EVALUATION AND MODELING OF ENERGY INPUT AND FIELD EFFICIENCY OF PLOUGH ON LOAMY SAND SOIL IN ABIA STATE, NIGERIA

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ABSTRACT

A research was conducted to evaluate and model the energy intake rate and field efficiency of plough on loamy sand soil in Abia State, Nigeria to assist farmers in the area scrutinize and select appropriate ploughing implement for efficacious and increased production. The tractor model of MF430E and capacity of 55.2 kw made by Massey Ferguson Company and a disc plough with operating units of 3 bottom discs was used for the study. The operational speed and depth of cut were adopted as factors for the study of the energy intake and field efficiency of the plough. Results revealed that the highest fuel intake of 31.25 lha^{-1} was recorded when the plough was operated at the depth of 30 cm for the different speeds and that the highest field efficiency of 80.0% was recorded at the cutting depth of 30 cm and speed of 5 kmh^{-1} while the least efficiency of 68.1% was achieved at speed of 9 kmh^{-1} and depth of 10cm. A quadratic model was statistically significant ($P < 0.05$) for the prediction of field efficiency with coefficient of determination, R^2 of 0.9767 while a linear model was significant ($P < 0.05$) for the evaluation of energy requirements of the disc plough with coefficient of determination, R^2 of 0.6500, which indicated good correlations between the variables. The optimum field efficiency and the desirability of 77.50% and 1.00 were respectively achieved at optimum speed of 7 kmh^{-1} and ploughing depth of 30 cm. While the optimum fuel consumption rate and the desirability of 20.51 lha^{-1} and 1.00 were respectively gotten at optimal operational speed of 6.7 kmh^{-1} and ploughing depth of 18.56cm. Finally, results of simulation revealed that the fuel consumption rate and field efficiency obtained from the generated models fall within the experimental range. Farmers can therefore, evaluate and chose the implements using the developed model as a guide.

KEYWORDS: Disc plough, energy intake, field efficiency, farmers, models.

1. INTRODUCTION

Literally, energy is described as the ability or capacity to do work. It is the main factor that influences the farming operations everywhere in the world A research was conducted to evaluate and model the energy intake rate and field efficiency of plough on loamy sand soil in Abia State, Nigeria, to assist farmers in the area scrutinize and select appropriate ploughing implement for efficacious and increased production. The tractor model of MF430E and capacity of 55.2 kw made by Massey Ferguson Company and a disc plough with operating units of 3 bottom discs was used for the study. The operational speed and depth of cut were adopted as because it plays dynamic role in diverse tillage tasks, planting, and application of fertilizers, controlling of weeds and pests, harvesting and processing of crops (Updhyaya *et al*., 1984). As a result, energy supplies for tillage and other farming activities have to be simply attained at a reduced amount to ensure that no level of work can raise the operative cost or place the charge at unaffordable height (Oduma and Oluka, 2017). Farming is increasingly automated, demanding extensive energy usage at specific stages of the production level to achieve best yield (Moitiz *et al*., 2013). Hence, energy is consumed as fuel or electric power to drive agricultural mechanisms. Moitzi *et al*. (2009) maintained that, in conservative tillage methods with plough, more than fifty percent of total fuel input is regularly required in soil preparation. Moitzi *et al*. (2006) perceived that the whole fuel consumption in land tillage is largely affected by soil type; and the consumption increases progressively with the cutting depth of the plough. Furthermore, other soil factors, such as soil coarseness and organic matter content, affects fuel consumption rate during tillage (McLaughlin *et al*., 2002).

Boydas and Turgut (2007) noted that, tillage is a vital field operation in plant growing because of its effect on soil properties, environment, and produce and to ensure consistent growth of crops, soil supposed to be worked in a way that will allow roots access to soil moisture, air and nutrients.

Consequently, Onwualu *et al*. (2006) emphasized on the need for farmers to ascertain in what capacity any machine carries out a specific farm operation and the frequency of its performances; they advocated that this information is critical as it reassures equipment management and use, and other economic facets in addition to timeliness of farm processes. Witney (1988) suggested that active machinery manipulation and management necessitate responsiveness of the performance data on the efficiencies of the equipment in order to undertake a stated work design and to generate a steady system of mechanization which will match the abilities of different machines. Agri-business activities are enormously elusive to season and climatic conditions and enough monies are devoted in the project, hence, it is wise to assess the abilities of farm machines/implements for better selection, greatest production and appropriate farm planning (Sale *et al*., 2013).

According to Grisso *et al*. (2002), field efficiency is a dynamic pointer for considering the field capabilities and for applying essential machinery regulation/management procedures. Field efficiency involves executing an indicated field assignment at minimum loss of time, energy and other farm inputs (Von Bargen and Cunney, 1994). Hunt (2013) noted that, it considers time wastage along with the ability to apply the whole width of device in field work. Anazodo (1983) inferred that due to divergences in the soil conditions, machine routine/performance data in different soil situations and types are vital for its selection.

Evaluation and development of equation models of the energy input and field efficiency of plough on loamy sand soil is a decisive and easy method of aiding the famers and/or users of farm machineries in Abia State, Nigeria in assessing and predicting the credible energy (fuel) consumption capacities of ploughing implements, for seemly selection of the implement in view of the soil type/conditions prior to purchase or putting the contrivance to work. The aim of this study is to evaluate, model and optimize the energy requirements and field efficiency of disc plough in loamy-sand soil that will help farmers in assessing and selecting the tillage implement to reduce cost, decrease energy loss, and improve production in Abia State and other agro-ecological regions with similar soil conditions.

2. MATERIALS AND METHODS

2.1 Trial Site

The assessment was done at the trial farm of Michael Okpara University of Agriculture, Umudike, in Abia State. The climate of the area is characterized by average temperature of 27°C, annual rainfall range from 2250 – 2500 mm and average relative humidity of 75% (Amanze *et al*., 2020). Loamy-sand soil is suitable for arable farming.

The trial site was divided into nine equal portions for random investigation. Each partition was disjointed by space of 2.5 m to check interaction within the margins and for turning at headland.

2.2 Measurement of Moisture Content of the Soil

The oven-dry system of moisture content determination was adopted to measure the moisture content of the soil samples collected at the trial site according to Bahram *et al*. (2014). The weight of initial samples of soil (wet soils) collected from the site and the weight of oven-dry samples of the same soils (dry soils) were determined in the laboratory and the moisture content was evaluated from Equation 1.

$$M_C = \frac{Ws-Ds}{Ds} \times 100\% \qquad (1)$$

where:

M_C = moisture content of the soil, %;

W_S = weight of wet soil (initial soil sample), kg and

D_S = Wight of oven-dry soil, kg.

2.3 Tractor and Plough Used for the Study

The tractor model of MF430E and capacity of 55.2 kw manufactured by Massey Ferguson Company and a disc plough with full width of 1.8 m and 3 bottom discs was used for the study.

2.4 Test Procedure

The ploughing process was conducted in length wise with the implement full width at selected working speeds of 5, 7 and 9 kmh^{-1} and cutting depths of 10, 20 and 30 cm. The area ploughed and the equivalent time taken to till the area was recorded according to Oduma and Oluka (2019).

2.5 Measurement of Energy Input

A standardized calibrated cylindrical vessel was used to measure the amount of diesel required to fill-up diesel tank of the tractor after every operation according to Udo and Akubuo (2000). This process measures the quantity of diesel consumed in every trial. The energy intake rate was calculated using Equation 2 according to Alnahas (2003).

$$\text{Fuel intake rate } (\text{lha}^{-1}) = \frac{Reading\ of\ cylinder, litres}{Area\ of\ land\ covered,\ hacters} \quad (2)$$

2.6 Evaluation of Field Efficiency

Field efficiency was calculated using Equation 3 as proposed by Kepner *et al*. (1982)

$$\mathcal{E}_f = \frac{100Tp}{Tt} \quad (3)$$

where:

$\mathcal{E}_f$ = field efficiency, %;
Tp = productive time, h;
Tt = total working time, h.

$$Tt = Tp + Ti \quad (4)$$

where:

Ti = idle or delay time, h

2.7 Design of Experiment

Design expert software (version 11.0) was used in the optimization of energy intake (fuel/diesel consumption rate) and field efficiency of the disc plough. The experimental design used in the study was a three level – two factor full factorial design. The experiment comprises of two factors that were varied at three levels of operational speed (5, 7, 9 kmh^{-1}) and three levels of cutting depth (10, 20 and 30 cm). These factors and the levels were selected because the capacitive performance and energy consumption rate of agricultural tillage machinery are highly dependent on the factors according to Moitiz *et al*. (2013) and Mclaughlin *et al*. (2002). Central Composite Response Design which gives 13 test runs were conducted for each sample according to Umani *et al*. (2019) using Equation 5.

$$N = 2^k + 2k + n_c \quad (5)$$

where:

N = number of test runs,
k = experimental factors and
n_c = center point

To obtain the needed data, the array of values of every one of the two factors (k) was evaluated (Table 1). Operational speed and depth of cut were adopted as independent factors for the energy requirement and field efficiency study of the tillage implement. The responses where therefore, the fuel consumption rate (lha^{-1}) and field efficiency of the disc plough.

Table 1: Actual values, codes and levels of the test variables for design of experiments

Factors	Symbols	Codes and levels		
		-1	0	1
Operational speed (km/hr)	A	5	7	9
Depth of cut (cm)	B	10	20	30

2.8 Response Surface Methodology (RSM)

The Design Expert of version 11.0 was employed in the experimental design, to analyze the data obtained, optimize the functional factors and to generate model equations for the prediction of the energy requirement (fuel intake rate) and field efficiency of the disc plough. The quadratic, cubic, linear and two factorial interaction (2F1) models were selected and used to analyze the fuel consumption rate and field efficiency of the implement; and the models were fitted to the generated experimental data. Data obtained were analyzed using the Response Surface Methodology to fit the quadratic polynomial equation obtained from the Design Expert Software version 11.0 expressed in Equation (6) according to Chih *et al*. (2012).

$$Y = \beta_0 + \sum_{i=1}^{2} \beta i X i + \sum_{i=1}^{2} \beta i i X i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{2} \beta i j X i X j \quad (6)$$

where:

Y = Response;

β_0 = constant term;

$\sum_{i=1}^{2} \beta i$ = Summation of coefficient of linear terms;

$\sum_{i=1}^{2} \beta ii$ = Summation of quadratic terms;

$\sum_{i=1}^{2} \sum_{j=i+1}^{2} \beta ij$ = summation of coefficient of interaction terms;

$XiXj$ = independent variables.

Also, the multiple regressions were equally used in fitting the coefficient of the polynomial model so that the response variables may be correlated with the independent variables. The consistency of fit of the model, the individual and interaction effect of the tillage parameters (operational speed and depth of cut) on the responses (fuel consumption rate) and field efficiency of the implement were premeditated using ANOVA. Furthermore the results were also analyzed statistically to determine the effects of the factors and their interactions on the total fuel consumption rate and field efficiency at $\propto = 0.05$ by means of Minitab 17.0.

3. RESULTS AND DISCUSSION

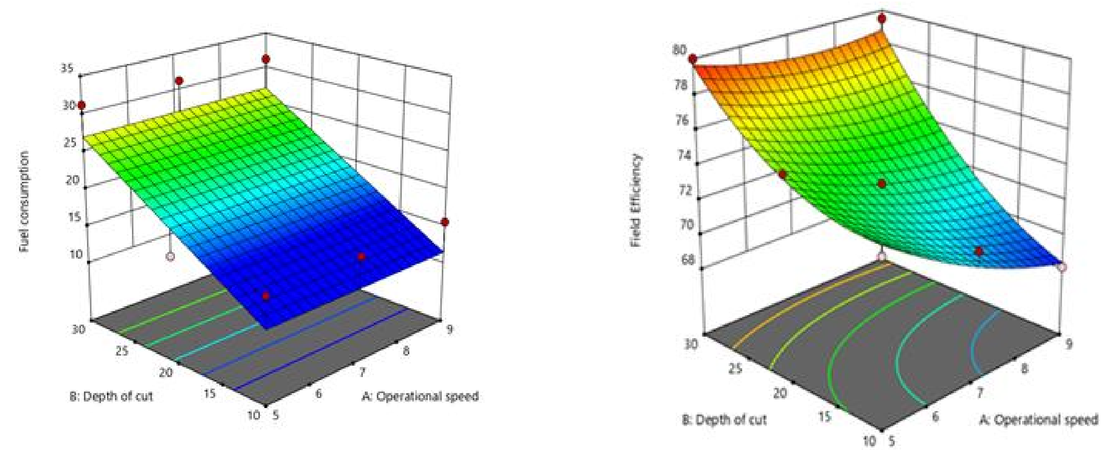
3.1 Ploughing Process

The ploughing operation was performed with the full width of the plough at selected operational speeds and ploughing depths, at average soil moisture content of 12.5% and the results of the energy requirement and field efficiency of the disc plough were shown in Table 2. Results revealed that, the disc plough operation requires the range of 15.63 – 31.25 lha^{-1} of fuel for tilling depths between 10 – 30 cm. The highest fuel consumption rate (energy requirement) of 31.25 l/ha was recorded when the plough was operated at the cutting depth of 30cm for the different selected operational speeds. The fuel consumption rate of the machine decreases by 49.98% when operating at cutting depth of 10 and 20 cm irrespective of the operational speed. On the other hand, the values of field efficiency obtained during the tillage operation ranged from 68.1 – 80.0% for the range of operational speed (5 – 9 kmh^{-1}) and cutting depth range from (10 – 30cm). Results indicated that the highest field efficiency of 80.0% was recorded when the plough was operated at the cutting depth of 30cm and operational speed of 5 kmh^{-1} while the least field efficiency of 68.1% was obtained at operational speed of 9 kmh^{-1} and cutting depth of 10cm. It was generally observed that at the different operational speeds, the field efficiency increases with the increase in cutting depth and increases to a maximum point of 80.0% at operational speed of 5 kmh^{-1} and cutting depth of 30 cm. The field efficiency of the implement decreases by 9.7 % when ploughing at cutting depth of 10 cm and 8.0% at cutting depth of 20cm. This is in agreement with the findings of Sale *et al* (2013) and Oduma *et al* (2015).

Table 2: Three levels – two factors full factorial composite design layout of the experiment with experimental and predicted values of fuel consumption rate and field efficiency

Run order	Coded factors		Actual factors		Energy Requirements		Efficiencies, %	
	A	B	Operational speed (kmh^{-1})	Cutting depth (cm)	Experimental values of fuel consumption rate, lha^{-1}	Predicted values of fuel consumption rate, lha^{-1}	Experimental values of field efficiency, %	Predicted values of field efficiency, %
1	0	1	7	30	31.25	27.04	77.3	72.04
2	1	1	9	20	15.63	19.23	71.6	68.66
3	1	-1	9	10	15.63	11.42	68.1	68.19
4	1	1	9	30	31.25	27.04	79.5	69.13
5	0	1	7	20	15.63	19.23	73.0	71.69
6	0	1	7	20	15.63	19.23	73.0	71.69
7	-1	-1	5	10	15.63	11.42	73.3	75.86
8	0	1	7	20	15.63	19.23	73.0	71.69
9	0	1	7	20	15.63	19.23	73.0	71.69
10	0	-1	7	10	15.63	11.42	71.3	71.34
11	-1	1	5	30	31.25	27.04	80.0	76.32
12	0	1	7	20	15.63	19.23	73.0	71.69
13	0	1	7	30	31.25	27.04	77.5	72.04

Figure 1 (a) shows the response surface plot of operational speeds and cutting depths against the fuel consumption rate showing the relationship between the factors (operational speed and ploughing depth) and the response (fuel consumption rate). Results as presented in the figure revealed that the fuel consumption rate increases with cutting depth and that the resultant impact of increasing the cutting depth as from 30 cm depth on fuel consumption rate is higher than the resultant impact observed in increasing the operational speed between 5 and 9 kmh^{-1}. Figure 1(b) is the response surface plot of speeds and cutting depths against the field efficiency showing the relationship between the factors and the response. Results of this figure showed that the highest field efficiency of 80% was observed at least operational speed of 5 kmh^{-1} at cutting depth of 30 cm. The highest field efficiency achieved at low working speed of 5 kmh^{-1} was attributed to the high tractive and draft force related with low working speed enabling the implement to pierce deep and collapse the resistance force offered by the soil to implement penetration thereby creating an adequate environmental condition for plant root to penetrate deep into the soil as observed by Sale *et al*. (2013).



(a) (b)

Figure 1(a) Response surface plot of cutting depth of the disc plough and operational speed against fuel consumption; (b) Response surface plot of cutting depth of the disc plough and operational speed against field efficiency.

3.2 Statistical analysis of results

The statistical analysis of results of the effects of tillage parameters on the energy requirements of the plough is presented in Table 3. Results of this table revealed that the effect of cutting depth on the fuel consumption rate is significant ($P < 0.05$). Thus, the mean fuel consumption rate varies for the different ploughing depth. On the other hand, the effect of the operational speed on fuel consumption rate is not statistically significant ($P > 0.05$) which is an indication that the mean fuel consumption rate is not different for the operational speed.

Table 3: Analysis of variance for fuel consumption rate

Source of variation	Sum of Squares	df	Mean Square	F-value	p-value
Operational speed	0.0000	1	0.0000	0.0000	1.0000
Depth of cut	365.98	1	365.98	18.57	0.0015*
Error	197.06	10	19.71		
Total	563.04	12			

* significant

Furthermore, the analysis of the effects of tillage factors (operational speed and cutting depth) on the field efficiency of the plough is presented in the ANOVA results for field efficiency in Table 4. This result shows that the effect of cutting depth and operational speed on the field efficiency are statistically significant ($P < 0.05$). It therefore implies that the mean field efficiency vary for the different cutting depths and operational speeds.

Table 4: Analysis of variance for field efficiency

Source	Sum of Squares	df	Mean Square	F-value	p-value
A-Operational speed	15.36	1	15.36	34.38	0.0006
B-Depth of cut	98.41	1	98.41	220.30	< 0.0001
Error	0.0000	4	0.0000		
Total	134.10	12			

3.3 Model Equation of Energy Requirements (Fuel Consumption Rate) and Field Efficiency of Disc Plough

The energy requirement of the disc plough in loamy-sand soil is dependent on the results displaying significant difference of the tillage factors. The contributions, effects, coefficient of model terms, lack of-fit test and significance of the factors and their interactions on the fuel consumption rate were examined according to Fakayode *et al*. (2016) and Umani *et al*. (2019). A linear equation model occurred significant for the response ($P < 0.05$) implying that the model term could be noted at 95% level of significant. The linear model developed to estimate the energy requirement (fuel consumption rate) with respect to the independent variables or functional operating parameters (operational speed and cutting depth) is as expressed in Equation 7.

$$F_{cr} = 3.61462 + 4.29641e^{-16}A + 0.78100B \tag{7}$$

where:

F_{cr} = fuel consumption rate, lha^{-1};
A = operational speed, kmh^{-1};
B = cutting depth of the disc plough, cm

The p-value of the model term is 0.0053 (Table 5) which is below α- level of 0.05 and suggests that the model is significant, meaning that, the tillage factors have significant effects on the fuel consumption rate of the implement except the operational speed in which the p-value is 1.0000 which is greater than the chosen α- level of 0.05. Thus, depth of cut has major influence on consumption rate of disc plough as compared to the operational speed of the machine. This is consistence with the findings of Ajav and Adewoyin (2012).

Table 5: ANOVA of response surface linear model for fuel consumption rate

Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value
Model	365.98	2	182.99	9.29	0.0053*
A-Operational speed	0.0000	1	0.0000	0.0000	1.0000
B-Depth of cut	365.98	1	365.98	18.57	0.0015*
Residual	197.06	10	19.71		
Lack of Fit	197.06	6	32.84		
Pure Error	0.0000	4	0.0000		
Cor Total	563.04	12			

* significant

Similarly, the field efficiency of the disc plough in loamy-sand soil is also dependent on the results revealing the significant variation for combination of the speed and ploughing depth. The model coefficient, effect, contribution, test of lack of-fit and the significance of the factors and their interactions on the field efficiency were determined according to Fakayode *et al*. (2016) and Umani *et al*. (2019). A quadratic model was significant for the response ($P \leq 0.05$). This implies that the significant model term was identified at 95% significance level. The quadratic model equation generated to predict the field efficiency with respect to the independent variables or functional operating parameters (operational speed and cutting depth) is as expressed in Equation 8.

$$\varepsilon_f = 93.18190 - 4.36466A - 0.619353B + 0.058750AB + 0.170690A^2 + 0.015328B^2 \quad (8)$$

where:

ε_f = field efficiency, %;
A = operational speed, kmh^{-1};
B = cutting depth of the disc plough, cm.

The model p-value of 0.0001 (Table 6) is less than the selected α- level of 0.05 meaning that the model is significant. Hence, the operational speed and plouhing depth have significant effects on the field efficiency of the implement. Thus, the model term p-values of 0.0006, 0.0001, 0.0098 and 0.0066 that are less than the chosen α- level of 0.05 specify that the model terms are significant. Thus, A-Operational speeds, B-Depth of cut, AB, B^2 are significant model terms as presented in Table 6. This result is consistence with the findings of Ajav and Adewoyin (2012).

Table 6: ANOVA of response surface quadratic model for field efficiency

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	130.97	5	26.19	58.63	< 0.0001*
A-Operational speed	15.36	1	15.36	34.38	0.0006*
B-Depth of cut	98.41	1	98.41	220.30	< 0.0001*
AB	5.52	1	5.52	12.36	0.0098*
A^2	1.29	1	1.29	2.88	0.1334
B^2	6.49	1	6.49	14.52	0.0066*
Residual	3.13	7	0.4467		
Lack of Fit	3.13	3	1.04		
Pure Error	0.0000	4	0.0000		
Cor Total	134.10	12			

* significant

3.4 Model validation of Energy requirements and Field efficiency of the plough

The results of the validation of the developed model equation for energy requirements are presented in Table 7. The results revealed that the model is significant with coefficient of determination, R^2 of 0.6500, which shows good relationships among the independent variables. It is an indication that the response model (fuel consumption rate) could describe 65% of the overall changeability in the response.

The simulation of the model equation obtained indicated that the fuel consumption rate (energy requirements) is in the trial array. The predicted R^2 value of 0.3129 is consistent with the adjusted R^2 value of 0.5800 which showed that the investigational data fitted well according to Kothari (2014).

Table 7: Model Summary Statistics/validation of model term

Source	**Std. Dev.**	**R^2**	**Adjusted R^2**	**Predicted R^2**	**PRESS**	
Linear	**4.44**	**0.6500**	**0.5800**	**0.3129**	**386.88**	**Suggested**
2FI	4.68	0.6500	0.5333	-0.4144	796.35	
Quadratic	0.0000	1.0000	1.0000		*	
Cubic	0.0000	1.0000	1.0000		*	Aliased

More so, the results of the validation of the developed model equation for the field efficiency of the plough are presented in Table 8. The results revealed that the model is significant with coefficient of determination, R^2 of 0.9767, which shows remarkable relationships amid the independent variables. This is a sign that the response model can clarify 97.7% of the total variability in the response.

The simulation of the model equation obtained showed that the field efficiency is within the experimental range. The Predicted R^2 of 0.7639 is consistent with the Adjusted R^2 of 0.9600; i.e. the difference is less than 0.2 showing that the investigational data fitted excellently in accordance with Kothari (2014). The adequacy Precision of 24.886 proportions as obtained is greater than 4 is desirable, indicating an acceptable signal and that the model could be accepted to navigate the design space.

Table 8: Model Summary Statistics/validation of model term

Std. Dev.	0.6684	R^2	0.9767
Mean	73.98	Adjusted R^2	0.9600
C.V. %	0.9034	Predicted R^2	0.7639
		Adeq Precision	24.8856

3.5 Optimization of the energy requirements and field efficiency of disc plough

The optimization of the energy input and field efficiency of disc plough were conducted using design expert in response surface methodology (RSM). Figure 2a shows the curve of the optimization process with the optimal operating factors of operational speed of 6.7 kmh^{-1} and cutting depth of 18.56cm. Equally, the optimum fuel consumption rate and the desirability of 20.51 l/ha and 1.00 were respectively obtained.

Lastly, the optimization of the functional factors (operating speed and cutting depth) of disc plough on loamy-sand soil was also conducted to get the optimum field efficiency. Figure 2b displays the curve of the optimization process with the optimal operating factors of operational speed of 7 kmh^{-1} and cutting depth of 30cm. Thus, the optimum field efficiency and the desirability of 77.5% and 1.00 were respectively obtained.

4. CONCLUSIONS

The modeling of the energy requirements (fuel consumption rate) and field efficiency of the disc plough on loamy-sand soil was successfully conducted. In the analysis of the field operation, it was observed that at cutting depth of 10 and 20 cm, the plough recorded the lowest fuel consumption rate at various selected operational speeds while at cutting depth of 30 cm, it had the highest fuel consumption rate irrespective of the operational speed. Furthermore, it was observed that the highest field efficiency was recorded when the plough was operated at the cutting depth of 30 cm and operational speed of 5 kmh^{-1} while the least field efficiency was obtained at operational speed of 9 kmh^{-1} and cutting depth of 10 cm.

The energy requirement (fuel consumption rate) of the disc plough increase with increase in cutting depth as compared to the operational speed. Also at the different operational speeds, the field efficiency increases with the increase in cutting depth.

A linear mathematical model equation was suggested for the prediction of the energy requirement of the machine while a quadratic model was suggested for the estimation of the field efficiency of the plough.

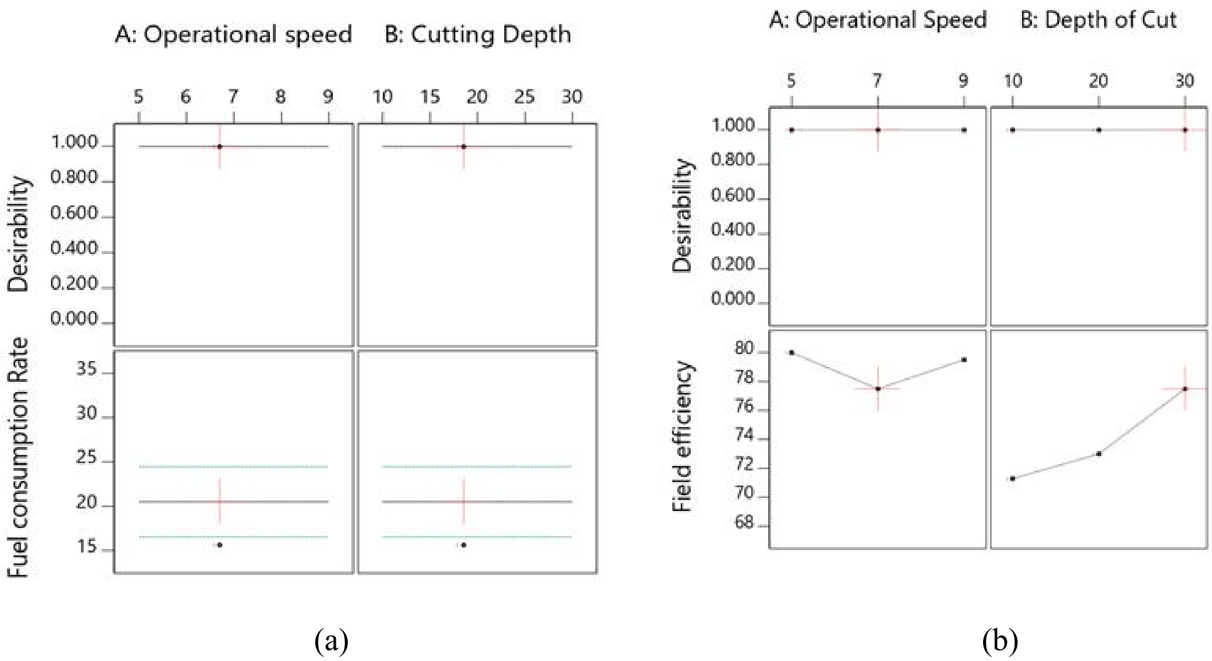


Figure 2 (a) Optimization curve of the energy requirements of disc plough; (b) Optimization curve of the field efficiency of disc plough

The developed models and their coefficients were statistically significant. The predicted and the adjusted R^2 values were closely in agreement.

The developed mathematical models will help the farmers to assess the performance capability of the implement for proper selection and assignation to work.

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