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MODELING OF CUTTING FORCE FOR PALM OIL FRONDS

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KEYWORDS

oil palm fronds,
cutting force model,
cutting strategy.

ABSTRACT

Cutting oil palm fronds is an important activity in the harvesting and upkeep of this tree, and this is currently done manually, meaning that it is subject to uncertain labor supplies and low efficiency. Manual cutting is primarily done with a harvesting knife, using a linear motion. Mechanization of this action has been achieved based on an oscillating cutting motion, which is prone to high levels of vibration and inefficiency due to the accelerating and decelerating motion of the oscillating mass. There is therefore a need for a technique based on a circular cutting motion, in order to reduce the power consumption of the mechanized cutter, but there is a lack of in-depth research on the mechanics of the cutting force for palm oil fronds using a circular saw. In this study, we explore the effects of the feed rate, rotation speed, frond width, and entrance angle on the cutting force when using a circular saw, and an equation relating these parameters is derived to calculate the cutting force based on experimental results. No significant difference is found between cutting force models for oil palm fronds ($0.92 < R^2 < 0.99$, $P < 0.05$) under different cutting conditions.

INTRODUCTION

Oil palm harvesting requires cutting of the fronds, which is still done manually using a sickle and a chisel-type harvesting knife. Machinery manufacturers have developed various forms of equipment for harvesting oil palm fruits with a view to automating this labor-intensive procedure (Bakar et al., 2018). A more efficient cutting process is the use of a circular saw, which has been widely adopted for lumber processing but is not yet in use for oil palm harvesting. An analysis of the cutting force needed for oil palm fronds with a circular saw has not been reported in the literature. A validated model of the cutting force required for a circular saw could be used to optimize the harvesting of palm fronds by minimizing the cutting force: this could lead to improved work efficiency and an increase in the cutting cycle for a single charge of a battery-powered electric harvester (Jiangyi & Fan, 2023), thus paving the way for carbon-free agricultural activity.

The cutting force is an important parameter for optimizing such machines. Boyda et al. (2019), Li et al. (2022a) and Moradpour et al. (2013) have shown that factors influencing the process of cutting can be divided into two types: the characteristics of the material (such as the moisture content, density, and diameter), and the cutting parameters (such as the cutting speed, feed rate, and entrance angle). Cai et al. (2019) reported that the effect of the diameter (cutting width) had been carefully evaluated by several studies, and that a linear relationship existed between the diameter and the cutting force. The moisture content is generally considered the main factor affecting the cutting force, but existing studies have given opposing results: Krenke et al. (2017) found that the cutting force needed for spruce with a moisture content of 6% was significantly lower than for a moisture content of 18%, whereas Lucic et al. (2004) reported that the cutting force for green wood was significantly lower than for dry wood.

The cutting force required is influenced by the cutting speed, feed rate, and entrance angle. Research findings by Meng et al. (2019), Turchetta & Sorrentino (2019), Wang et al. (2022) and Li et al. (2022b) indicated that the cutting force decreased with an increase in rotation speed, whereas it increased with an

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increase in feed rate. Ghahraei et al. (2011) showed that the rotary cutting speed had a significant effect on the cutting torque, which was reduced by 26.3% when the cutting speed was increased from 308 to 788 rpm. Johnson et al. (2012) found that the cutting energy required for corn stalks increased at higher cutting speeds, but more energy was absorbed by shock, vibration, and deformation, meaning that energy was wasted. A large increase in cutting speed had little effect on the efficiency of the cutting process. The findings of Porankiewicz et al. (2011) indicated rapid growth in the main force needed with an increase in the entrance angle from 0° to 84.53°, and that a maximum force was required when cutting against the grain. Wilczyński et al. (2023) studied the cutting force for corn stalks at different entrance angles, and found that it was significantly impacted by the entrance angle of the circular saw. They reported that as the angle of inclination of a disc cutter increased, the contact and collision area between its non-working surface and the straw increased, resulting in an increased frictional resistance and axial force, ultimately leading to a significant increase in cutting force.

In this study, the characteristic behavior of the cutting force is determined for a circular saw with various rotation speeds, feed rates, entrance angles, and frond widths. Regression equations are developed that include these variables as independent factors, and calculation models are established for the cutting force needed for oil palm fronds. These models reveal a dynamic transmission law for the circular saw during the cutting process of oil palm fronds, and provide a valuable method for accurately calculating the cutting force. Further research in this field has the potential to provide valuable insights in terms of optimizing the cutting process and enhancing its efficiency for practical applications.

MATERIAL AND METHODS

Stress analysis of circular saw cutting on oil palm fronds

In their natural growth state, the fronds of the oil palm can be characterized as an outcome of the complex interplay between the root and the tree, resulting in their intricate formation. The elongated portion of oil palm fronds can be regarded as the free end, which undergoes pushing and cutting by a cutter edge or blade during the harvesting process. When the fronds come into contact with the circular saw, they exhibit behavior similar to that of a cantilever beam, where a concentrated load is applied at the point of contact. The cantilever beam model is therefore adopted as an appropriate model for the oil palm fronds, and they are treated as a long rod with a fixed base and a free extended end.

When the blade or cutter edge makes initial contact with the fronds, they are cut from the root L, resulting in bending and deformation of the fronds as illustrated in Figure 1.

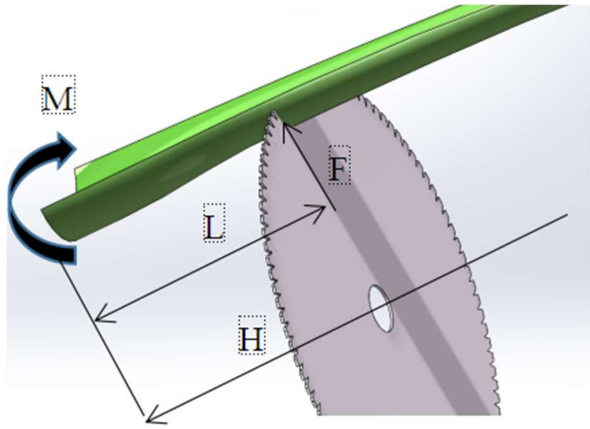


FIGURE 1. Force analysis diagram.

The cutting force, denoted as F, induces plastic deformation and bending in the stem, leading to a deflection curve described by the following equations for y:

$$\begin{cases} y = -\dfrac{F \cdot x^2(3L-x)}{6EI}, 0 \le x \le h \\ y = -\dfrac{FL^2(3x-L)}{6EI}, h \le x \le H \end{cases} \tag{1}$$

in which:

h - distance from the cutting force F to the root;

E - elastic modulus in GPa,

I - moment of inertia of the section in m^4.

The displacement S_{displace} along the horizontal direction at the cutting point is:

$$S_{displace} = -\frac{F \cdot h^3}{3EI} \tag{2}$$

The variations in force experienced by the circular saw during the cutting process can be categorized into two distinct stages: the initial contact of the saw blade with the surface of the stem (shown in Figure 2(a)), and the subsequent complete penetration of the saw blade into the interior of the stem (shown in Figure 2(b)). A schematic representation of the forces exerted on the stem at different relative positions during the cutting process is depicted in Figure 2.

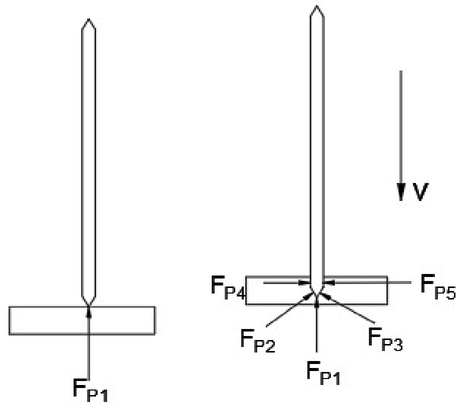


FIGURE 2. (a) Initial contact of circular saw; (b) full penetration.

As illustrated in Figure 2(a), the total cutting resistance force on the circular saw $F_p(x)$ is applied when the edge of the saw first comes into contact with the frond. The force acting on the circular saw F_{p1} can be mathematically represented as:

$$F_p(x) = F_{p1} \tag{3}$$

From Figure 2(b), it can be seen that the circular saw exerts a total cutting resistance force $F_p(x)$ as it severs the fronds. This force is sustained throughout the cutting process, as evidenced by the repetitive occurrence of the values $F_{p1}, F_{p2}, F_{p3}, F_{p4}, F_{p5}$ in the following expression:

$$F_p(x) = F_{p1} + F_{p2} + F_{p3} + F_{p4} + F_{p5} \tag{4}$$

Where:

F_{p1}- resistance exerted by the frond on the top surface of the blade edge;

F_{p2}- resistance exerted by the frond on the left surface of the blade edge;

F_{p3}- resistance exerted by the frond on the right surface of the blade edge;

F_{p4}- resistance exerted by the petiole on the left surface of the blade;

F_{p5}- resistance exerted by the frond on the upper surface of the blade.

Selection and design of the circular saw

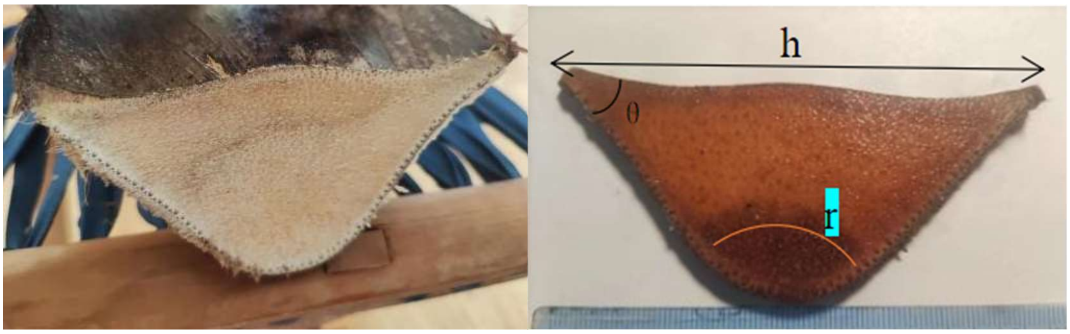
Numerous academic studies have focused on optimizing the design of circular saws. For example, Meulenberg et al. (2022) and Hlásková et al. (2015) optimized the tooth profile of circular saws through methods such as orthogonal experiments and simulation, in order to obtain the optimal design parameters. Tan et al. (2014) carried out simulations and experimental validation to determine the optimal design for the teeth of a circular saw. Zhang et al. (2009) employed a dynamic analysis to find the optimal thickness for different diameters. Based on the contributions in the literature and taking into consideration the cutting dimensions for oil palm fronds, the specific design parameters are given in Table 1 below.

TABLE 1. Parameters of the circular saw.

Diameter (mm)	Thickness (mm)	Root circle (mm)	Rake angle (°)	Addendum angle (°)	Material
250	2	1.6	0	0	65Mn

Experimental materials

Fresh oil palm fronds sourced from Hainan, China were used as the experimental material. To investigate the influence of the frond width on the cutting force, the fronds were systematically categorized into three groups based on their width: moderate (100–105 mm), large (122–126 mm), and very large (143–145 mm). The cutting section, shown in Figure 3, was described by key parameters such as the frond width coefficient (h), the included angle (θ), and the fillet (r), which were carefully measured and recorded for analysis.



(a) **(b)**

FIGURE 3. Fresh fronds: (a) test frond; (b) sample.

Structure and operation of a test bench for frond analysis

Frond analysis is important in terms of gaining an understanding of the structural and functional characteristics of plants. To accurately analyze fronds, it is essential to use a well-designed test bench that can provide precise control and measurement capabilities. In this study, we present a detailed structure and working principle of a test bench that was specifically designed for frond analysis. The test bench consists of several key components, including a circular saw cutting mechanism, a feed transmission system, a frond clamping device, a data acquisition system, and a drive for frond analysis.

Figure 4 shows the cutting mechanism of the circular saw, which allows for precise control over the rotation speed, while the frond clamping device enables adjustments to be made to the horizontal inclination of the rotation plane. The drive system provides a variable-speed feed motion to the circular saw cutting mechanism, which enables accurate and consistent cutting of fronds for analysis. The feed transmission system is designed to provide a variable-speed feed motion to the circular saw cutting mechanism, allowing for controlled cutting of fronds at different speeds. The frond clamping device allows for adjustments to the horizontal inclination of the rotation plane, thereby ensuring precise positioning of fronds during cutting. The data acquisition system is used for real-time monitoring and recording of the key parameters during frond analysis, such as the rotation speed, feed rate and cutting depth. The drive control system provides seamless control over the entire test bench, allowing for precise and efficient operation.

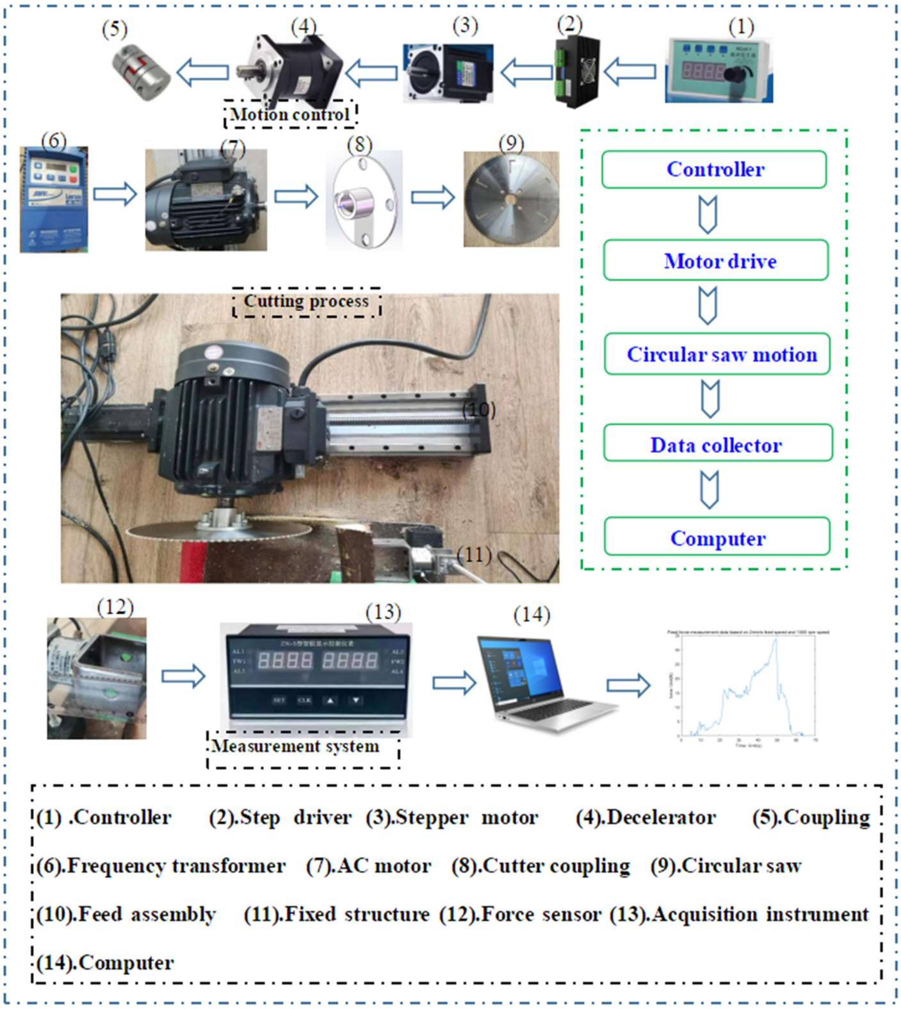


FIGURE 4. Collection of data on cutting force.

Precise control over the rotation speed of the circular saw is possible, which enables accurate and consistent frond cutting for analysis. The feed transmission system provides a variable-speed feed motion, allowing for controlled cutting at different speeds for specific experiments. The frond clamping device ensures precise positioning during cutting, thus allowing for accurate results. The data acquisition system monitors and records key parameters in real time, providing valuable data for analysis. The drive control system ensures smooth and efficient operation of the test bench, ensuring reliable and reproducible outcomes.

Multi-factor test and experimental design

To determine the optimal working parameters and explore the interactive effects of various parameters on the cutting force, an experiment was conducted with different values of the circular saw feed rate (v), rotation speed (ω), angle of entry (α), and frond width (h). Since the circular saw undergoes nonlinear deformation and periodic stress under high-speed rotation, we accounted for randomness and minimized the error by choosing the cutting force of the circular saw as the evaluation index in the orthogonal test after the test was repeated three times at each level. A four-factor central combination test was conducted using a quadratic regression combination design, based on the parameter values shown in Table 2.

TABLE 2. Four-factor experimental design.

Parameter	Symbol	Value			
Rotation speed (rpm)	v	1000	1500	2000	2500
Feed rate (mm/s)	n	3	6	9	12
Entrance angle (°)	α	0	5	10	15
Maximum width (mm)	h	105	124	142	-

RESULTS AND DISCUSSION

Analysis of the results of multi-factor experiments

Multi-factor test results

The cutting process can be defined as the relative motion between the frond and the circular saw. A sliding table driven by motor rotation was employed to supply the feed motion of the circular saw during the cutting tests. The force exerted by the circular saw during the cutting of oil palm fronds was measured, and the findings are presented in Tables 3–8.

TABLE 3. Dimensions of medium-sized fronds.

Size	Average width (mm)	Average angle (°)	Average fillet (mm)	Average area (mm^2)
Moderate	103	39	13	2111.4

TABLE 4. Results for cutting force (N) for medium-sized fronds.

Rotation speed (rpm)	Feed rate (mm/s)	Entrance angle (°)			
		0°	5°	10°	15°
1000	3	17.74	19.04	20.97	21.23
	6	20.36	21.85	22.89	25.01
	9	24.67	25.76	26.87	27.98
	12	26.75	28.02	29.36	30.09
1500	3	13.07	14.48	15.54	17.76
	6	16.11	17.23	18.67	19.69
	9	20.56	21.25	22.24	23.45
	12	23.78	24.23	25.67	26.98
2000	3	10.56	11.22	12.90	14.29
	6	12.97	14.43	15.94	17.73
3	9	14.99	16.24	17.45	18.98
	12	17.88	19.34	20.21	21.12
2500	3	8.21	9.81	11.23	12.04
	6	11.01	12.32	13.45	15.79
	9	13.23	14.56	15.55	17.98
	12	15.23	16.38	18.29	21.59

TABLE 5. Dimensions of large fronds.

Size	Average width (mm)	Average angle (°)	Average fillet (mm)	Average area (mm^2)
Larger size	124	41	14	3299.3

TABLE 6. Results for cutting force (N) for large fronds.

Rotation speed (rpm)	Feed rate (mm/s)	Entrance angle (°)			
		0°	5°	10°	15°
1000	3	24.54	25.47	25.87	26.23
	6	29.36	28.92	30.14	30.01
	9	32.67	33.42	35.23	33.98
	12	35.35	37.62	37.66	38.45
1500	3	19.20	21.23	22.32	22.89
	6	23.43	24.84	25.24	26.69
	9	26.73	28.35	30.58	33.50
	12	30.46	33.96	35.09	36.23
2000	3	15.12	16.34	17.56	19.21
	6	17.92	18.22	20.72	22.34
3	9	22.34	23.45	24.39	27.64
	12	27.99	28.22	30.20	32.97
2500	3	13.84	14.31	15.26	16.84
	6	16.31	17.12	18.23	19.37
	9	20.72	21.08	23.45	28.60
	12	25.87	26.73	28.24	29.52

TABLE 7. Dimensions of very large fronds.

Size	Average width (mm)	Average angle (°)	Average fillet (mm)	Average area (mm^2)
Very large	143	43	16	4388.9

TABLE 8. Results for cutting force (N) for very large fronds.

Rotation speed (rpm)	Feed rate (mm/s)	Entrance angle (°)			
		0°	5°	10°	15°
1000	3	33.42	33.78	36.87	38.48
	6	36.34	39.63	42.23	42.67
	9	41.21	43.23	44.20	45.48
	12	46.56	48.34	50.53	52.45
1500	3	27.26	29.81	32.13	34.27
	6	28.71	33.30	37.46	38.52
	9	36.45	37.17	40.98	43.77
	12	40.50	43.25	43.11	44.23
2000	3	23.17	25.11	28.04	29.69
	6	27.99	29.72	29.42	32.18
3	9	30.68	34.74	35.34	37.63
	12	35.90	38.27	40.71	41.32
2500	3	21.64	24.12	25.88	26.46
	6	26.26	28.55	28.31	29.89
	9	28.65	31.74	33.69	35.07
	12	33.34	36.30	37.01	38.24

Statistical model

A binary quadratic regression equation was derived by fitting the results of the four-factor test described above. The parameters considered in this equation were the feed rate, entrance angle, and rotation speed of the circular saw, and the width of the fronds. The statistical significance of each coefficient in the equation was assessed using a variance analysis, and the coefficient values were evaluated accordingly. The results of the variance analysis can be found in Table 9.

TABLE 9. Significance analysis of the parameters in the regression equation.

Source	bj	P	Assessment
Rotation speed (A)	−0.012	<0.05	Significant
Feed rate (B)	−0.041	>0.05	Significant
Maximum width (C)	−0.758	<0.001	Significant
Entrance angle (D)	−0.057	<0.05	Not significant
AB	<0.001	<0.001	Significant
AC	<0.001	<0.05	Significant
AD	<0.001	<0.05	Significant
BC	0.01032	<0.001	Significant
BD	0.002	>0.05	Not significant
CD	0.003	<0.001	Significant
A^2	<0.001	<0.05	Significant
B^2	0.0175	>0.05	Not significant
C^2	0.0047	<0.001	Significant
D^2	-0.0067	<0.05	Not significant
K	56.42	—	—
R^2	0.987		

The coefficients obtained from this process indicate that R^2=0.987 in the response variable can be explained by the regression model, suggesting a strong fit to the underlying data and robust predictive capabilities.

The reliability of the model is also affirmed by its ability to accurately reflect and predict the actual experimental values. In instances where the regression coefficients b_j were not statistically significant or were close to zero, they were excluded from the regression equation. In this case, the regression coefficients for factors AB, AC, and AD were found to be negligible, and the parameters AD and D^2 did not significantly affect the equation. After removing these non-significant factors and coefficients, we obtained the refined standard regression model in [eq. (5)]:

$$F = 56.42 - 0.0124A - 0.0418B - 0.7585C - 0.4132D + 0.0103BC + \ldots$$

$$+0.0054BD + 0.0084CD + 2.64 \times 10^{-6}A^2 + 0.0176B^2 + 0.0047C^2 \tag{5}$$

Optimization of the cutting parameters

In the graph in Figure 5, the feed rate and rotation speed of the circular saw are shown on the X and Y axes, respectively, and the cutting force is represented on the Z axis. The cutting force (curved surface) is determined by Equation (5). Our findings indicate that the feed rate has a substantial and linearly increasing influence on the cutting force, whereas the effect of the rotation speed on the cutting force is strong but decreasing.

The width of the cut fronds is also a significant factor affecting the cutting force, and a higher cutting force can be observed for larger frond widths from the left-hand side of Figure 5. A larger entrance angle results in an increased cutting force, as shown to the right of Figure 5, and the influence of both factors together on the cutting force is approximately linear.

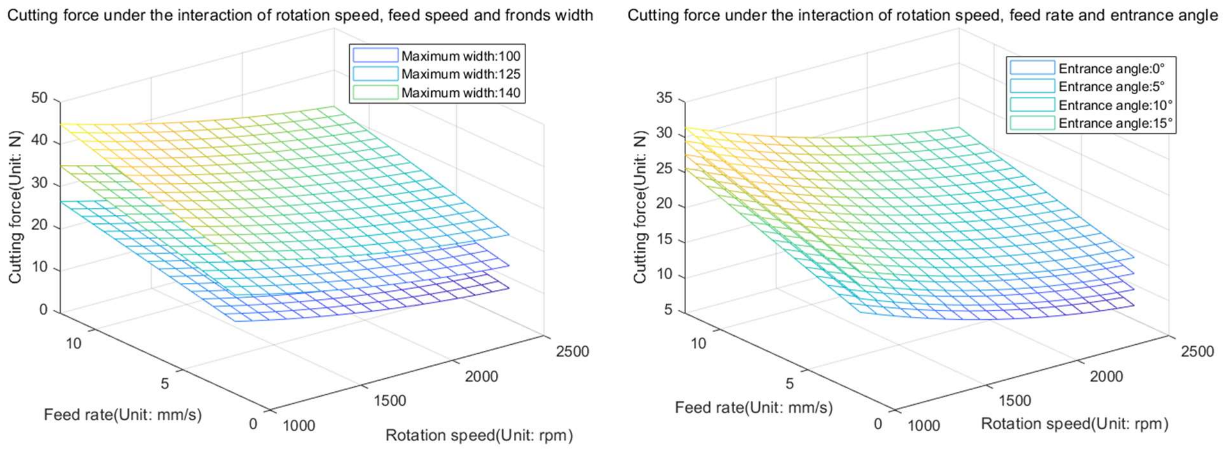


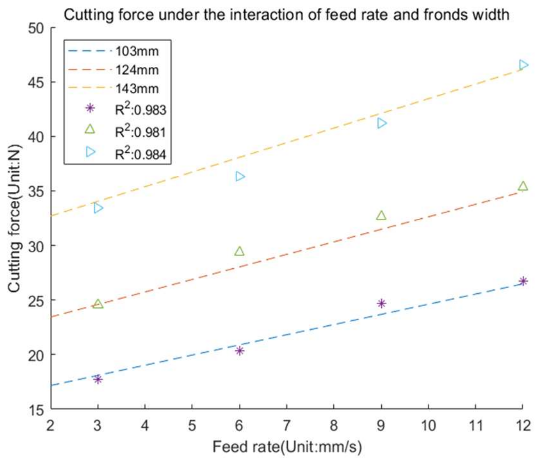
FIGURE 5. Response of the cutting force to variations in the feed rate, rotation speed, entrance angle and frond width.

An analysis of Figure 5 reveals that the cutting force of the circular saw is influenced by multiple factors, including the feed rate rotation speed, frond width and entrance angle. Notably, the feed rate (2–12mm/s), frond width (100–140mm) and entrance angle (0–15°) exert a significant and approximately linearly increasing impact on the cutting force, whereas the rotation speed (1000–2500 rpm) exhibits a strong but decreasing influence on the cutting force. When the rotational speed of a circular saw exceeds 2000 rpm, the cutting force shows a limited decrease, and further increasing the rotational speed may reduce the stability of the system.

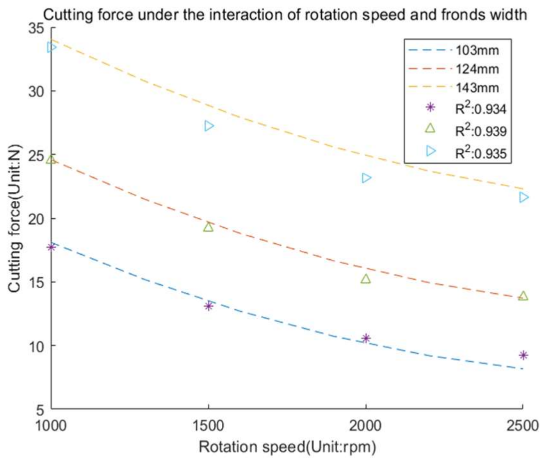
During cutting operations with a circular saw, it is customary to maintain a cutting speed of no less than 1000 rpm. However, a cutting speed of 2000 rpm can be considered an optimal balance between the cutting force and cutting noise, representing a globally optimal solution for the cutting of oil palm fronds. Based on the principle that smaller cutting angles result in reduced cutting forces, an entrance angle of 0° is the preferred choice for the overall cutting strategy. Although increasing the feed rate of the circular saw leads to higher cutting forces, it is important to consider the cutting efficiency. As a result of the experimental trials reported here, a locally optimal solution is proposed with a feed rate of 10 mm/s, with the aim of minimizing the cutting forces. Lastly, for improved efficacy, it is advisable to select positions with thinner frond handles for the final cutting operation, as this approach effectively reduces the cutting force required

Evaluation of results

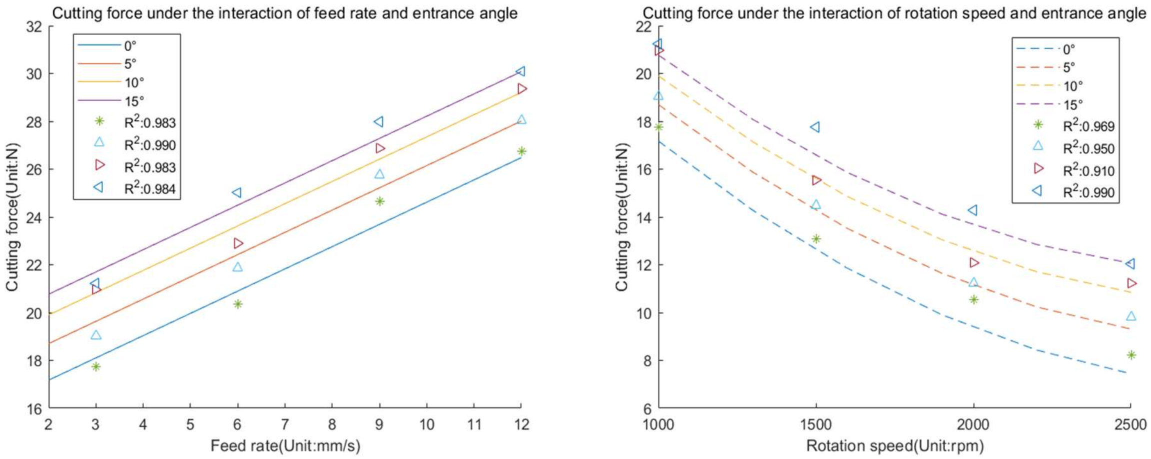
The cutting force tends to increase linearly with an increase in the feed rate, and decreases with an increase in the rotational speed. The model curves in Figures 6(a) and 6(b) accurately reflect this behavior. It can also be observed from Figures 6(c) and 6(d) that with an increase in the cutting width and entrance angle, the cutting force increases, and the values recorded in the experiments are distributed around the line predicted by the model.



(a) Change in cutting force with varying feed rate and frond width



(b) Change in cutting force with varying rotation speed and frond width



(c) Change in cutting force with varying feed rate and entrance angle

(d) Change in cutting force with varying rotation speed and entrance angle

FIGURE 6. Effect on the cutting force of varying feed rate, frond width, rotation speed and entrance angle.

The data for the cutting force has a certain degree of dispersion, as can be seen from Figure 6(a)–(d), which is a normal finding in tests of this sort. In general, it can be observed that there is a significant relationship between the test data and the cutting force model for oil palm fronds for a rotation speed of 1000–2500 rpm and a feed rate of 2–12 mm/s. The distribution correlation coefficient R^2 ranges from 0.91 to 0.99.

The cutting force calculation results obtained by inputting the corresponding values of feed rate, rotation speed, entrance angle, and frond width into the regression equation found from the parameter experiment were compared with the experimentally collected cutting force obtained from model calculation. The maximum relative error between the results calculated by the regression equation and the experimental results was 14.77%, the minimum was 0.09%, and the average error was less than 5%, indicating a good fit and high accuracy for the regression equation.

CONCLUSIONS

A regression equation for the cutting force of oil palm fronds, with a high correlation coefficient ($p < 0.05$, $R^2 = 0.987$, $Adj R^2 = 0.95$) , was derived from statistical analyses of experiment tests. We found that the feed rate, rotation speed, frond width, and entrance angle had a significant effect on the cutting force. Our findings indicate that the cutting force increases linearly with increasing feed rate, frond width, and entrance angle, whereas it decreases with rotation speed. The recommended cutting parameters, from the perspective of reducing the cutting force to an optimal level, are a rotation speed of 2000 rpm, an entrance angle of 0°, and a feed rate not exceeding 10 mm/s.

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