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Effect of operational parameters on the performance of a kenaf harvester

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Abstract

Aim of study: To develop a kenaf harvesting technology, that will improve kenaf production efficiency. This study evaluated the effect of some operation parameters on the performance of a tractor-mounted kenaf (*Hibiscus cannabinus* L.) harvester.

Area of study: The experiment was performed at the Teaching and Research Farm of the Obafemi Awolowo University, Ile Ife, Nigeria.

Material and methods: The experiment was initiated after 10 weeks of planting kenaf on the experimental field. The experimental design was a 3 × 4 × 5 experiment evaluating the effect of kenaf maturity (average stem diameter at week after planting (WAP) 10, 12, 14 and 16), kenaf varieties ('Cuba 108', 'Ifeken 400' and 'Ifeken Di 400') and forward speed of the tractor (2, 3.5, 5, 6.5 and 7.7 km/h) on effective field capacity, field efficiency, and operational loses of the machine.

*Main results:*The effective field capacity of the machine decreased with increase in plant maturity and increased with increase in forward speed of the machine. The optimal value of the effective field capacity was 2.13 ha/day, when harvesting 'Ifeken 400', at crop maturity of 10 WAP, and forward speed was 5 km/h. The field efficiency of the machine was found to decrease with increase in crop maturity and forward speed of the machine. The field efficiency of the machine was 97%, with 'Ifeken 400' crop maturity of 10 WAP and forward speed of 2 km/h.

Research highlights: The crop maturity, kenaf variety and forward speed of tractor have effect on the effective field capacity, field efficiency and the operational loss of the tractor-mounted kenaf harvester.

Additional key words: operation parameters; crop maturity; varieties; forward speed; effective field capacity; field efficiency.

Abbreviations used: FS (forward speed of machine); PTO (power take-off); V (crop varieties); WAP (weeks after planting).

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Introduction

Kenaf (*Hibiscus cannabinus* L.) is an annual fibre crop grown during the warm season (Bourguignon et al., 2016). It is closely related to cotton and okro and matures in three to four months. It is native to east-central Africa and grows very well in Nigeria (Webber et al., 2002; Makanjuola et al., 2019). The global need for sustainable raw materials for industrial applications and particularly as renewable energy resources has led to the identification and recent acceptance of kenaf as an industrial crop (Jamadi et al., 2021). In terms of cultivation and distribution in Africa,

Table 1. Specification of tractor mounted kenaf harvester.

Parameter	Specification
Dimension (L × W × H)	2240 × 2192 × 800 mm
Ground clearance	150 (mm)
Total weight	850 (kg)
Power source	Tractor PTO
Tractor power required	55-70 (hp)
PTO speed	540 rpm
Transmission	PTO, gears, chain drive, shafts, bevel and spur gears
Height adjustment	Hydraulic
Cutting system	Carbonized circular saw blade
Cutting width	900 mm
Number of tyres	4

PTO = power take-off

kenaf is quite significant. It is a valuable crop in the area due to its adaptability and numerous uses. Africa's kenaf cultivation areas have grown, with job creating potential and encouraging sustainable practices (Yahaya et al., 2019). This consciousness of kenaf as a natural source of fibre has also expanded worldwide because it is an alternative source of natural fibre, that has carbon dioxide assimilation capability and water purification ability (Kobayashi et al., 2003; Dauda et al., 2013).

Kenaf stems have about 30% and 70% bast fibre and core fibre, in the bark and in the inner core (center of the stems), respectively. It has enormous industrial applications in automobiles, agriculture, building construction, chemical processing, and packaging. Kenaf can be blended with synthetic fibre to make carpets. Its other end-uses include oil and chemical absorbents, animal bedding and horticulture potting mix from the core, livestock feed from the leaf, fibreboard and particle board. The fibre also serves as raw material for jute bags, paper, twine, and plaster of paris production and hence there is a need for serious improvement in the mechanization of kenaf cultivation (Makanjuola et al., 2019).

Kenaf harvesting, which is a major unit operation in kenaf raw material production, is still carried out through labour-intensive manual methods in most parts of Africa and particularly in Nigeria. The use of forage harvesters is still adopted in most cases because kenaf whole stalk harvesters are yet to be available. Dauda et al. (2013) developed a tractor-mounted kenaf harvester that does not have a bailing system. Ayorinde & Owolarafe (2023) designed a kenaf harvester that uses a circular blade cutter for severing and a bailing system for proper on-field packing of the stem to improve the efficiency of the kenaf harvesting system. It is therefore essential to evaluate the effect of operational parameters on the performance of the machine.

Material and methods

Description of the kenaf harvester

The kenaf harvester in Fig.1a was designed to operate with the mechanism of a rotary disc harvester, and its components include circular cutting blades, spur and bevel gears, chains and sprockets, and shafts (with design specifications shown in Table 1). The power train of the machine is driven by the tractor power take-off (PTO), which drives the chain drive system.

The bevel gear is driven by the chain drive at the designed velocity ratio. The bevel gear then transmits power to the second chain drive at a constant velocity ratio, which drives the first and second cutting blades in a concentric motion. The harvester was mounted on the 3-point linkage of the tractor and driven by the PTO of the tractor, as shown in

Table 2. Experimental design for the evaluation.

Independent parameters	Indices
Variety	Cuba 108, Ifeken 400 and Ifeken Di 400
Age of plant (weeks)	10, 12, 14 and 16
Forward speed (km/h)	2, 3.5, 5.0, 6.5 and 7.7

Figure 1. The fabricated kenaf harvester: (a) front view of the fabricated kenaf harvester; (b) the developed kenaf harvester mounted on a tractor.

Fig. 1b. The machine was designed to accommodate a rack, which will enhance the packing of the stem in bundles (Ayorinde, 2022). This machine was evaluated by varying crop varieties (‘Cuba 108’, ‘Ifeken 400’ and ‘Ifeken Di 400’), week of harvesting after planting (average stem diameter at Week 10, 12, 14 and 16) and forward speed of machine (2, 3.5, 5, 6.5 and 7.7 km/h).

Experimental procedure for evaluation of the machine

Three varieties of kenaf crop varieties (‘Cuba 108’, ‘Ifeken 400’ and ‘Ifeken Di 400’) were planted at the Obafemi Awolowo University, Ile-Ife Teaching and Research Farm and monitored till the 10^{th} week after planting (WAP). The experimental design for the performance evaluation of the machine (Table 2), is a $3 \times 4 \times 5$ factorial experiment making 60 experimental runs, with 3 replicates, giving 180 runs. The design was subjected to Box-Behnken randomized methodology of the response surface standard design to get the experimental runs (Table 3). Data collected on theoretic field capacity, effective field capacity, and field efficiency were statistically analyzed, to determine the best operation condition of the machine.

Evaluation variables

The performance evaluation variables, which include crop and machine variables, are listed as follows:

(a) Crop variables

- Row-to-row spacing was set at 0.10 m intercrop spacing and 0.30 m row spacing during planting.
- Plant stem diameter was measured using a Vernier calliper.
- The crop height of ten randomly selected plants was measured with a meter rule.

Table 3. Prevailing crop and field condition during field evaluation of kenaf harvester.

Parameter	Kenaf varieties		
	Cuba 108	**Ifeken Di 400**	**Ifeken 400**
Age of plants (weeks)	10-16	10-16	10-16
Row spacing (m)	0.3 × 0.1	0.3 × 0.1	0.3 × 0.1
Average numbers of stem in 1 row	190-240	100-170	100-120
Plant population on the field (plants/ha)	333,333	333,333	333,333
Approximate yield of kenaf stem (t/ha)	18.52	21.43	16.67
Average height of kenaf stem above ground surface (m)	2.7	2.9	2.5
Average cutting height of kenaf stem above ground surface (cm)	15	15	15
Average moisture content of kenaf stem at harvest time (%) wb	69	72	62
Average diameter of kenaf stems (mm)	20.55	21.06	18.98

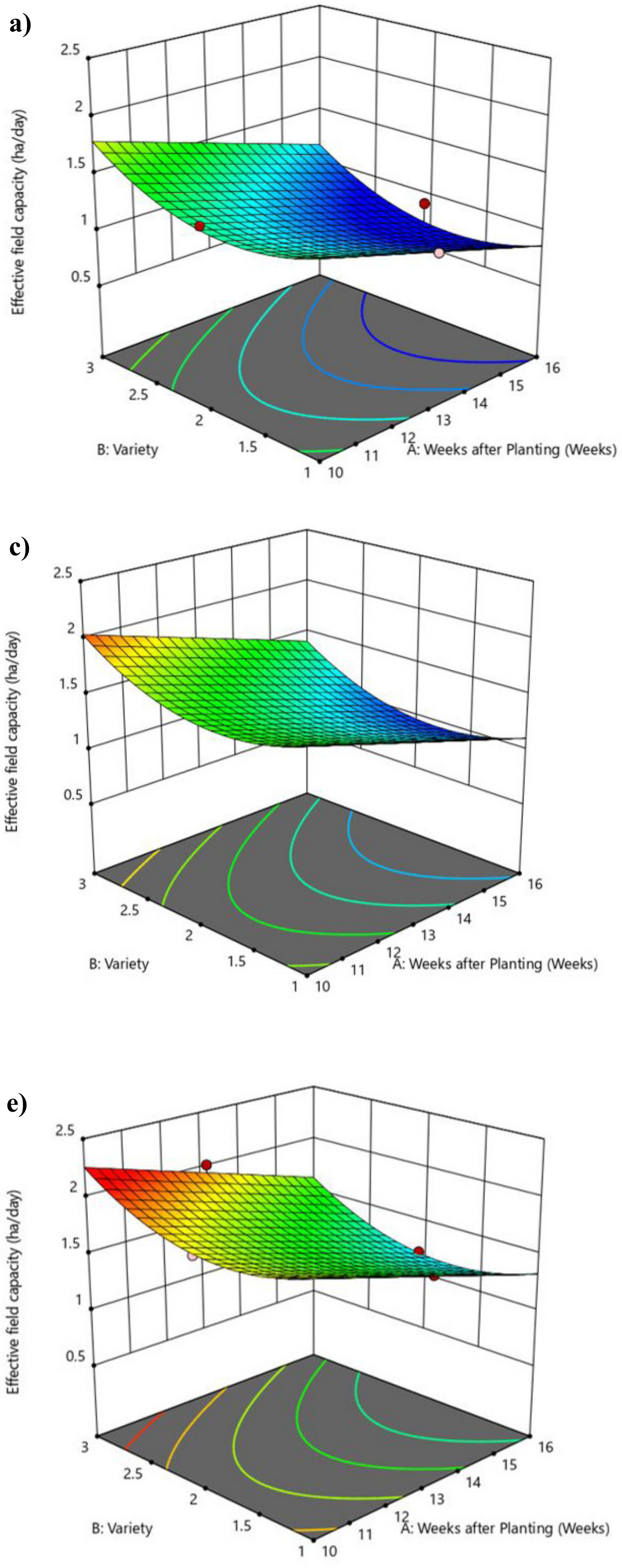


Figure 2. Effect of variety and weeks after planting (WAP) on effective field capacity when forward speed was (a) 2 km/h; (b) 3.5 km/h; (c) 5 km/h; (d) 6.5 km/h; (e) 7.7 km/h. Variety 1 = Cuba 108; Variety 2 = Ifeken Di 400; Variety 3 = Ifeken 400.

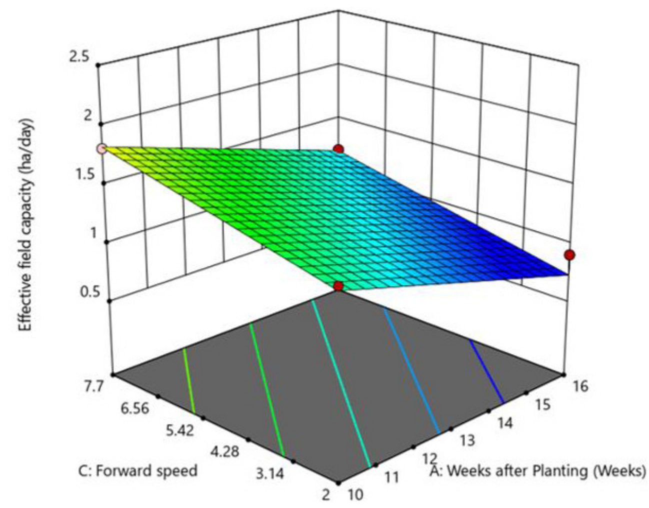


Figure 3. Effect of forward speed on effective field capacity of the machine.

Table 4. Kenaf harvester machine performance.

	Run	WAP[1] (weeks)	Variety[2]	Forward speed (km/h)	TFC[3] (ha/day)	EFC[4] (ha/day)	FE[5] (%)	OL[6] (%)
5	1	10	I4	2	1.44	1.40	97	71.22
10	2	13	I1	2	1.44	1.34	93	74.58
7	3	10	I4	7.7	5.54	1.81	33	42.11
15	4	13	I4	5	3.49	1.21	35	19.72
12	5	13	I1	7.7	5.54	2.02	36	41.01
4	6	16	I1	5	3.49	1.34	38	17.88
8	7	16	I4	7.7	5.54	1.21	22	42.11
1	8	10	C1	5	3.49	1.73	49	19.72
2	9	16	C1	5	3.49	1.10	31	24.13
9	10	13	C1	2	1.44	1.17	81	6.9
3	11	10	I1	5	3.49	2.13	61	46.23
13	12	13	I4	5	3.49	1.21	35	23.28
6	13	16	I4	2	1.44	0.91	63	42.11
11	14	13	C1	7.7	5.54	1.65	30	69.82
14	15	13	I4	5	3.49	1.21	35	47.83

[1] WAP = weeks after planting. [2] C1 = Cuba 108; I4 = Ifeken Di 400; I1 = Ifeken 400. [3] TFC = theoretic field capacity. [4] EFC = effective field capacity. [5] FC = field capacity. [6] OL = Operational loss.

- Plant population: the number of plants per portion was recorded.

(b) Machine variables

The output parameters were measured as follows:

- Theoretic field capacity, ha/h = $\frac{w \times s}{10}$ (1)

  where w = effective harvest width (m); s = forward speed (km/h)

- Effective field capacity, ha/h = $\frac{Actual\ area\ covered\,(ha)}{Time\ required\ to\ cover\ the\ area\,(h)}$ (2)

- Field efficiency (%) = $\frac{Effective\ field\ capacity}{Theoretic\ field\ capacity}$ (3)

- Operational/harvesting losses (%) = $\frac{Mass\ of\ stem\ left\ on\ the\ field}{Total\ mass\ of\ stem\ on\ the\ field}$ (4)

(Dauda et al., 2013)

Results and discussion

The prevailing field condition during evaluation

The prevailing fields condition during the evaluation of this kenaf harvester is presented in Table 3. The row spacing for the experimental was 0.3 × 0.1 m^2 and all the varieties of the plant were harvested between the 10th and 16th WAP. The average height of the kenaf stem was above 2.5 m, while the cutting height was around 15 cm above the ground surface.

Effect of operating parameters on the effective field capacity of the machine

The results of the effect of machine operating parameter; crop maturity (WAP), crop variety (V), and forward speed of tractor (FS) on the effective field capacity are presented in Table 4.

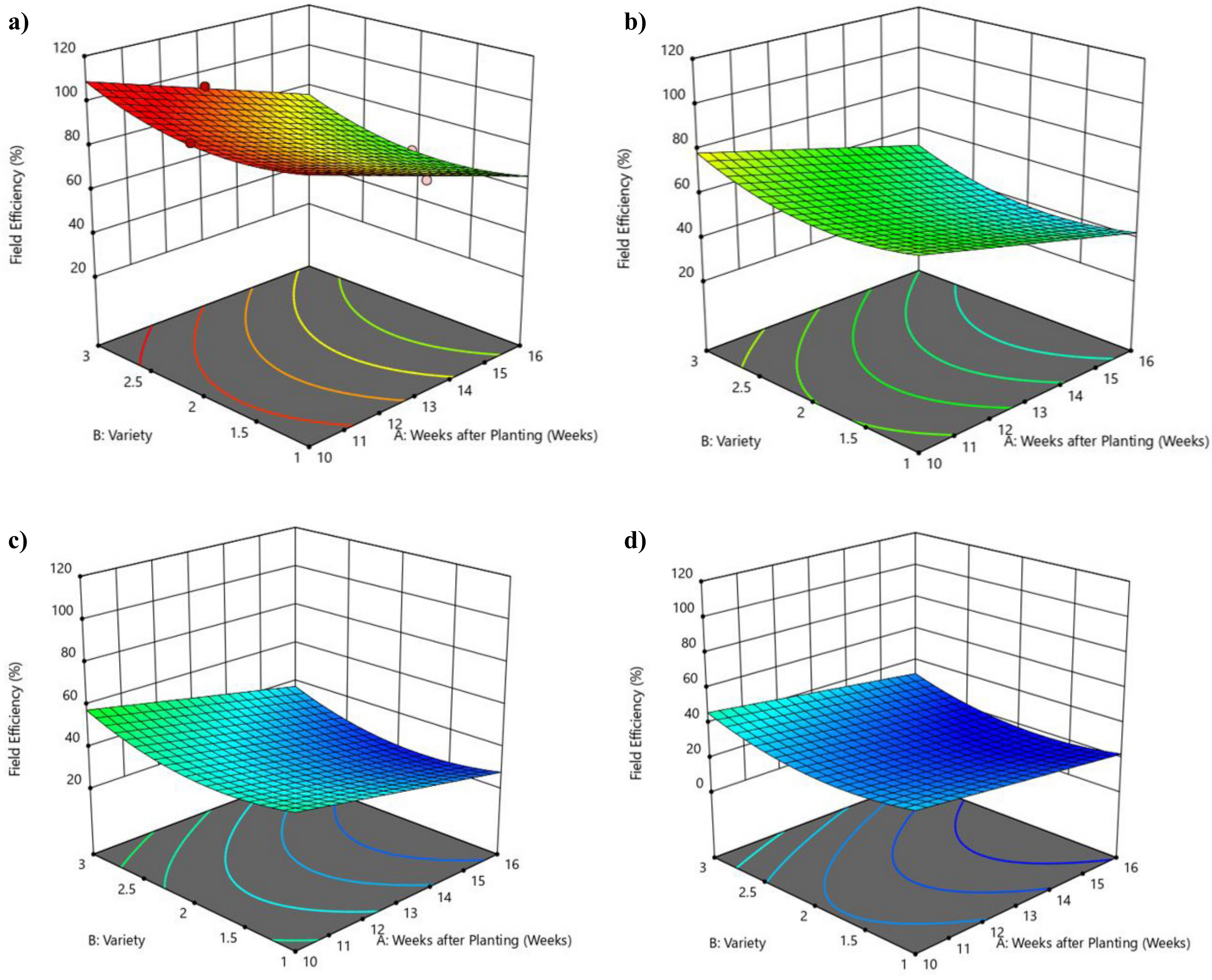
i. Effect of plant maturity on the effective field capacity of the machine

Figure 2 shows that crop maturity affected the effective field capacity of the machine. As the plant matures from week 10 to week 16, the effective field capacity decreased from 2.13 to 0.91 ha/day when other factors remained constant (Table 4). The machine functioned at the highest effective field capacity when the crop was in week 10, and the lowest when the crop was almost drying at week 16 (Fig. 2). This implies that plant maturity increased the crop sectional area and load at maximum tensile stress which had an effect on the effective cutting of the kenaf stem during harvesting.

Table 5. ANOVA of the effect of operation parameters on effective field capacity, field efficiency and operational losses

Source	Sum of squares	DF	Mean square	F-value	p-value
a) On effective field capacity					
Model [1]	1.70	4	0.4250	50.16	< 0.0001
WAP	0.7889	1	0.7889	93.11	< 0.0001
V	0.1773	1	0.1773	20.92	0.0010
FS	0.4380	1	0.4380	51.70	< 0.0001
V^2	0.2956	1	0.2956	34.89	0.0001
Residual	0.0847	10	0.0085		
Lack of fit	0.0847	8	0.0106		
Pure error	0.0000	2	0.0000		
Cor Total	1.78	14			
b) On field efficiency					
Model	8185.65	6	1364.27	357.45	< 0.0001
WAP	913.07	1	913.07	239.23	< 0.0001
V	173.87	1	173.87	45.56	0.0001
FS	5718.38	1	5718.38	1498.27	< 0.0001
WAP*FS	132.41	1	132.41	34.69	0.0004
V^2	261.24	1	261.24	68.45	< 0.0001
FS^2	1055.32	1	1055.32	276.50	< 0.0001
Residual	30.53	8	3.82		
Lack of fit	30.53	6	5.09		
Pure error	0.0000	2	0.0000		
Cor Total	8216.18	14			
c) On operational losses					
Model	4308.25	4	1077.06	6.00	0.0100
V	437.04	1	437.04	2.43	0.1499
FS	0.0072	1	0.0072	0.0000	0.9951
V*FS	2327.58	1	2327.58	12.96	0.0049
FS^2	1543.62	1	1543.62	8.59	0.0150
Residual	1796.24	10	179.62		
Lack of fit	1327.72	8	165.96	0.7085	0.7015
Pure error	468.52	2	234.26		
Cor Total	6104.48	14			

[1] WAP = weeks after planting. V = variety of kenaf. FS = forward speed



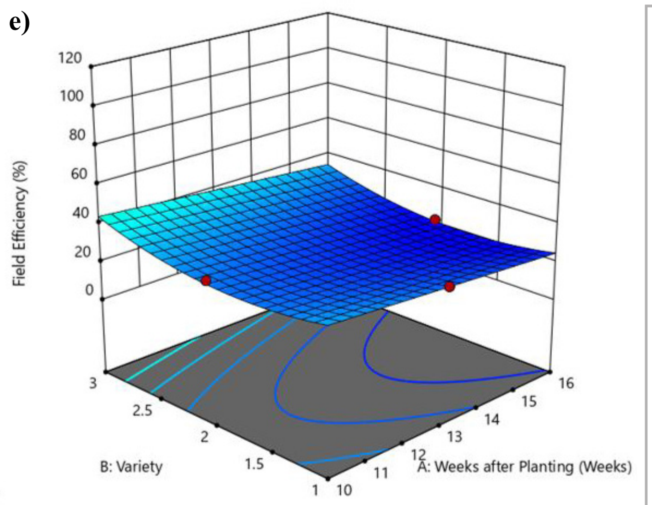


Figure 4. Effect of variety and weeks after planting on field efficiency when forward speed was (a) 2 km/h; (b) 3.5 km/h; (c) 5 km/h; (d) 6.5 km/h; and (e) 7.7 km/h.

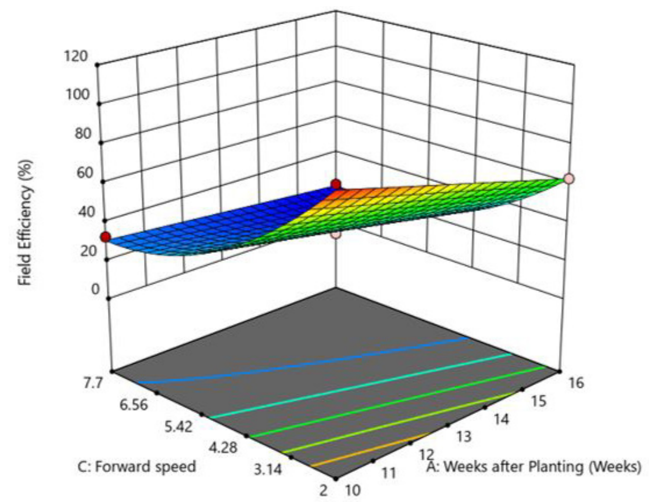


Figure 5. Effect of forward speed on field efficiency of the machine.

This finding is in agreement with previous research reports on cutting tests for the kenaf stem (Ghahraei et al., 2011) and on the mechanical properties of varieties of kenaf (Raji & Aremu, 2017). The analysis of variance of the effect of operational parameters of the machine on the effective field capacity (Table 5a) showed that the p-values of WAP, V, and FS were 0.0001, 0.0010 and 0.0001 respectively, which implies that the effect of all the operation parameters was statistically significant.

ii. Effect of plant variety on the effective field capacity of the machine

The effect of crop variety on the effective field capacity of the machine was high because of variation in the morphology of each of the plant varieties. The maximum (2.13 ha/day) and minimum (0.91 ha/day) effective field capacity were recorded when 'Ifeken 400' and 'Ifeken Di 400' were harvested, respectively. Similar findings were reported by Dauda et al. (2013) and Falana et al. (2020).

iii. Effect of forward speed on the effective field capacity of the machine

Figure 3 shows that as the speed increased from 2.0 to 7.7 km/h, the effective field capacity increased from 0.91 to 2.13 ha/day. The lowest effective field capacity was recorded at 2 km/h and the highest at 7.7 km/h. This agrees with similar researches conducted by Helmy et al. (2010) on rice, Ismail & Abdel-Mageed (2010) on wheat, and Dauda et al. (2013) on kenaf. Analysis of the variance of the effect of the forward speed of tractor on the effective field capacity of machine showed that the forward speed is significant since it has a p-value lower than 0.0500.

Effect of operating parameters on the field efficiency

The result of the effect of machine operation parameters; crop maturity (WAP), crop varieties (V) and forward speed of tractor (FS) on the field efficiency is presented in Table 4.

i. Effect of plant maturity on the field efficiency of machine

The field efficiency of the machine decreased with increasing plant maturity when other factors remained constant. The maximum field efficiency recorded was 97% in the 10^{th} week while the minimum was 22% in 16^{th} week. The 3D surface graph in Fig. 4 shows a similar trend of drop in the machine efficiency at forward speed and crop variety to as low as 22%. A similar result was reported by Falana et al. (2020). The analysis of variance showed that all machine operational factors had a significant effect on the field efficiency. Table 5b shows that the p values of the effect of all the selected parameters were lower than 0.05.

ii. Effect of plant variety on the field efficiency of the machine

It could be observed from Fig. 4 that plant variety affected the field efficiency. The highest field efficiency (97%) and the lowest field efficiency (22%) were recorded when 'Ifeken Di 400' was harvested (when other machine operation parameters were constant). The result aligns with the findings of Dauda et al. (2013) for a tractor-mounted kenaf harvester and those of Abd-El Mawla (2015) for a sugarcane harvester.

iii. Effect of forward speed of the tractor on the field efficiency of the machine

The field efficiency of the machine increased as the forward speed of the tractor decreased from 7.7 to 2.0 km/h as shown in Fig. 5. The highest and the lowest field efficiencies were 97 and 22%, respectively. This result agrees with an earlier report on a tractor-mounted kenaf harvester by Dauda et al. (2013). This effect was observed to be statistically significant as shown in Table 5b.

Effect of operation parameters on operational loss of the machine

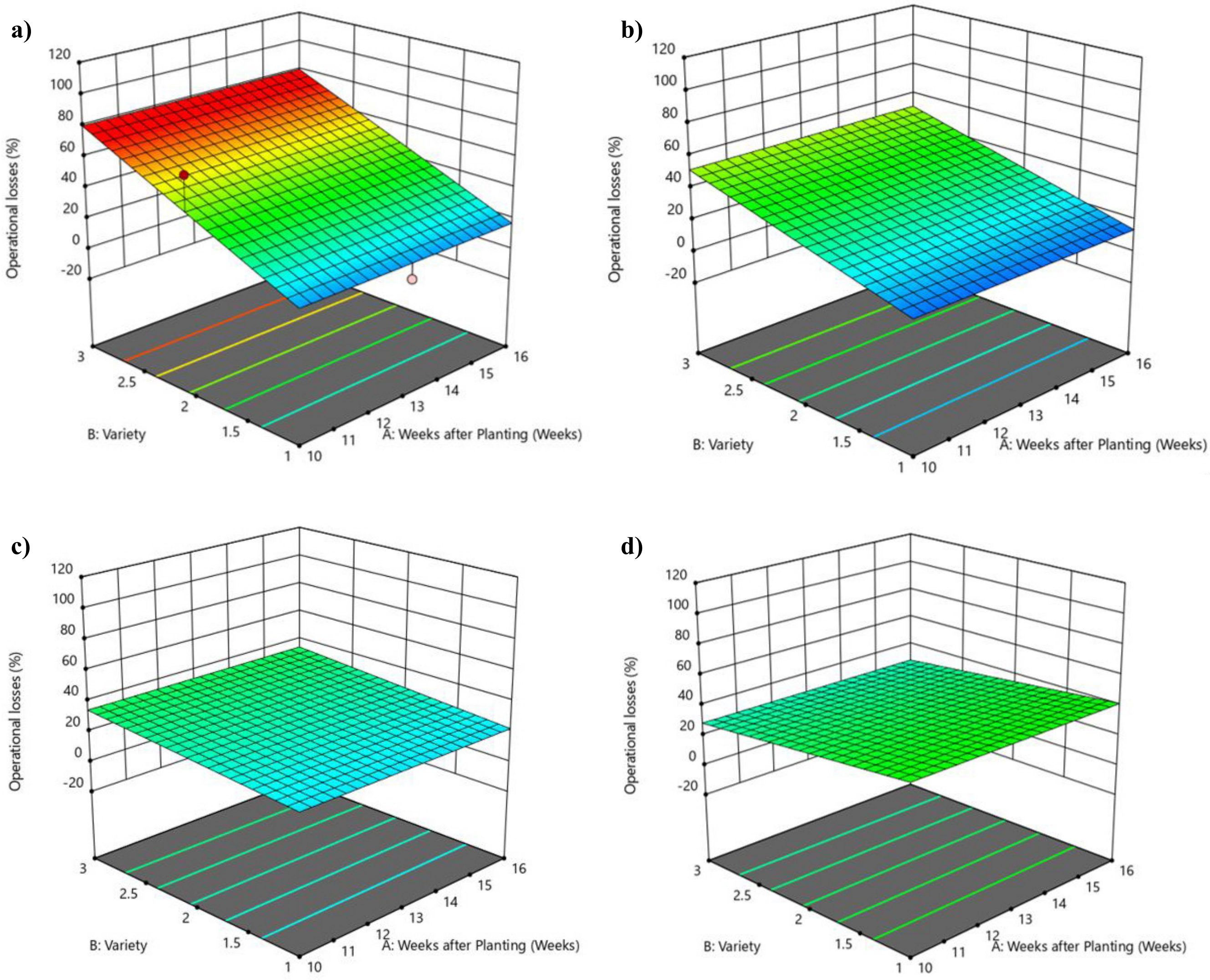
The effect of the operation parameters on the operational loss of the machine is shown in Fig. 6. The operational loss of the machine is the head loss, which accounts for the quality of cut of the plant stem during harvesting.

i. Effect of plant maturity on the operational loss of the machine

The effect of crop maturity on the operational loss of the machine as shown is the 3D response surface graphs in Fig. 6. The operational loss of the machine decreased as the crop matured. The highest operational loss was 71.6%, which was obtained when the crop was at 10 WAP and the lowest (6.9%) was obtained at 16 WAP. This implies that high value of operational loss was obtained when the crop was 10 WAP. The high value of percentage operational loss was because the plant was not able to provide the counter shear needed for effective cutting when the crop had a large surface area and height.

ii. Effect of plant variety on the field operational loss of the machine

The crop variety also affects the operating loss of the machine. The graph showed that the lowest operational loss (6.9%) was obtained when 'Cuba 108' was evaluated, while the highest (74.6%) was obtained when 'Ifeken 400' was evaluated. Analysis of variance (Table 5c) showed



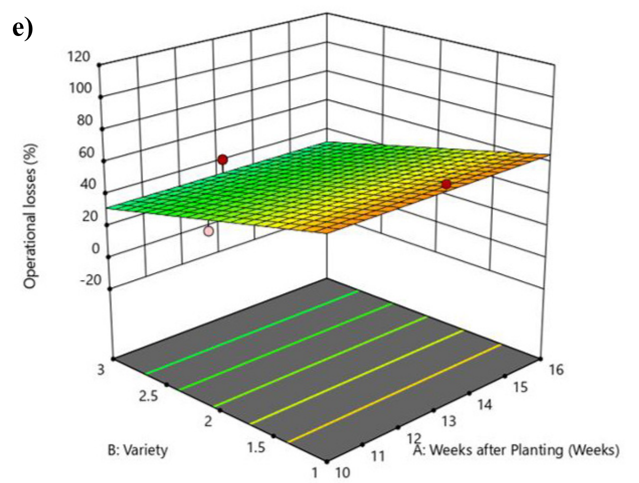


Figure 6. Plot of the effect of operational parameters on operational losses when forward speed of tractor was (a) 2.0 km/h; (b) 3.5 km/h; (c) 5.0 km/h; (d) 6.5 km/h; and (e) 7.7 km/h.

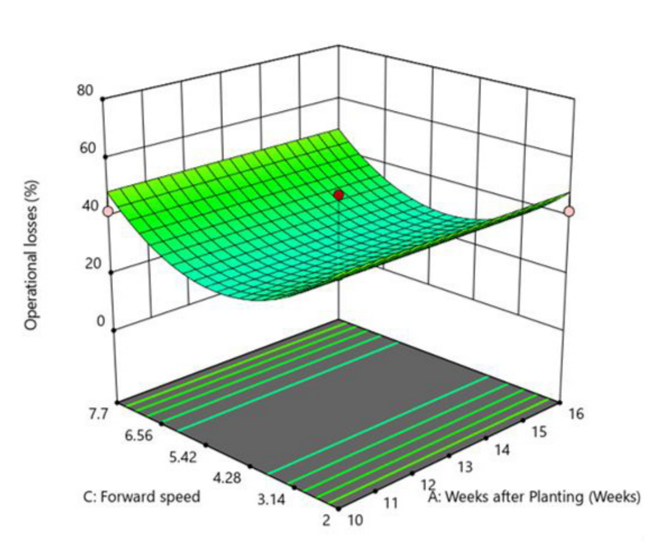


Figure 7. Plot of the effect of forward speed and weeks after planting on operational losses of the machine

that the effect of plant variety on the operational loss of the machine was not significant because the p-value of the plant variety was 0.1499. Similar research by Alandkar (2017) on sorghum stalk cutter supports this observation.

iii. Effect of forward speed of the tractor on the operational loss of the machine

The 3D response surface graph in Fig. 7 and Table 4 shows that the operational loss decreased as the forward speed of the machine decreased. The highest and the lowest operational loss is 74.6% at 5 km/h and 6.9% at 2 km/h, respectively. The analysis of variance in Table 5c shows that the effect of forward speed on the operational loss of the machine is not statistically significant because the p-value was 0.9951. This result agrees with the report of Alandkar (2017) on sorghum stalk cutter.

Conclusions

The study shows that the tractor mounted kenaf harvester has a high effective field capacity of 2.13 ha/day when the crop maturity is 10 WAP, 'Ifeken 400' is harvested, and the forward speed of the machine is 7 km/h, with the highest field efficiency of 97% when the crop maturity is 10 WAP, 'Ifeken 400' is harvested, and the forward speed of the machine is 2 km/h, but operational loss is high when kenaf is harvested at 10 WAP, 'Ifeken 400' is harvested, and the machine forward speed is 5 km/h. The operation parameters have an effect on the performance of the tractor-mounted kenaf harvester, and during further research, a countershear mechanism should be incorporated into the machine design to minimize operational loss of the machine.

Authors' contributions

Conceptualization: O.K. Owolarafe, T. A. Ayorinde
Data curation: T. A. Ayorinde
Formal analysis: T. A. Ayorinde
Funding acquisition: T. A. Ayorinde
Investigation: T. A. Ayorinde
Methodology: O. K. Owolarafe, T. A. Ayorinde
Project administration: O. K. Owolarafe
Resources: T. A. Ayorinde
Software: T. A. Ayorinde
Supervision: O. K. Owolarafe
Validation: T. A. Ayorinde
Visualization: T. A. Ayorinde
Writing – original draft: T. A. Ayorinde
Writing – review & editing: O. K. Owolarafe, T. A. Ayorinde

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