mesocarp region. In combination with the soft spongy tissue near perianth, the tender coconut possesses an exceptional internal structure. The arrangement of fibers in the mesocarp section of tender coconut depicts that the top section of tender coconut husk (near to perianth) contains spongy tissue (absence of fiber) and middle and bottom section of the husk are composed of fibers (Figure 4). The lignin present in the fiber provides it the rigidity and resistance (da Costa, Sanches, Ramos, Boueri, & Guimarães, 2013). Hence, the absence of fiber at top orientation may offer less resistance and consequently requires less punching force and accordingly the presence of fiber at the bottom section requires more punching force. The genotype, loading position, and the interaction of genotype and loading position are significantly ($p \leq .01$) influenced by the punching force (Table 2).

Lomelí-Ramírez et al. (2018) reported that the fiber of the green coconuts has lower tensile properties compared to the brown fibers. Thus, the green coconuts may require less cutting and/or punching force. This could be attributed to the moisture content of the fiber. The moisture content of the tender coconut husk is in the range of 83–90% w.b. (Pandiselvam et al., 2019). da Costa et al. (2013) also reported that the tender coconut husk fiber is smooth and white in color and has moisture of 85%. The moisture content depends on the genotype and maturity. In our previous study (Pandiselvam et al., 2018), we have found that the coconut husk of 12 months (green husk) and 13 months (dry/brown husk) maturity showed the moisture content of 53–64 and 24–36% (w.b.), respectively. Hence, unlike the matured coconuts, the presence of high moisture in the tender coconut husk may facilitate easy punching. Similarly, Selvam, Manikantan, Chand, Sharma, and Seeranguraya (2014) also reported that the interaction of variety and moisture content has a significant effect on rupture force and initial cracking force for sunflower kernel and seed.

3.2 | Cutting force

Minimally processed tender coconut has been widely available in the Indian market. To make the minimally processed nut (pentagonal shape), the husk has to be trimmed in all sides. Hence, it is important to understand the mechanical properties of tender coconuts in all the sides to design the trimming machine. The variations of the cutting force of tender coconuts as a function of genotype and loading position are shown in Table 3. Genotype AGT required more cutting force in four different locations (flat top (474.58 N), flat middle (632.40 N), flat bottom (799.52 N), and ridge top (501.45 N)) of tender coconut than other genotypes. The lowest cutting force was observed at three different positions such as flat top (372.16 N), ridge middle (472.74 N), and ridge bottom (512.83 N) section of KGD. GBGD has the lowest cutting force in the other three loading positions (ridge top [343.03 N], flat middle [483.49 N], and flat bottom [560.02 N]). This could be attributed to the relatively high husk thickness, and strong and dense fiber (more fiber per unit area) characteristics of AGT with reference to other three genotypes. The cutting force required for flat bottom orientation of AGT, COD, KGD, and GBGD was 68.47, 75.83, 70.04, and 27.90%, respectively, more than flat top orientation. Similarly, the force required to cut ridge bottom orientation of AGT, COD, KGD, and GBGD was 33.41, 101.10, 16.63, and 93.27%, respectively,

FIGURE 3 Cross sectional view of tender coconut

TABLE 1 Effects of genotype and loading position on the punching force (N)

	Flat-top	Flat-middle	Flat-bottom	Ridge-top	Ridge-middle	Ridge-bottom
AGT	118.29 ± 13.38	402.93 ± 25.42	536.40 ± 55.30	111.04 ± 11.05	255.95 ± 22.37	339.51 ± 52.45
COD	126.97 ± 17.53	151.06 ± 11.68	239.06 ± 15.45	122.95 ± 16.08	152.81 ± 7.97	256.30 ± 18.54
KGD	107.09 ± 25.80	136.12 ± 9.04	185.00 ± 23.92	120.52 ± 6.41	156.29 ± 17.17	188.93 ± 15.93
GBGD	121.16 ± 5.07	203.49 ± 24.66	261.79 ± 14.63	102.80 ± 2.99	231.95 ± 10.80	272.77 ± 15.25

Abbreviations: AGT, Andaman Giant Tall; COD, Chowghat Orange Dwarf; GBGD, Ganga Bondam Green Dwarf; KGD, Kulasekaran Green Dwarf.

more than ridge top orientation. Hence, the spongy white tissue located in the top section (near the perianth) of the husk tends to be the softest part. Matured fiber is located on the bottom section (near to fruit base) of husk tends to be the firmest. The statistical analysis indicated that the genotype and loading position of tender coconuts had a significant effect ($p \leq .01$) on cutting force (Table 2). Similarly, the interaction of genotype and loading position also had a significant effect ($p < .01$) on the cutting force.

The force required for cutting the tender coconuts has been more than the punching. It could be due to the size and orientation of the

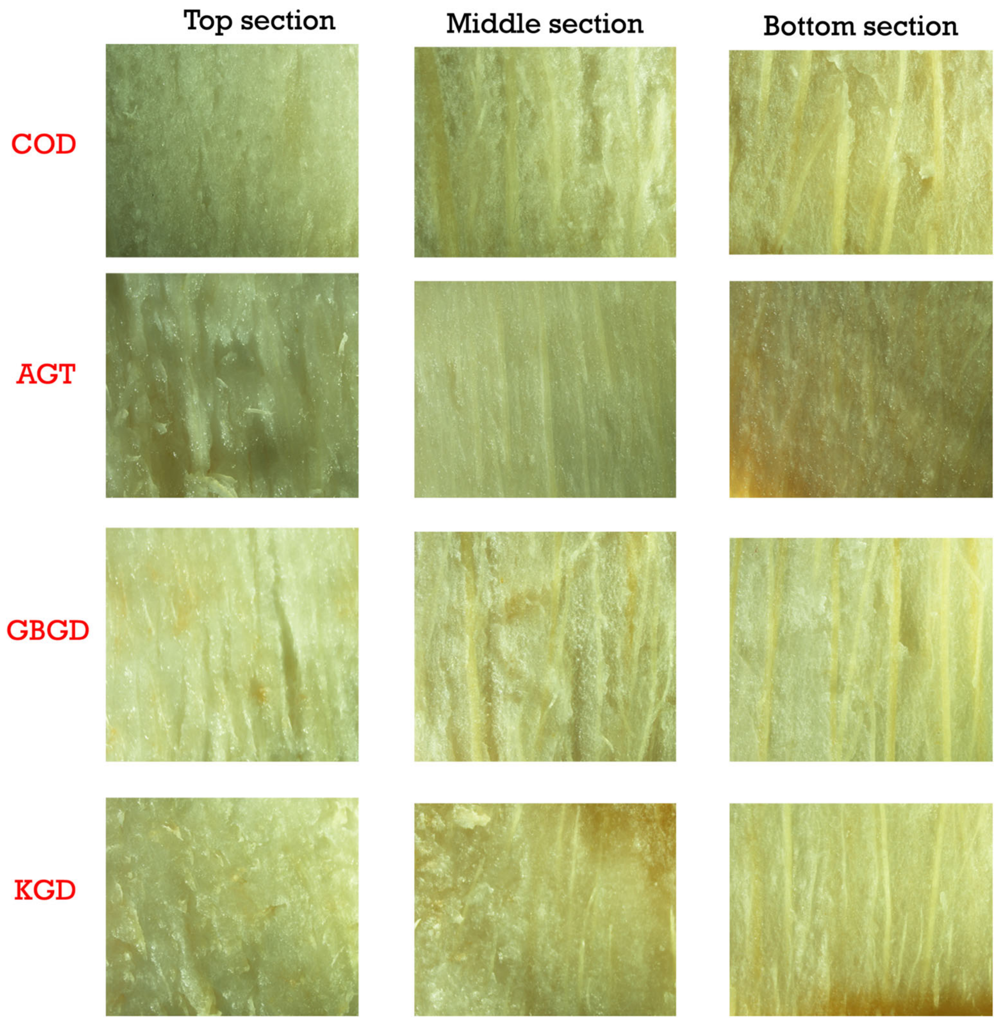

FIGURE 4 Fiber arrangement in tender coconut husk (mesocarp section) at different locations

TABLE 2 ANOVA for different mechanical properties of tender coconuts

	df	Punching force	Cutting force	Punching deformation	Cutting deformation	Punching energy	Cutting energy
Loading position (L)	5	185.29**	86.86**	5.87**	2.64 NS	7.20**	13.43**
Genotype (G)	3	192.17**	79.48**	19.49**	8.15**	8.20**	32.43**
L × G	15	36.50**	11.14**	13.32**	0.74 NS	2.94*	1.83 NS
Error	72	1.00	1.00	1.00	1.00	1.00	1.00
Total	95	22.34	12.50	3.78	1.36	1.86	3.38
CV (%)		11.58	8.00	25.51	15.63	55.76	18.03
CD		0.05	0.05	0.05	0.05	0.05	0.05
L		1.62	3.67	4.39	3.79	109.76	176.02
G		1.32	2.99	3.58	3.10	89.62	143.72
L × G		3.24	7.34	8.79	7.59	219.53	352.05

Note: ***p* is significant at .01 level, **p* is significant at .05 level.
Abbreviations: CD, critical difference; CV, Coefficient of variation; NS, nonsignificant.

TABLE 3 Effect of genotype and loading position on the cutting force (N)

	Flat-top	Flat-middle	Flat-bottom	Ridge-top	Ridge-middle	Ridge-bottom
AGT	474.58 ± 49.67	632.40 ± 12.5	799.52 ± 46.72	501.45 ± 14.56	614.06 ± 30.49	669.01 ± 49.57
COD	443.94 ± 25.88	605.15 ± 96.03	780.60 ± 53.84	491.04 ± 42.20	824.28 ± 45.17	987.48 ± 80.03
KGD	372.16 ± 37.64	540.23 ± 31.35	632.82 ± 34.76	439.67 ± 20.20	472.74 ± 32.31	512.83 ± 32.98
GBGD	437.83 ± 51.53	483.49 ± 25.81	560.02 ± 35.61	343.03 ± 23.26	539.00 ± 45.09	662.98 ± 47.20

Abbreviations: AGT, Andaman Giant Tall; COD, Chowghat Orange Dwarf; GBGD, Ganga Bondam Green Dwarf; KGD, Kulasekaran Green Dwarf.

TABLE 4 Effect of genotype and loading position on the deformation (mm) while punching

	Flat-top	Flat-middle	Flat-bottom	Ridge-top	Ridge-middle	Ridge-bottom
AGT	10.09 ± 3.41	42.39 ± 4.50	35.79 ± 4.82	6.34 ± 1.28	44.80 ± 2.41	35.27 ± 12.38
COD	30.49 ± 7.65	18.31 ± 5.96	16.85 ± 6.42	12.38 ± 6.61	8.12 ± 1.51	23.71 ± 4.63
KGD	24.28 ± 8.45	14.82 ± 9.50	13.07 ± 7.19	8.94 ± 4.93	25.38 ± 9.47	19.95 ± 4.63
GBGD	35.47 ± 7.13	20.30 ± 4.95	17.59 ± 1.11	34.92 ± 3.42	22.05 ± 6.87	23.68 ± 5.54

Abbreviations: AGT, Andaman Giant Tall; COD, Chowghat Orange Dwarf; GBGD, Ganga Bondam Green Dwarf; KGD, Kulasekaran Green Dwarf.

probe. The dimension of the cutting probe is more than the punching probe. The probe used for cutting covered more unit area while performing the test. Hence, it could be concluded that the force required for cutting or punching a tender coconut could be directly proportional to the contact area of the tool. The radius of curvature of the tender coconut and the dimension of the punching and cutting probe are the major functions influencing the contact area.

3.3 | Punching deformation

The values of punching deformation are the determining factor of the sharpness and shape of the punching tool. Also, deformation data could be useful for developing the coconut sorting machine based on the variety and the tender coconut maturity. The variation of the genotype and loading position on deformation at the rupture point are shown in Table 4. It was observed that the deformation at ridge top position (6.34–34.92 mm) recorded lower values than the flat top position (10.09–35.47 mm) for all the four genotypes. Among the four genotypes, the highest and lowest deformation values were documented for AGT (ridge middle position [44.80 mm]) and AGT (ridge top position [6.34 mm]), respectively. This may be due to the soft nature of the ridge top section and the presence of fiber at the middle and bottom sections. Hence, the top section of the tender coconut (near perianth) may have less elastic nature than the middle and bottom sections. The ridge-top position of AGT, COD, KGD, and GBGD recorded 37.16, 59.39, 63.17, and 1.55%, lower deformation than flat-top position. In contrast, most of the ridge middle and bottom positions recorded more deformation than flat-middle and flat bottom position. This trend was found to be true in the genotypes KGD and GBGD than other genotypes (Table 4).

The flexibility of husk in the ridge-middle and the ridge-bottom position was higher than the flat-middle and flat bottom position. The size of the ridge section of tender coconut was more than the flat section. Khodabakhshian, Emadi, Fard, and Saiedirad (2011) reported that the deformation exhibited by the larger size sunflower kernels and the seed was substantially higher (0.85–2.86 mm) than the smaller counterparts (0.47–2.54 mm). These results could be attributed to the ratio of spongy tissue to fiber, difference in hardness of exocarp area, cell wall thickness, lumen diameter, fiber size, tensile strength of fiber at ridge and flat region, and differences in the micro-fibril angle between different cells of the same fiber (Satyanarayana, Kulkarni, & Rohatgi, 1981). The genotype and position had a significant effect ($p \leq .01$) on tender coconut husk deformation. The interaction effects of genotype and loading position were significant at 1% level on deformation (Table 2).

3.4 | Cutting deformation

The cutting deformation data is a crucial factor for the design of cutting knife thickness and bevel angle of knife. The effect of genotypes and loading position on the deformation value while cutting are shown in Table 5. From Table 5, it is apparent that except for a few cases, the deformation values for AGT genotype were higher than other genotypes. The highest (35.66 mm) and lowest (24.93 mm) deformation values were observed at the ridge middle (AGT) and ridge-top (GBGD) position, respectively. It could be due to the presence of less flexible fiber in the middle section than the fiber located at the top section. Lomelí-Ramírez et al. (2018) observed that the fibers with a smaller diameter had higher tensile strength and young modulus compared with the larger diameter fibers. Also, the flexibility of the coconut fiber depends on the fiber diameter, crystallinity, chemical composition, degree of polymerization, and micro-fibril angle (Khan & Alam, 2012).

The deformation of the spongy tissue located at the ridge-top position was low as compared to other ridge positions. This tendency was more obvious for all four genotypes (Table 5). Also, Table 5 showed that the deformation of three different flat positions of tender coconut was significantly different. The different responses exhibited by the flat positions of tender coconut as a result of nonhomogenous texture and

TABLE 5 Effect of genotype and loading position on the deformation (mm) while determining cutting force

	Flat-top	Flat-middle	Flat-bottom	Ridge-top	Ridge-middle	Ridge-bottom
AGT	32.91 ± 3.62	34.99 ± 0.02	34.97 ± 0.15	33.85 ± 1.96	35.66 ± 0.53	35.34 ± 0.97
COD	28.71 ± 3.80	32.39 ± 2.81	27.40 ± 1.37	25.27 ± 6.94	34.85 ± 0.26	33.20 ± 1.46
KGD	33.65 ± 2.32	28.66 ± 9.99	25.75 ± 2.21	27.55 ± 7.31	35.33 ± 0.58	34.48 ± 0.69
GBGD	25.13 ± 7.92	26.27 ± 5.99	28.38 ± 5.73	24.93 ± 8.96	27.34 ± 6.73	29.65 ± 2.74

Abbreviations: AGT, Andaman Giant Tall; COD, Chowghat Orange Dwarf; GBGD, Ganga Bondam Green Dwarf; KGD, Kulasekaran Green Dwarf.

TABLE 6 Effect of genotype and loading position on the punching energy (J)

	Flat-top	Flat-middle	Flat-bottom	Ridge-top	Ridge-middle	Ridge-bottom
AGT	0.82 ± 0.77	6.49 ± 2.11	7.05 ± 4.37	0.47 ± 0.05	4.32 ± 1.06	4.38 ± 0.38
COD	1.51 ± 0.83	1.52 ± 0.85	2.08 ± 0.79	1.52 ± 1.09	1.57 ± 0.36	3.57 ± 1.61
KGD	1.50 ± 1.40	1.97 ± 1.75	2.42 ± 1.18	0.84 ± 0.58	2.92 ± 2.09	3.00 ± 1.37
GBGD	2.23 ± 1.42	2.67 ± 0.36	2.71 ± 0.13	2.54 ± 0.68	2.59 ± 1.54	3.89 ± 2.57

Abbreviations: AGT, Andaman Giant Tall; COD, Chowghat Orange Dwarf; GBGD, Ganga Bondam Green Dwarf; KGD, Kulasekaran Green Dwarf.

TABLE 7 Effect of genotype and loading position on the cutting energy (J)

	Flat-top	Flat-middle	Flat-bottom	Ridge-top	Ridge-middle	Ridge-bottom
AGT	11.79 ± 0.82	15.53 ± 0.98	16.59 ± 2.10	12.41 ± 0.41	15.57 ± 2.50	15.87 ± 0.16
COD	9.05 ± 2.16	12.75 ± 2.72	12.77 ± 0.25	7.93 ± 3.11	16.32 ± 1.54	19.33 ± 1.95
KGD	7.45 ± 3.26	8.91 ± 2.59	9.42 ± 0.87	7.45 ± 2.79	10.67 ± 1.59	11.89 ± 2.34
GBGD	8.85 ± 1.63	8.86 ± 1.29	9.35 ± 1.75	6.18 ± 2.47	8.15 ± 3.96	11.30 ± 2.12

Abbreviations: AGT, Andaman Giant Tall; COD, Chowghat Orange Dwarf; GBGD, Ganga Bondam Green Dwarf; KGD, Kulasekaran Green Dwarf.

fiber profile. Similar results were reported by Khodabakhshian, Emadi, Khojastehpour, and Golzarian (2019) for pomegranate fruit at three different positions on the fruit. The effects of genotype, loading position and its interaction were found to be significant ($p \leq .01$) for deformation at rupture point (Table 2).

3.5 | Punching energy

Table 6 shows the experimental data pertaining to the punching energy of tender coconut husk as affected by genotypes and loading positions. The maximum punching energy required to initiate the rupture was found maximum of 7.05 J at the flat-bottom position and a minimum of 0.47 J at ridge top position for AGT genotype. The results showed that punching energy values of tender coconut husk increased when the position is changed from top to bottom. It could be due to the difference in the orientation of fiber, the difference in fiber development at the mesocarp region, the strength of fiber, and the number of fibers per unit area in exocarp and mesocarp section. Advances in the development and/or maturity of fiber at the bottom position (both flat and ridge) of the tender coconut may require higher punching energy than other positions. Akash, Chikkanna, Girisha, and Sreenivas Rao (2015) reported that the tensile and hardness properties of the Jute/Hemp laminate composites are strongly dependent on the fiber orientation. The statistical analysis illustrated a significant difference ($p \leq .01$) between the punching energy for all loading positions for all genotypes.

3.6 | Cutting energy

The mean values of the cutting energy of the four tender coconut genotypes at six loading position are shown in Table 7. Irrespective of the genotypes, cutting energy values have decreased by changing the loading position from the bottom section (near to the fruit base) to the top section (near to perianth). It indicates that greater forces are necessary to cut the bottom section of the tender coconut. The street vendors used to cut the tender coconut at the top section because of this reason. Cutting energy required to rupture the husk in six loading positions was more than punching rupture energy. This could be because of the high contact area of the cutting probe with the husk results in the expansion of low stress (Khodabakhshian et al., 2011). The effects of genotype, loading position and its interactions were found significant at $p \leq .01$ level to cutting energy according to variance analysis.

4 | CONCLUSIONS

The determination of mechanical properties of tender coconuts is necessary for the design and development of harvest and postharvest machines. The range of punching force for all genotypes of tender coconuts is from 102.80 to 536.40 N and the cutting force between 372.16 to 987.48 N. The variety AGT requires more punching and cutting strength at most of the loading position. The force required for punching or cutting at the top orientation is significantly less than the bottom orientation. The mechanical properties of tender coconuts exhibited a significant dependence ($p \le .01$) on the genotypes and loading position. These findings are instrumental to determine the torque and energy required for minimal processing of tender coconuts. Grading the coconuts and/or identification of the maturity of the coconut based on the mechanical properties could be the future line of work.

ACKNOWLEDGMENTS

The authors are grateful to PC Unit, AICRP on Post-Harvest Engineering and Technology, Ludhiana for the financial support. We express our sincere gratitude to the Director, ICAR-CPCRI, Kerala and Director, ICAR-DCR, Karnataka for providing the necessary facilities. We would like to thank Dr. M. Sujithra, Dr. Rajkumar, and Dr. V.H. Prathibha, ICAR-CPCRI for their valuable help in the microscopic observations.

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How to cite this article: Pandiselvam R, Manikantan MR, Balasubramanian D, et al. Mechanical properties of tender coconut (*Cocos nucifera* L.): Implications for the design of processing machineries. *J Food Process Eng*. 2020;43:e13349. https://doi.org/10.1111/jfpe.13349