International Journal of Agricultural Technology 2020 Vol. 16(1): 63-76
Available online http://www.ijat-aatsea.com
ISSN 2630-0192 (Online)

A Study on the Mechanical Characteristics of Cassava Tuber Cutter

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Lomchangkum, C., Junsiri, C., Sudajan, S. and Laloon, K. (2020). A Study on the Mechanical Characteristics of Cassava Tuber Cutter. International Journal of Agricultural Technology 16(1): 63-76.

Abstract The mechanical characteristics of cassava tuber cutter were determined the mechanical behaviour and its effect during shear cutting and evaluated variables (maximum cutting shear force, maximum cutting shear stress, specific cutting energy and amount of post-cutting loss) using 4 cutting tilt angles (30°, 45°, 60° and 90°) and 4 cutting speeds (20, 40, 60 and 100 mm/min). These variables were set in order to provide basic information and guidelines to design the cutting blade of the cutting machine to separate cassava tuber from its rhizome. The cassava variety of Kasetsart 50 was tested with tuber ages of 10-12 months, planted in the area of Mueang district, Khon Kaen province. A universal testing machine with maximum force of 50 kN was operated. The test results indicated that the maximum cutting shear force and the maximum cutting shear stress increased with increasing tuber age which was due to the increase in density and starch content. The cutting tilt angle at 30° with the cutting speed at 100 mm/min provided the least values for the maximum cutting shear force, the maximum cutting shear stress and the specific cutting energy. For tubers aged 10, 11 and 12 months, the average maximum cutting shear forces were 1.61±0.61, 3.60±0.24 and 4.08±0.11 kN respectively, while the average maximum cutting shear stresses were 2.01±0.76, 7.20±0.12 and 8.17±2.97 MPa respectively and the average specific cutting energies were 24.74±15.56, 26.15±10.81 and 30.38±11.10 mJ/mm^2 respectively. The amounts of post-cutting loss were slightly different within the range of 0.5-1% for different tuber ages.

Keywords: Cutting cassava tuber from rhizome, maximum cutting shear force, maximum cutting shear stress, specific cutting energy

Introduction

Cassava is one of the important economic crops of Thailand, following sugar cane and rice. In 2016 to 2017, the total area of cassava cultivation in Thailand was approximately 8.9 to9.5 million rai distributed over the country except in the southern region. Most cultivation areas are located in the northeast

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followed by the central and the northern regions. Cassava can be harvested throughout the year, especially from December to July. Total yields of fresh cassava tuber in the country are processed into raw materials for industries, such as, cassava flour for paper and textile industries, cassava pellets for animal feeds, cassava chips for ethanol and other industrial sectors. From the total harvest of a year, about 25-28% of cassava products were used within the country while the rest (75-80%) were exported. For Thailand, a major export markets are Asian countries within the region and China (Office of Agricultural Economics, 2019).

The current method of cassava harvesting begins with cutting the plant leaving about 30 cm of trunk above the ground. The cassava tubers are then unearthed and gathered by labor or digging machine. These tubers are, later, separated from their rhizomes by labor or cutting machine. The assemblage of tubers after harvesting can be operated only by one process which is by labor. The gathered tubers are placed in baskets and transported onto the trucks. The process requires about 7-10 people in each operation (Sarathulpitak *et al.*, 1994; Bunart, 2000; Chiawchanwattana, 2006; Chamsing *et al.*, 2009). In order to avoid the issues of fresh cassava deterioration that rapidly occurs, fresh tubers must be transported to the factories and done on the same day. Otherwise, the fresh tuber with high moisture will rapidly deteriorate and consequently cause low amount of starch content affecting the purchase price of fresh cassava (Suvanapa and Wongpichet, 2015). For the harvesting process, especially the cutting of tuber off its rhizome, many researchers proposed guidelines for major development and research for machine prototype, for example, a research and development of cassava tuber cutter and plucker machines. These prototypes were in the early stages of development and the operational principles were different, nevertheless, all types are still dependent on labor to deliver cassava tuber into the cutter or plucker machines (Khonphutsa and Kitsamphanwong, 2012; Langkapin *et al.*, 2012; Junyusen *et al.*, 2014; Arsawang *et al.*, 2016). Ultimately, current harvesting processes require large number of laborers.

This research aimed to study the factors affecting the efficiency of cassava tuber cutter by investigating its mechanical behavior, its effect during shear cutting and to evaluate variables: maximum cutting shear force, maximum cutting shear stress, specific cutting energy and amount of post-cutting loss, by using different cutting tilt angles and cutting speeds.

Materials and methods

In this study, cassava tubers of variety Kasetsart 50 were used, with ages of 10, 11 and 12 months grown in Mueang district, Khon Kaen province. A

Universal Testing Machine (UTM) with maximum force of 50 kN was used as a testing device. The procedure and methods were as follows:

The Universal Testing Machine (UTM) with maximum force of 50 kN as shown in Figure 1 and a digital weighing scale served as control. Four cutting blades with different tilt angles of 30°, 45°, 60° and a control factor of 90° were evaluated. Each blade had a diameter of 5 cm, based on the physical properties of rhizome diameter as shown in Table 1. Cassava tuber used in this study was a variety of Kasetsart 50 with ages of 10, 11 and 12 months, with physical properties as shown in Table 1.

Table 1. Physical properties of cassava rhizome, Kasetsart 50 variety, in average values

Rank	Physical properties of cassava rhizome	Cassava Age		
		10 months	**11 months**	**12 months**
1.	Rhizome's height, cm	33.6±1.0	33.1±1.6	34.7±3.7
2.	Rhizome's diameter ,cm	4.4±0.5	4.6±1.6	4.8±2.4
3.	Tuber's spread width, cm	56.7±7.9	57.4±6.3	58.8±5.4
4.	Weight + rhizome, kg	6.1±1.0	7.3±1.3	8.4±2.6
5.	Moisture content of fresh tuber , % w.b.	57.3±2.3	60.6±1.8	62.4±3.3
6.	Percentage starch content of fresh tuber, %	23.4±3.4	24.6±4.1	25.8±3.8

Average data with ± a standard deviation.

Figure 1. The Universal Testing Machine (UTM) with maximum force of 50 kN and its main components

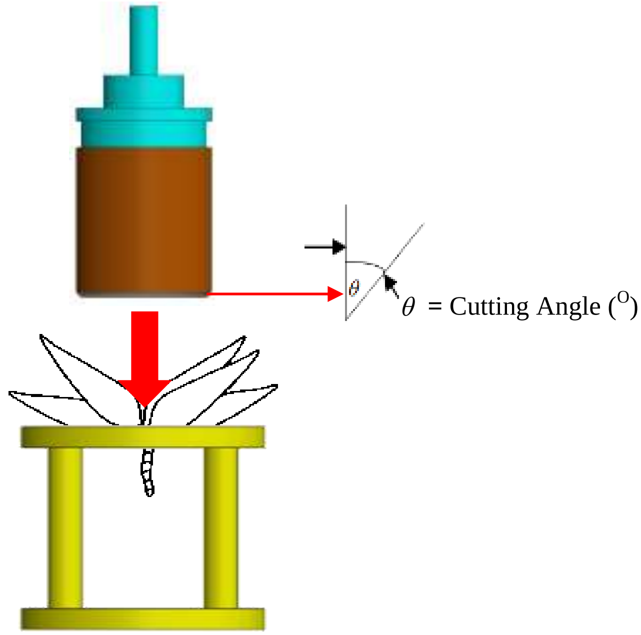

Figure 2. Illustration of cutting shear force and cutting angle for separating cassava tuber from its rhizome

The samples

The cassava rhizomes and equipment was setting up in steady state at the material testing laboratory at the Department of Agricultural Engineering, Khon Kaen University. The cutting blade was installed on the plinth of the universal testing machine, as shown in Figure 3. The cutting test was performed with different tilt angles at 30°, 45°, 60° and 90° being the control factor. The blade wwas then pressed vertically down onto the rhizome. Four levels of cutting speeds of 20, 40, 60 and 100 mm/min being the control factor were set for each tilt angle. The cutting was estabilized at the range of 20 to 100 mm/min since it appeared that the range of 101-500 mm/min was too fast. Therefore, the tesing speeds were set at 4 levels: 20, 40, 60 and 100 mm/min as control factor. Testing was repeated using 30 samples. Data were collected, calculated, and evaluated accordingly. The procedure 1 and 2 were repeated for each cutting speed in accordance with the method of 4x4 factorial experimental test by using the methods of Kutsamrong and Kbrave, 2015; Chattopadhyay and Pandey, 1998; Xue *et al.*, 2015; Persson, 1987) and consistent with the Standards of ASAE (1998).

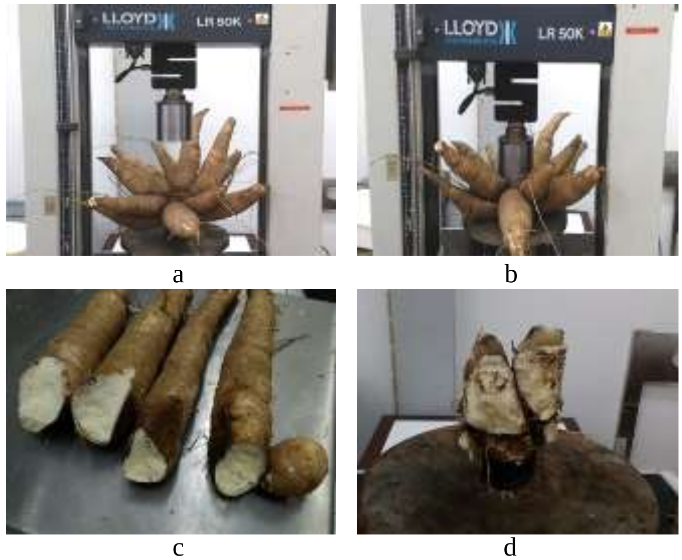

Figure 3. a-The set-up of testing machine and prepared cassava rhizome, b-The cutting of cassava tubers from their rhizome, c-Cassava tubers after cutting and d-Cassava tuber parts left on rhizome after cutting

Indicators

The indicators in this study were average values of the maximum cutting shear force, the maximum cutting shear stress, the specific cutting energy and the amount of post-cutting loss among different tilt angles and cutting speeds. These values were calculated by using the equations below:

1. Determination the maximum cutting shear stress: this could be obtained by having the maximum cutting shear force, which was applied in the direction of the cutting shear force acting across the distance pressed through the tuber, divided by the cross-sectional shear area of cutting blade, Equation (1). (O'Dogherty *et al.*, 1995).

$$\sigma_s = \frac{F_{\max}}{A} \qquad (1)$$

When σ_s = Maximum shear stress (Pa)

F_{max} = Maximum shear force (N)

A = Cross-sectional shear area of cutting blade (m^2)

2. Determination of the specific cutting energy: in accordance with the calculation principle by Heidari et al., 2012 and Prapakarn (2008), it could be obtained from the area under the curve of cutting shear force across the distance pressed through the tuber, Equation (2).

$$E_{ss} = \frac{1}{A}\int F.dx = n \times \frac{f}{A} \qquad (2)$$

When E_{ss} = Specific cutting energy (mJ/mm^2)
A= Cross-sectional shear area of cutting blade (m^2)
F = Shear force (N)
x = Distance of blade pressed through the tuber (mm)
n = Number of areas under curves of cutting shear force across distance pressed through the tuber
f = Area unit multiplier

3. Determination of the amount of post-cutting loss: this could be obtained by using the formulata in Equation (3) (Chancellor, 1958).

$$L = \frac{W_1}{W} \times 100 \qquad (3)$$

When L = Amount of post-cutting loss (%)
W_1 = Weight of tuber left on the rhizome after cutting (kg)
W = Weight of total tuber (including both the cut tuber and the tuber left on the rhizome after cutting (kg)

4. Correlation between the physical and mechanical characteristics of cutting cassava tuber from rhizome: the multiple linear regression analysis could be calculated as shown in Equation (4) (Prapakarn, 2008).

$$Y = \alpha + \beta_i X_i + \varepsilon \qquad (4)$$

When Y = Dependent variable which was a random variable
X_i = Independent variable which was an observed variable
α = Y intercept (Y value when X equalled 0)
β_i = Slope of the linear line, a ratio between Y and X when X value changed by one increment
Ɛ = Error or the differences of Y and X on linear regression
i = Index of the independent variable 1, 2,…, n

Results

The test results showed that the maximum cutting shear force and maximum cutting shear stress for tuber aged 12 months were higher than those of ages 10 and 11 months. This was because older tubers are more dense and the amount of starch is usually high. The maximum cutting shear force, maximum cutting shear stress and specific cutting energy directly varied with the cutting tilt angle and cutting speed. The tilt angle at 30 ° with cutting speed at 100 mm/min was found to require lower maximum cutting shear force, maximum cutting shear stress, specific cutting energy and amount of post-cutting loss than tilt angles at 45°, 60°, and 90°. Furthermore, the increase in cutting speed exponentially decreased the maximum cutting shear force, maximum cutting shear stress and specific cutting energy for every tested angle. The average maximum cutting shear forces for tuber ages 10, 11 and 12 months were 1.61±0.61, 3.60±0.24 and 4.08±0.11 kN respectively, while the average maximum shear stresses were 2.01±0.76, 7.20±0.12 and 8.17±2.97 MPa respectively and the average specific cutting energies were 24.74±15.56, 26.15±10.81 and 30.38±11.10 mJ/mm^2 respectively. The amounts of post-cutting loss were slightly different within the range 0.5-1% because the loss did not depend on the effects of shear force and shear stress but on the cutting tilt angle for increased tuber's age, as shown in Tables 2, 3 and 4, and Figures 4, 5, 6 and 7.

Table 2. Average values of maximum cutting shear force, maximum cutting shear stress, specific cutting energy and amount of post-cutting loss at different cutting tilt angles and cutting speeds (cassava tubers aged 10 months)

Cutting speed (mm/min)	Cutting tilt angle (°)	Maximum cutting shear force (kN)	Maximum cutting shear stress (MPa)	Specific cutting energy (mJ/mm^2)	Post-cutting loss (%)
20	30	2.53^a±0.38	3.17^a±0.47	35.28^a±8.65	12.44^a±4.07
	45	3.20^b±0.21	3.90^b±0.26	51.16^b±16.77	23.86^b±5.91
	60	3.99^c±0.13	4.76^c±0.16	62.96^c±11.54	30.72^c±5.06
	90**	4.52^d±0.25	5.31^d±0.29	70.13^d±10.99	74.23^d±12.01
40	30	2.21^a±0.34	2.76^a±0.42	30.56^a±14.35	11.43^a±4.39
	45	3.17^b±0.20	3.86^b±0.25	42.11^b±10.72	23.67^b±4.37
	60	3.98^c±0.14	4.75^c±0.71	57.35^c±13.18	30.35^c±4.97
	90**	4.50^d±0.21	5.26^d±0.24	65.16^d±18.47	72.31^d±13.47
60	30	1.94^a±0.46	2.42^a±0.57	27.35^a±14.60	10.75^a±2.83
	45	3.07^b±0.24	3.75^b±0.29	45.44^b±10.46	22.68^b±4.33
	60	3.96^c±0.13	4.70^c±0.16	50.76^c±17.79	29.00^c±5.07
	90**	4.48^d±0.27	5.24^d±0.31	58.58^d±18.80	71.93^d±12.68
100**	30	1.61^a±0.61	2.01^a±0.76	24.74^a±15.56	8.44^a±3.08
	45	2.97^b±0.41	3.63^b±0.18	40.55^b±16.61	20.35^b±5.00
	60	3.76^c±0.10	4.61^c±0.12	48.32^c±13.44	28.85^c±3.17
	90**	4.26^d±0.31	5.12^d±0.36	50.04^d±14.63	64.11^d±11.09

Means in the same column followed by the same superscript are not statistically different at ($P < 0.05$)
Average data with ± is a standard deviation
**The control factors

Table 3. Average values of maximum cutting shear force, maximum cutting shear stress, specific cutting energy and amount of post-cutting loss at different cutting tilt angles and cutting speeds (cassava tubers aged 11 months)

Cutting speed (mm/min)	Cutting tilt angle (°)	Maximum cutting shear force (kN)	Maximum cutting shear stress (MPa)	Specific cutting energy (mJ/mm^2)	Post-cutting loss (%)
20	30	$4.55^a \pm 0.30$	$9.10^a \pm 0.44$	$37.68^a \pm 9.64$	$12.65^a \pm 4.10$
	45	$5.12^b \pm 0.26$	$10.24^b \pm 2.62$	$54.35^b \pm 17.51$	$24.01^b \pm 6.44$
	60	$5.98^c \pm 0.11$	$11.97^c \pm 2.52$	$68.83^c \pm 15.21$	$31.86^c \pm 5.16$
	90^{**}	$6.53^d \pm 0.34$	$13.06^d \pm 0.20$	$73.23^d \pm 17.28$	$74.66^d \pm 13.65$
40	30	$4.23^a \pm 0.28$	$8.47^a \pm 0.37$	$35.46^a \pm 8.41$	$11.76^a \pm 5.18$
	45	$5.09^b \pm 0.41$	$10.18^b \pm 2.45$	$51.16^b \pm 16.42$	$24.78^b \pm 4.69$
	60	$5.65^c \pm 0.36$	$11.30^c \pm 2.77$	$66.74^c \pm 10.31$	$30.35^c \pm 4.97$
	90^{**}	$6.48^d \pm 0.14$	$12.97^d \pm 3.51$	$70.30^d \pm 17.82$	$72.31^d \pm 13.47$
60	30	$3.95^a \pm 0.17$	$7.90^a \pm 0.11$	$32.64^a \pm 7.18$	$10.86^a \pm 3.66$
	45	$4.85^b \pm 0.33$	$9.70^b \pm 0.38$	$48.58^b \pm 11.19$	$23.14^b \pm 4.65$
	60	$5.25^c \pm 0.42$	$10.50^c \pm 2.47$	$60.87^c \pm 18.21$	$29.11^c \pm 5.66$
	90^{**}	$6.43^d \pm 0.18$	$12.86^d \pm 4.23$	$67.34^d \pm 16.24$	$71.18^d \pm 13.44$
100^{**}	30	$3.60^a \pm 0.24$	$7.20^a \pm 0.12$	$26.15^a \pm 10.81$	$8.89^a \pm 3.98$
	45	$4.03^b \pm 0.36$	$8.06^b \pm 0.22$	$48.28^b \pm 16.41$	$20.71^b \pm 5.17$
	60	$5.12^c \pm 0.26$	$10.25^c \pm 2.43$	$58.46^c \pm 12.83$	$28.90^c \pm 3.65$
	90^{**}	$6.28^d \pm 0.19$	$12.64^d \pm 4.16$	$62.20^d \pm 19.22$	$64.65^d \pm 11.61$

Means in the same column followed by the same superscript are not statistically different at ($P < 0.05$)
Average data with ± is a standard deviation
**The control factors

An analysis of the relationship between the physical and mechanical characteristics of cutting cassava tubers aged 10, 11 and 12 months could be obtained from Equation 4. The relationship could be predicted as shown by the highest coefficient of determination (R^2). From the predicted equation, the R^2 values for the maximum cutting shear force and maximum cutting shear stress were equal for all ages of tuber: 10, 11 and 12 months at 0.976, 0.957 and 0.936 respectively, followed by that for the specific cutting energy at R^2 = 0.972, 0.953 and 0.932 respectively. Besides the determination of cutting tilt angle, Equations 1, 2, 3 and 4 gave important indicators for the mechanical characteristics and the cutting speed, as shown in Table 5.

Table 4. Average values of maximum cutting shear force, maximum cutting shear stress, specific cutting energy and amount of post-cutting loss at different cutting tilt angles and cutting speeds (cassava tubers aged 12 months)

Cutting speed (mm/min)	Cutting tilt angle (°)	Maximum cutting shear force (kN)	Maximum cutting shear stress (MPa)	Specific cutting energy (mJ/mm^2)	Post-cutting loss (%)
20	30	6.16^{a} ±0.43	12.33^{a} ±4.08	40.38^{a} ±10.01	13.10^{a} ±4.19
	45	7.44^{b} ±0.26	14.88^{b} ±3.17	58.25^{b} ±16.77	24.65^{b} ±6.01
	60	8.16^{c} ±0.54	16.32^{c} ±4.14	72.46^{c} ±18.53	31.98^{c} ±6.18
	90**	9.33^{d} ±0.68	18.67^{d} ±3.68	76.92^{d} ±19.12	74.87^{d} ±12.14
40	30	5.86^{a} ±0.37	11.72^{a} ±2.14	37.51^{a} ±8.96	11.90^{a} ±4.59
	45	6.58^{b} ±0.29	13.36^{b} ±4.66	54.32^{b} ±17.16	24.88^{b} ±4.44
	60	6.96^{c} ±0.23	13.90^{c} ±3.94	70.82^{c} ±15.44	30.67^{c} ±5.01
	90**	9.01^{d} ±0.72	18.02^{d} ±4.26	75.02^{d} ±20.26	72.54^{d} ±12.77
60	30	4.77^{a} ±0.37	9.54^{a} ±0.56	34.88^{a} ±9.69	10.96^{a} ±2.49
	45	5.38^{b} ±0.58	10.76^{b} ±2.28	51.46^{b} ±18.66	23.24^{b} ±4.63
	60	6.14^{c} ±0.16	12.28^{c} ±4.63	68.75^{c} ±14.11	29.56^{c} ±5.21
	90**	8.74^{d} ±0.42	17.50^{d} ±3.18	72.47^{d} ±16.13	72.98^{d} ±13.76
100**	30	4.08^{a} ±0.11	8.17^{a} ±2.97	30.38^{a} ±11.10	9.10^{a} ±3.76
	45	5.01^{b} ±0.41	10.03^{b} ±2.76	50.26^{b} ±14.70	20.75^{b} ±5.08
	60	5.86^{c} ±0.32	11.72^{c} ±2.32	60.61^{c} ±12.77	29.16^{c} ±3.50
	90**	7.48^{d} ±0.76	14.96^{d} ±4.52	65.19^{d} ±10.94	64.75^{d} ±11.25

Means in the same column followed by the same superscript are not statistically different at ($P < 0.05$)
Average data with ± is a standard deviation
**The control factors

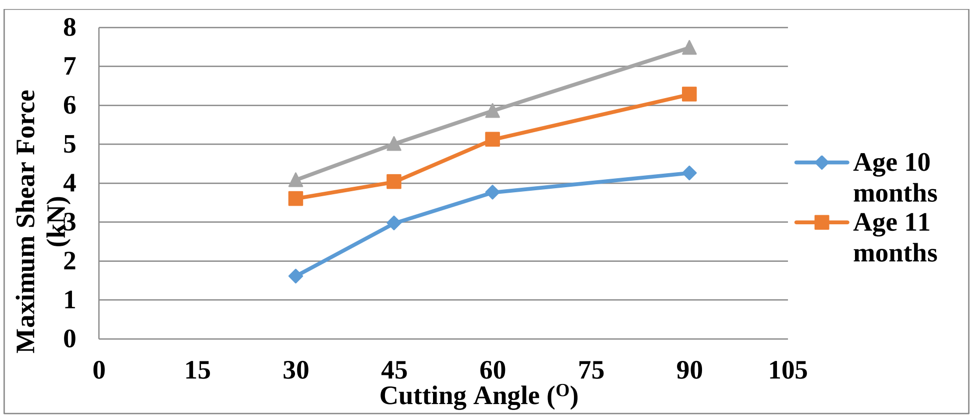

Figure 4. The relationship between cutting tilt angle and maximum cutting shear force on cassava tubers aged 10, 11 and 12 months (based on the cutting speed 100 mm/min)

Table 5. The predicted equation and coefficient of determination for the study of mechanical characteristics of cutting cassava tuber from rhizome

Cassava Age (month)	Mechanical characteristics	Predicted value	coefficient of determination (R^2)
10	Maximum cutting shear force, kN	1.8823+0.00814K-0.0055S	0.976
	Maximum cutting shear stress , MPa	3.8156+0.04069K-0.00326S	0.976
	Specific cutting energy, mJ/mm^2	22.3161+0.02134K-0.0387S	0.972
11	Maximum cutting shear force, kN	1.6379+0.00556K-0.0043S	0.957
	Maximum cutting shear stress, MPa	3.1174+0.02184K-0.0030S	0.957
	Specific cutting energy, mJ/mm^2	25.1020+0.03753K-0.0216S	0.953
12	Maximum cutting shear force, kN	0.5784+0.00296K-0.0048S	0.936
	Maximum cutting shear stress, MPa	3.5951+0.01030K-0.0335S	0.936
	Specific cutting energy, mJ/mm^2	28.5453+0.57586K-0.4151S	0.932

When K= cutting tilt angle (°) and S = cutting speed (mm/min)

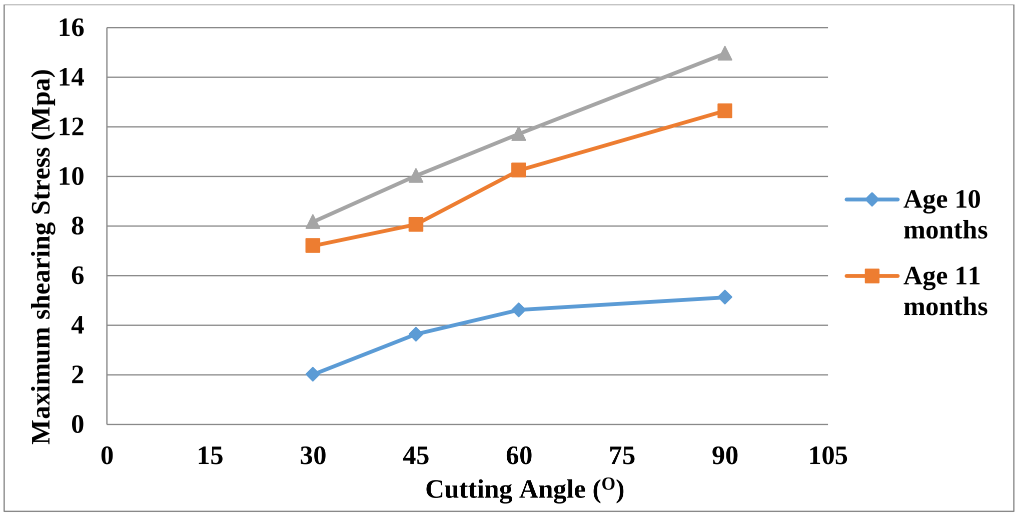

Figure 5. The relationship between cutting tilt angle and maximum cutting shear stress on cassava tubers aged 10, 11 and 12 months (based on the cutting speed 100 mm/min)

Therefore, this study suggests that the cutting tilt angle of 30 °is the most practical angle to cut cassava tuber from its rhizome by the shear technique. Nn actual design in accordance with engineering principles is needed to be carried out to find the optimal cutting speed to effectively separate cassava tuber from its rhizome.

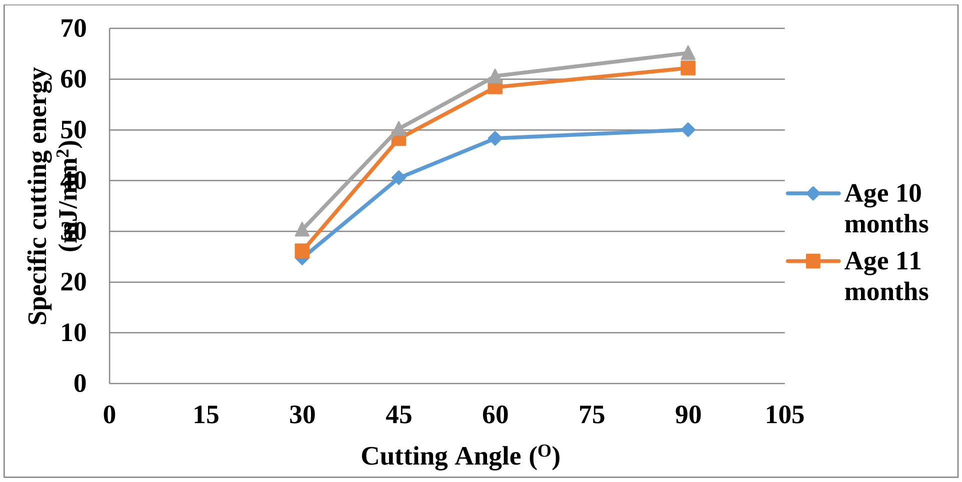

Figure 6. The relationship between cutting tilt angle and specific cuttingenergy of cassava tubers aged 10, 11 and 12 months (based on the cutting speed 100 mm/min)

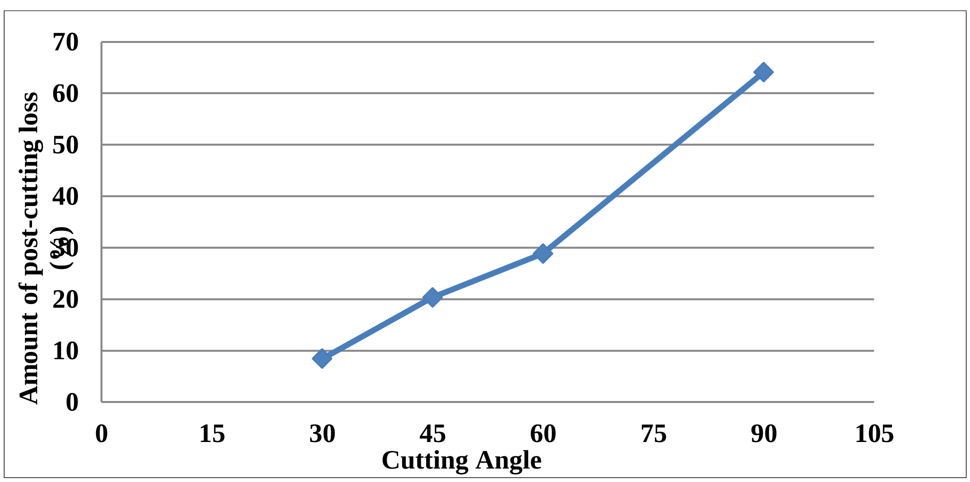

Figure 7. The relationships between cutting tilt angle and amount of post-cutting loss (based on the cutting speed 100 mm/min)

Discussion

The study on the mechanical characteristics of cassava tuber cutter indicated that tubers aged 12 months required higher maximum cutting shear force and maximum cutting shear stress than those aged 10 and 11 months. This is due to the increased density and amount of starch content of older tubers. The maximum cutting shear force, the maximum cutting shear stress and the specific cutting energy varied directly with the cutting tilt angle at any cutting speed. The tilt angle at 30° with cutting speed of 100 mm/min contributed to lower maximum cutting shear force, maximum cutting shear stress, specific cutting energy and amount of post-cutting loss than tilt angles at 45°, 60° and 90°. The cassava tubers aged 10, 11 and 12 months provided the average maximum cutting shear force of 1.61±0.61, 3.60±0.24 and 4.08±0.11 kN respectively. The average maximum cutting shear stresses were 2.01±0.76, 7.20±0.12 and 8.17±2.97 MPa respectively, while the average specific cutting energies were 24.74±15.56, 26.15±10.81 and 30.38±11.10 mJ/mm^2 respectively. The amounts of post-cutting loss were slightly different within the range of 0.5-1%, because the loss did not depend on the effects of shear force and shear stress but on the cutting tilt angle. This result corroborated with the results from the study of Chattopadhyay and Pandey (1999)on the mechanical properties of sorghum stalk cutter in relation to quasi-static deformation wherein thecutting tilt angles: 30°, 40°, 50°, 60° and 70° and cutting speeds: 10, 20, 40, 60 and 100 mm/min were evaluated. Their results showed that with the cutting tilt angle of 30° and cutting speed of 100mm/min, less maximum shear stress and specific cutting energy were obtained with average value of 2.20 MPa and 36.50 mJ/mm^2, respectively. Also, the amount of post-cutting loss was about 1%.

Similar findings were also observed from the study of Heidari *et al*. (2012) on the influence of knife bevel angle, rate of loading and stalk section on some engineering parameters of lilium stalk which cutting tilt angles were set at 30°, 45° and 60°, the cutting speeds were selected at 30, 40 and 50 mm/min. With the cutting tilt angle of 30^O and cutting speed of 50mm/min, maximum shear stress and specific cutting energy were less than those with the cutting tilt angle of 45° and 60°. The average value of maximum shear stress was 2.90 MPa. and the average value of specific cutting energy was 21.34 mJ/mm^2.

Furthermore, the study on the mechanical properties of cassava cutter at various cutting angles in which the cutting tilt angles were 30°, 45° and 60°, and the cutting speeds were 20, 40, 60 and 100 mm/min showed that with the cutting tilt angle of 30^O at all values of cutting speed, maximum shear stress and specific cutting energy were less than those with the cutting tilt angle of 45° and 60°. The average value of maximum shear stress was 4.57 MPa. and the average value of specific cutting energy was 30.46 mJ/mm^2 (Koodsamrong and Klajring, 2015; Xue *et al*., 2014).

Therefore, according to the results of the actual testing and the relevant studies, the cutting tilt angle of 30° was concluded to be suitable for the cutting blade design, in order to cut cassava tuber from rhizome by using a shear technique. To effectively separate cassava tuber from its rhizome for actual usability an actual design, engineering principles and agricultural machinery design is needed to find the optimal speed for cutting (Shigley and Mischke, 1989 and Krutz *et al*., 1994).

Acknowledgement

Thanks are due to the Postharvest Technology Innovation Center, Office of the Higher Education Commission, Bangkok and the Agricultural Machinery and Postharvest Technology Research Center, Khon Kaen University, and also to the Farm Engineering and Automation Technology Research Group which funded this study.

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(Received: 2 May 2019, accepted: 30 December 2019)