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Model development and optimisation of the disc plough efficiency on loamy-sand soil in South-East Nigeria

Okechukwu Oduma[1], Precious Ehiomogue[1], Dilibe Ifanyi Ntunde[2]*

[1]*Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umudike, Nigeria*

[2]*Department of Mechanical Engineering, Michael Okpara University of Agriculture, Umudike, Nigeria*

**Corresponding author: oduma.okechukwu@mouau.edu.ng*

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Abstract: This study was conducted to model and optimise the efficiency of a disc plough on loamy-sand soil in South-East Nigeria to aid farmers to examine and choose the right ploughing implement based on the soil type for an effective and bountiful production. The operational speed and cutting depth were taken as factors for the study of the plough efficiency. The results revealed that the highest field efficiency of 80% was noted when the plough worked at the cutting depth of 30 cm and a speed of 5 km·h^{-1} while the lowest efficiency of 68.10% was achieved at a speed of 9 km·h^{-1} and a depth of 10 cm. The quadratic model was significant for the response (P < 0.05). The results indicated that the coefficient of determination (R^2) was 0.98, which specified the high correlation among the factors. The predicted R^2 (0.76) was consistent with the adjusted R^2 of 0.96. The adequacy precision of 24.89 showed a suitable indicator and that the model could navigate the design space. The optimum field efficiency and the desirability of 77.50% and 1.00 were, respectively, obtained at an optimum speed of 7 km·h^{-1} and a cutting depth of 30 cm. Farmers can, however, assess and select the implements with the aid of the developed model.

Keywords: depth; farmers; implement; selection; speed

The field efficiency is the comparative extent or fraction of the overall output of any particular machine depending on the condition of the farm (ASAE 1999). It specifies in what manner the machine/implement can achieve its tasks; thus, a knowledgeable farmer is continually cognisant of the operative and proficient usage of his/her farm machines since their poor performance or the unsuitable application of the tools might lead to excessive operational expenditures and reduce the production or cause the complete loss of money and/or output (Oduma et al. 2015). Consequently, field efficiency is the primary indicator for the selection of machinery (Olatunji 2011; Ranjbarian et al. 2017). According to Onwualu et al. (2006), it is vital to find out in which manner an implement handles a particular farm task and the frequency of its use; the authors state that this fact is essential as it encourages the application and management of appropriate machine practices and other fiscal aspects in addition to the proper management of farm operations. Witney (1988) postulated that both dynamic machinery exploitation and management call for the awareness of performance records on the efficiencies of the machines in the directive to accomplish a specified work plan and to create a stable mechanisation scheme that will be suited to the potential of diverse equipment.

According to Sale et al. (2013), farming operations are extremely susceptible to seasonal and climate

https://doi.org/10.17221/72/2021-RAE

situations, in which sufficient amounts of cash are required for each venture, thus, it is prudent to evaluate the proficiencies of farm equipment for their enhanced selection, best output and suitable farm planning. Anazodo (1983) posited that owing to dissimilarities in the soil conditions, machine performance records in different soil environments and types are very important for farm equipment selection. The implementation of routine data is a crucial factor in evaluating the performance of farm machines. Grisso et al. (2002) upheld that the field efficiency is a vital indicator for considering the field capacity and for implementing required machinery regulation/management policies. According to Von Bargen et al. (1974), field efficiency means carrying out a specified field task with the least waste of time, energy and other farm capital. Field efficiency considers time wastage and the capacity to utilise the complete width of the implement in the field work (Hunt 2008). Soil tillage is the main field task in farming that effects the soil properties, and the crop's environment and yield. Soil tillage is a cultural practice that influences the soil's physico-chemical properties, and, hereafter, creates changes in the crop development, the aerial cover, the growth of roots, and the overall yield of the crop (Bako et al. 2021). According to Boydas and Turgut (2007), to guarantee regular growth of every plant, a soil needs to be prepared in a condition that ensures that the plant roots gain access to ample air, moisture and nutrients. Ojha and Michael (2012) said that ploughing is physically influencing soils to obtain the preferred condition of the seed bed for the propagation and suitable growth of crops. Tillage processes are fundamentally intended to mend the soil's physical characteristics where tilling activities can be affected by the soil types and the environmental conditions, hence, the selection of suitable tillage tools to match particular soil types and situations are critical indicators in decreasing the labour costs, energy losses and, as a result, exploiting the capabilities of the farm machines and sustaining the soil usefulness in addition to lessening the adversative effects of soil compaction or hardness (Coates and Thacker 2001).

Obtaining a field efficiency model for a disc plough operation on a loamy-sand soil is a vital and swift means of helping the farm proprietors, at any level, in assessing and predicting the field efficiency of the implement for right choice of equipment before acquiring or engaging the machinery for the work at hand (Oduma et al. 2020). The intention of this work is to evaluate, model and optimise the field efficiency of a disc plough on a loamy–sand soil that may aid farmers in selecting a suitable plough implement for seed bed preparation to lower the cost, reduce the energy losses and enhance the production.

MATERIAL AND METHODS

Experimental area. The research was carried out at the trial farm of Michael Okpara University of Agriculture, Umudike in Abia State, Nigeria. Umudike is situated at a latitude and longitude of 50°251'N and 70°341'E. The climate at the farm is categorised by a mean temperature of 27 °C and an average annual rainfall of 2.375 mm with a mean relative humidity of 82.5%, typical of tropical rain forest regions (Amanze et al. 2020). The loamy-sand soil is suitable for arable cropping in South-East Nigeria.

The experimental farm has a land area of 0.81 ha (8 100 m^2) and was sectioned into nine partitions of 30 × 30 m^2 for random investigations/observations (Figure 1). Each section was demarcated by a space of 2.50 m from each other to check the interaction within the plot margins and to be likewise used for turning and continuation of the operations at the head land (Oduma et al. 2019). The experimental area has average soil bulk density of 1.68 $g \cdot cm^{-3}$, porosity of 37.40%, moisture content range from 12.35–18.90% wet basis (w.b) and is granular in structure (Oduma et al. 2019).

Determination of the soil moisture content. The oven-dry technique (universal hot air oven; Scientico, India) was used to determine the moisture content of the soil with the oven temperature set at 105 ± 3 °C for 2 days according to Bahram et al. (2014). The initial weight of the soil samples collected from the site and the weight of oven-dry soil

Figure 1. The experimental plot

https://doi.org/10.17221/72/2021-RAE

samples were determined in the laboratory and the moisture content was evaluated using Equation (1).

$$M_c = \frac{W_s - D_s}{D_s} \times 100\% \quad (1)$$

where: M_C – moisture content of the soil (%); W_S – weight of the initial soil sample (kg); D_S – weight of the oven-dried soil (kg).

Machine and implement used for the research. A model MF430E tractor with a capacity of 55.2 kW made by Massey Ferguson Company (Canada) and a disc plough (MF430E; Massey Ferguson Company, Canada) having a complete width of 1.8 m and operating units of 3 bottom discs were used for the study.

Field test process. The tillage process was conducted longitudinally with the full width of the plough at the chosen speeds of 5, 7 and 9 km·h^{-1} and cutting depths of 10, 20 and 30 cm. The area of the tilled space and the time used to work the area were noted (Oduma and Oluka 2019).

Evaluation of the field efficiency. The field efficiency was calculated using Equation (2) as proposed by Kepner et al. (1982).

$$\varepsilon_f = \frac{100\, T_p}{T_t} \quad (2)$$

where: ε_f – field efficiency (%); T_p – productive time (h); T_t – total working time (h).

$$T_t = T_p + T_i \quad (3)$$

where: T_i – idle or delay time (h).

Design of the experiment. The experimental design used was a three level – two factor full factorial design. The experiment consists of two factors which were varied at three levels of the working speed (5, 7 and 9 km·h^{-1}) and three levels of the cutting depth of 10, 20 and 30 cm. These factors and the levels were selected because the capacitive performances of the tillage machinery are exceedingly dependent on the indicators (McLaughlin et al. 2002; Moitzi et al. 2013). A Central Composite Response Design, which ensures 13 test runs, was performed for each sample as adopted by Umani et al. (2019) using Equation (4).

$$N = 2^k + 2k + n_c \quad (4)$$

where: N – number of test runs; k – experimental factors; n_c – centre point.

To achieve the needed data, the range of values of the two factors (k) was evaluated (Table 1). The speed and cutting depth were the independent factors for the field efficiency study of the disc plough [i.e. the response was the field efficiency (%) of the disc plough]. The field experiments were conducted in a randomised order.

Response surface methodology. Design Expert Software (version 11.0) was used to design the experiment, analyse the obtained data, optimise the purposeful factors and generate model equations for the prediction of the field efficiency of the disc plough. The quadratic, cubic, linear and two factorial interaction (2F1) models were designated to analyse the field efficiency of the implement; and the models were fixed to the generated experimental data.

The obtained data were analysed using the response surface methodology (RSM) to fit the quadratic polynomial equation acquired from the Design Expert Software as expressed in Equation (5) according to Tsai et al. (2010).

$$Y = \beta_0 + \sum_{i=1}^{2} \beta_i X_i + \sum_{i=1}^{2} \beta_{ii} X_i^2 + + \sum_{i=1}^{2} \sum_{j=i+1}^{2} \beta_{ij} X_i X_j \quad (5)$$

where: Y – response; β_0 – constant term; $X_i X_j$ – independent variables;

$\sum_{i=1}^{2} \beta_i$ – summation of the coefficient of linear terms;

$\sum_{i=1}^{2} \beta_{ii}$ – summation of the quadratic terms;

$\sum_{i=1}^{2} \sum_{j=i+1}^{2} \beta_{ij}$ – summation of the coefficient of interaction terms.

Also, the multiple regressions were adopted to fit the coefficient of the polynomial model to enable the response variable to be correlated with the independent variables. The reliability of the fit of the model, the discrete and interaction effect

Table 1. Actual values, coded values and levels of the independent test variables for the design of the experiment

Factors	Symbols	Codes and levels		
		–1	0	1
Operational speed (km·h^{-1})	*A*	5	7	9
Cutting depth (cm)	*B*	10	20	30

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of the tillage parameters (operational speed and cutting depth) on the response (field efficiency) of the implement were assessed using an analysis of variance (ANOVA). The obtained data were likewise subjected to a statistical analysis to obtain the effects of the operational speed and cutting depth and their interactions on the field efficiency of the implement at $\alpha = 0.05$ via Minitab 17.0.

RESULTS AND DISCUSSION

Tillage process. The ploughing operation was performed with the full width of the device (1.8 m) at selected speeds and cutting depths, at a soil moisture content range from 12.35–18.90% (w.b) and the results of the field efficiency of the disc plough are presented in Table 2 and Figure 2. Figure 2 is the response surface plot of the speeds and cutting depths against the field efficiency showing the relationship among the factors and the response. The results of the interaction among the experimental factors (operational speeds and cutting depths) with the field efficiency of the plough are presented in Table 2. The highest field efficiency of 80% was recorded when the plough was operated at a cutting depth of 30 cm and an operational speed of 5 km·h^{-1} while the lowest field efficiency of 68.14% was obtained at an operational speed of 9 km·h^{-1} and a cutting depth of 10 cm. At this working level, the field efficiency of the implement decreased by 9.70%, which therefore implies that the field efficiency of the plough decreases with an increase in the working speed (Hunt 2008). This is in agreement with the findings of Sale et al. (2013) and Oduma et al. (2015). The results also fall within the range of the field efficiencies of 80.1–85.0% obtained by El Naim et al. (2014) in their study of the computer modelling used to predict implement field performance variables. However, the highest field efficiency obtained at 5 km·h^{-1} (80%) in this research work is slightly lower than the field efficiency of 83% obtained by El Naim et al. (2014) for a plough at a speed of 5 km·h^{-1}, thus, the slight variations noticed in the efficiencies obtained may be attributed to the differences that exist in the soil conditions among the different agricultural or ecological areas as pointed out by Anazodo et al. (1983).

Effects of the tillage factors on the field efficiency of the disc plough. The values of the actual field efficiency obtained during the tillage operation ranged from 68.14 to 80% with regards to the range of the operational speed and cutting depth of the disc plough. This field efficiency is within the range of efficiency of 88–74% recommended by Hunt (2008) for a plough at speed range of 5–9 km·h^{-1}. It was generally observed that at the different operational speeds, the actual field efficiency increases with an increase in the

Table 2. Layout of the three level – two factor full factorial composite design of the experiment with the actual and predicted values of the field efficiency

Run order	Coded factors		Actual factors		Field efficiency (%)	
	A	*B*	*A*	*B*	actual values	predicted values
1	0	1	7	30	77.31	72.04
2	1	1	9	20	71.63	68.66
3	1	–1	9	10	68.14	68.19
4	1	1	9	30	79.50	69.13
5	0	1	7	20	73.01	71.69
6	0	1	7	20	73.02	71.69
7	–1	–1	5	10	73.31	75.86
8	0	1	7	20	73.02	71.69
9	0	1	7	20	73.02	71.69
10	0	–1	7	10	71.31	71.34
11	–1	1	5	30	80.00	76.32
12	0	1	7	20	73.02	71.69
13	0	1	7	30	77.50	72.04

A – operational speed (km·h^{-1}); *B* – cutting depth (cm)

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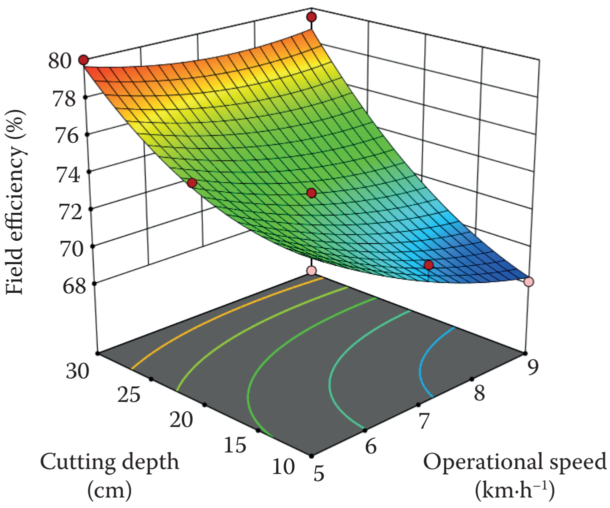

Figure 2. Response surface plot of the cutting depth of the disc plough and the operational speed against the field efficiency

cutting depth and increases to a maximum point of 80% at an operational speed of 5 km·h^{-1} and a cutting depth of 30 cm. The actual field efficiency of the implement decreases by 9.70% when ploughing at a cutting depth of 10 cm and 8% at a cutting depth of 20 cm. The maximum field efficiency (80%) was achieved at the lowest forward speed (5 km·h^{-1}) which is closely in line with the observation of Chandrashekar and Singh (2018) in a study on the performance evaluation of a vertical rotary plough in which the maximum field efficiency of the rotary plough (88.09%) was recorded at a very low forward speed of 2 km·h^{-1}. The highest field efficiency achieved at the low working speed of 5 km·h^{-1} may be due to the high tractive and draught force allied with low working speed facilitating the implement to penetrate deep and break the resistance force offered by the soil to the implement penetration, thereby creating an adequate environmental condition for the plant's roots to penetrate deep into the soil as observed by Sale et al. (2013). Furthermore, the predicted field efficiency (Table 2) is also within the range of the field efficiency of 72.90–78.80% obtained by Sale et al. (2013) in their study on the performance of selected tillage implements. The results achieved from this study specify that the cutting depth has greater influence on the field efficiency of the tillage implement than the operational speed. Thus, the cutting depth should be determined based on the root length of the crop in order to optimise the field efficiency of a disc plough as specified by Ajav andAdewoyin (2012).

Statistical analysis of the results. The analysis of the effects of the tillage factors (operational speed and cutting depth) on the field efficiency of the plough is presented in the ANOVA results for the field efficiency in Table 3. The results show that the field efficiency was significantly ($P \leq 0.05$) affected by the cutting depth and operational speed and increases with an increase in the cutting depth as observed by Wandkar et al. (2013) in their study of the influence of the forward speed and cutting depth on draught of primary tillage implements in a sandy loam soil. The field efficiency decreases with an increase in the tillage speed, which may be attributed to a high drawbar pull associated with the high working speed (Hensh et al. 2022). Thus, the *P*-value for the operational speed and cutting depth are 0.0006 and 0.0001, respectively, which therefore implies that the mean field efficiency varies for the different cutting depths and operational speeds.

Model evaluation of the disc plough efficiency. The field efficiency of the disc plough in a loamy-sand soil is reliant on the results, revealing a significant variation with regards to the combination of the speed and cutting depth. The model coefficient, effect, contribution, test of the 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).

Table 3. Analysis of variance for the field efficiency

Source	Sum of squares	*df*	Mean square	*F*-value	*P*-value
A	15.36	1	15.36	34.38	0.0006
B	98.41	1	98.41	220.30	< 0.0001
Error	0.0000	4	0.0000	–	–
Total	134.10	12	–	–	–

df – degree of freedom; *A* – operational speed (km·h^{-1}); *B* – cutting depth (cm)

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Table 4. Analysis of variance of the response surface quadratic model for the field efficiency

Source	Sum of squares	*df*	Mean square	*F*-value	*P*-value
Model	130.97	5	26.1900	58.63	< 0.0001*
A	15.36	1	15.3600	34.38	0.0006*
B	98.41	1	98.4100	220.30	< 0.0001*
AB	5.52	1	5.5200	12.36	0.0098*
A^2	1.29	1	1.2900	2.88	0.1334
B^2	6.49	1	6.4900	14.52	0.0066*
Residual	3.13	7	0.4467	–	–
Lack of fit	3.13	3	1.0400	–	–
Pure error	0.0000	4	0.0000	–	–
Corrected total	134.10	12	–	–	–

*significant; *df* – degree of freedom; *A* – operational speed ($km \cdot h^{-1}$); *B* – cutting depth (cm)

A quadratic model was significant for the response ($P \leq 0.05$). This implies that the significant model term was identified at a 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 expressed in Equation (6).

$$\varepsilon_f = 93.18190 - 4.36466\,A - 0.619353\,B + 0.058750\,AB + 0.170690\,A^2 + 0.015328\,B^2 \quad (6)$$

where: ε_f – field efficiency (%); *A* – operational speed ($km \cdot h^{-1}$); *B* – cutting depth of the disc plough (cm).

The quadratic model obtained in this study is in line with the observations of Oduma et al. (2019) in their study on the development of empirical regression equations for predicting the performances of a disc plough and harrow in a clay-loam soil.

The model *P*-value of 0.0001 (Table 4) is less than the selected α-level of 0.05 meaning that the model is significant. Hence, the operational speed and cutting 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 speed, *B* – cutting depth, *AB*, B^2 are the significant model terms as presented in Table 4. This result is consistent with the findings of Ajav and Adewoyin (2012). However, it is statistically inconsistent with the findings of Ranjbarian et al. (2017) in their study on the performance of tractor and tillage implements in a clay soil in which the *P*-value of the efficiency obtained is 0.00 at $P \leq 0.05$. This may be ascribed to the differences in the soil and/or environmental conditions of the different study areas as noted by Bako et al. (2021).

Model validation. The results of the validation of the developed model equation are presented in Table 5. The results revealed that the model is significant with an R^2 (coefficient of determination) of 0.98, which shows tremendous relationships among the independent variables. This is an indication that the response model can clarify 98% of the total erraticism in the response (Umani et al. 2019). The simulation of the obtained model equation showed that the field efficiency is within the trial range. The predicted R^2 of 0.76 is consistent with the adjusted R^2 of 0.96; i.e. the difference is less than 0.2 showing that the investigational data fitted very well, according to Kothari (2014). The adjusted R^2 obtained in this study is in agree-

Table 5. Model summary statistics/validation of the model term

Validation instrument	Validation values
SD	0.6684
Mean	73.9800
CV (%)	0.9034
R^2	0.98
Adjusted R^2	0.96
Predicted R^2	0.76
Adequacy precision	24.89

CV – coefficient of variation

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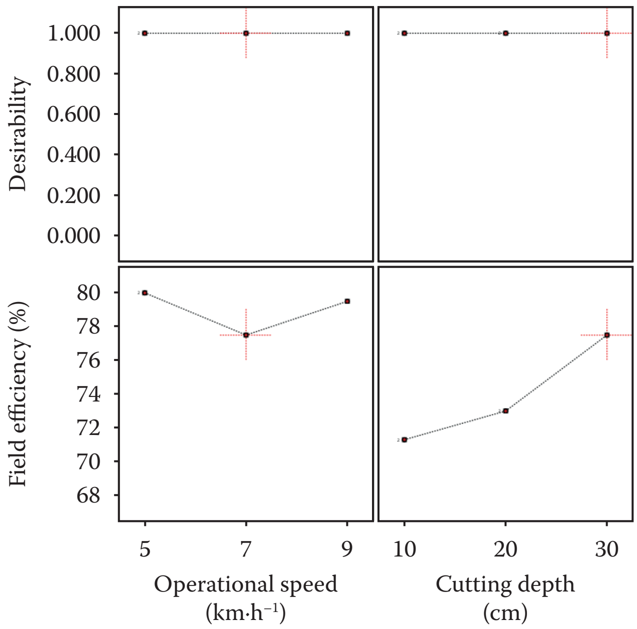

Figure 3. Optimisation curve of the field efficiency of the disc plough

ment with the R^2 of 0.9615 obtained by Oduma et al. (2020). The obtained adequacy precision ratio of 24.89 is greater than 4, which is desirable, signifying a tolerable signal and that the model could be adopted to navigate the design space.

Optimum field efficiency of disc plough. The optimisation of the functional factors (operating speed and cutting depth) of a disc plough on a loamy-sand soil was conducted with the aid of Design Expert Software with the RSM to obtain the optimum field efficiency. Figure 3 displays the curve of the optimisation process with the optimal operating factors of the operational speed of 7 km·h^{-1} and cutting depth of 30 cm. Thus, the optimum field efficiency and the desirability of 77.50% and 1.00 were, respectively, obtained. The optimum depth, as revealed by the result of the optimisation, is consistent with the specifications of Ajav and Adewoyin (2012) which range from 20–30 cm due to the variation in the roots' length with regards to the crop penetration for a better yield, as applicable in different crops. On the other hand, the optimum speed of 1.94 m·s^{-1} obtained by Olatunji (2011) in his study on the evaluation of the plough disc performance on a sandy loam soil at different soil moisture levels is lower than the optimum speed obtained in this study. This may be due to the differences in the soil conditions, especially the moisture contents of the different study areas as pointed out by Anazodo (1983).

CONCLUSION

The modelling of the field efficiency of the disc plough on loamy-sand soil was effectively undertaken. In the study of the field operation, it was observed that the highest field efficiency was recorded when the plough was operated at a cutting depth of 30 cm and an operational speed of 5 km·h^{-1} while the lowest field efficiency was obtained at an operational speed of 9 km·h^{-1} and a cutting depth of 10 cm.

It was also detected that, at the different operational speeds, the field efficiency increases with an increase in the cutting depth.

From the conducted statistical analyses, the quadratic mathematical model equation was suggested for the estimation of the field efficiency of the disc plough.

The generated model equation and the coefficients were statistically significant. The predicted and the adjusted R^2 values were firmly consistent. Thus, the trial values were suitable with the coefficient of determination (R^2 = 0.98) specifying a great correlation among the independent variables.

The developed mathematical model will help farmers to assess the performance capability of the implement for its proper choice and engagement to perform the work.

The optimum field efficiency and the desirability of 77.50% and 1.00 were, respectively, obtained

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at an optimal operational speed of 7 km·h^{-1} and a cutting depth of 30 cm.

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