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FORCE AND ENERGY REQUIREMENTS FOR CUTTING OIL PALM FROND

Keywords: Oil palm, harvesting, cutting force and cutter

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A study was conducted to investigate the effect of cutter design, cutting angle and frond maturity on the specific cutting force (FOCSA) and energy (ENCSA) requirement per unit cut area for cutting oil palm fronds. Two designs were tested, (i) sickle cutter and (ii) claw cutter. Cutting angles of 90°, 60° and 45° were tested on the three levels of frond maturity.

The results showed significant effects of cutter design, cutting angle, frond maturity and interaction of cutter design and cutting angle on FOCSA and ENCSA requirement for cutting oil palm fronds. The maximum FOCSA for the sickle and claw cutters were 12.2kg/cm^2 and 22.9kg/cm^2 respectively, while the maximum ENCSA for the sickle cutter and claw cutters were 65.4kg-cm/cm^2 and 115.5kg-cm/cm^2 respectively. This indicated that the sickle cutter required 47% less FOCSA and 76.5% less ENCSA than the claw cutter. Increasing the cutting angle resulted in higher FOCSA and ENCSA requirements. Also, the more mature the frond, the higher the FOCSA and ENCSA required to accomplish the cutting.

INTRODUCTION

Harvesting of oil palm involves four inter-related activities, *viz.* cutting the fronds and fruit bunches, stacking the fronds, collecting the loose fruits, and carrying the harvested fruit to the collection point. With the exception of cutting and frond stacking the other activities have already been mechanized. Over the years, much effort has been taken by the industry to develop an effective cutting device.

Although earlier effort showed some interesting results, the chisel and sickle commonly used still remained the most cost-effective.

Because of the urgent requirement, most tools have been developed without considering the necessary technical information for cutting fronds and fruit bunches. The physical properties of the material, reaction of the material against the cutting edge, method of cutting, cutting angle and speed of cutting have not really been considered. Researchers have designed and developed prototypes without much engineering input.

Hadi (1993) studied the effect of cutting tool design parameters on the specific cutting force and energy for cutting oil palm stalks and spikelets. However, he worked at a very low speed. Studies made by Prince et al. (1958) and Chancellor (1965) showed that the usefulness of such results in designing proper cutting tools were very limited as it is very far from the actual practices. Actual practice of cutting of oil palm fronds and fruits bunches by using either chisel or sickle, is at very high speed in order to benefit from the momentum generated from the weight of tool and the speed of cutting.

The chisel and sickle are widely used as cutting tools in this country. They are effective and affordable and no new tools have surpassed them. However, even with them, the harvesters have to expend a lot of energy to cut.

Harvesting fruits from short palm is relatively easy. A chisel attached to a short steel pole is normally used. To cut, the harvesterjabs the tool at a very fast speed to the target. The angle of attack greatly affects the effectiveness of cut.

Harvesting fruits from tall palms, on the other hand, requires a different technique. A sickle attached to an aluminium pole is used. Two activities are to be done. First, to lift the pole upright and, second, to cut the fronds and fruit bunches. The two activities (lifting and cutting) require high skill and energy. Skill in handling the tool and energy for lifting and cutting. Most harvesters cannot work longer than four hours a day due to the strain involved. The harvesting productivity of workers for various heights of palm is shown in *Table 1.*

TABLE 1. WORKERS' PRODUCTIVITY
(joint labour - 2 workers)

Palm height (m)	Productivity (bunches/day)
<3	400-1000
3-6	150-250
6-12	100-150
>12	50-90

Source: Turner and Gillbanks, 1982
Razak et al., 1995

Although no attempt was made to quantify the energy expended in lifting and cutting, a survey conducted showed that most harvesters feel that cutting requires more energy than lifting the pole (Razak, 1997). Thus, if there is a mechanical tool that requires 'less energy' for cutting, the harvesters would be able to work longer and increase their productivity. Less energy used means that the harvesters are not so tired out by the cutting process. They only have to put the tool on the frond or bunch stalk and push a switch to activate the tool.

OBJECTIVE OF THE STUDY

The objective of this study was to investigate the effect of cutter design, cutting angle and frond maturity on the specific cutting force (FOCSA) and energy (ENCSA) required per unit cut area,

The specific objectives of the study were to:

1. Design and develop two test cutters, *viz* (i) sickle with countershear cutter ***(Figure I),*** and (ii) claw cutter ***(Figure 2).***

2. Design and develop a test rig to carry out the first objective.

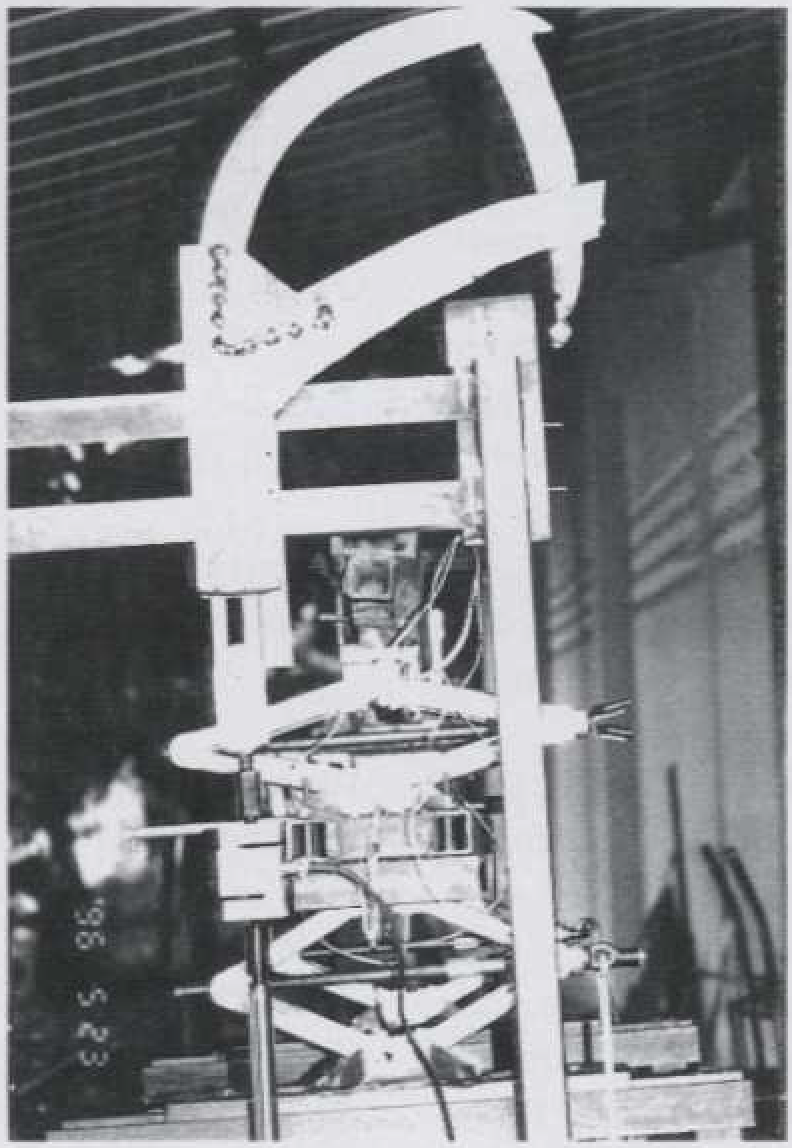


Figure 1. Experimental test rig of sickle cutter

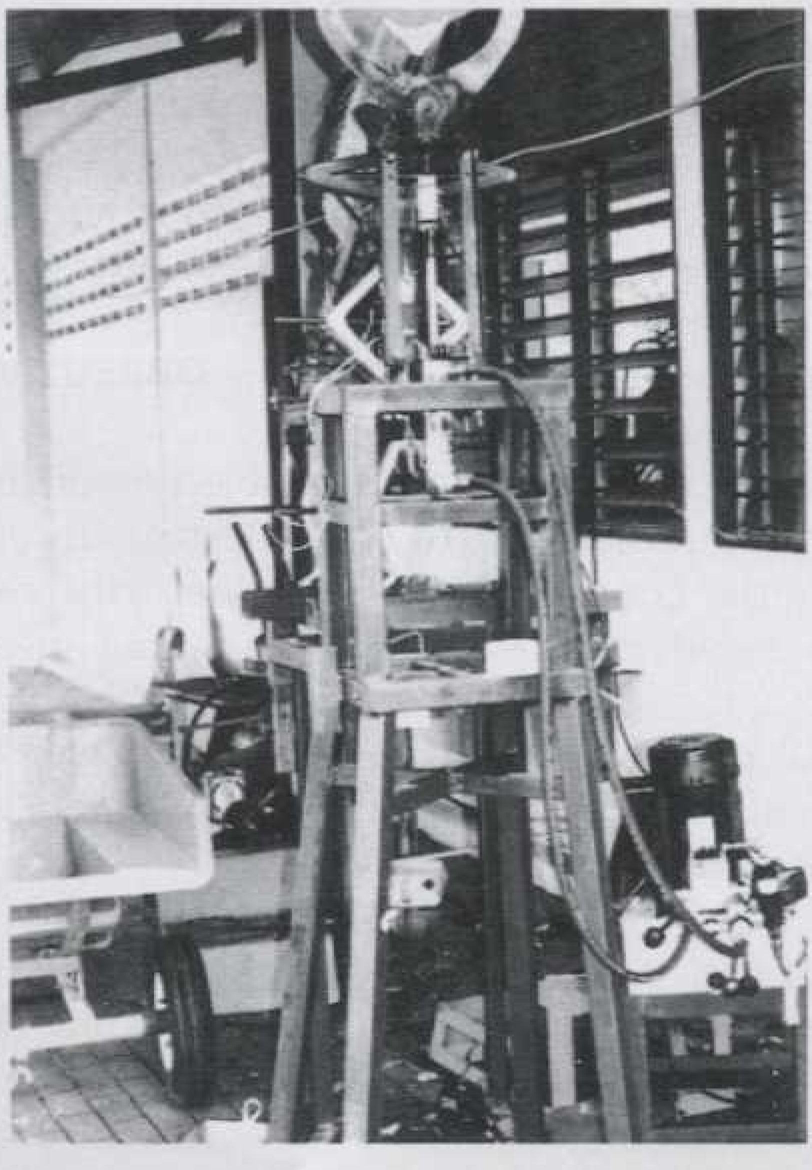


Figure 2. Experimental test rig of claw cutter

EXPERIMENTAL PROCEDURES

Definition

The ‘cutting force’ is defined as the external force needed to be applied by the cutting device on the material to accomplish the cut. More precisely, the cutting force is ‘the resultant of stressesapplied on the material’. Although, the cutting force can have its components in XYZ directions, only the X component along the line of cut contributes to the cutting energy as the active cutting force (Wieneke, 1972, O’ Dogherty, 1981). The cutting force consists of two parts - edge force and wedge force. The edge force cuts the material by creating a high local stress on the material in contact with the edge or close to the edge, while the wedge force pries apart the sides of the cut widening it for passage of the knife.

The cutting force originated by a knife is balanced by a reaction force. The reaction force is either forces from the countershear or inertia forces from the material itself or a combination of the two forces.

Although many factors influence the magnitude of the cutting force and energy required, only a few factors are important. These are the speed of cutting, knife edge angle (α), oblique angle (β), effects of slicing and countershear.

Terminology

The terms used in this study are mostly derived from Persson (1987) and Prasad and Gupta (1975):

1. Knife edge angle (a). The angle between the two cutting faces of a knife at the edge.

2. Oblique angle (β). The angle between edge of knife and normal to the direction of travel of the knife.

3. Cutting angle (S). The angle between the edge of the knife and longitudinal axis of the fibres cut.

4. Specific cutting force per unit cut area (FOCSA). The maximum value of cutting force per unit cross-sectional area of material under the knife (kg/cm^2).

5. Specific cutting energy per cut area (ENCSA). The cutting energy for cut per unit cross-sectional area ($kg\text{-}cm/cm^2$).

DESIGN AND DEVELOPMENT OF TEST CUTTERS

As stated in the objective, two methods of cutting were investigated, *viz.* using a claw cutter and a sickle cutter with countershear.

Claw Cutter (scissors)

The designs and dimensions of the blade and its set up are shown in *Figure* 3. The blade was made of high carbon steel and weighed about 0.6kg with thickness of 3mm. Its length and width were 31.7cm and 15.5cm respectively. The cutting edge had the curvature of 17cm radius so that it can grasp and cut frond effectively. The edge angle (α) was designed at 10°, and its oblique angle was kept constant at 24.2” in all positions. The two blades were joined by a pivot. The pivot was connected to a hydraulic pusher rod to enable the blade to perform. A load cell was fixed to the middle of this rod to measure the pulling force required for cutting. The blades were supported by two linkages to prevent lateral movement.

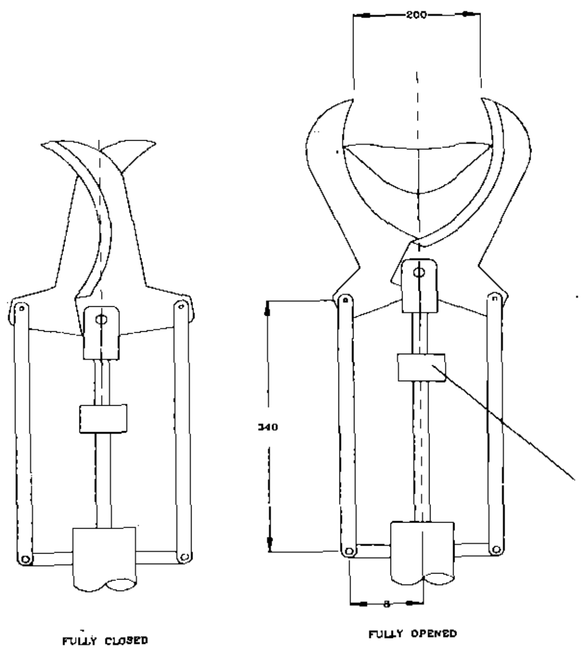
As the cutting force was done by the two edges of the two blades, the pulling force sensed by the load cell was the resultant force required by both blades to accomplish the cutting. The cutting force required is equal to the resistance force given by the material. Assuming the friction force at the pivot Z is negligible compared to the pulling force (f), the following equation represents the maximum cutting force required at the cutting point (by taking moments about the point 0, *Figure 4a).*

$$Fc_{max} = 2f(x)/k \quad [1]$$

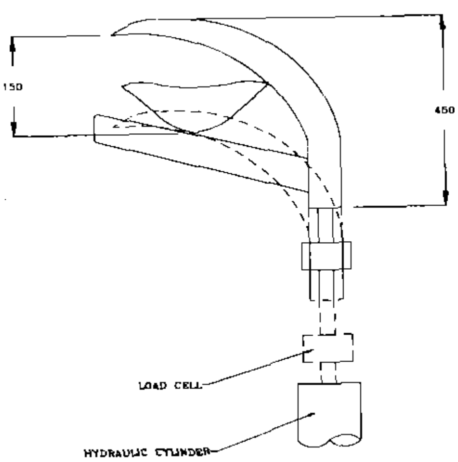
where

Fc_{max} = maximum cutting force by the two edges (kg)

Fc = cutting force (kg)
f = force sensed by the load cell (kg)
k = perpendicular distance from the pivot to the line Fc (set a 23cm)
x = horizontal distance from the pivot to the linkages (cm)
Z = pivot where the two blades are bolted

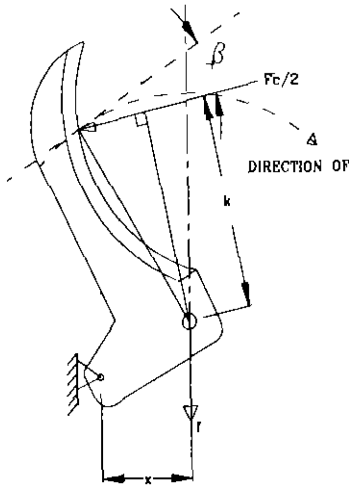


(a) Claw cutter



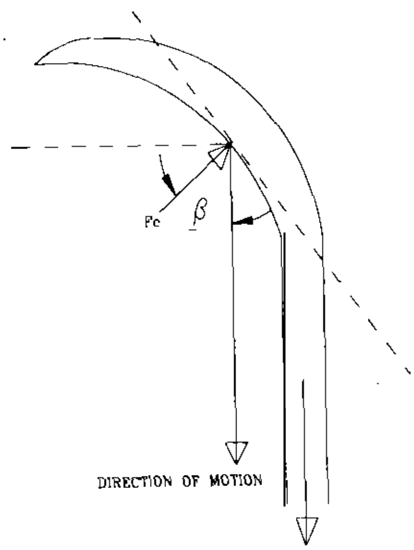
(b) Sickle cutter

Figure 3. Cutting test rig for (a) claw *cutter (b) sickle cutter*



Forces acting on a claw cutters' edge (1 off)

(a) Claw cutter



Forces acting on sickles' edge

(b) Sickle cutter

Figure 4. Forces acting on the blades edges

A dynamic simulation using AutoCAD showed that the maximum cutting force was needed when the direction of Fc was horizontal that is, when the value of x was 10cm. Substituting for the values of k and x and also for the force sensed by the load cell (f) into Equation 1, the maximum force for cutting the frond can be obtained.

Sickle Cutter

An ordinary sickle was used. The edge angle and the thickness were 10” 3mm respectively. The sickle was made of hardened steel tempered with heat. A countershear to react the cutting force was fixed 15cm from the tip of the sickle at 15” with respect to the horizontal line. The end of the sickle was connected to a hydraulic pusher rod to enable the sickle to perform. A load cell was placed in the middle of the rod to measure the pulling force required for cutting. Figure *lb* shows the design and dimensions of the blade and the experimental set-up.

By solving for the involved forces vertically ***(Figure 4b)***, the maximum cutting force required is given by the following equation:

$$f = Fc\cos\beta$$
$$Fc = f/\cos\beta$$
$$Fc_{max} = f \quad \text{when } b \Rightarrow 0 \qquad [2]$$

where

Fc_{max} = maximum cutting force (kg)
FC = cutting force (kg)
f = force measured by the load cell (kg)
β = cutting oblique angle (degree)

The test cutters were installed on a designed test rig. They were actuated by a 4-tonne hydraulic cylinder run by a single-phase Enerpac Hydraulic pumpset. The linear velocity of the pusher rod was maintained at 0.6m/s. A load cell model Kyowa LT-500 KF was used to measure the force produced by the cutters. The force measured was then amplified by an amplifier, Kyowa WGA-710A, which had an ability to record the forces ranged from Okg to 1000kg. The force pattern during cutting was not recorded in this study as only the maximum force is relevant for design purposes.

Force and Energy Measurements

The parameters investigated were:

1. Cutter design (T). Methods of cutting, *viz.* claw and sickle with countershear
2. Cutting angle (S). Angle of the knife travel with respect to the frond longitudinally. The angles tested were varied from 90” (S1), 60” (S2) and 45” (S3) as in most cases fronds are positioned within this range of angle.
3. Frond maturity (F). Three classes of frond maturity were used: (i) F1, the second frond below a ripe bunch (the most matured frond tested), (ii) F2, the frond above a ripe bunch, and (iii) F3, the frond above F2. All fronds were taken from palms of similar age and type.

PREPARATION OF TEST SAMPLES

Fronds were taken from eight year old *Tenera* (DxP) palms from PORIM Bangi. The weights, lengths and centres of gravity were recorded just after they were cut. Each sample was hung with a rope to get the centre of gravity. A spring balance was attached to the rope to record the weight of the frond. The centre of gravity and the length of frond were measured by a measuring tape. The results are given in ***Table 2.***

The fronds were cut at a length according to their distance of centre of gravity. This was purposely done for easy handling of the samples. The samples taken showed that the average length of fronds were 6.18m ± 0.38m, 6.61m ± 0.27m and 6.60m ± 0.28m for F1, F2 and F3 respectively. The average distances of centres of gravity from the base of frond were 1.84m ± 0.15m, 2.28m ± 0.08m and 2.29m ± 0.13m respectively.

In the experiment, a frond was clamped firmly by a gripper with its angle adjustable. The clearance between the cutting blade and countershear (for the sickle) and between the

TABLE 2. THE WEIGHT, LENGTH AND CENTRE OF GRAVITY OF FRONDS

Sample No.	F1 W (kg)	F1 l (m)	F1 cofg* (m)	F2 w (kg)	F2 l (m)	F2 cofg* (m)	F3 w (kg)	F3 l (m)	F3 cofg* (m)
1	6	5.6	1.9	6	5.9	2.1	8	6.9	2.4
2	5	5	1.9	9.5	7.2	2.3	8.5	7	2.4
3	8	7	2.2	8	6	2	5.5	5.8	1.7
4	8	6.2	2.1	7.5	6.9	2.3	8	7	2.4
5	6.5	6.1	2.1	6.8	6.5	2.2	5	6.3	2.2
6	8	6.5	2.1	7.5	7.1	2.5	7	7	2.4
7	5.5	6.1	2.1	8	6.8	2.3	7.8	6.5	2.3
8	9	7.3	2.4	7.5	7.2	2.4	7.7	6	2.4
9	5.5	6.4	2.2	6	5.9	2.4	9	7.2	2.3
10	5	5.6	1.4	7.6	6.6	2.3	6.8	6.3	2.4
Mean	6.65	6.18	1.84	7.44	6.61	2.28	7.33	6.60	2.29
SD	2.04	0.62	0.24	0.95	0.47	0.14	1.17	0.47	0.21
Confident Interval at 95%	1.26	0.38	0.15	0.59	0.27	0.08	0.69	0.28	0.13

(Note:* distance from base of frond)

two blades (for the claw cutter) were kept as small as possible to avoid any effect caused by the clearance such as distortion of the cutting edge and cutting misalignment.

The effects of cutter design, cutting angle and frond maturity on cutting force and energy were studied using a 2x3x3 factorial experiment in Randomized Complete Block (RCB) design with six replicates. The effects of cut such as depth (d), width of cut (w) and cut area (A) were measured manually using graph paper after each cut. The data were used to calculate the specific cutting force (FOCSA) and specific cutting energy (ENCSA).

The maximum cutting force and energy were calculated by:

Components	Claw cutter	Sickle cutter
1. Max. cutting Force, Fc_{max} (kg)	$Fc_{max} = 2f(x)/k$	$Fc_{max} = f$
2. Max. specific cutting force, FOCSA (kg/cm^2)	$FOCSA = Fc_{max}/A$ Area = half of cut area	$FOCSA = Fc_{max}/A$ Area = total cut area
3. Max. specific cutting energy, ENCSA ($kg\text{-}cm/cm^2$)	$ENCSA = FOCSA.w/2$	$ENCSA = FOCSA.d$

where
f = force sensed by load cell (kg)
d = depth of cut (cm)
w = width of cut (cm)
A = cut area (cm^2)
k = perpendicular distance from the pivot to the line Fc (cm)
x = horizontal distance from the pivot to the linkage (cm)

The area of cut was estimated by plotting the cut area on graph paper after each cut. The area was estimated by counting the squares.

RESULTS AND DISCUSSION

Analyses of variance for specific cutting force (FOCSA) and specific cutting energy (ENCSA) are shown in *Table* 3. They indicate significant effects of design, cutting angle, frond maturity and interaction of design and cutting angle. Other interactions did not affect the FOCSA and ENCSA.

The highest FOCSA was obtained through the interaction of T2S1F1 (22.90kg/cm^2), and the lowest FOCSA from T1S3F3 (7.70kg/cm^2) interaction. The maximum FOCSA for the sickle and claw cutters were 12.18kg/cm^2 and 22.90kg/cm^2 respectively. For ENCSA, the highest value was from the interaction of T2S1F1 (115.52kg-cm/cm^2) and the lowest value from the interaction of T1S3F3 (29.27kg-cm/cm^2). The maximum ENCSA for the sickle and claw cutters were 65.41kg/cm-cm^2 and 115.50kg/cm-cm^2 respectively.

The effect of these factors on the cutting force and energy requirement are shown in *Figures 5* to *15.*

TABLE 3. ANALYSIS OF VARIANCE FOR SPECIFIC CUTTING FORCE (FOCSA) AND ENERGY (ENCSA) PER UNIT CUT AREA

source of variation	Degrees of freedom	ANOVA	Mean squares	F value	Pr>F
FOCSA					
Design (T)	1	685.8	685.6	112*	0.0001
cutting angle (S)	2	867.1	433.6	70.8*	0.0001
Frond maturity (F)	2	418.7	209.4	34.2*	0.0001
T*S	2	192.6	96.3	15.7*	0.0001
T*F	2	8.74	4.37	0.71	0.4925
S*F	4	15.4	4.00	0.65	0.6264
T*S*F	4	11.13	2.78	0.45	0.7686
ENCSA					
Design (T)	1	15925.2	15925.2	53.5*	0.0001
Cutting angle (S)	2	16103.7	8051.9	27*	0.0001
Frond maturity (F)	2	16120.8	8060.4	27.1*	0.0001
T*S	2	8756.7	4378.3	14.7*	0.0001
T*F	2	201.2	100.6	0.34	0.7140
S*F	4	868.6	217.1	0.73	0.5741
T*S*F	4	181.3	45.3	0.15	0.9615

*Significant at 1% level

Note: Speed of cutting = 0.6m/s

α = 10

Distance of cofg: F1 = 1.84m, F2 = 2.28m, F3 = 2.29m

Effect of Design

The effect of design of the cutters on the specific cutting force and energy per unit cut area required are shown in *Figures 5* and 6. LSD was used to test the differences between the means affected by cutter design. The average specific cutting force and energy were less for the sickle cutter (9.36kg/cm^2 and 42.98 kg-cm/cm^2 respectively) than for the claw cutter (14.40kg/cm^2 and 67.27kg-cm/cm^2 respectively).

The results showed that the sickle cutter (T1) needed a lower cutting force and energy than the claw cutter (T2). The differences by the two cutters can be explained by how the cutting edges penetrate into the material. Generally, a sickle cutter applies slicing method where the cutting begins from the bottom side of the cutting edge and would finish at about three quarters of this edge. This method of cutting applies a higher oblique angle that is about 45" to 90°, depending on the position of the material being penetrated by the cutter. This angle approaches 90" at the bottom of the cutting edge and gets smaller at the end of the edge (at the end point of cutting). With these oblique angles, the cutting force required to accomplish the cutting is not high as the cutting edge is just only to slide on the material and slowly penetrating into it. As the cutting edge penetrated into the material, it would cut through the material to complete the cutting process. Furthermore, cutting using a sickle

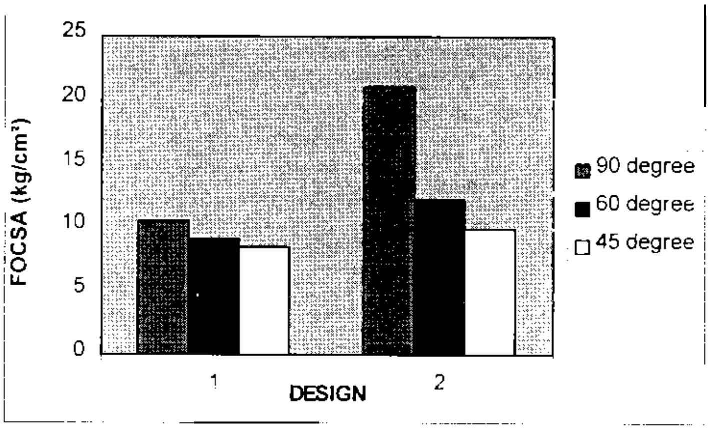


Figure 5. Effect of design on FOCSA for all frond maturities

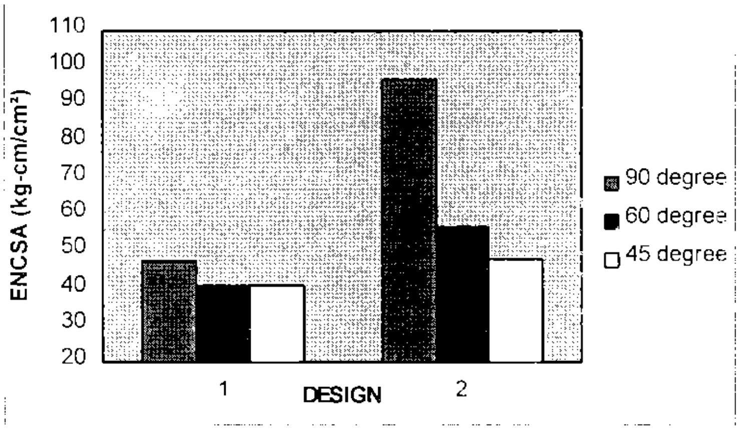


Figure 6. Effect of design on ENCSA for all frond maturities

is started from the top of the material, thus the material would be hung once it was cut and this makes the fibres in the stressed state, making the rest of cutting much easier and would require less cutting force.

On the other hand, claw cutter cuts the material by directly penetrating into it without any slicing movement. The oblique angle is kept constant. In this case, it was found that the oblique angle is maintained at 24.2" in all positions. Therefore, this method requires a higher cutting force as compared to sickle cutter.

Effect of Cutting Angle

The relationships of cutting angle to the specific cutting force and energy per unit cut area are shown in Figures 7 to *12*. The related regressions are:

Sickle cutter (T1)

From the points in ***Figure*** 7, the following linear equations were derived:

FOCSA = 0.06 S + 6.86;	$r^2 = 0.960$	(F1)	[3]
FOCSA = 0.055 S + 5.54;	$r^2 = 0.920$	(F2)	[4]
FOCSA = 0.025 S + 6.6;	$r^2 = 0.990$	(F3)	[5]

From the points in ***Figure 10***, the following linear equations were derived:

ENCSA = 0.314 S + 37.1;	$r^2 = 1.000$	(F1)	[6]
ENCSA = 0.102 S + 34.22;	$r^2 = 0.310$	(F2)	[7]
ENCSA = 0.076 S + 25.5;	$r^2 = 0.950$	(F3)	[8]

Claw cutter (T2)

From the points in ***Figure*** 8, the following linear equations were derived:

FOCSA = 0.26 S 0.47;	$r^2 = 0.990$	(F1)	[9]
FOCSA = 0.232 S 0.78;	$r^2 = 0.940$	(F2)	[10]
FOCSA = 0.27 S 5.08;	$r^2 = 0.960$	(F3)	[11]

From the points in Figure ***11***, the following linear equations were derived:

ENCSA = 1.285 S + 0.141;	$r^2 = 0.990$	(F1)	[12]
ENCSA = 0.9866 S + 3.066;	$r^2 = 0.920$	(F2)	[13]
ENCSA = 1.089 S 0.252 ;	$r^2 = 0.920$	(F3)	[14]

where the range of S is from 45" to 90"

In general, the effect of cutting angle on specific cutting force and energy are given by the following linear equations:

Sickle cutt (T1))

From the points in Figures 9 and ***12***, the following linear equations were derived:

FOCSA = 0.0456 S + 6.407;	$r^2 = 0.990$	[15]
ENCSA = 0.1619 S + 32.5;	$r^2 = 0.880$	[16]

Claw cutter (T2)

The following linear equations were derived ***(Figures 9*** and ***12):***

FOCSA = 0.252 S - 2.0279;	$r^2 = 0.980$	[17]
ENCSA = 1.117 S - 5.33;	$r^2 = 0.970$	[18]

where the range of cutting angle is from 45" to 90"

It was previously shown that the claw cutter required more specific cutting force and energy than the sickle cutter. For both cutters, a higher cutting angle increased the cutting force and energy required. This is shown by the slopes of the graphs *(Figures* 9 and 121 where the slopes were 0.045 and 0.252 for the sickle cutter and the claw cutter respectively for FOCSA. The slopes for specific cutting energy ENCSA were 0.162 and 1.117 for the sickle cutter and the claw cutter respectively. The differences in the slope indicated that an interaction between design and cutting angle (T*S). The specific cutting force and energy did not differ much at 45°, but as the cutting angle increased, there was a rapid increase for the claw cutter *(Figure 9).* It was also noticed that increasing the cutting angle from 45" to 90" increased the cutting force by 24% for the sickle and 111% for the claw cutter, and also increased the cutting energy by 17% for the sickle and 110% for the claw cutter.

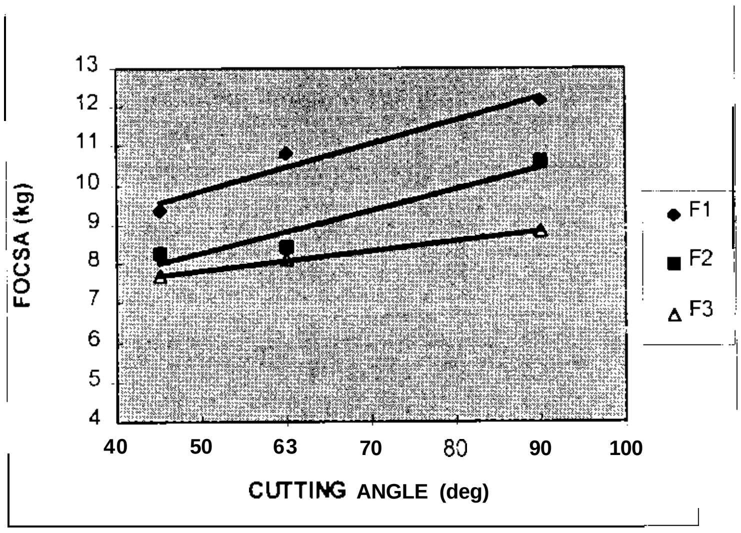


Figure 7. Effect of cutting angle on FOCSA required for cutting frond (sickle cutter)

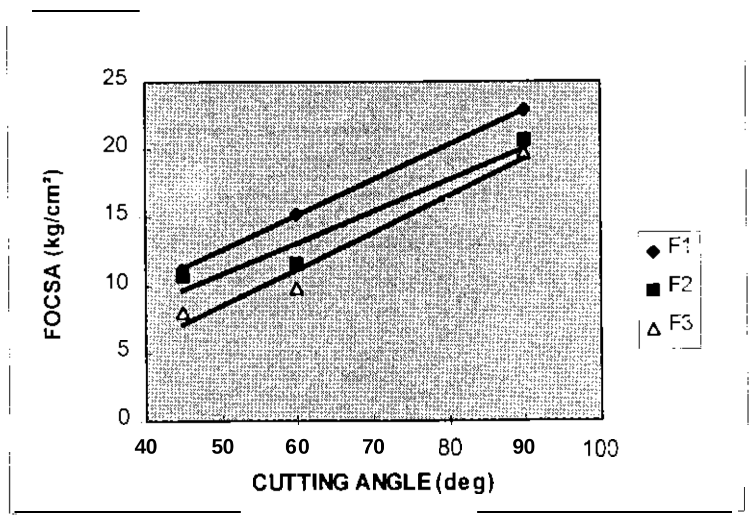


Figure 8. Effect of cutting angle on FOCSA required for cutting frond (claw cutter)

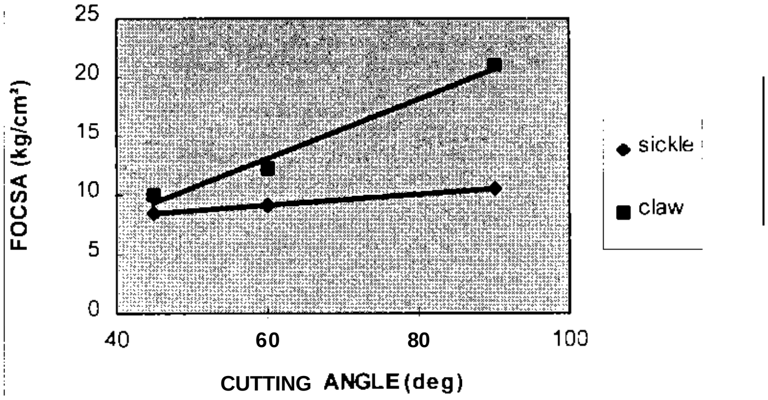


Figure 9. Effect of cutting angle on FOCSA required for cutting frond

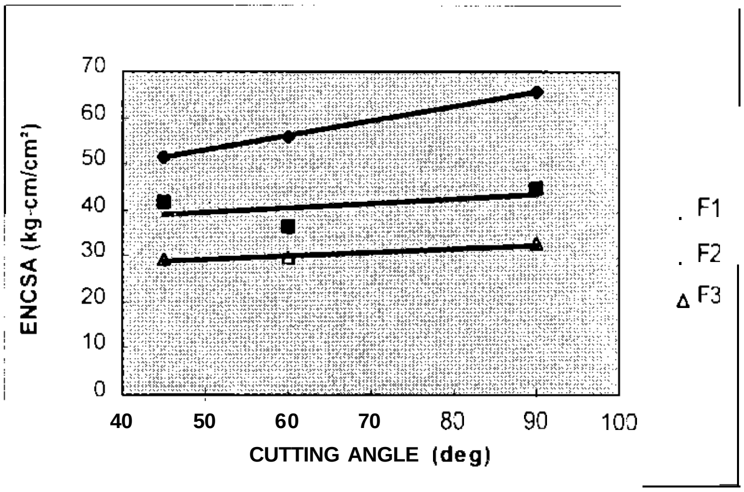


Figure 10. Effect of cutting angle on ENCSA required for cutting frond (sickle cutter)

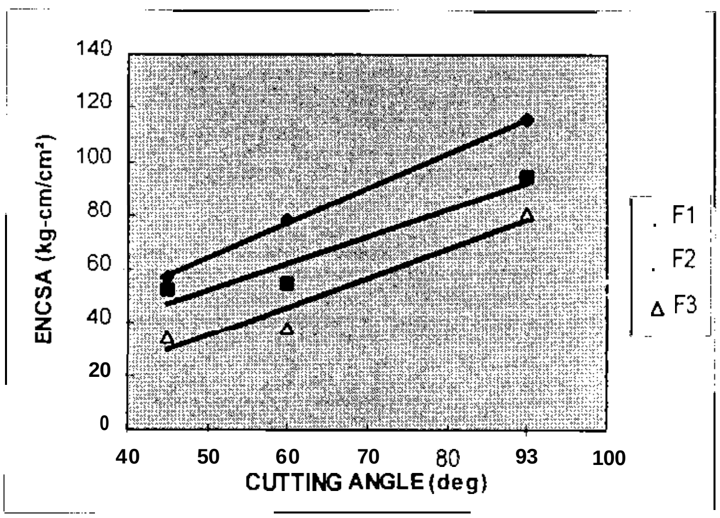


Figure 11. Effect of cutting angle on ENCSA required for cutting frond (claw cutter)

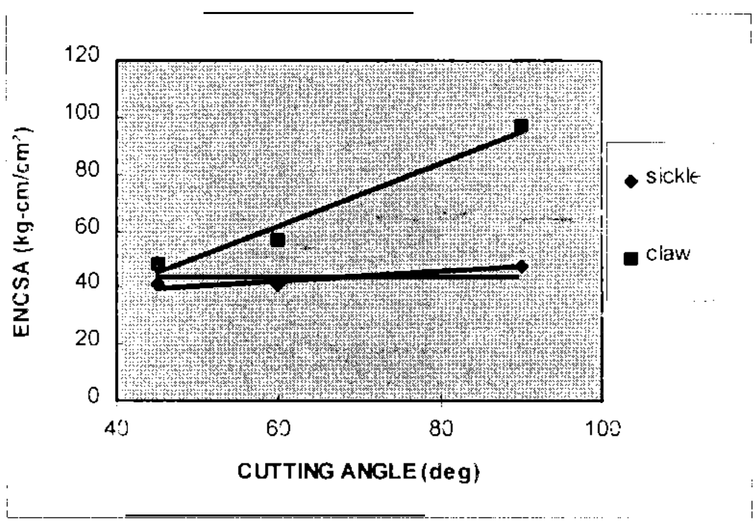


Figure 12. Effect of cutting angle on ENCSA required for cutting frond

Effect of Frond Maturity

Figures 13 and *14* illustrate the effect, of frond maturity on the specific cutting force and energy per unit cut area required to cut, a frond. The specific cutting force and energy required to accomplish the cutting increased as the frond matured.

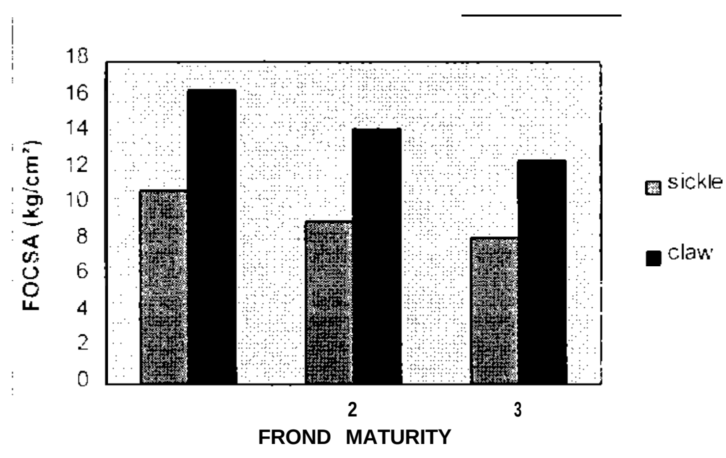


Figure 13. Effect of frond maturity on FOCSA required for cutting frond

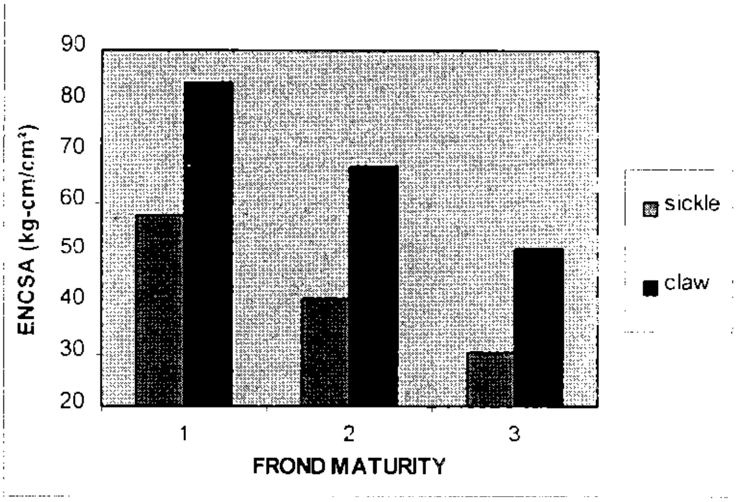


Figure 14. Effect of frond maturity on ENCSA required for cutting frond

SUMMARY AND CONCLUSION

Summary

1. This study showed that cutter design, cutting angle and frond maturity had significant effects on the specific cutting force and energy per unit cut area required for cutting a frond (p-value = 0.0001).

2. The sickle cutter required 47% less cutting force as compared to the claw cutter. On average, the sickle cutter required about 9.36kg/cm² compared to about 14.40kg/cm² for the claw cutter.

3. An increase in FOCSA also increased the ENCSA in which the claw cutter required more energy than the sickle cutter. On average, the claw cutter required about 67.27kg-cm/cm² as compared to about, 42.98kg-cm/cm² by the sickle cutter. The sickle cutter required 76.5% less energy than the claw cutter.

4. The cutting angle also played an important role in the cutting force and energy required. Cutting at 45” required less force than cutting at 90”. Generally, the lower the cutting angle, the lower the cutting force and energy required. Therefore, for cutting in the field. the harvester has to bring the pole close to the palm trunk as to lower the cutting angle as this could lower the cutting force required.

5. Mature fronds seemed to be a bit difficult to cut. The more mature the frond, the higher the cutting force and energy required to cut. It is due to the fibres becoming harder as it gets mature.

Conclusion

1. Statistical analysis showed that of all the factors studied, cutter design, cutting angle and frond maturity affected the specific cutting force and energy required for cutting fronds significantly.

2. The maximum specific cutting force for the sickle cutter was 88% lower than that required by the claw cutter

3. Increasing the cutting angle from 45” to 90°, increased the maximum specific cutting force by about 24% for the sickle cutter and by about 111% for the claw cutter.

4. Frond maturity had a great effect on the specific cutting force and energy required. The more mature the frond, the more the specific cutting force was required to cut

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