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Effect of Cutting Speed on Cutting Torque and Cutting Power of Varying Kenaf-Stem Diameters at Different Moisture Contents

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ABSTRACT

This study focused on the development of an efficient cutting system for kenaf harvesters. Laboratory experiments were conducted on cutting kenaf stems of variety V36 using a rotary serrated cutting system. The Torque Trak 10k data acquisition system was used for the experiment. The effect of cutting speed on cutting torque and cutting power of varying kenaf-stem diameters and at different moisture contents was investigated. Four different cutting speeds of 400 rpm, 500 rpm, 600 rpm and 700 rpm were used. The experiments showed that cutting speed had significant effect on cutting torque and cutting power requirements. The cutting speed was directly proportional to the specific cutting power, while the cutting torque was inversely proportional to the moisture content. Increasing the rotational speed from 400 rpm to 700 rpm reduced the cutting torque from 1.91 Nm to 1.49 Nm. The cutting torque was observed to be higher at lower moisture levels of less than 35%. As the moisture content was increased to values greater than 35%, the torque decreased considerably. This invariably indicated that an increase in moisture content reduced cutting torque as shown by the model coefficient of moisture content. Thus, more energy saving and hence, high efficiency, were achieved at high cutting speeds as compared to impact cutting system at similar speeds. Regression equations capable of predicting cutting torque and cutting power at varying stem diameters and cutting speeds, in relation to kenaf stem moisture contents, are presented.

Keywords: Cutting power, cutting speed, cutting torque, harvester, kenaf stem, moisture content

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INTRODUCTION

Kenaf (*Hibiscus cannabinus*), a relatively new crop to Malaysia, is a fibre crop that can grow very well in most parts of the country and matures in 4 to 5 months (Mat Daham, 2009).Kenaf has been known as a fibre crop with high earnings, but the cultivation process, which includes harvesting, transportation, storage and post-harvest, are still labour intensive and takes up a lot of time (Ghahraei *et al*., 2011). The assessment of techniques for kenaf harvesting remains a significant aspect of exploitation (Charles *et al*., 2002; Manuel, 2011; Dauda *et al.*, 2013).

The constituents of harvester power and its theoretical approaches along with results of field experiments on harvesters made the major sources of its power demand known. Cutting power highly relies on chop length and crop moisture content. However, the major constituent of power can be identified as that due to cutting, supplying kinetic energy to the material while overcoming the frictional resistance of the material (O'Dogherty, 1982).

Generally, harvester power consumption has been found to increase linearly with an increasing rate of forage throughput, above a value which represents the no-load power requirement of the machine (O'Dogherty, 1982).

Persson (1987) reviewed various studies on cutting speed and came to the conclusion that cutting speed had slight effect on cutting power; furthermore, power losses resulting from material acceleration often increased when there was an increase in cutting speed. When a critical value of pressure caused by the blade was reached, plant stem cutting occurred and resulted in multiple modes of tissue failure (Persson, 1987; Srivastava *et al*., 2006).

Critical cutting speed of 25-30 m/s for grass was reported by O'Dogherty & Gale, (1991), while speeds lower than that resulted in higher stubble heights and large stem deflections. O'Dogherty and Gale (1991) defined cutting speed as the speed at which there is a rapid increase in stubble length as cutting becomes rapidly less efficient. Many plant parameters influence cutting energy and force these parameters include stem structure, fibre ultimate tensile strength and fibre stiffness (Persson, 1987). Other parameters of importance are the design of the knife blade, cutting material properties and the mode of operation (Prince *et al*., 1958; Suryanto *et al.,* 1993; Womac *et al*., 2005; Ghahraei *et al*., 2011)**.**

However, some researchers studied specific biomass materials; Mesquita and Hanna (1995) studied soybean stalks El Hag *et al*. (1971) studied cotton stalks Prasad and Gupta (1975) studied maize stalks Prince *et al*. (1969) studied alfalfa stems and Chen *et al*., (2004) studied hemp. Igathinathane *et al*., (2008) reported a study on knife grid size reduction of switch grass revealed that cutting energy is related to stem diameter, moisture content, stem shear strength, dry matter density and maximum cutting force.

The thickness of blunt cutting blades over a range 1 to 3 mm had no significant effect on critical cutting speed or on specific cutting energy when cutting at or above the critical speed. At lower speeds, the 3-mm thick blade required much larger specific cutting energies than the blades of 1 and 2-mm thickness. Blade thickness had no marked effect on specific peak cutting force (O'Dogherty & Gale, 1991).

Low blade velocities are satisfactory for thick-stemmed plants but higher velocities are required for light-stemmed plants such as grass. Thus, disc and drum type rotary mowers typically employ blade velocities of 71-84 m/s. (McRandal & McNulty, 1978).

Cutting energy measurement is considered a significant criterion for comparing any cutting system effectiveness. The cutting element operational principle adopted in any harvesting tool or machine can largely be categorised into two classes: impact cutting and counter edge cutting. Manually operated swinging type tools such as the cradle, scythe, long bladed hoe and power-operated harvesters are such implemets where crops are cut by impact. Generally, scientists are of the resolve that in impact cutting, the energy expended to overcome the stem shearing resistance is similar to the energy needed for quasi static cutting plus the energy expended to overcome friction (Koloor & Kiani, 2007; Reza, 2007).

Data on plant physical and mechanical properties and the power or energy requirement of equipment have been very important to carefully choose design and operational parameters of the equipment (Persson, 1987). Such data are desired for the design of kenaf harvesters in order to achieve appropriate machine functions and efficient energy utilisation. The objective of this study was to determine the cutting torque and power requirements to cut kenaf stems using a rotary serrated cutting system.

MATERIALS AND METHODS

Kenaf variety V36 from INTROP/TPU research field located at $2^{o}58.844^{'}$N, $101^{o}42.722^{'}$E, Universiti Putra Malaysia was used for the experiment. Kenaf stems were manually harvested at 12 weeks after planting (WAP). The stems were cut close to the ground, leaving stubble about 10 cm in height. Moisture content (Mc), weight (W), height (H) and diameter (D) of the stems were recorded. The diameter was measured using Mitutoyo absolute digimatic vernier callipers (precision 0.010). The diameter was measured at the point where the cutting blade was expected to cut the stem each time in the experiment. The moisture content (Mc) was determined using the oven-dry method at 104^{o}C for 24 hours (ASABE, 2008, 2012). The stems were divided into three major parts: bottom, middle and top (Ghahraei *et al*., 2011). As the stem size differed, the cutting torque was determined per unit area of the cut stem measured over the cutting plane and expressed as the specific cutting torque.

The torque required to cut the stems was determined using a rotary serrated cutting system with 25^{o} knife edge angle (Ghahraei *et al*., 2011) incorporated in the stem cutting setup (Suryanto *et al*., 2009). The setup was driven by a low voltage speed drive Toshiba model VFNC1S-2015P-W-1HP-200V, single phase input and three phase output. The speeds were varied at 400, 500, 600 and 700 rpm.

The kenaf stems were manually fed into the rotating blade as shown in Fig.1. A torque data acquisition system TorqueTrak 10k telemetry system was used to acquire the data at Gain and Transmitter settings of 4000. During the cutting tests, kenaf stem samples were brought to the biomaterial processing laboratory of the Department of Biological and Agricultural Engineering, Universiti Putra Malaysia. Some of the stems were stored in the cold room at an average temperature of 4^{o}C to monitor the stems' moisture contents. At each test, voltage signal on the TorqueTrak digital receiver and rotational speeds were recorded and AutoZero turned on to zero out the offset voltage at zero torque in relation to the installed strain gauge.

A full-scale torque calculator available at http:www.binsfeld.com/calculators/tt10k_range (Binsfeld, 2013) was used to determine the full-scale torque on the shaft and the sensitivity per unit volt output (Fig.2) and the cutting power was calculated using equation 1.

$$P_{rot} = M \chi \omega \qquad \text{Eqn. 1}$$

Where:

P_{rot} = rotational mechanical power (watts)

M = torque (Nm)

ω = angular velocity (rads/sec)

In calculating rotational power, it is necessary to convert the velocity from rpm to rads/sec. Therefore,

$$\omega_{rad/\sec} = \omega_{rpm} \chi \frac{2\pi}{60} \qquad \text{Eqn. 2}$$

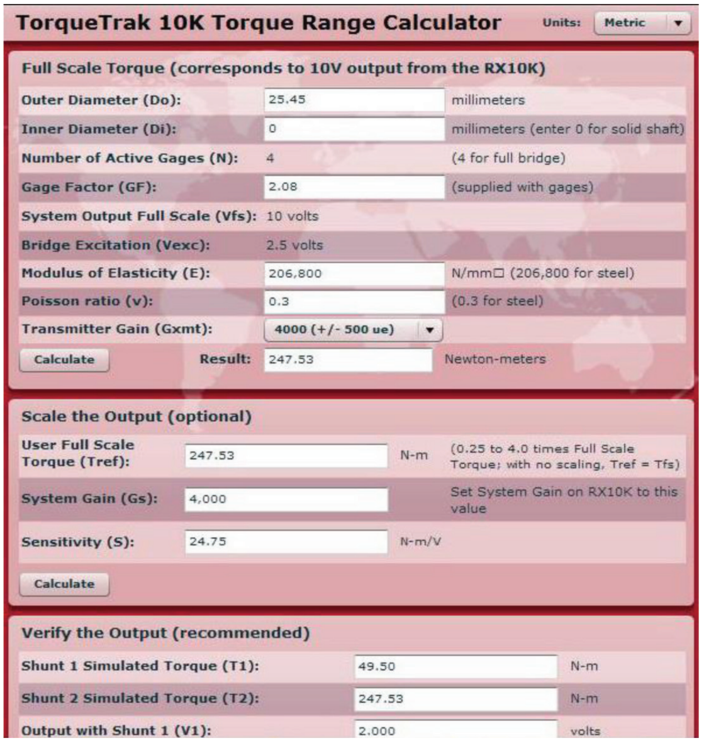
The experiments were replicated three times.

Fig.1: Kenaf stem cutting setup.

Statistical Analysis for Cutting Speeds, Cutting Torque and Cutting Power Requirements for Cutting Blade

All data generated were subjected to analysis of variance (ANOVA) to evaluate the level of significance ($p = 0.05$) and the trend of linear relationship between various parameters of kenaf stems and cutting speeds estimated using SPSS statistics software version 20.

A single-factor-ANOVA was run to evaluate the effect of different levels of cutting speed on the cutting torque, cutting power and moisture content. For this purpose, the cutting speeds used for the experiment were set at 400, 500, 600 and 700 rpm. Furthermore, a simple trend



Full Scale Torque (corresponds to 10V output from the RX10K)

Outer Diameter (Do):	25.45	millimeters
Inner Diameter (Di):	0	millimeters (enter 0 for solid shaft)
Number of Active Gages (N):	4	(4 for full bridge)
Gage Factor (GF):	2.08	(supplied with gages)
System Output Full Scale (Vfs):	10 volts	
Bridge Excitation (Vexc):	2.5 volts	
Modulus of Elasticity (E):	206,800	N/mm□ (206,800 for steel)
Poisson ratio (v):	0.3	(0.3 for steel)
Transmitter Gain (Gxmt):	4000 (+/- 500 ue)	
Result:	247.53	Newton-meters

Scale the Output (optional)

User Full Scale Torque (Tref):	247.53	N-m	(0.25 to 4.0 times Full Scale Torque; with no scaling, Tref = Tfs)
System Gain (Gs):	4,000		Set System Gain on RX10K to this value
Sensitivity (S):	24.75	N-m/V	

Verify the Output (recommended)

Shunt 1 Simulated Torque (T1):	49.50	N-m
Shunt 2 Simulated Torque (T2):	247.53	N-m
Output with Shunt 1 (V1):	2.000	volts

Fig.2: Torque range calculator. Source: (Binsfeld, 2013).

analysis was performed to fit the data among variables such as cutting speed (rpm), torque (N.m), cutting power (W), moisture content (%) and stem diameter (mm).

The data generated were configured in a Randomized Complete Block Design (RCBD) in which Analysis of Variance (ANOVA) was performed to determine the statistical significance of the independent factors of study, namely, cutting speed (cs) and stem diameter (sd) on cutting torque (ct) and cutting power (cp), respectively. Duncan's Multiple Range Test (DMRT) was performed in each case for factors that were significantly different. All tests were conducted at 5% levels of significance. The need for a predictive model that would also offer an explanation for the relationship between the variables of the study gave rise to the use of multiple and simple regression analyses. These models were:

$$m_1 : ct = f(cs, sd) + \varepsilon_1 \qquad \text{Eqn. 3}$$

$$m_2 : cp = f(cs, sd) + \varepsilon_2 \qquad \text{Eqn. 4}$$

$$m_3 : ct = f(mc) + \varepsilon_3 \qquad \text{Eqn. 5}$$

$$m_4 : ct = f(cs) + \varepsilon_4 \qquad \text{Eqn. 6}$$

$$m_5 : cp = f(cs) + \varepsilon_5 \qquad \text{Eqn. 7}$$

The direction and magnitude of the coefficient enabled the interpretation of existing relationships along with the correlation matrix. Basically, two forms of relationship were of interest, namely, positive (direct relationship) or negative (inverse relationship).

Model Development on Cutting Torque (ct) and Cutting Power (cp)

Randomized Complete Block Design (RCBD) with replication was used in designing the experiment. The experimental factors considered were cutting speed (cs) at 4 levels and kenaf stem diameter (sd) at 3 levels, namely, bottom (1), middle (2) and top (3) with the 3 replicates at each condition of cutting speed and stem diameter, respectively for cutting torque (ct) and cutting power (cp), respectively. The model corresponding to the RCBD with replication is given as follows (Equations 8 and 9):

$$y_{ij} = m + cs_i + sd_j + \varepsilon_{ij} \qquad \text{Eqn. 8}$$

$$y_{ij} = m + t_i + b_j + \varepsilon_{ij} \qquad \text{Eqn. 9}$$

Where:

m = overall mean effect

t_i = treatment effect due to cutting speed

b_j = treatment effect due to stem diameter

ε_{ij} = random error which is being minimised

Testing

$$H_{01}: T_1 = T_2 = T_3 + T_4 \qquad \text{Eqn. 10}$$

(non significant)

$$H_{11}: T_1 \neq T_2 \neq T_3 \neq T_4 \qquad \text{Eqn. 11}$$

(significant)

$\alpha = 5\%$

Consequently, H_0 is rejected if $F_c > F_\alpha$ (v1,v2) ($P < 0.05$).

RESULTS AND DISCUSSION

Analysis of Variance on Cutting Torque (ct)

From the result, the model was significant with F = 261.407 ($P < 0.05$) as shown in Table 1. Similarly, both content term and levels of cutting speed were statistically significant with $P < 0.05$. However, stem diameter was not significant with F = 1.114 and $P=0.341 > 0.05$.

It was therefore worthwhile at this point to investigate the level of cutting speed that made the difference, so Duncan's Multiple Range Test (DMRT) was performed in investigation.

TABLE 1
Analysis of Variance Dependent Variable: Cutting Torque (ct)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.883[a]	5	.177	261.407	.000
Intercept	104.721	1	104.721	154972.321	.000
cs	.882	3	.294	434.936	.000
sd	.002	2	.001	1.114	.341
Error	.020	30	.001		
Total	105.625	36			
Corrected Total	.903	35			

a. R Squared = .978 (Adjusted R Squared = .974), cs = cutting speed, sd = stem diameter

$$H_0: T_1 = T'_1 \qquad \text{Eqn. 12}$$

The results in Table 2 suggest that subset 1 level 4 (700 rpm) provided the most significant difference since the interest was on minimum torque, thus cutting torque was most significant. It also follows that levels 3 (600 rpm), 2 (500 rpm) and 1 (400 rpm) were significant in that order.

TABLE 2
Duncan's Multiple Range Test on Cutting Torque (ct)

Duncan a, b

cs	N	Subset			
		1	2	3	4
700	9	1.4878			
600	9		1.6344		
500	9			1.8067	
400	9				1.8933
Sig.		1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = .001.

Linear Regression Model on Cutting Torque

Model 1:

$$ct = f(cs, sd, \varepsilon) \qquad \text{Eqn. 13}$$

The coefficient of multiple determinations predicted a measure of goodness of fit of the model Equation 13. This gave the predictive power of the model specified. The closer R^2 is to 1, the more adequate is the model.

H_0: the model is not significant
H_1: the model is significant

From Table 3, $F_c = 422.323 > F_{0.05\,(2,33)} = 19.46$ or $P < 0.05$. H_0 was rejected and it can be concluded that the model was statistically significant at 5% level as shown in Table 3. The level of relativity of this was 0.960, which was an indication that the model provided a good fit.

The model is thus given as:

$$ct = 2.412 + 0.003sd - 0.001cs \qquad \text{Eqn. 14}$$

TABLE 3
Cutting Torque Model

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.981[a]	.962	.960	.03208	.962	422.323	2	33	.000

a. Predictors: (Constant), cs1, sd1

TABLE 4
Cutting Power Model

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.972a	.945	.941	2.74229	.945	281.536	2	33	.000

a. Predictors: (Constant), cs1, sd1

Testing $H_{0(1)}$: $\beta(sd) = 0$ (not significant)
$H_{0(2)}$: $\beta(cs) = 0$ (not significant)

Against

$H_{1(1)}$: $\beta(sd) \neq 0$ (significant)
$H_{1(2)}$: $\beta(cs) \neq 0$ (significant)

Therefore, the statistic test was:

$$t = \frac{\beta}{s\beta} \qquad \text{Eqn. 15}$$

It also means that H_0 was rejected if $t_c > t_{\alpha,\,(2,33)}$ or ($P < 0.05$). Here, it was clear that the constant was significant. Similarly, β(cs) was significant but negative. The implication was that cutting speed constituted the significant factor but was inversely related with cutting torque. This was also evidenced by the correlation matrix, indicating that the correlation coefficient between cutting torque and cutting speed was 0.98, which was a very strong negative correlation.

Model 2:

$$\text{cutting power} = f(cs, sd, \varepsilon) \qquad \text{Eqn. 16}$$

The model is given as:

$$cp = 39.070 + 0.220sd + 0.097cs \qquad \text{Eqn. 17}$$

The coefficient of determination was 0.941, indicating a good fit (Table 4). Thus from the ANOVA and model summary statistics, $F_c = 281.536 > F = 19.46$ ($P < 0.05$) also indicated that the model was good.

On the model parameters, it was clear that the coefficient of cutting speed was significant and positive while that of the stem diameter was not significant. Obviously, cutting speed had a strong positive correlation with cutting power. Consequently, as cutting speed increased, cutting power also increased.

Analysis of Variance on Cutting Power (cp)

The model is:

$$y_{ij} = m + cs_i + sd_j + \varepsilon_{ij} \qquad \text{Eqn. 18}$$

$$y_{ij} = m + t_i + b_j + \varepsilon_{ij} \qquad \text{Eqn. 19}$$

The results in Table 5 show that the overall model was significant with F = 410.107 ($P < 0.05$). The intercept, which was the mean effect, was also significant with F = 155375.287 ($P < 0.05$). Similarly, cutting speed was significant with F = 682.808 (P

TABLE 5
Analysis of Variance Table Dependent Variable: Cutting Power (cp)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4417.916[a]	5	883.583	410.107	.000
Intercept	334758.674	1	334758.674	155375.287	.000
Cs	4413.366	3	1471.122	682.808	.000
Sd	4.551	2	2.275	1.056	.360
Error	64.636	30	2.155		
Total	339241.226	36			
Corrected Total	4482.552	35			

a. R Squared = .986 (Adjusted R Squared = .983)

TABLE 6
Duncan's Multiple Range Test on Cutting Power (cp)

		Duncan^{a,b}			
cs	N	Subset			
		1	2	3	4
400	9	79.4311			
500	9		94.5767		
600	9			102.6767	
700	9				109.0378
Sig.		1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = 2.155.
a. Uses Harmonic Mean Sample Size = 9.000.
b. Alpha = 0.05

< 0.05). However, stem diameter was not significant with $F = 1.056$ ($P > 0.05$), and this suggested that the independent variable cutting speed was statistically significant.

On the level of cutting speed that was significantly different, Duncan's Multiple Range Test was performed in investigation as shown in Table 6. Since the interest here was in the minimum power, subset 1 on level 1(400 rpm) provided the minimum power required while subset 4 on level 4 (700 rpm) provided the maximum power required to cut the kenaf stems.

Effects of Cutting Speed on Cutting Power

From the results obtained from the experiment to determine the effect of cutting speed on cutting power, it could be deduced from Fig.3 that the best rotational speed ranged between 600 and 700 rpm. From the regression analysis conducted, it could be seen that cutting speed had strong positive correlation with cutting power. Consequently, as cutting speed increased, cutting power also increased. At speeds less than 600 rpm, the cutter tended to break the smaller stems rather than cut them. This possibly occurred due to the fact that at lower speeds, the cutting impact was less, sufficiently causing tissue failure in the stem. Power consumption of the cutting knife increased as the speed also increased from 79.99 W at 400 rpm to 109.2 W at 700 rpm. The increase in power may be attributed to increase in speed. This was in conformity with studies conducted by Gupta and Oduori (1992), Persson (1987) and Veikle (2011).

Effects of Cutting Speed on Cutting Torque

Regression analysis conducted on the data indicated a correlation between the blade rotational speed and the specific cutting torque. The cutting torque linearly decreased from about 1.9 Nm/cm^2 to 1.5 Nm/cm^2 as the speed increased from 400 rpm to 700 rpm (Fig.4). This trend of result was in agreement with a similar study conducted

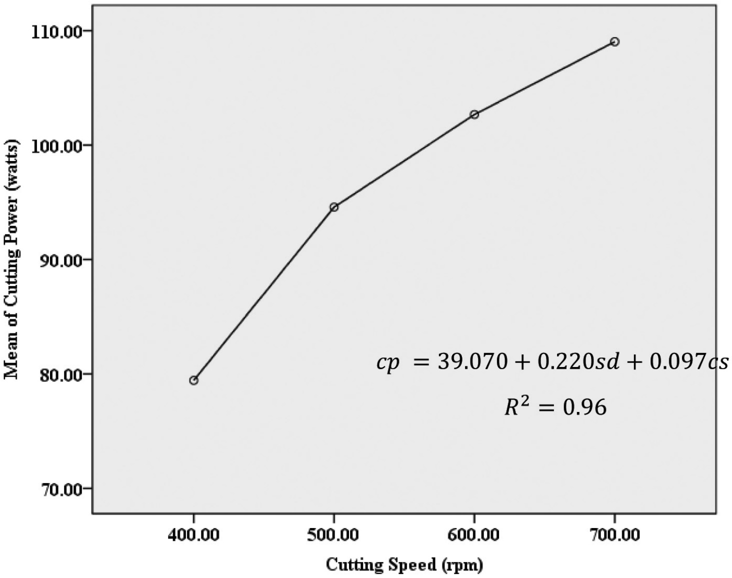


Fig.3: Effect of cutting speed on cutting power.

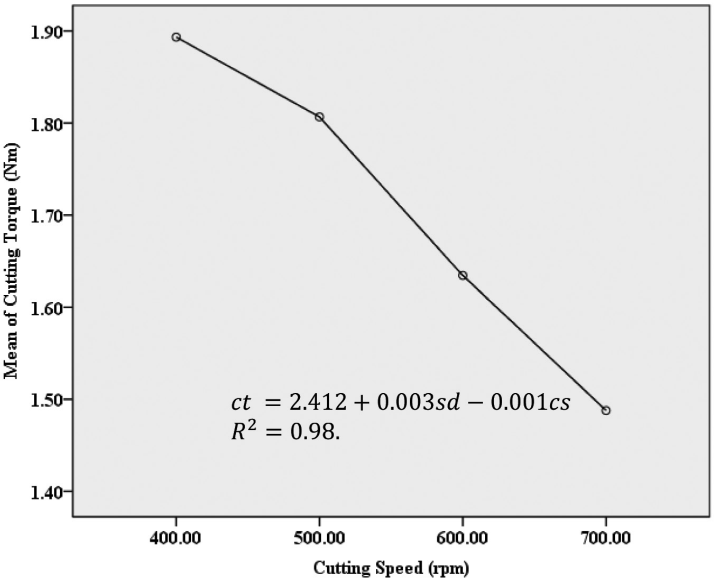


Fig.4: Effect of cutting speed on cutting torque.

on impact cutting of kenaf stems to predict the cutting torque with regard to the blade rotational speed by Ghahraei *et al*. (2011). In comparison with the results obtained by Ghahraei *et al*. (2011), it was discovered that using a rotary serrated cutting blade reduced the cutting torque and the cutting power requirement by about 60%.

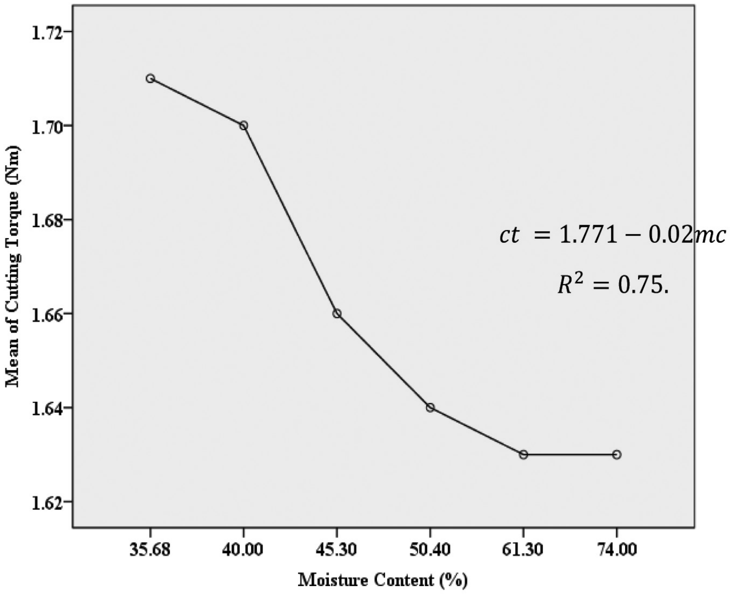


Fig.5: Effect of stem moisture content on cutting torque.

In determining the relationship between kenaf stem moisture content and cutting torque, the regression model is in the form of Equation 20:

$$ct = 1.771 - 0.02mc \qquad \text{Eqn. 20}$$

The result showed that an increase in moisture content reduced cutting torque as shown in the model coefficient of moisture content (Fig.5).

In the analysis of variance at 0.05 level, the cutting torque was observed to be higher at lower moisture levels of less than 35%. As the moisture content increased to values greater than 35%, the torque decreased to a constant value at about 50% (Fig.5), indicating that the power requirement reduced with increase in moisture content. This result conforms to similar studies conducted by Nowakowski (2012a, 2012b) and Veikle (2011). It was also observed that the highest value of cutting power required was recorded at the lowest moisture contents.

CONCLUSION

Kenaf stem cutting speed studied in this research greatly influenced cutting torque and cutting power with varying stem diameters and moisture contents. Higher cutting speed resulted in a decrease in cutting torque from 1.91-1.49 Nm. It was also observed that cutting torque was higher at lower moisture levels of less than 35%. As the moisture content increased to values greater than 35%, the cutting torque decreased to a constant value of about 50%. The effect of cutting speed on cutting torque and cutting power was statistically significant. The data generated will help engineers in developing effective harvesting machinery for kenaf stems.

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