Klover Journal of Law and Public Policy
Volume 1, Issue 1 October 2023
ISSN: Pending….

MODELING MATERIAL CAPACITY AND ENERGY REQUIREMENTS OF ACHA HARVESTERS THROUGH OPERATING PARAMETERS

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Article Info

Keywords:
Acha Harvesting, Harvester Performance, Material Capacity, Energy Requirements, Operational Parameters

Abstract

Harvesting machinery's performance is fundamentally gauged by its efficiency in accomplishing its designated task. The effective field capacity stands as a crucial metric, signifying a machine's ability to efficiently cover a field while executing its intended function. This study delves into the performance evaluation of a harvester with a focus on material capacity and energy requirements, considering the specific context of acha harvesting.

The harvesting performance of a harvester is governed by multifaceted factors, including operational speed, knife cutting speed, reel index, knife-reel clearance, and other parameters. The interaction of these variables can significantly impact the material capacity and overall efficiency of the harvester. Failure to accurately calibrate and adapt these parameters can lead to notable losses in the harvesting process. To address this, a comprehensive understanding of the relationships between these operating parameters and the harvester's material capacity is imperative.

This research addresses the specific challenges posed by acha harvesting, where a distinct set of factors comes into play due to the absence of specialized acha harvesters. Shattering losses at low moisture levels and the improper selection of machine parameters have been identified as obstacles in grain crop harvesting, prompting the need for tailored solutions. The study investigates the interplay between operating parameters and material capacity in acha harvesting and explores the energy requirements associated with the process.

By establishing a comprehensive understanding of the relationships between key operational parameters and harvesting performance, this study contributes to the development of efficient harvesting techniques for acha, which can potentially extend to other similar crops. The insights gained from this research aid in budgeting time, labor, and resources effectively, leading to optimized harvesting processes and reduced losses. In the broader context, this work holds the potential to enhance overall agricultural practices and the sustainability of crop production

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1. INTRODUCTION

The performance of a field machine is measured by effectiveness, on the basis of the function it is designed to perform. Effective field capacity is a measure of the rate at which a machine is able to cover the field effectively while performing its designed task (Tanam and Babatunde, 1995; Olaoye and Bolufawi, 2001; Veerangouda et al., 2010 and Olowojola et al., 2011). Performance of a harvester is measured either by the quantity of crop retrieved from the field, referred to as its material capacity, or the amount of losses incurred in the process of harvesting (Junsiri and Chinsuwan, 2009; Abdi and Jalali, 2013).

Performance of a harvester is influenced by several factors that include, but not limited to operating speed or forward travel speed (Hummel and Nave, 1979, cited by Junsiri and Chinsuwan, 2009; Olowojola et al., 2011; Jalali and Abdi, 2014), knife cutting speed (Tanam, 2021), reel index (Chinsuwan et al., 2004; Junsiri and Chinsuwan, 2009), knife – reel clearance (Quick, 1999; Jalali and Abdi, 2014), knife approach angle (Chattopadhyay and Pandey, 1999; Jalali and Abdi, 2014), reel position ahead of cutter bar, crop density (Yore et al., 2002), timeliness of operation, crop moisture content (Chinsuwan et al., 1997; Sangwijit and Chinsuwan, 2010), crop height (Olowojola et al., 2011), crop maturity, combine harvester threshing and cleaning efficiency (Veerangouda et al., 2010), service life of cutter bar (Klenin et al., 1985) and stem length (Siebenmorgrn et al., 1994). Failure to properly select and adjust these factors leads to considerable losses (Junsiri and Chinsuwan, 2009) and hence low material capacity of the harvester. For a reciprocating cutter bar harvester, the most critical of these factors are operating speed, knife cutting speed and reel index (Tanam, 2021). Predicting the performance of the harvester is essential for proper budgeting of time, money and labour. Several systems exist for predicting the performance of various harvesters designed for various crops, but none exits for acha harvesting because acha harvesters do not exist. Identified challenges in grain crop harvesting include shattering losses at low moisture and improper selection of machine parameters (Olaoye, 2000; Ogunlowo and Olaoye, 2017; Tanam and Olaoye, 2022; Olaoye and Ariyo, 2020). Operating a mechanical harvester at a considerable high moisture is desirable. The purpose of this study was to derive the relationship that exists between the operating parameters of an acha harvester and it material capacity and energy requirement.

2. MATERIALS AND METHODS

Figure 1 shows the schematic diagram of the operation of the harvester. The relevant component of the machine for this study is the reaping unit, carried forward in the direction of travel. The reaping unit consists primarily of a cutter bar and a reel. While the cutter bar blade cuts the stalk, the reel deflects and holds the erect crop in position for cutting and sweeps cut materials onto the transport unit to be conveyed into the collection tank.

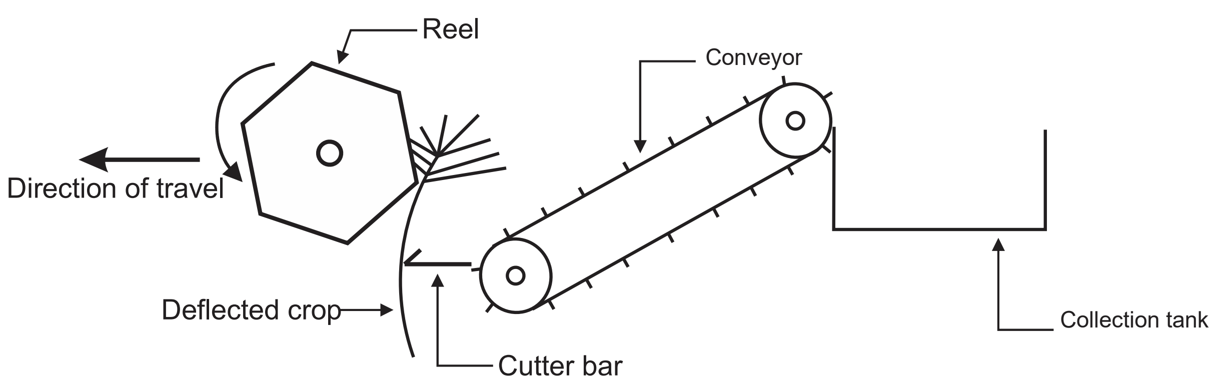


Figure 1: Schematic Drawing of the Harvester Operation

Material in the collection tank was threshed manually with care. The quantity of grain retrieved depends on the machine operating (forward) speed (V), the reciprocating speed of the cutting tool (S), and the rate of sweep of the cut material by the reel away from the cutting region. The rate of sweeping cut material is governed by reel

index (I) which is the ratio of reel speed to the forward speed of the machine. A high speed forward speed of the harvester would produce a high field capacity but a low material capacity, because the machine would glide over the crop without cutting. An attempt to sweep cut materials at high reel speed would cause some grains to fall off before the stem is cut. The same would occur when knife speed is excessive. The quantity of material (Q) retrieved by the harvester therefore is a function of these three parameters and be expressed as Equation 1.

Q = f(V, S, I) (1)

Using the "all possible regression models" procedure described by Larsen (2005), Twenty three polynomial

A	$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_3^2 + \beta_7 x_1 x_2 + \beta_8 x_1 x_3 + \beta_9 x_2 x_3 + \beta_{10} x_1 x_2 x_3 + \varepsilon$
B	$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_3^2 + \beta_7 x_1 x_2 + \beta_8 x_1 x_3 + \beta_9 x_2 x_3 + \varepsilon$
C	$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_3^2 + \beta_7 x_1 x_2 + \beta_8 x_1 x_3 + \varepsilon$
D	$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_3^2 + \beta_7 x_1 x_2 + \varepsilon$
E	$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_3^2 + \varepsilon$
F	$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \varepsilon$
G	$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \varepsilon$
H	$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \varepsilon$
I	$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2^2 + \beta_3 x_3 + \varepsilon$

equations were constructed from the three parameters and presented in Table 1.

Table 1: All Possible Models from Three Parameters

Label Model

J $y = \beta_0 + \beta_1 x_1^2 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon$

K y = β0 + β1x1 + β2x2 + β3x3 + β4x12 + β5x22 + β6x32 + β7x1x2 + β8x2x3 + β9x1x2x3 + ε L y = β0 + β1x1 + β2x2 + β3x3 + β4x12 + β5x22 + β6x32 + β7x1x3 + β8x2x3 + β9x 1x2x3 + ε

M y = β0 + β1x1 + β2x2 + β3x3 + β4x12 + β5x22 + β6x 1x 2 + β7x1x3 + β8x2x3 + β9x 1x2x3 + ε

N y = β0 + β1x1 + β2x2 + β3x3 + β4x12 + β5x32 + β6x 1x 2 + β7x1x3 + β8x2x3 + β9x 1x2x3 + ε

O $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_2^2 + \beta_5 x_3^2 + \beta_6 x_1 x_2 + \beta_7 x_1 x_3 + \beta_8 x_2 x_3 + \beta_9 x_1 x_2 x_3 + \varepsilon$

P y = β0 + β1x32 + β2x1x32 + β3x1 + β4x2 + β5x3 + β6x12 + β7x12x3 + β8x1x3 + β9x12x2 + β10x12x2x3 + β11x1x2x3 + β12x22 + β13x1x2 + β14x2x3 + ε

Q y = β0 + β1x32 + β2x1x32 + β3x1 + β4x2 + β5x3 + β6x12 + β7x12x3 + β8x1x3 + β9x12x2 + β10x1x22 + β11x12x2x3 + β12x1x2x3 + β13x22 + ε

R y = β0 + β1x32 + β2x1x32 + β3x1 + β4x2 + β5x3 + β6x12 + β7x12x3 + β8x1x3 + β9x12x2 + β10x1x22 + β11x12x2x3 + β12x1x2x3 + β13x22 + β 14x 1x 2 + β 15x 2x 3 + ε

S y = β0 + β1x32 + β2x1x32 + β3x2 + β4x2 + β5x12 + β6x3 + β7x12x3 + β8x1x3 + β9x12x2 + β10x1x22 + β11x12x2x3 + β12x1x2x3 + ε

T y = β0 + β1x32 + β2x1x32 + β3x1 + β4x2 + β5x3 + β6x12 + β7x12x3 + β8x1x3 + β9x12x2 + β10x12x2x3 + β11x1x2x3 + β12x 1x 2 + β 13x 2x 3 + ε

U y = β0 + β1x1 + β2x2 + β3x3 + β4x1x22 + β5x12x2 + β6x12x2x3 + β7x12x3 + β8x1x2x3 + ε

V $y = \beta0 + \beta1x2 + \beta2x3 + \beta3x1x22 + \beta4x12x2 + \beta5x12x2x3 + \beta6x1x3 + \beta7x1x2x3 + \varepsilon$
W $y = \beta0 + \beta1x1 + \beta2x12 + \beta3x32 + \beta4x22 + \beta5x1x22 + \beta6x2 + \beta7x12 + \beta8x3 + \beta9x12x3 + \beta10x1x2 + \beta 11x1x3 + \beta12x2x3 + \beta13x12x2 + \beta14x12x2 + \beta15x1x2x3 + \varepsilon$

β_i are coefficients determined by regression analysis and x_1, x_2 and x_3 represent operating speed, knife speed and reel index respectively while y represent the material capacity or energy consumed. Microsoft Excel 2016 version was used to carry out a multiple regression analyses on the data collected to select the "best" functional relationship between the harvester material capacity and the operating parameters on the one hand, and between energy consumption and the operating parameters on the other. Data collection and analysis were based on the 3^3 Factorial experimental design described by Davies (1956). Table 2 is a general layout for treatments involved in the experiment. Quantities varied were operating speed (V) with values 1, 3, and 5 km/h; knife speed (S) with values 300, 400 and 500 rpm; and reel index (I) with values 1, 1.25 and 1.5, while quantities measured were quantity of grain gathered (Y) and fuel consumption (E). Subscripts 0, 1 and 2 in Table 2 represent low, intermediate and high levels of parameters in each treatment. Each of 27 treatments was performed twice to give a total of 54 runs.

Table 2: Factor Level Combinations for a 3^3 Factorial Experiment

Treatments		
V0S0I0	V0S0I1	V0S0I2
V0S1I0	V0S1I1	V0S1I2
V0S2I0	V0S2I1	V0S2I2
V1S0I0	V1S0I1	V1S0I2
V1S1I0	V1S1I1	V1S1I2
V1S2I0	V1S2I1	V1S2I2
V2S0I0	V2S0I1	V2S0I2
V2S1I0	V2S1I1	V2S1I2
V2S2I0	V2S2I1	V2S2I2

Each of the equations were tested for practical utility and the best selected for both material capacity and fuel consumption, fuel consumption being an indication of energy requirement. Adjusted coefficient of determination (R^2_a) was used to select the best function. The relation with the highest value of R^2_a and lowest standard error level was considered the best. Analysis of variance (ANOVA) was used to determine the significance of each equations, while their adequacies verified graphically.

3. RESULTS AND DISCUSION

3.1 Relationship between Material Capacity of the Acha Harvester Operating Parameters

Table 3 shows the quantity of grain collected from each run based on the treatment combination levels and arrangement presented in Table 2.

Table 4 shows that all the equations have p-values < 0.01 and are all therefore significant (Larson, 2005), implying that any of them could be selected as good enough relation between the factors. However, in comparing regression equations, the equation with the highest R_a^2 is regarded as most practically useful (Ott and Mendenhall, 1994). The equation selected has $R^2 = 0.94$ and $R_a^2 = 0.88$ with a standard error of estimate of 2.465, which is the lowest in the series. The R^2 obtained is higher than 0.8 described by Gregory and Fedler (1986) as good enough for agricultural experiments. The regression coefficients for this equation giving rise to equation 2 are $\beta_0 = 56.63$, $\beta1 = -35.04$, $\beta2 = -10.44$, $\beta3 = -4.29$, $\beta4 = -135.23$, $\beta5 = -0.044$, $\beta6 = 23.00$, $\beta7 = -22.20$, $\beta8 = 143.57$, $\beta9 = -0.06$, $\beta_{10} = 0.06$, $\beta_{11} = -0.32$, $\beta_{12} = -0.0002$, $\beta_{13} = 0.35$, $\beta_{14} = 0.24$. Therefore the estimated material capacity (C_m) can be described by Equation 2.

$$C_m = 56.63 - 35.04I^2 - 10.442\,VI^2 - 4.29I - 135.23V - 0.04S + 23.00V^2 - 22.20V^2I + 143.57VI - 0.06V^2S + 0.06V^2SI - 0.32VSI - 0.00025S^2 + 0.35VS + 0.24SI \qquad 2$$

Table 3: Quantity of Acha Grain Harvested based on the 3^3 Factorial Experiment (kg/ha)

Quantity grain collected (kg/ha)

273.60	270.50	266.50
238.87	272.40	245.50
274.50	281.00	270.30
298.70	262.75	271.45
275.05	290.30	265.70
273.4	277.65	267.00
266.00	301.00	271.50
268.70	285.55	269.20
283.20	300.00	270.00
279.45	304.45	243.80
285.00	255.05	200.00
280.34	283.00	205.55
255.70	257.50	179.00
258.75	197.35	190.1
220.35	268.35	208.05
232.25	237.40	213.10
241.50	207.50	199.25
213.55	250.90	201.50

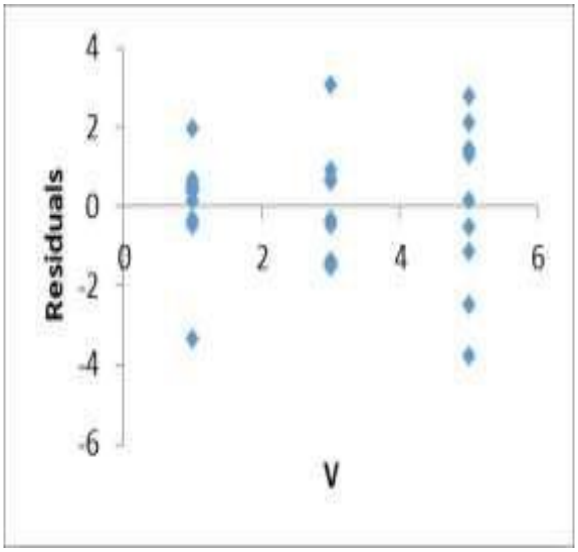
Table 4 is a summary of relevant statistics obtained for each regression equations for material capacity.

Table 4: Summary of Regression Statistics for Material Capacity

Equation	Multiple R	R^2	Ra^2	Standard Error	F	Significance F
A	0.91	0.83	0.72	3.75	7.63	0.0002073
B	0.90	0.81	0.71	3.79	8.17	0.0001217
C	0.90	0.81	0.72	3.75	9.31	0.0000495
D	0.88	0.78	0.69	3.91	9.45	0.0000470
E	0.88	0.77	0.70	3.89	10.99	0.0000191
F	0.83	0.69	0.61	4.39	9.25	0.0000900
G	0.81	0.66	0.60	4.49	10.58	0.0000619
H	0.73	0.53	0.47	5.17	8.53	0.0005441
I	0.74	0.54	0.48	5.10	9.01	0.0003946
J	0.78	0.61	0.56	4.69	11.97	0.0000634
K	0.90	0.80	0.70	3.87	7.73	0.0001718
L	0.90	0.81	0.71	3.82	7.98	0.0001411
M	0.86	0.75	0.61	4.39	5.58	0.0011866
N	0.89	0.80	0.69	3.94	7.40	0.0002254
O	0.84	0.71	0.55	4.73	4.56	0.0035166
P	0.97	0.94	0.88	2.46	14.49	0.0000209
Q	0.95	0.91	0.82	3.01	10.02	0.0000956
R	0.97	0.94	0.87	2.57	12.40	0.0000833
S	0.63	0.40	0.38	5.57	16.81	0.0003831
T	0.96	0.91	0.83	2.93	10.66	0.0000679
U	0.96	0.93	0.86	2.56	12.42	0.00008327
V	0.96	0.91	0.82	2.97	10.65	0.00006719
W	0.94	0.89	0.80	3.16	9.65	0.00008188

This equation is statistically significant as shown by the F – statistic of 14.49 and P-value of 0.0000209 obtained from the analysis of variance (ANOVA). Equation 2 is considered the best among all tested and is therefore good to predict the acha harvester material capacity. The contribution and direction of each of the parameters and their interaction is shown by the observed coefficients. Operating speed made the highest contribution to the predicted material capacity, though in a negative sense. This is in agreement with the observation of Sangwijit and Chinsuwan (2010) and Jalali and Abdi (2014) in their study of harvester losses in wheat and Khaw Dok Mali 105 Rice variety respectively. This shows that although higher operating speed would increase harvester field capacity, as inferred from Veerangouda et al. (2010), it would not necessarily increase material capacity. This can be explained by the fact that high speed of operation would cause the blade to ride over uncut crop before the knife cuts the crop. Knife speed and reel index had similar behaviour. Positive contributions were observed with all two-factor interactions with the interaction between operating speed and reel index being the highest. The explanation is that as forward speed increases, the rate at which the reel sweeps cut material must proportionately equally increase, provided the knife is able to cut at high speed without causing losses.This observation was similar to the observed trend in the result of the investigation of the analysis of the motion of weeding tools and development of a rotary power weeder by Olaoye and Adekanye (2011).

The adequacy or otherwise of Equation 2 was verified by graphical means described by Larsen (2005) and NIST (2013) and some are presented in Figures 2 to 5.



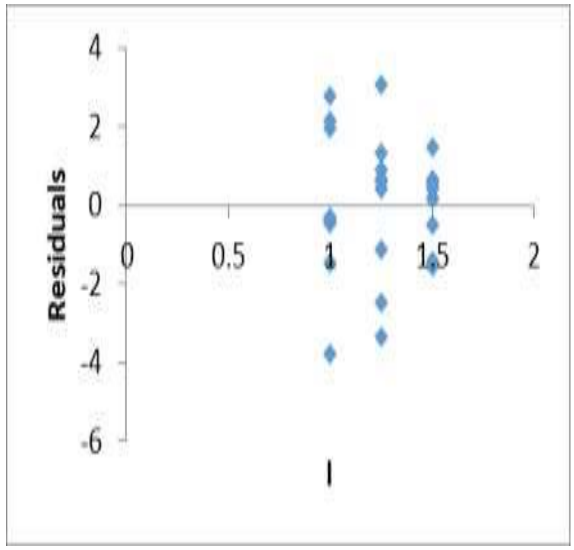
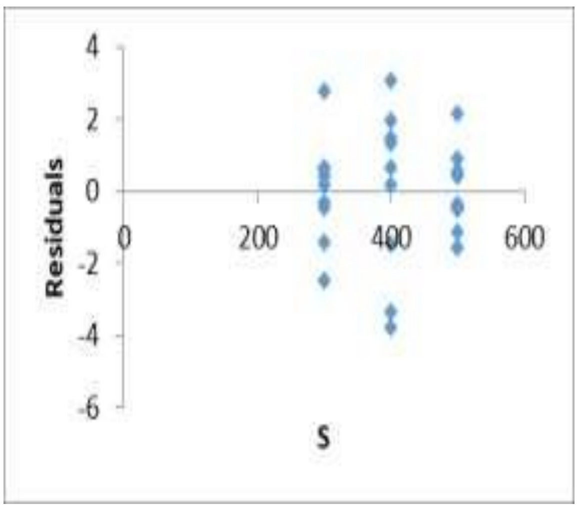


Figure 2: Residual Plot of Operating Speed Figure 3: Residual Plot of Reel Index



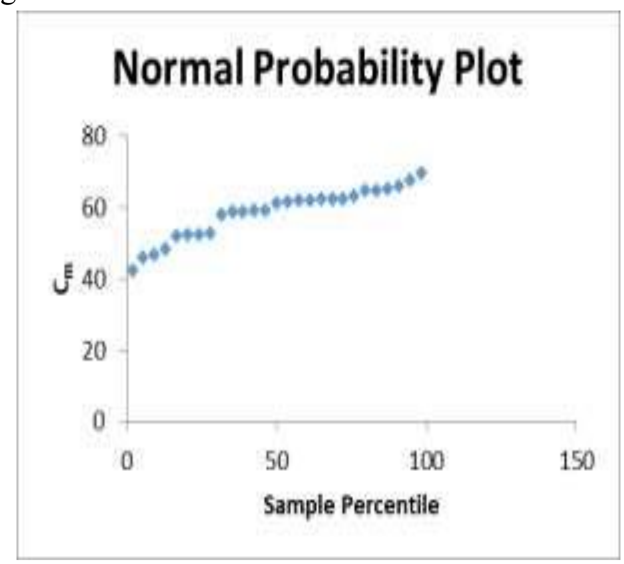


Figure 4: Residual Plot of Knife Speed
Figure 5: Normal Probability Plot of Material Capacity

The plots of the residuals against the independent variable do not show any traceable pattern. This shows that there is no relationship between the random errors and the predicted observations, thereby satisfying the independence of the random errors criterion. Each of the plots also show that the residuals have equal spread about zero, thereby satisfying the assumption that the residuals have constant variance and zero mean. The normal probability plot of material capacity shows a straight line pattern, indicating that the data obtained were normally distributed. Larson (2005) described equations satisfying these conditions as good.

3.2 Relationship between Energy Consumption of the Acha Harvester Operating Parameters

Table 5 shows the quantity of fuel consumed in each run based on the treatment combination levels and arrangement presented in Table 2

Table 5: Quantity of Fuel Consumed based on 3^3 Factorial Experiment (l/ha) Fuel Consumed (l/ha)

5.17	4.67	4.50
5.00	5.17	4.83
4.67	5.17	4.50
4.67	4.83	4.83
4.17	4.00	4.33
4.50	4.17	3.67
3.83	4.17	3.17
4.17	4.00	3.50
3.83	3.00	3.67
3.17	3.33	3.67
3.50	4.00	4.67
4.00	4.50	5.17
3.33	2.83	3.33
3.00	2.50	3.50
3.67	4.67	3.00
4.17	4.00	3.33
3.33	3.00	3.33
5.00	3.17	2.83

Table 6 is a summary of relevant statistics obtained for each regression equation for fuel consumption.
Table 6 shows that the relation selected as most appropriate for predicting the harvester energy consumption has $R^2 = 0.73$ and $R_a^2 = 0.60$. The statistical utility of the equation is shown by Fstatistic = 5.93, which is highly significant with p-value of 0.0008454. The regression coefficients, βi, for this equation are β0 = 24.23, β1 = -0.000007, β2 = 0.003, β3 = -0.0035, β4 = 0.50, β5 = -5.95, β6 = -0.02, β7 = -6.47, β8 = 0.01
Equation 3 is the derived regression equation for estimating the rate of the harvester fuel consumption.

$$E = 24.23 - 0.000007VS^2 + 0.003V^2S - 0.0035V^2 + 0.50V^2I - 5.95I - 0.02S - 6.47V + 0.01VSI \quad (3)$$

Table 6: Summary of Regression Statistics for Fuel Consumption

Equation	Multiple R	R^2	Ra2	Standard Error	F	Significance F
A	0.78	0.60	0.40	1.07	2.89	0.0284086
B	0.78	0.60	0.43	1.04	3.41	0.0145499
C	0.77	0.60	0.45	1.02	4.04	0.0071977
D	0.72	0.52	0.38	1.08	3.64	0.0131510
E	0.70	0.49	0.45	1.02	11.67	0.0002884
F	0.71	0.51	0.46	1.00	12.25	0.0002158
G	0.70	0.49	0.47	1.00	24.26	0.0000452
H	0.73	0.53	0.47	1.00	8.63	0.0005089
I	0.89	0.79	0.50	0.97	2.73	0.0496069
J	0.88	0.78	0.52	0.95	2.98	0.0327498
K	0.88	0.78	0.55	0.92	3.47	0.0162669
L	0.87	0.75	0.54	0.93	3.55	0.0133892
M	0.87	0.75	0.57	0.90	4.15	0.0061050
N	0.87	0.75	0.59	0.87	4.81	0.0027662
O	0.85	0.72	0.57	0.90	4.76	0.0028255
P	0.86	0.74	0.58	0.89	4.56	0.0036196
Q	0.84	0.70	0.57	0.90	5.31	0.0015909
R	0.85	0.72	0.57	0.90	4.85	0.0025492
S	0.89	0.78	0.57	0.90	3.62	0.0136689
T	0.89	0.78	0.53	0.94	3.11	0.0279832
U	0.85	0.73	0.60	0.86	5.93	0.0008454
V	0.84	0.71	0.55	0.92	4.57	0.0034953
W	0.89	0.79	0.50	0.97	2.73	0.0496069

The adequacy of equation 3 was verified graphically as prescribed by Larsen (2005) and NIST (2013), some of which are presented in Figures 6 - 9. Again, the residuals spread evenly about zero but do not have any pattern. This also indicates that the assumptions of constant variance, zero mean and independence of error are satisfied. The normal probability plot for fuel consumption shows that the random errors are normally distributed. The equation can therefore be described as good, (Larson, 2005).

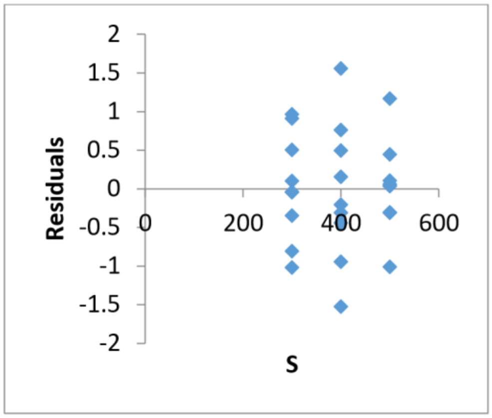


Figure 6: Residual Plot of Linear Knife Speed

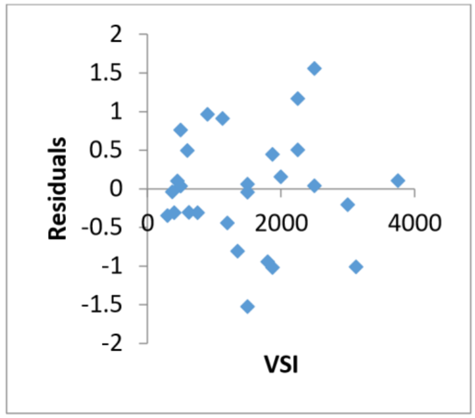


Figure 7: Residual Plot of Interaction of Operating Speed, Knife Speed and Reel Index

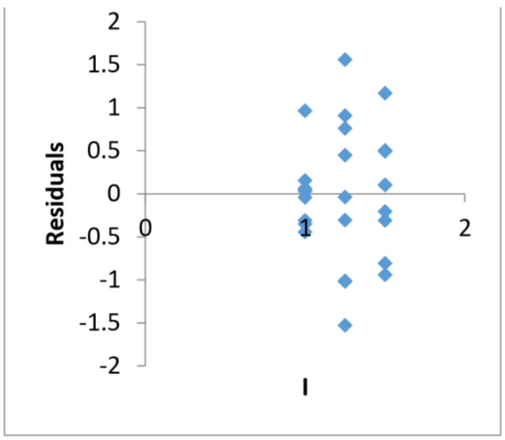


Figure 8: Residual Plot of Linear Reel Index

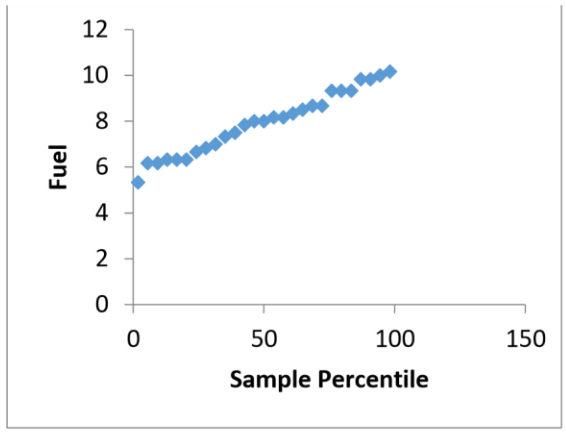


Figure 9: Normal Probability Plot of Fuel Consumption

4. CONCLUSION

Equations relating harvester material capacity (C_{mat}) and energy consumption (E) to the fundamental operating parameters and found to be polynomials in three variables. The equations relating material capacity to the fundamental operating parameters had $R^2 = 0.94$, $R^2a = 0.88$, SE = 2.47, F-statistic = 14.49 and p-value = 0.0000209 and that relating energy consumption (E) to the fundamental parameters had $R^2 = 0.73$, $R^2a = 0.60$, SE = 0.68, F-statistic = 5.93 and p-value = 0.0008454. Based on these values the equations were considered good for predicting the performance of the harvesting machine.

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