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THE EFFECT OF DESIGN PARAMETERS ON THE FORCE AND ENERGY REQUIREMENT FOR CUTTING OIL PALM FRONDS USING MAGNETIC FORCE

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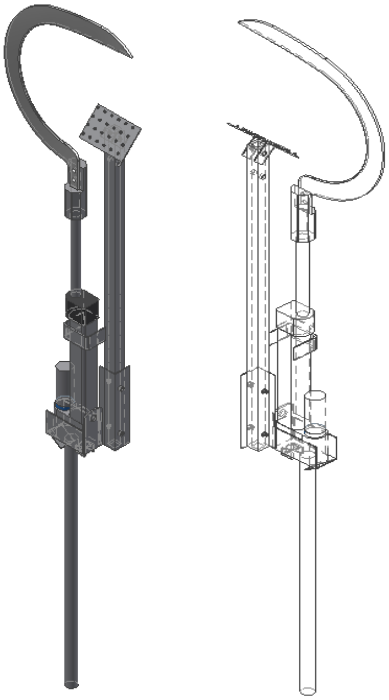
Graphical abstract



Abstract

Harvesting is one of the main activities in the oil palm plantation which has a high labour requirement. Efforts in developing harvesting technology have been initiated since the beginning of oil palm cultivation in Malaysia. Some of the harvesting tools/machines were developed without considering essential technical information such as the physical properties of fronds and bunch stalk as well as power requirements in the cutting processes. The research objective was to investigate several technical parameters prior to the development of a harvesting tool. The study investigated the effects of the magnetic actuator force, cutting angle, and frond moisture content on the specific cutting force (SCF) and specific cutting energy (SCE) for cutting oil palm fronds. Two types of linear magnetic actuators (500 N and 750 N) and three cutting angles (30°, 45°, and 60°) were tested on two levels of frond moisture contents (< 50% and > 50% moisture contents). Experiments conducted revealed that cutting angle and frond moisture content had a significant effect on SCF and SCE, but not the magnetic force. The minimum values of SCF and SCE were 0.39 N/cm2 and 2.04 N/cm (cutting angle of 45°, moisture content > 50%), while the maximum values were 2.94 N/cm2 and 4.12 N/cm, respectively (cutting angle of 60° and moisture content < 50%). The study also revealed that cutting drier fronds (low moisture content) increased the SCF and SCE significantly. A prototype of an oil palm magnetic cutter was developed. Functional tests carried out showed its cutting performance was 254-frond/hour, proving that magnetic force is capable to be used as a cutter's actuator.

Keywords: Oil palm, harvesting, cutting force, magnetic actuator, magnetic oil palm cutter

Abstrak

Penuaian adalah salah satu aktiviti utama dalam ladang kelapa sawit yang memerlukan bilangan buruh yang tinggi. Usaha membangunkan teknologi penuaian telah dimulakan sejak penanaman kelapa sawit di Malaysia. Beberapa alat/mesin penuaian yang dibangunkan sebelum ini tidak mengambil kira maklumat teknikal yang penting seperti sifat fizikal pelepah dan tangkai tandan serta keperluan kuasa dalam proses pemotongan. Objektif kajian ini adalah untuk mengkaji data teknikal yang perlu dipertimbangkan sebelum membangunkan sesebuah alatan penuaian seperti kesan kekuatan penggerak magnetik, sudut pemotongan dan kelembapan pelepah ke atas daya pemotongan spesifik (SCF) dan tenaga pemotongan spesifik (SCE) yang diperlukan untuk memotong pelepah sawit. Dua jenis penggerak magnetik diuji, iaitu penggerak berkekuatan 500 N dan 750 N dan tiga sudut pemotongan i.e. 30°, 45°, dan 60° diuji ke atas dua tahap kelembapan pelepah (<50% dan >50%). Ujikaji yang dijalankan menunjukkan sudut pemotongan dan tahap kelembapan pelepah memberikan kesan yang signifikan terhadap daya pemotongan spesifik (SCF) dan tenaga pemotongan spesifik (SCE), manakala magnitud SCE dan SCF tidak dipengaruhi oleh kekuatan penggerak magnetik. Nilai minimum SCF dan SCE masing-masing adalah 0.3866 N/cm^2 dan 2.0459 N/cm (sudut potongan 45° dan kelembapan pelepah >50%) manakala nilai maksimum SCF dan SCE masing-masing adalah 2.9432 N/cm^2 dan 4.1219 N/cm (pada kedudukan sudut pemotongan 60° dan kelembapan pelepah <50%). Keputusan ujian juga menunjukkan bahawa kelembapan pelepah yang rendah akan meningkatkan nilai SCF dan SCE. Sebuah prototaip alat pemotong menggunakan penggerak magnetik telah direkabentuk, dibangun dan diuji. Ujian fungsi yang dijalankan mendedahkan bahawa prototaip mampu untuk memotong 254 pelepah/jam, membuktikan bahawa penggerak magnetik berpotensi digunakan sebagai penggerak bagi pemotong.

Kata kunci: Sawit, penuaian, daya pemotongan, penggerak magnetik, pemotong sawit magnetik

1.0 INTRODUCTION

The Malaysian palm oil industry is still growing, as shown by the increase in the planted area to about 5.85 million hectares in 2018 compared with 5.23 million hectares in 2013 [1]. Crude palm oil (CPO) exports in 2017 were recorded at approximately 19.92 million metric tonnes [2] with the leading importers being China, India, the Netherlands, and Pakistan [3]. Besides CPO, Malaysia also produces various oil palm-based products such as refined cooking oil, margarine, ice cream, toilet soap, cosmetics, personal care products, biodiesel, furniture, and animal feed for local consumption and exports. The total revenue from palm oil in 2018 was about RM67.49 billion [4]. Oil palm has been a major source of income for a large segment of the population in Malaysia who relies on this golden crop.

Statistics show that there are 446,368 foreign labourers working in oil palm plantations, which is approximately 69% of the total workers in the plantations sector [5]. The labour issue is becoming more critical as there are plantations that have to drag the harvesting round to 20 to 25 days because of a shortage of workers [6], which significantly affects the quality of harvested fresh fruit bunches (FFB). Another big issue facing the oil palm industry is the escalating labour cost. Labour cost increase mainly affects harvesting activities and its has risen to between 20 – 23% of the total production cost from 1980 to 2000, which has contributed to the high production cost [7].

Different categories of workers are employed to carry out several tasks in oil palm plantations. Table 1 shows an example of the different tasks and the number of workers in a team. The tasks include cutting and harvesting activities, fronds stacking, machine operation, and collecting loose fruits while the total number of workers required in a team is eight [8].

The harvesting operation includes four main activities viz; cutting of fronds and FFB, stacking of fronds, collecting of loose fruits, and evacuating FFBs and loose fruits from the palm base to the collection points.

Table 1 Classification of workers' tasks in oil palm harvesting

Task	Number of workers	Task classification
Harvester	4	Cuts fresh fruit bunches (FFB)
Fronds stacker	2	Stack fronds, cut off long stalks, and arrange FFB
Machine operator	1	Collects and reallocates FFB at the platform
Loose fruit collector	1	Collects loose fruits into a bag and bring it to the platform
Total	8	

Source: [8]

The chisel and sickle harvesting tools are common tools and widely used in oil palm plantations in Malaysia. Harvesters prefer these tools because they are cheap and effective. In the harvesting operation, harvesters are required to possess a high skill level to lift the pole up and sufficient strength for cutting the fronds and bunches, which is a very tough and challenging task. As the harvesting operation is an energy-intensive activity, most harvesters are not able to maintain the momentum for an extended period of time. They usually are only able to work productively for 4 to 5 hours per day become fatigue sets in. There is also the age factor to consider in older workers.

Efforts in developing harvesting technology have commenced since the 1990s with the introduction of an aluminium pole known as Zirafah [9]; [10] to complement the bamboo pole which was ineffective and difficult to obtain. This technology has been further expanded with the introduction of an improved version of the aluminium pole (Hi-Reach) that is lighter, more stable and suitable for taller palm trees (9 – 14 metres) [11].

In 2007, the MPOB introduced a hand-held oil palm motorised cutter (Cantas) which was considered as a revolution in harvesting technology. Its commercial use in various estates has shown that Cantas was able to double the harvesting productivity compared to the conventional harvesting tools. The use of Cantas was reported to reduce the number of workers in an estate by 30 – 40% [12].

The adoption of a useful cutting tool and competent workers are of importance to ensure effective and efficient harvesting. It is also vital to ensure that the harvesting round be in the range of 7 to 13 days [13]. It was reported that conventional harvesting (using sickle or chisel) could only produce about 1 t FFB worker^{-1} day^{-1} [8].

Palm height has a significant effect on workers' productivity (Table 2). The taller the tree, the more challenging the harvesting becomes, which results in lower productivity. Harvesting for short palm (< 3 m harvesting level) is relatively more straightforward than for tall palm. A team of two workers is able to harvest around 400 to 1000 bunches a day [14]. It is recognised that there are two main factors that contribute to the workers' productivity; firstly, the palm height and secondly is the size of bunches. As a result, harvesters will only be able to harvest between 50 to 90 bunches a day, especially when the palm height exceeds 12 metres [12].

Table 2 Workers Productivity (2 Workers)

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

Source: [14]

It is recognised that the industry has a pressing need to solve the shortage of labour. Meanwhile, some of the harvesting tools/machines were developed without considering essential technical information such as material physical properties, type of cutting tools to be used, force and energy requirement for cutting fronds and bunch stalks, and any other essential input.

These have resulted in the development of inefficient and ineffective harvesting technology that failed to perform as required. Therefore, a proper study is necessary to ensure a higher percentage of success and to finally produce a sustainable technology with excellent performance.

The research aims at investigating the effect of design parameters (magnetic actuator's force, cutting angle, and frond moisture content) on the specific cutting force (SCF) and specific cutting energy (SCE) for cutting oil palm fronds. Cutting force is defined as an external force supplied to the cutting tool to accomplish the cutting of a material. In the cutting process, even though the cutting force acts in the XYZ direction, only the X component's force will act towards the direction of the blade movement which contributes to the cutting energy, and is called the active cutting force [15]; [16].

To ensure that the objective is achieved, a test jig is designed and developed to conduct the required experiment. This experiment is crucial, as it will serve as a database for the development of harvesting tools.

One prototype unit will be developed based on the experimental data obtained and a functional test will be conducted to investigate the performance of the prototype.

2.0 METHODOLOGY

2.1 Definition of Cutting Force

Cutting force is defined as an external force supplied to the cutting tool to accomplish the cutting of a material. In the cutting process, even though the cutting force acts in the XYZ direction, only the X component's force will act towards the direction of the blade movement which contributes to the cutting energy, and is called the active cutting force [15]; [16].

Since this research is somewhat similar to earlier experiments carried out by [17]; [18]; [10], similar terminology will be used in this study, as follows:

a) Cutting tool edge angle (α) — the angle between the two faces of the cutting tool.
b) Oblique angle (β) — the angle at the cutting tool edge towards the cutting direction.
c) Cutting angle (S) — the angle between the cuttings tool edge and the longitudinal axis of the material being cut.
d) Specific cutting force per unit cutting area (SCF) (N/cm^2).
e) Specific cutting energy per unit area (SCE) (N/cm) — Cutting energy is defined as a combination of cutting power, which includes total blade movement starting from when it touches the cutting material until the end of the cutting process.

This section elaborates on the overall method in obtaining the result. The overall methodology was designed to achieve the objectives set in the Introduction section. Figure 1 shows the overall flowchart of the experiment.

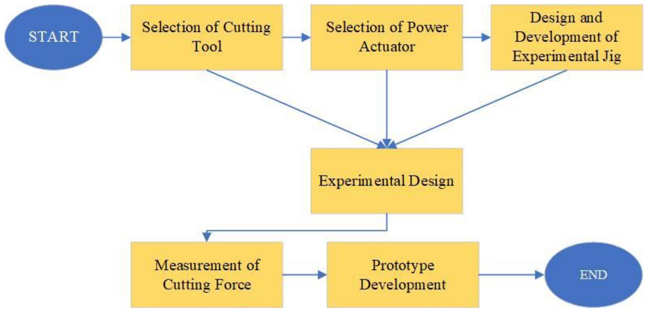


Figure 1 Flowchart of the experiment

2.2 Selection of Cutting Tool

There are several types of cutting tools currently available in the market, viz. sickle, chisel, chain saw, rotating disc, and so on. However, in this experiment, a sickle-type cutting tool was chosen after considering various factors which were based on past studies conducted by [9]; [10]. Other types of cutting tools such as a chainsaw and rotating disc have been reported impractical in cutting fibrous material like oil palm fronds as the tool would be quickly blunted and wear off. Moreover, the space between the bunch stalk and the trunk is very narrow (30 – 50 mm), which provides cutting tools like the chainsaw and rotating disc with insufficient space for access. Only a sickle with its unique design would be capable of being used in this kind of limited space [10].

2.3 Selection of Power Actuator

There are several types of actuators that are popularly used in the market, such as hydraulic, pneumatic, gear transmission, electromechanical, and so on. In this study, several criteria have been considered in the selection of the actuator, as shown in Table 3 [19]:

Table 3 Selection of actuator

Attribute	Electromechanical	Hydraulic	Pneumatic
Cleanliness	High	Low	Medium
Cost-Effectiveness	Low	Medium	High
Ease of Start-up	Low	Medium	High
Energy Requirements	High	Medium	Low
Energy Storage	N/A	High	Low
Force Output	High	High	Low
Environmental Leaks	N/A	High	Medium
Motion Control	High	Medium	Low
Noise Generation	Low	High	Medium
Ruggedness	Medium	High	Medium
Serviceability	Low	Medium	High

Based on the above analysis, the electromechanical or popularly known as magnetic actuator has been chosen as the actuator for the cutter in this study. Referring to Table 3, the ability of the electromechanical system is comparable to the hydraulic system and is better than the pneumatic system in terms of force output capability. The electromechanical system is also one of the eco-friendly systems in terms of cleanliness, leakage, and noise. So far, no oil palm harvesting tool has used this type of actuator. Past studies discovered that hydraulic, pneumatic, gear transmission, and petrol and diesel engines are the conventional actuators used in oil palm harvesting tools.

2.4 Design and Development of the Experimental Jig

A test jig (Figure 2) was designed and developed to carry out the required experiment. The main components of the jig are the mainframe, sickle, counter shear, magnetic actuator and load cell. The dimensions of the sickle are as shown in Figure 3; with the edge angle and thickness at 50 mm and 5 mm, respectively. The sickle was custom made from hardened high carbon steel. A counter shear was placed at 15 cm between both sickle parts. A linear magnetic actuator was attached to the sickle to activate the sickle in the vertical movement. A load cell was placed between the sickle and magnetic actuator to record the cutting force developed during the cutting operation.

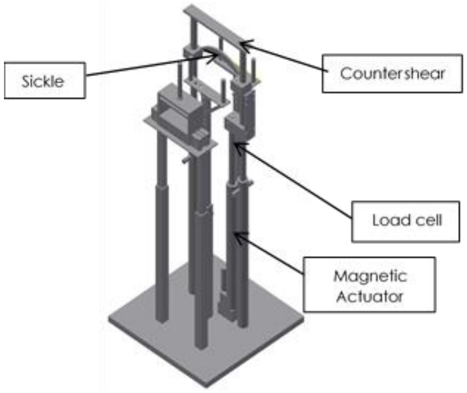


Figure 2 Experimental jig

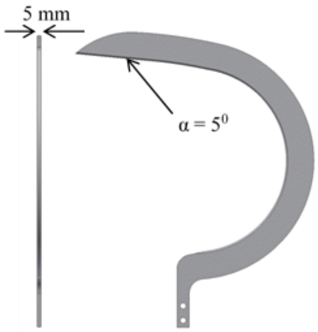


Figure 3 Dimension of the sickle

The sickle (Figure 3) was activated by the linear magnetic actuator (Model CAHB-10-B3A-050192-AAAAPA-000 and CAHB-10-B4A-050192-AAAAPA-000). The maximum loads of the actuators were 500 N and 700 N, with a linear speed of 16 and 10 mm s-1, respectively. The actuators used an electric source of 24 V direct current. It is capable of operating in a surrounding temperature of between -40 to 85°C. The actuator was equipped with a limit switch that deactivated the system when it reached the maximum operating limit

$$F_c + F_p + W > F_r \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

where:

F_c = cutting force required to accomplish the cutting, N.

F_p = pulling force applied by operator, N.

F_r = reaction force, *i.e.* the force from the operator to counter the cutting force developed.

W = weight of tool, N.

x = the maximum distance where the point of F_c can be applied.

δx = the distance of point F_c from the sickle holder.

Figure 4 Free body diagram of the sickle [12]

The maximum cutting force and energy were derived based on Figure 4 and the following equations:

Maximum cutting force (N), Fc_{max} = f …………[1]
Maximum specific cutting force
SCF (N/cm^2)= Fc_{max} / A …………………………..….[2]
Maximum specific cutting energy SCE (N/cm),
SCE = SCF (d)………………………………………....[3]

where f = measured force using load cell, N
d = cutting depth, cm
A = cutting area, cm^2

2.5 Experimental Design

In the experiment, frond samples would be placed on the jig prior to being cut. The purpose of this experiment was to investigate the magnitude of cutting force and energy required to accomplish the cutting process. The effect of actuator force, cutting angle, and frond moisture content were studied using a 2x2 Randomized Complete Block (RCBD) factorial experiment with six replications for each of the experiment. Table 4 indicates the experimental matrix. After each experiment, the cutting depth (d), cutting width (w) and cutting area (A) would be measured using a graph paper [10]. The data obtained from the experiment would be used to calculate the specific cutting force (SCF) and specific cutting energy (SCE) of each experiment.

Table 4 Experimental matrix

Magnetic Actuator	M1 (500N)	M2 (750N)
Moisture Content (%)	<50% / >50%	<50% / >50%
Cutting angle (deg)	30 / 45 / 60	30 / 45 / 60
Total Sample Number	6 samples for each test	

Details of the experiment are as follows:
Magnetic actuator force (M):
2 power ranges, i.e. 500N (M1) and 750N (M2).
Cutting angle (S) :
3 angles i.e. 30^0, 45^0 and 60^0
Moisture Content (MC) :
2 maturities i.e. < 50% (MC1) and > 50% (MC2) moisture content

Test samples (fronds) were taken from the MPOB Keratong Research Station, Pahang from 10 year old DxP (Tenera) palm clones.

2.6 Measurement of the Cutting Force

During the experiment, samples (fronds) would be firmly clamped to the test jig. The space between the cutting blade and counter shear was set to be as close as possible to ensure efficient cutting for accurate data recording. The samples would be tested at three different cutting angles, viz. 30°, 45° dan 60°.

A DACELL Model UM-K500 load cell was used to measure the magnitude of the force developed during the cutting process. The force was amplified by a Sirius-System SN: D00C018C2B amplifier model. The measurements were made utilising a similar standard used by other research [10]. In the experiment, the load cell was placed at the sickle's bottom end where the data would be recorded when the cutting operation began until the cutting process was completed.

3.0 RESULTS AND DISCUSSION

3.1 Labarotary Test to Identify the Cutting Force

3.1.1 Effect of Cutting Angle

The relationship between the cutting angle on the specific cutting force and energy per unit cutting area is shown in Figure 5 and Figure 6.

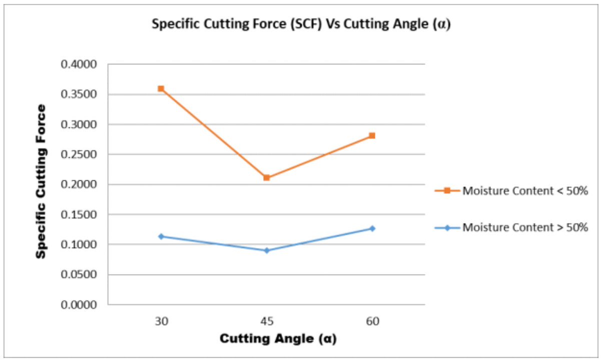


Figure 5 Effect of cutting angle on specific cutting force (SCF)

Based on the experiment, it was found that the magnitudes of cutting force were significantly influenced by the cutting angle. These are demonstrated in Figure 5. The minimum specific cutting force was found at the cutting angle of 45°. Increasing the cutting angle from 30° to 45° (for frond moisture content of more than 50%) reduced the cutting force by 20%. However, increasing the cutting angle from 45° to 60° increased the cutting force by 29%. For frond moisture content of less than 50%, it was found that increasing the cutting angle from 30° to 45° decreased the SCF by 21%, while the SCF was increased by 51% when the cutting angle was increased from 45° to 60°.

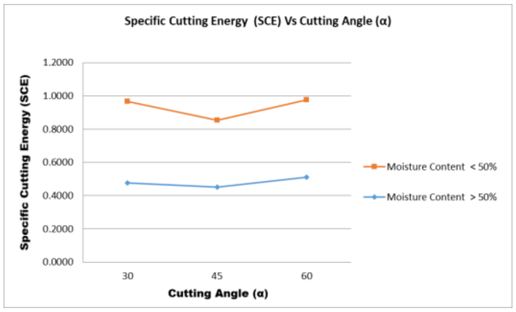


Figure 6 Effect of cutting angle on the specific cutting energy (SCE)

The changes are also seen in SCE (Figure 6) when the cutting angle is varied. For fronds with a moisture content of more than 50%, a SCE reduction of 5% was recorded when the cutting angle was increased from 30° to 45°, while SCE increased by 12% when the cutting angle was increased from 45° to 60°. For frond moisture content of less than 50%, the graphs show similar trends with a decrease in SCE by 13% when the cutting angle was increased from 30° to 45° and an increase of 18% when the cutting angle was increased from 45° to 60°. The minimum specific cutting energy was found at the cutting angle of 45°.

In a previous study conducted by [10], the author indicated that the minimum cutting force and energy requirement for cutting oil palm frond was at 45° instead of 60° and 90°. The study revealed that the optimum cutting force and energy required can be achieved at the cutting angle of 45°. Therefore, in the harvesting operation, the harvesting tool should be arranged in such a way to achieve the cutting angle of 45°.

3.1.2 Effect of Actuator Force

The relationship between the magnetic force on the specific cutting force and energy per unit cutting area are shown in Figures 7 and 8. The graphs show the effect of the actuator force on the SCF and SCE. The experiment concluded that the magnetic force did not affect the SCF and SCE significantly.

The experiment concluded that the magnetic force did not affect the magnitude of SCF and SCE significantly. The maximum cutting force required to accomplish the cutting process was 300.2 N which were 60% and 40% lower than the rated limits of both magnetic forces tested i.e. 500 N and 750 N. This finding revealed the future prototype development should consider the capability of a prototype to produce the minimum cutting force of 300 N.

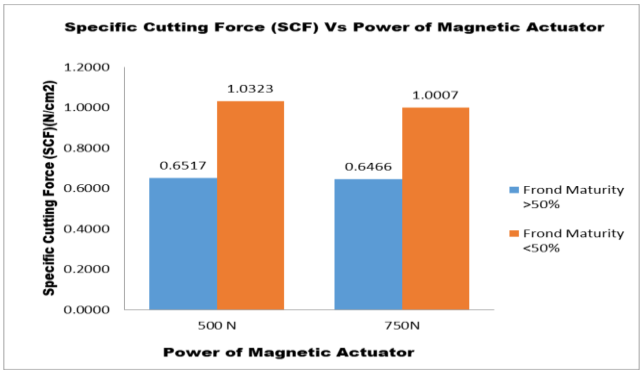


Figure 7 Effect of actuator force on Specific Cutting Force (SCF)

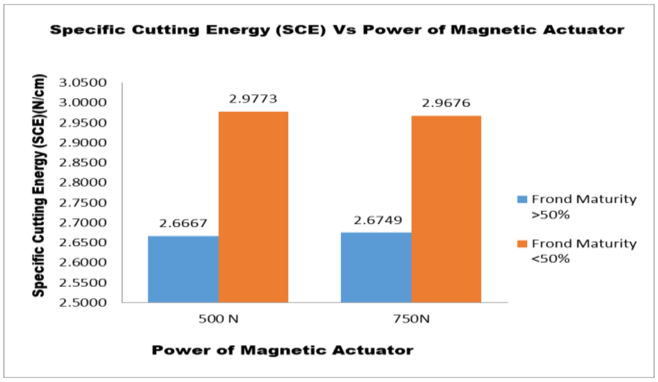


Figure 8 Effect of actuator force on Specific Cutting Energy (SCE)

3.1.3 Effect of Frond Moisture Content

The relationship between the frond moisture content on the specific cutting force and energy per unit cutting area are shown in Figures 9 and 10.

Figures 9 and 10 show the effect of moisture content on the SCF and SCE. It was found that moisture content affected the SCF and SCE significantly with the minimum SCF and SCE at the frond moisture content of > 50%. The graphs also show that the maximum value of SCF and SCE can be obtained when the moisture content is below 50%. Both graphs show the same pattern in which the SCF and SCE increase proportionally with the moisture content.

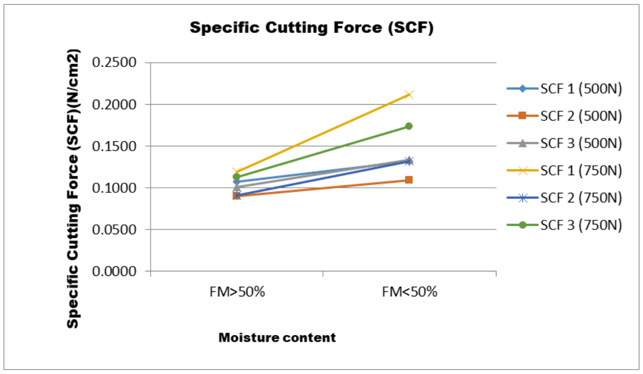


Figure 9 Effect of moisture content on Specific Cutting Force (SCF)

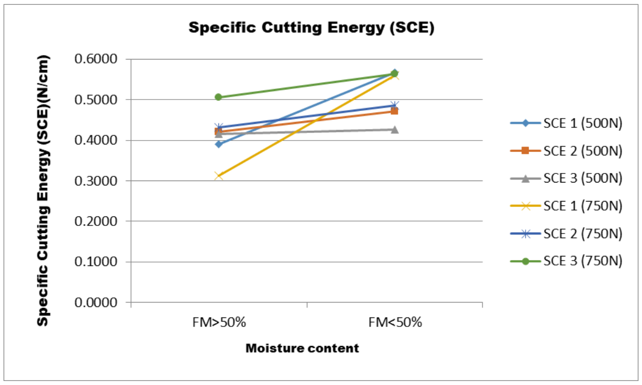


Figure 10 Effect of moisture content on Specific Cutting Energy (SCE)

[10] revealed that moisture content had a significant effect on the specific cutting force and energy. A low moisture content frond requires higher force and energy to accomplish the cutting process as the fibre is much harder than young fronds (high moisture content). Another study conducted by [20] on kenaf stems, revealed that higher torque was required for lower levels of moisture content (less than 35%).

The experiments conducted revealed that the minimum SCF and SCE were found at the cutting angle of 45° for all frond maturities. Cutting angles had a significant effect on SCF and SCE, where the changes in cutting angle would cause SCF and SCE values to change. The moisture content of the fronds also played a vital role in determining the maximum value of force required for the cutting process. For the purpose of designing the cutting tools, the maximum SCF and SCE values would be taken as the primary consideration in calculating the power source requirement, size of cutting machine, and so on. Table 5 shows a summary of the experimental results.

Table 5 Result Summary - Minimum and Maximum of SCF and SCE

FM <50% moisture content						
Cutting angle (S)	**30^{0}**		**45^{0}**		**60^{0}**	
	M*	**C****	**M***	**C****	**M***	**C****
Minimum SCF	0.5912	P48F2S1M2	0.4994	P20F2S2M1	0.7998	P31F2S3M1
Maximum SCF	1.4304	P7F2S1M1	1.3976	P21F2S2M1	2.9432	P36F2S3M1
Minimum SCE	2.4592	P8F2S1M1	2.1847	P59F2S2M2	2.7409	P34F2S3M1
Maximum SCE	4.0051	P7F2S1M1	3.2334	P19F2S2M1	4.1219	P68F2S3M2

FM > 50% moisture content						
Cutting angle (S)	**30°**		**45°**		**60°**	
	M*	**C****	**M***	**C****	**M***	**C****
Minimum SCF	0.4938	P39F1S1M2	0.3866	P14F1S2M1	0.5218	P29F1S3M1
Maximum SCF	0.8107	P4F1S1M1	0.7753	P18F1S2M1	1.0296	P65F1S3M2
Minimum SCE	2.3400	P1F1S1M1	2.0459	P16F1S2M1	2.7338	P25F1S3M1
Maximum SCE	3.5673	P4F1S1M1	3.3924	P53F1S2M2	3.9126	P65F1S3M2

Remark:
*M – magnitude
**C – combination

The data analysis was made using MiniTab statistical analysis software. The output of the results is shown in T, which shows the significant effect of the cutting angle and frond moisture content on the cutting force and energy requirement for cutting the fronds. However, the analysis shows that magnetic force did not have any significant effect on the SCF

Table 6 shows the correlation analysis using MiniTab. The Pearson correlation coefficient between cutting force and moisture content is −0.4240 and the p-value is 0.000, lower than the significance level of 0.05, indicating that the correlation is significant. As moisture content increases, cutting force tends to decrease. The Pearson correlation coefficient between cutting force and cutting angle is 0.401 and the p-value is 0.000. Since the p-value is less than the significance level of 0.05, it indicates that the correlation is significant. The correlation between cutting force and machine is -0164 with the p-value of 0.169, which is more than the significant level of 0.05. This indicates that the correlation is not significant.

Table 6 Correlation: Moisture Content, Cutting Angle, Machine, Cutting Force

Cutting Force		
	Pearson correlation	**P-value**
Moisture content (MC)	-0.424	0.000
Cutting angle (CA)	0.401	0.000
Magnetic force (M)	-0.164	0.169

Table 7 shows the analysis by one-way analysis of variance (ANOVA) between Cutting Force vs Cutting Angle (CFCA) and Cutting Force vs Moisture Content (CFMC). This analysis is to find out which parameters have a high correlation with cutting force based on R^2 and standard deviation (S). Based on the result, R^2 explains 55.53% of CFCA and 17.96% of CFMC for the variations in the response, respectively. The data also shows that the standard deviation (S) for CFCA and CFMC are 0.1449 and 0.1954, respectively. Standard deviation is measured in the units of the response variable and represents how far the data values fall from the fitted values. The lower the value of S, the better the model describes the response Based on the analysis, the model CFCA was better compared to CFMC. Based on the analysis cutting angle has a higher correlation with cutting force where the S value and R^2 are 0.1449 and 55.53%, respectively.

Table 7 One-way Anova

	Cutting Force vs Cutting Angle	Cutting Force vs Moisture Content
S	0.144868	0.195366
R-sq (R^2)	55.53%	17.96%
R-sq (R^2) (adj)	54.24%	16.79%
R-sq (R^2) (pred)	51.58%	13.20%

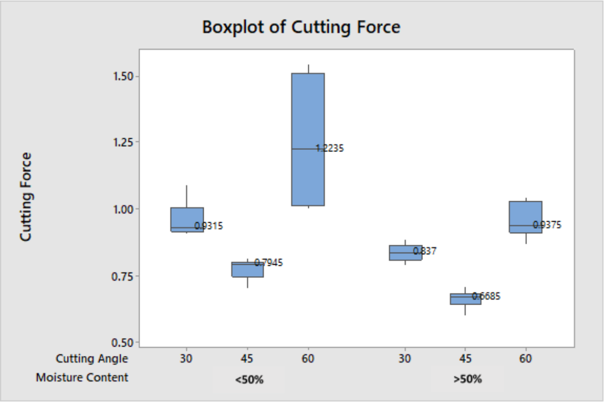


Figure 11 Effect of cutting angle on specific cutting force (SCF)

Figure 11 shows the boxplot analysis with two independent variables and one dependent variable. The analysis was carried out to identify the optimum cutting angle (CA) with the lowest cutting force. Median durability was found highest for the cutting angle of 60° with the moisture content (MC) < 50%. However, this angle also demonstrated the greatest variability, with an interquartile range of 0.49825. CA 30° with MC < 50% and CA 60° with MC > 50% had similar median durabilities (0.9315 and 0.9375. respectively). CA 30° with MC > 50% exhibited the least variability, with an interquartile range of only 0.05325. Based on the analysis, the optimum cutting angle with lowest required cutting force is at 45° with fronds at a moisture content of above 50%.

3.2 Prototype Development

A prototype of an oil palm cutter fixed with a countershear and powered by a magnetic actuator was designed and developed (Figure *12*). The countershear is a mechanism to hold the material being cut to ensure it would not move from its original position. This is to ensure the cutting is done effectively. A cutter fixed with a countershear seems to be more effective than a cutter without countershear which basically requires a higher force and cutting speed [17]. [17, 21] indicated that the reaction force to the material is similar to the force coming from the blade and is in the opposite direction. Several study conducted by previous researcher indicated that the cutting with countershear have required minimal energy [22]. A magnetic actuator of 500 N maximum force with a linear speed of 16 mm s^{-1} was attached to a harvesting pole, with a sickle fixed to the upper end of the magnetic actuator. The maximum length and weight of the tool were 5 m and 6.3 kg, respectively.

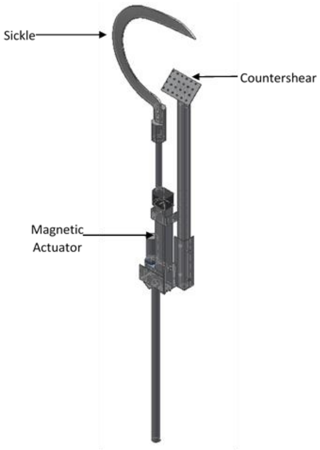


Figure 12 Prototype magnetic oil palm cutter

3.3 Functional Test of Prototype Magnetic Oil Palm Cutter

The prototype was tested functionally at the MPOB Bangi Research Station on palms of 4.6 metres harvesting height. Figure 13 shows the prototype at work, while Table 8 shows the results of the functional test.

Table 8 Results of Functional Test of Prototype of Magnetic Oil Palm Cutter

Palm No	Cutting fronds (s)	Cutting FFB (s)
1	12	
	14	
	13	10
2	14	
	15	9
3	13	
	16	
	15	9
4	14	
	15	11

Palm No	Cutting fronds (s)	Cutting FFB (s)
5	13	
	14	
	16	10
6	14	
	15	11
TOTAL	**213**	**60**
AVERAGE	**14.2**	**10**

Figure 13 The prototype of magnetic oil palm cutter at work

A total of 15 fronds and 10 FFB were cut with a total time of 213 sec and 60 sec for cutting the fronds and FFB, respectively. The average cutting time was 14.2 sec per frond and 10 sec per FFB, which were considered acceptable. The tests discovered that the magnetic force was applicable to be used as an actuator for an oil palm cutter. However, the cutting time was found relatively slow as it was highly influenced by the linear speed of the magnetic actuator itself. Therefore, a higher magnetic actuator speed is required to improve the cutting speed of the cutter. The magnitude of the hand-arm vibration of the magnetic oil palm cutter prototype was 1.20 m/s^2 which was 37% lower than the Cantas motorised cutter (1.90m/s^2) [23]. Note: the standard vibration level is 2.5 $m\ s^{-2}$ [ISO5349 (Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration)]. Therefore, the conducted test has proven that the prototype is safe to be used in an 8 hour working day.

4.0 CONCLUSION

The experiments conducted showed that cutting angle and moisture content have a significant effect on the cutting force and energy requirement per unit cutting area for cutting fronds (P-Value = 0.0001), while magnetic force does not have any significant effect on the magnitudes of SCF and SCE.

The minimum SCF and SCE were 0.3866 N/cm^2 and 2.0459 N/cm, respectively, obtained at the cutting angle of 45° and moisture content of > 50%, while the maximum SCF and SCE were 2.9423 N/cm2 and 4.1031 N/cm, respectively, obtained at the cutting angle of 60° and moisture content of < 50%.

Fronds with lower moisture content (dry fronds) were found to be more difficult to cut. The experiments conducted showed that the SCF and SCE required to cut fronds with low moisture content were 21.57% and 9.04% higher than fronds with higher moisture content, respectively. This is due to the fact that matured fronds would have higher fibre strength, which makes it difficult to cut.

The functional test on the prototype of the magnetic oil palm cutter revealed that the average time taken to cut fronds and bunches were 14.2 and 10.0 seconds, respectively. It only required one moving action to complete the cutting process. The performance of the prototype was 254 fronds per hour, which was considerably acceptable. However, several aspects need to be improved, such as increasing the actuator speed, reducing the total weight, and increasing the length of the machine.

The experiments have discovered some primary essential data. These are mainly the effect of the cutting angle and moisture content on the SCF and SCE requirement in cutting oil palm fronds. The experiment also revealed that magnetic force is capable to be used as the actuator of a harvesting tool. However, a further study on its characteristics such as dimensions, weight, working speed, type of cutting blade, and so on should be carried out to discover more detailed information.

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