

Optimization of Operational Parameters to Minimize Cutting Energy during Kenaf Harvesting

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Abstract

This study evaluated the cutting and specific cutting energy of different kenaf varieties at different maturity stages during mechanical harvesting, while evaluating an improved kenaf harvester. The effects of operation parameters (related to the crop's biological properties; crop varieties "Cuba 108," "Ifeken 400," and "Ifeken Di 400"; and crop maturity: 10 to 16 weeks after planting) on the machine performance were optimized in a 3×4 factorial experiment using randomized response surface methodology (optimal custom design) to optimize the energy consumption. The results showed that the cutting energy required for harvesting kenaf increased from 1.8 to 3.3 joules as the crop matured from 10 to 16 weeks after planting (WAP). Among the tested crop varieties, "Ifeken 400" consistently required the highest cutting energy, followed by "Cuba 108", while "Ifeken Di 400" required the least energy. The specific cutting energy increased from 5000 to 11661 J.m⁻² as the crop matured, indicating differences in energy demand among the kenaf cultivars. These findings imply that the physical and mechanical properties of kenaf directly affect its stiffness. The stiffness factor of the crop is determined by crop maturity (weeks after planting) and crop variety. Therefore, the proper estimation of these operational parameters is vital for increasing the energy efficiency during the harvesting of kenaf.

Keywords: *Crop parameters, Crop maturity, Crop varieties, Cutting energy, Specific cutting energy.*

1. Introduction

Global concerns over environmental impact, climate change, and resource waste have spurred the exploration of biodegradable and renewable materials. Kenaf (*Hibiscus cannabinus*) is a significant industrial crop owing to its biodegradability, sustainability, and diverse applications. As a low-cost, biodegradable packaging material, kenaf offers an excellent alternative to synthetic fibers and non-biodegradable plastics [1], [2], [3]. As a fast-growing plant with a significant biomass output, it efficiently absorbs atmospheric CO₂, thereby assisting in lowering global carbon levels and playing a role in

minimizing the effects of climate change [4]. Kenaf is used in packaging, biobased composites, textiles, and biofuels, demonstrating its potential to make a substantial contribution to the circular economy and a sustainable future. Among renewable and low-impact materials, kenaf stands out as a promising option for addressing industrial demands while considering ecological factors [1], [5], [6], [7].

Kenaf (*Hibiscus cannabinus L.*) is a fibrous annual fibre crop native to tropical and subtropical regions, grown during the warm and wet seasons and matures in three to four months [2], [3], [4], [6] [7]. It belongs to the

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Hibiscus family and has more than 400 annual and perennial species closely related to cotton (*Gossypium hirsutum* L., *Malvaceae*) and okra (*Abelmoschus esculentus* L., *Malvaceae*) [8], [9], [10]. Kenaf's three main morphological components are the bark containing bast fibre, the core, and the hollow centre with pith. Kenaf stems have approximately 30% and 70% bast and core fibers in the bark and inner core (center of the stems), respectively [7], [11], [12], [13]. This crop has the potential to be a sustainable biomaterial with numerous industrial applications, including the packaging of agricultural products, textiles and fabrics, biocomposites, construction, biochar, and bioenergy [2], [3], [10], [14], [15], [16], [17], [18], [19]. The adaptability of kenaf has been examined, and it has been discovered to have potential for producing bioproducts, specifically, biocomposites and biofuels [20]. This crop is versatile and can be used for several purposes, such as making paper products and textiles [21] [22].

Kenaf is a high-yielding crop suitable for various sectors of manufacturing owing to its diverse applications [2], [23], [24], [25], [26], [27]. However, the cultivation, harvesting, and post-harvest processes can be daunting because of their labor-intensive nature. The harvest and postharvest process stages, including harvesting, transporting, storing, and post-harvest, require significant time and resources [28]. The optimal harvesting techniques for kenaf can be optimized and automated using appropriate tools and methods [7], [26]. A careful evaluation of these methods is vital to ensure an optimal and energy-efficient harvest [3], [29]. Kenaf whole-stalk harvesting has evolved from being dependent on forage harvesters to the design of modern cutting systems like rotary discs, rotary drum mechanisms, and modified brush cutters, enhancing efficiency [10], [28], [29], [30]. A tractor-mounted harvester was developed to sieve kenaf stems during harvesting. The technology features a powertrain with a rotating disc harvester mechanism driven by the tractor power take-off (PTO). The chain drive system rotates the bevel gear at a predetermined velocity ratio and transfers power to the secondary chain drive at a constant velocity. This setup drives both the primary and secondary cutting blades in a circular motion, allowing effective crop stem harvesting [10]. The harvesting powertrain was mounted on the tractor's 3-point linkage and powered by the tractor's PTO.

Cutting kenaf stems is a crucial stage in the harvesting and processing of the plant, where the stem is a homogeneous cantilever beam supported at the base [31], with a cutting force applied as a point load on the material until the yield point is reached. The cutting force required was determined by the cutting resistance, which is related to the stem's inertia and the bending forces at the impact site, and is also responsible for the shearing of the cutting edge through the plant stem [32], [33], [34]. The energy required for cutting crop stems depends on the design of the cutting device operating parameters and the physical properties of the plant material, considering factors such as growing conditions, material storage duration, crop maturity, and plant type [28], [35]. The literature also suggests that the energy required to shear agricultural materials is influenced by their physical and mechanical properties, and the process of cutting and fragmenting depends on the interaction between crop properties, machine parameters, and energy consumption [36], [37]. Assessing the cutting energy required for a material is vital for constructing an efficient cutting machine. The cutting resistance of a crop stem during harvesting depends on the angle of the blade, sharpness, cutting mechanisms, and speed of operation. Additionally, it is determined by the intrinsic texture of the plant material, which may be homogeneous or heterogeneous [38], [39].

This study aimed to optimize the efficiency of kenaf harvesting by estimating the optimal cutting energy and specific energy required for the harvesting process. The biological characteristics of crops have been exploited to develop simulations and establish mathematical models for the cutting process. These models attempt to enhance the operation and minimize the energy required for kenaf harvesting. The novelty of this research lies in its potential to appreciate the interaction between the operational parameters of the crop, biological traits, stage of maturity, and variety in relation to the energy expended during harvesting. This information enables the precise calibration of harvesting equipment and adjustments to procedures. It provides not only economic benefits but also contributes to environmental sustainability by increasing energy efficiency and optimizing the mechanical harvesting of kenaf, thereby improving harvesting techniques and sustainable farming practices.

2. Materials and Methods

The methods and experimental procedures for assessing the energy parameters during the harvesting process are described in this section.

2.1. Experimental procedures

The tractor-mounted kenaf harvester shown in Figure 1 and Figure 2 was designed by Ayorinde and Owolarafe [10] to improve the efficiency of kenaf harvesting systems. This experiment was conducted on a kenaf plot cultivated at the teaching and research farm of the Obafemi Awolowo University, Ile-Ife, Nigeria, where three varieties of Kenaf crops ('Cuba 108', 'Ifeken 400', and 'Ifeken Di 400') were planted under the same climatic and weather conditions and monitored until the 10th week.

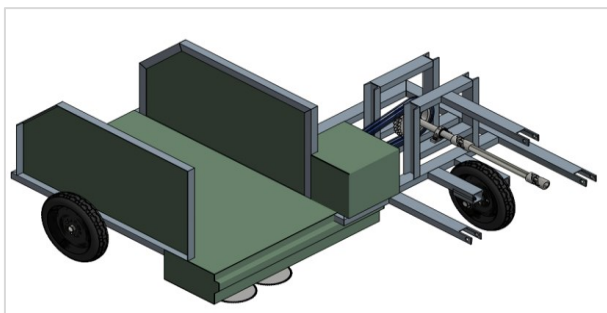


Figure 1. Isometric view of the kenaf harvester [10].

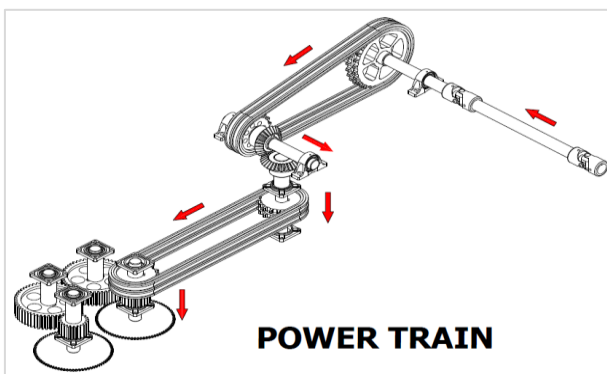


Figure 2. Power train of the kenaf harvester [3], [19].

2.2. Experimental design

A 3×4 factorial experiment was designed by subjecting the machine operation parameters related to the crop's biological properties, crop varieties "Cuba 108," "Ifeken 400," and "Ifeken Di 400," and crop maturity (10,

12, 14, and 16 weeks after planting) to randomized response surface methodology (optimal custom design) using Design Expert software 11.1.2.0. The randomized response surface methodology generated 17 runs (Table 1), and the experiment was conducted in three replicates. The effects of the operational parameters on the cutting energy and specific cutting energy were evaluated, and an analysis of variance was performed using Design Expert software. Additionally, the final equations for predicting the cutting energy and specific cutting energy for kenaf harvesting were developed.

Table 1. Experimental design for cutting and specific cutting energy required during kenaf harvesting.

Run	Crop maturity (WAP)	Variety	Cutting energy (J)	Specific cutting energy (J.m ⁻²)
1	12	IfeKen Di 400	2.23	6408
2	16	IfeKen 400	3.3	11,661
3	14	IfeKen Di 400	2.77	7960
4	10	IfeKen 400	1.83	6466
5	14	Cuba 108	2.77	8343
6	10	IfeKen Di 400	1.74	5000
7	16	Cuba 108	3.19	9608
8	10	IfeKen Di 400	1.74	5000
9	10	Cuba 108	1.80	5422
10	14	Cuba 108	2.77	8343
11	14	IfeKen Di 400	2.77	7960
12	10	Cuba 108	1.80	5422
13	16	IfeKen 400	3.30	11,661
14	12	IfeKen 400	2.36	8339
15	16	IfeKen Di 400	3.14	9023
16	12	IfeKen 400	2.36	8339
17	12	Cuba 108	2.36	7108

2.3. Estimation of energy parameters

In this section, we discuss the cutting energy and specific cutting energy during kenaf harvesting.

2.3.1. Cutting energy

The cutting energy (E_c) was estimated by determining the product of the cutting power and cutting time, as shown in Equation 1. Stem deflection during harvesting was assumed to be negligible, while the kenaf stalk was cut at the critical cutting speed (0.67–0.81 m/s). The machine harvested the crop at 15 cm from the ground surface, where it was rigidly fixed to the ground [40].

$$E_c = P_c t_c \tag{1}$$

Where; P_c = cutting power,
 t_c = cutting time
 Ayorinde [19]

The cutting power (P_c) required during operation by the kenaf harvester is the product of the cutting torque and angular speed of the PTO shaft on the tractor.

$$P_c = F_c V_0 \tag{2}$$

$$t = \frac{S}{V_0} \tag{3}$$

Where; F_c = cutting force,
 V_0 = cutting speed of the blade,
 t = time taken during harvesting,
 S = cutting arc
 Ayorinde [19]

2.3.2. Specific cutting energy

The specific energy required by the tractor-mounted kenaf harvester during field operation was calculated using Equation 4 [19]. The cut area was estimated using the data obtained from [3]. The average kenaf stem diameters of the three crop varieties were 20.55, 21.06, and 18.98 mm, respectively.

$$\text{Specific cutting energy} = \frac{\text{Cutting energy}}{\text{Area of cut}} \tag{4}$$

Ayorinde [19]

2.3.3. Final equations for predicting cutting energy and specific cutting energy.

The final equations were generated during the analysis of the randomized response surface experimental samples (Table 1) to predict the cutting energy (E_c) and specific cutting energy (E_{sc}) expended during the field evaluation (Table 2). The model was developed in terms of the three varieties of kenaf and crop maturity and can be used to make predictions about the response for given levels of each factor.

Table 2. Final equations in terms of actual factors.

V	E_c	E_{sc}
C1	$-1.66721 + 0.421214m - 0.007378m^2$	$-5064.59789 + 1275.66694m - 22.49608m^2$
ID4	$-1.82084 + 0.429396m - 0.007378m^2$	$-5435.70615 + 1266.85426m - 22.49608m^2$
I4	$-1.82902 + 0.438415m - 0.007378m^2$	$-5848.14896 + 1453.84350m - 22.49608m^2$

Note: E_c = Cutting energy; V = Crop variety; M = Crop maturity; C1 = Cuba 108; ID4 = IfeKen Di 400; I4 = IfeKen 400.

3. Results and Discussion

The effects of machine operation parameters on the cutting energy and specific cutting energy are discussed in this section. Multiple regression analyses were also performed for the cutting and specific cutting energy.

3.1. Effect of operation parameters on cutting energy

Figure 3 shows the impact of crop operation parameters (maturity and variety) on the energy expended during harvesting. The cutting energy gradually increased from 1.8 to 3.3 J as the crop matured from week 10 to 16 weeks after planting (WAP). The highest cutting energy was expended at 16 WAP, which agrees with the findings of Raji and Aremu [41], Ghahreii et al. [28], and Ayorinde and Owolarafe. [3]. "Ifeken 400" required the highest cutting energies of 1.83 and 2.36 J at week 12, 3.0 J at week 14, and 3.3 J at weeks 10, 12, 14, and 16, respectively. This was closely followed by "Cuba 108," whereas "Ifeken di 400" required the lowest energy during the mechanical harvesting of kenaf. This result is consistent with those of Falana et al. [9] and Dauda et al. [29], [42].

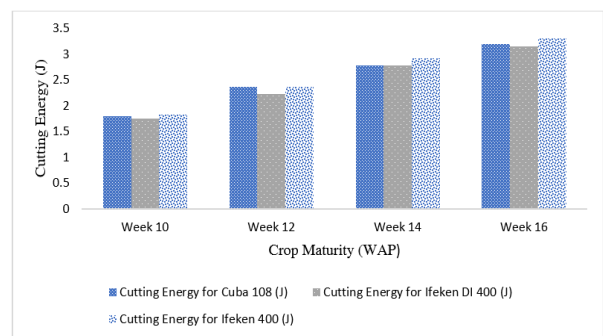


Figure 3. Cutting energy of kenaf varieties at different maturities.

The analysis of variance of the effect of kenaf varieties at different crop maturities on cutting energy (Table 3) shows the significant effect of crop maturity and variety on the energy required to cut the kenaf stem during harvesting, thereby corroborating the findings shown in Figure 4. Although the interactive effect of both operation parameters (crop maturity and variety) was insignificant in imparting cutting energy, the quadratic effect of the model on crop maturity was found to be significant. The Model F-value of 1584.01 implies that the model is

significant, and there is only a 0.01% chance that an F-value this large could occur because of noise. This suggests a continuous increase in cutting energy as the crop matures until it reaches a yield point, beyond which the stiffness of the crop decreases during cutting. Crop stiffness is directly proportional to cutting resistance and is a function of increased fiber and lignin content during crop maturity [40]. These findings agree with those of Uche [37], who showed that cutting energy depends on the intrinsic texture, moisture content, and hardness, which are functions of the variety/type of material and crop maturity [37]. The cutting and fragmentation of crop materials depend on the operational parameters of the processing machinery [3], [34], [43].

Table 3. ANOVA for the effect of operation parameters on the cutting energy.

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	5.16	6	0.8606	1584.01	< 0.0001 significant
M	4.99	1	4.99	9186.45	< 0.0001
V	0.0323	2	0.0162	29.73	< 0.0001
MV	0.0039	2	0.0020	3.63	0.0651
M ²	0.0130	1	0.0130	23.90	0.0006
Residual	0.0054	10	0.0005		
Lack of Fit	0.0054	4	0.0014		
Pure Error	0.0000	6	0.0000		
Cor Total	5.17	16			

Note: Ec = Cutting energy; V = Crop variety; M = Crop maturity in weeks after planting.

3.2. Effect of operation parameters on specific cutting energy

The operational parameters significantly influenced the specific cutting energy expended during kenaf harvesting. As the plant matures from week 10 to 16 WAP, there is an obvious increase in specific cutting energy, with notable variation observed across different kenaf varieties harvested [19], [29]. The specific cutting energy increased significantly from 5000 J.m⁻² at 10 WAP to 11661 J.m⁻² at 16 WAP, indicating a substantial increment in the specific cutting energy. This study aligns with the report by Jyoti et al., who found that varying operational parameters, including the characteristics of the cassava stem, affect the specific cutting energy during the mechanical harvesting process [44].

At week 10, "Ifeken DI 400" required the least specific cutting energy at 5000 J.m⁻², followed by Cuba 108 with 5422 J.m⁻². In contrast, "Ifeken 400" required the highest

specific cutting energy of 11661 J.m⁻². "Ifeken 400" continued to require the highest cutting energy at 12, 14, and 16 WAP, as shown in Figure 4.

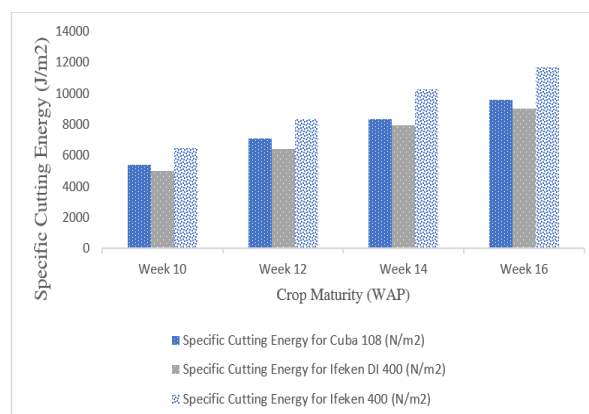


Figure 4. Specific cutting energy of different kenaf varieties at different maturity stages.

The analysis of variance of the effect of kenaf maturity and variety on the specific cutting energy required for mechanical harvesting showed P-values below 0.0500, indicating that the model terms were statistically significant. Similarly, all additional combinations of the model terms were significant. The model F-value of 2525.46 implies that the model is highly significant, with only a 0.01% probability that such a large F-value could arise from noise. The increase in specific cutting energy with increasing crop maturity during harvesting may be due to the increased shearing area during blade penetration. Similarly, the variation in the specific cutting energy of the different kenaf varieties can be ascribed to the heterogeneous mechanical properties of the plant stalk, resulting in different stiffnesses of the kenaf stem. Allameh and Alizadeh [45] also observed in their research on the specific cutting energy variations under different rice stem cultivars and blade parameters that operation parameters have a notable effect on the specific cutting energy of machinery [34], [46]. The analysis of variance (Table 4) shows that both crop maturity and variety significantly affected the specific cutting energy during kenaf harvesting, which validates the observation in Figure 5. The interactive effect of the variables was also significant.

Table 4. ANOVA for the effect of kenaf maturity and variety on the specific cutting energy.

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	6.693E+07	6	1.115E+07	2525.46	< 0.0001 significant
M	4.917E+07	1	4.917E+07	11132.57	< 0.0001
V	1.147E+07	2	5.736E+06	1298.75	< 0.0001
MV	5.766E+05	2	2.883E+05	65.28	< 0.0001
M ²	1.207E+05	1	1.207E+05	27.33	0.0004
Residual	44167.94	10	4416.79		
Lack of Fit	44167.94	4	11041.98	2.591E+08	< 0.0001 significant
Pure Error	0.0003	6	0.0000		
Cor Total	6.697E+07	16			

Note: E_c = Cutting energy, V = Crop variety, M = Crop maturity in weeks after planting.

3.3. Multiple regression analysis of the cutting energy and the specific cutting energy

The multiple regression analysis for the cutting energy and specific cutting energy expended during the field evaluation is discussed in this section.

3.3.1. Multiple regression analysis of cutting energy

The diagnostic plot in Figure 5 shows that both crop maturity and crop variety can accurately predict the cutting energy required during kenaf harvesting. The analysis revealed that the residuals were normally distributed and evenly scattered around zero, indicating that the model accurately captured the relationship between these operation parameters (crop varieties and maturity) and cutting energy without signs of nonlinearity or heteroscedasticity [31], [40], [41]. The Residuals were randomly distributed around zero with no significant outliers, suggesting a good model fit (Figure 6). Additionally, the box-cox analysis supports the use of untransformed data, and the Cook's distance plot in Figure 7 shows no overly influential data points, further reinforcing the model's reliability and validity. The findings also show that as kenaf crops mature, stem density and diameter variations significantly affect the energy required for cutting [19], [35], [41]. Similarly, structural differences among kenaf varieties, such as differences in lignin content, stem hardness, and moisture levels, play a crucial role in determining the cutting energy. These insights offer practical guidance for optimizing harvesting operations by strategically selecting the optimal crop maturity stage and favorable varieties that minimize energy consumption [11].

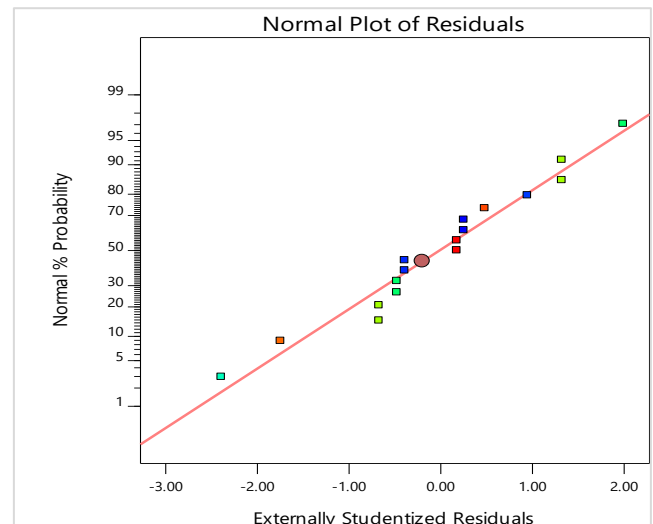


Figure 5. Normal plot of residuals of multiple regression of cutting energy.

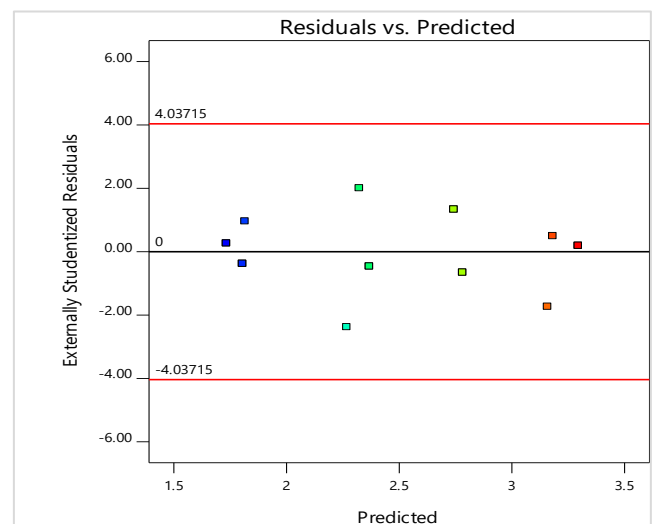


Figure 6. Residuals vs. predicted multiple regression of cutting energy.

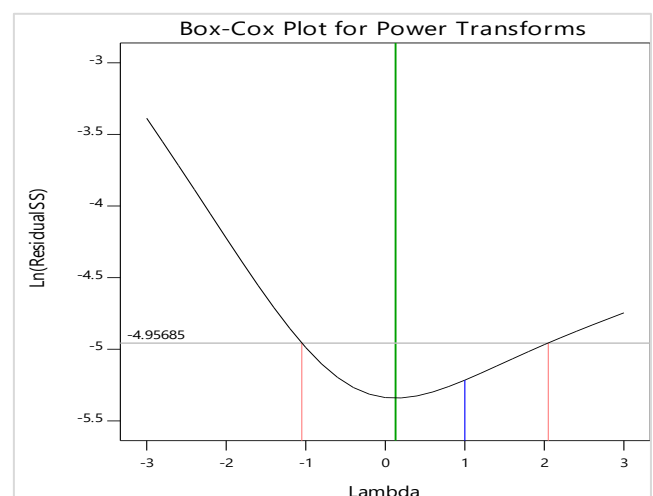


Figure 7. Box-Cox plot for power transforms of the multiple regression of cutting energy.

3.3.2. Analysis of the multiple regression of specific cutting energy

The multiple regression analysis in Figure 8 shows the effect of kenaf maturity and variety on the specific cutting energy required for kenaf harvesting. The normal plot of the residuals (Figure 8) shows that the residuals (errors) follow a normal distribution, indicating that the model adequately represents the relationship between the machine operation parameters and specific cutting energy. The residuals vs. predicted plot (Figure 9) further supports this, as the residuals are randomly distributed around zero with no significant outliers, suggesting a good fit of the model. However, a slight spread of residuals at higher predicted specific cutting energy values suggests some variation in cutting energy owing to differences in crop maturity and variety [41].

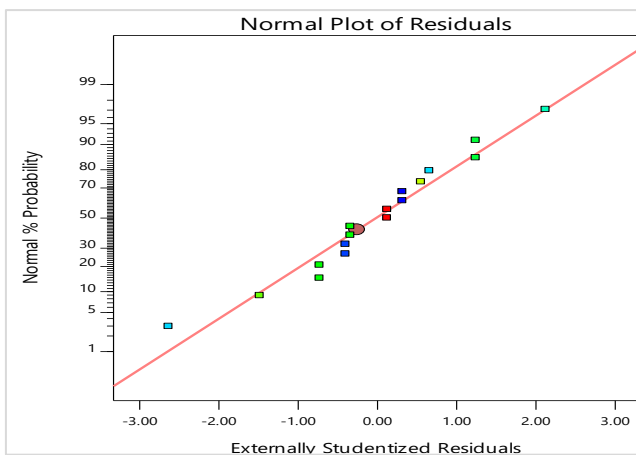


Figure 8. Normal plot of the residuals of the multiple regression of specific cutting energy.

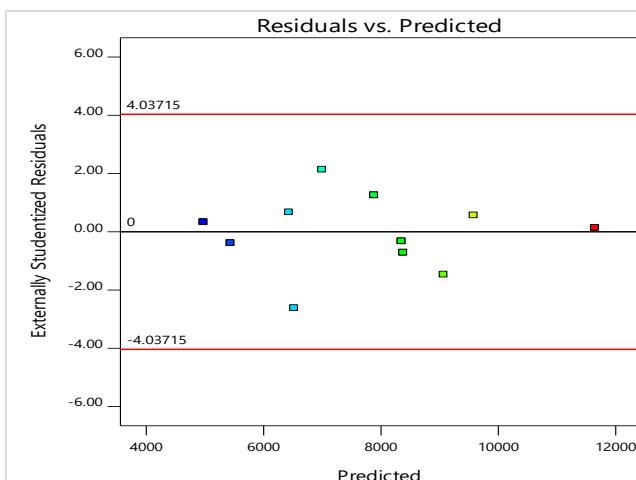


Figure 9. Residuals vs. predicted multiple regression of the specific cutting energy.

The effect of kenaf maturity on specific cutting energy becomes evident as more mature kenaf plants require higher cutting energy owing to increased stem thickness, moisture content, fiber content, and lignification [32], [47]. The kenaf variety also plays a role, as different varieties have varying morphologies and fiber structures, influencing the cutting force required [41], [48]. The residual plots indicate that the model effectively captured these effects without introducing significant bias. The Box-Cox plot (Figure 10) also confirms that no transformation is needed, as the best lambda value (0.63) is close to 1. This suggests that the specific cutting energy data are well suited for regression analysis. However, if heteroscedasticity (non-constant variance) becomes more pronounced, a minor transformation can help stabilize the variance and improve accuracy.

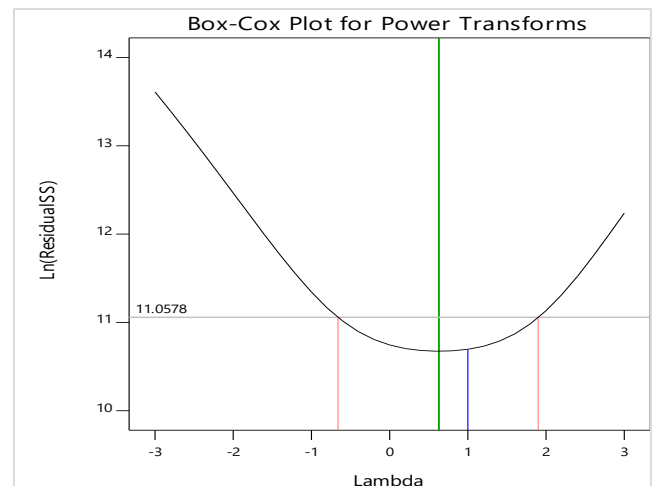


Figure 10. Box-Cox Plot for power transforms of the multiple regression of specific cutting energy.

4. Conclusion

This study showed that the crop parameters related to the biological properties of kenaf, crop maturity, and variety significantly influenced the cutting energy and the specific cutting energy required during mechanical harvesting. The cutting energy used for harvesting kenaf increased from 1.8 to 3.3 joules as the crop matured from 10 to 16 WAP. Among the crop varieties studied, "Ifeken 400" consistently required the highest cutting energy, followed by "Cuba 108", while "Ifeken Di 400" required the least energy. The specific cutting energy ranged from 5000 to 11661 J.m⁻² as the crop matured, demonstrating variances in energy requirements between kenaf cultivars. The analysis of variance confirmed that both operation

parameters (crop maturity and variety) had statistically significant model terms, with P-values less than 0.0500 for all combinations of the factors. The high Model F-value further reinforces the reliability of the model, indicating that the observed effects are not due to random chance. Additionally, the regression models for predicting the cutting and specific cutting energy showed statistical robustness, as evidenced by the significant p-values for all coefficients. The confidence intervals for the coefficients indicated dependable estimations, whereas the diagnostic plots, encompassing the residuals and Box-Cox analysis, validated that the models were appropriately fitted. There were no substantial biases, and no transformation was required for the model because the current lambda of the model was 1.

This study highlights that crop maturity and variety significantly influence the cutting energy and specific cutting energy. The stiffness of kenaf is a function of both crop maturity and variety, and consequently, it affects the harvesting process. Therefore, the proper selection of kenaf maturity and variety can optimize energy consumption, potentially improving harvesting efficiency and reducing operational costs. However, the study has drawbacks, such as a limited range of maturity and variety and neglect of environmental influences.

Future studies should investigate a wider selection of varieties, extend the maturity range, and consider the environmental factors. By improving these elements, subsequent research can optimize kenaf harvesting, rendering the process more efficient and economically viable for farmers.

Competing Interest Statement

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this study.

Data Availability Statement

Supplementary materials and data used in this study are available upon request. For access, please contact the corresponding author at ayorindeadedayo@gmail.com.

Author Contributions

Conceptualization and methodology: T.A.A.; Software: T.A.A.; Validation: T.A.A.; Investigation, T.A.A.; Original draft preparation: T.A.A.; Writing–review: O.K.O. and T. J.; Writing, review and editing: T.A.A., O. K. O., P.F.L.R., and T. J.; Supervision: O.K.O., P.F.L.R., and T.J. All authors have read and agreed to the published version of this article.

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