Prediction of tractive force model for disc harrowing using sensitivity analysis

S. O. Nkakini[1*], I. E Douglas[2]

(1. *Department of Agricultural and Environmental Engineering, Rivers State University of Science and Technology, Port Harcourt, Nigeria;*

2. *Department of Marine Engineering, Rivers State University of Science and Technology, Port Harcourt, Nigeria*)

Abstract: In this study, a comparative evaluation of tractive force models for disc harrowing, at different tillage speeds was carried out in order to determine optimal tillage speeds. The predictive models were developed using dimensional analysis. The tillage operation in a loamy sand soil, at tillage speeds of 1.94 m s^{-1}, 2.22 m s^{-1} and 2.5 m s^{-1} respectively was conducted, using trace tractor techniques. Parameters such as drawbar pull, rolling resistance, wheel slip, moisture content, cone index, wheel numeric, contact pressure, speed, width of harrow, depth of harrow, and tractive force were measured. The developed mathematical models describing the tractors tyre-soil interactions parameters were evaluated using sensitivity analysis of the measured parameters. The wheel tractors tractive force models depicted highest sensitivity coefficients of 0.2405, 0.2331 and 0.3041 for drawbar pull during harrowing with tillage speeds at 1.94 m s^{-1}, 2.22 m s^{-1} and 2.50 m s^{-1} respectively. The results obtained showed that 10%, 50% and 100% changes of independent variables (U1) would cause dependent variables (N) negligible changes. These indicate that the sensitivity of developed predicted models to changes in the constituent independent variables are negligible and insignificant. This result also indicates that at tillage speed of 2.22 m s^{-1} the lowest sensitivity coefficient of 0.2331 was obtained among others, which is an indication of the best tillage speed for harrowing operation.

Keywords: predictive, tractive force, disc harrowing, modelling, sensitivity measurement, soil moisture

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1 Introduction

Soil is generally conceived to exhibit high in-built resistance to degradation even under intensive traction operations (Afolayan, et al., 2005). However, any abuse can accentuate total pore collapse beyond the plastic limit allowable for sustainable agricultural production. Unfortunately, about 0.3% to 0.5% of arable lands are lost due to soil degradation annually in the tropics, a product of uncontrolled tillage systems (Afolayan et al., 2005). Tillage can be defined as any positive action when forces are reasonably applied with the aim of altering the soil conditions for agricultural purposes.

Tillage is the mechanical manipulation of the soil, for crop production in agriculture (ASAE standards, 2002). A good tillage operation provides suitable soil pulverization (Nwokedi, 1992). Tillage, though, could pose some problems to organic matters rejuvenation, it is an unavoidable practice.

Secondary tillage operation involves the use of such secondary tillage implements as discs harrows, spike tooth and spring tooth harrows after primary tillage. This is to provide a more effective improvement of soil tilth resulting in adequate and sufficient soil contact (Nwokedi 1992). In harrowing, the initial soil strength is reduced while tractive force is likely to decrease because of the level of soil pulverization.(Nkakini,2012). Thangaradivelu and Colvin (1990) stated that the decision of whether or not to carry out field operation is largely

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*** Corresponding author: S. O. Nkakini,** Engr. Department of Agricultural and Environmental Engineering, Rivers State University of Science and Technology, Port Harcourt, Nigeria. Email: nkakini@yahoo.com.

influenced by the traffic ability of the prevailing field conditions.

Tractive force is derived from contact between the tyre and a medium such as soil. This plays a vital role in tillage operations. Therefore, the need to determine the appropriate tractive force models becomes evident in order to balance the variables in operations. Thus, the need to improve on the efficiency of tillage operations in order to increase productivity in mechanized agriculture becomes obvious. Such positive effects can only be realized through the use of appropriate models that include all important compounding variables of the earlier tillage models (Nkakini,2012), which do not include variables such as depth of cut and width of cut.

There exists an optimum condition for efficient tillage operations, which must include the appropriate compounding variables in the models. This research has much of its roots in the need for improving the energy-efficiency, and tractive performance of agricultural tractor in field operations. It is necessary to be able to predict how a machine and implements perform a given task under a given condition.

The assessment of developed models for field operations using sensitivity analysis is important in creating a condition that allows for the optimization of the dependent and independent variables.

The developed tractive force models were validated using sensitivity of measured parameters. According to the theories of Mc Cueu (1973) as reported by Simonyan (2006), sensitivity of a model to a given parameter was defined as the rate of change in the output of the model with respect to the change in the value of the parameter while keeping other parameters constant. Hence, sensitivity analysis of any developed model makes the relative role of each variable to that model known. This is done by taking notice of the change of dependent variable in the model with respect to the change in each of the several independent variables (Simonyan, 2006).

A tractive device is powered to provide tractive capability to the vehicle. Pneumatic tyres are the most commonly used traction device for off-road vehicles (Georing et al., 2006). The forces transmitted to the vehicle through the contact area of its traction devices are important to determine the vehicles tractive performance. All of these forces are developed through interaction of the traction device with the terrain upon which the vehicle is operating.

The objective of the study is to predict the variation of dependent and independent variables in disc harrowing, so as to optimize tractive force generation.

2 Materials and methods

2.1 Site

Experiments were conducted in the field (in-situ) using trace tractor technique. It was conducted at National Root Crops Research Institute - (NRCRI) experimental farm, in Umudike, Umuahia, Abia State of Nigeria. Umudike is under the derived tropical humid ecological zone of Nigeria, and is 122 m above sea level and lies on latitude 05°29′^{1}N and longitude 07°33′E. The loamy sand soil, where the experiment was conducted consists of clay-11.04% silt -4% and sand 84.96%.

2.2 Experimental procedure

The instruments and implements used in measuring the tractive forces and other parameters are two tractors of the Massey Ferguson 435 model of 72 hp, cone penetrometer, dynamometer, measuring tape, disc harrow, auger, stop watch and static hydraulic press for measuring tractor weight. All field tests were conducted in a loamy sand soil. Before the field experiment started, experimental layout area of 90 m by 90 m was designed with three different blocks of 90 m × 27 m each. Each block was divided into 9 (nine) strips of 90 m by 2 m wide with a space of 3m between each strip. Disc harrowing operation was carried out daily on each of the blocks with three replications for 20 days with decreasing moisture content till the last day. Figure 1 shows the experimental field layout of the tillage operations.

Soil data were collected to the depths of 50 mm, 150 mm and 200 mm respectively using soil auger, core sampler and a hand-operated soil cone penetrometer having an enclosed angle of 30^{o} for the determination of moisture content, bulk density and soil resistance before tillage operation. The towing force and drawbar-pull forces were determined using trace- tractor technique (Ani et al., 2004). The tractor carrying the implement

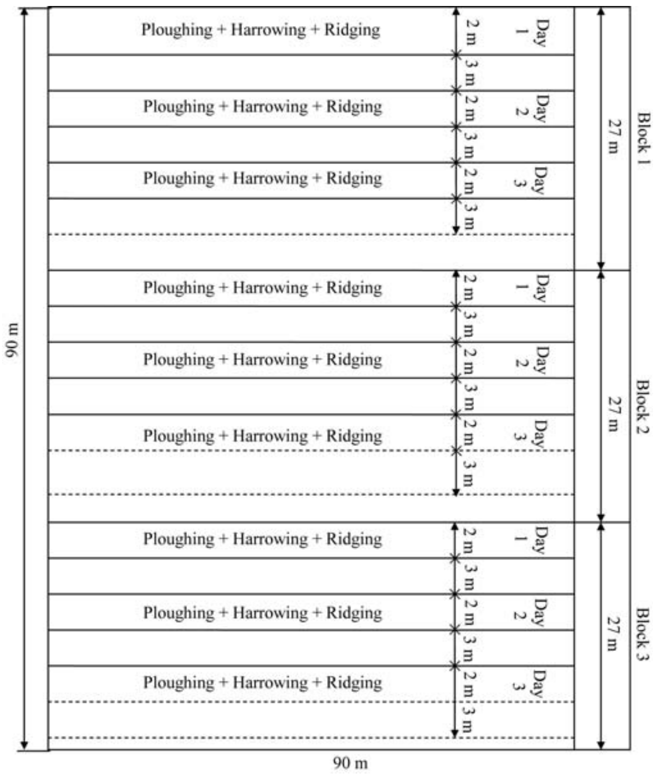

Figure 1 Experimental field layout

with its engine disengaged (neutral gear) was coupled to another tractor which towed it with the dynamometer in between them. The first tractor pulled the second tractor coupled to the implement (disc harrow). The dynamometer reading was taken to determine the towing force. The drawbar-pull was the difference between the towing force in neutral gear without implements in tillage operation and towing force when the implement was engaged in tillage operations. Depth and width of cuts were measured with a steel tape. The speeds of operations were obtained by setting the tractor at suitable gears for targeted speed of 1.94 m s^{-1}, 2.22 m s^{-1} and 2.5 m s^{-1} respectively. Simultaneously, the time taken to cover a fixed distance of 90m was recorded using a stopwatch to calculate the operating speed of the tractor and implement combination. Figure 2, shows the tractor –dynamometer- tractor-implement combination in disc harrowing operations.

Figure 2 A photograph depicting tractor-dynamometer, implement mounted position during disc harrowing operations

3 Results and discussion

The sensitivity of measured parameters to the wheel tractor tractive force model was determined. Table 1, depicts the independent variables and their respective sensitivity coefficients. The sensitivity coefficients ranging from -0.00131 to 0.2405, -0.00143 to 0.2331, -0.00233 to 0.3041 for disc harrowing at various tillage speeds of 1.94 m s^{-1}, 2.22 m s^{-1} and 2.50 m s^{-1} respectively are shown in Table 1.

Table1 Sensitivity coefficients of the tractive force model parameters for harrowing at 1.94 m s^{-1}, 2.22 m s^{-1}, 2.5 m s^{-1} tillage speeds

Parameters	Sensitivity Coefficients	Parameters	Sensitivity Coefficients	Parameters	Sensitivity Coefficients
at 1.94 m s^{-1}		at 2.22 m s^{-1}		at 2.5 m s^{-1}	
F_P	0.2405	F_P	0.2331	F_P	0.3041
F_R	0.00105	F_R	0.00143	F_R	0.00036
b	0.00126	b	0.00143	b	0.00036
P_C	-0.00131	P_C	-0.00143	P_C	-0.00233
μ	0.00132	μ	0.00142	μ	0.00130

Considering the results obtained in this tillage operations, it is obvious that a 10% change in independent variable (U_1) would cause dependent variable (N) a negligible change. The same negligible changes occur at 50% and 100% changes, in harrowing operations. This indicates that the sensitivity of developed predicted model to changes in the constituent independent variables is negligible and insignificant. The highest sensitivity coefficient value of 0.3041 for draw- bar pull was obtained at 2.5 m s^{-1} tillage speed.

This indicates the best tillage speed operation for harrowing.

4 Validated model

The model equations developed, were employed to test the validity of tractive force by showing the graphical comparison between the measured and predicted forces.

Validation of the developed model for predicting the tractive force of wheel tractor for tillage operation is important for reliability of the models. Figure 3, Figure 4 and Figure 5, show that the validated developed models of disc harrowing operations at 1.94 m s^{-1}, 2.22 m s^{-1} and 2.5 m s^{-1}, respectively had relationship between measured and predicted tractive forces with coefficients of determination R^2 = 0.990, R^2 = 0.9 and R^2 = 0.995, respectively. The linear regression analyses of the predicted models are represented by equations, Measured = 0.990 Predicted + 165.4, Measured = 0.899 Predicted + 1725 and Measured = 1 Predicted – 0.052 respectively.

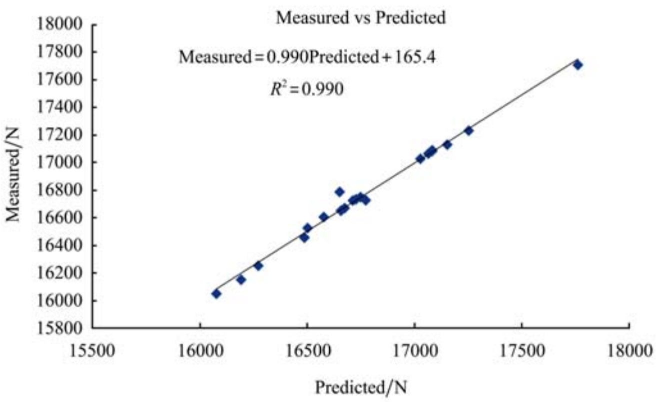

Figure 3 A plot of relationship between measured and predicted tractive force, N at tillage speed of 1.94 m s^{-1} harrowing

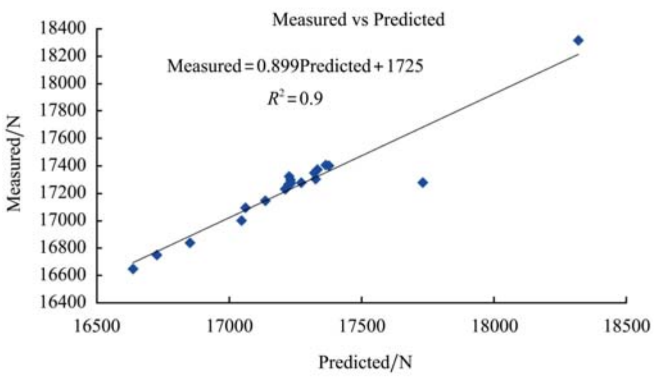

Figure 4 A plot of relationship between measured and predicted tractive force, N at tillage speed of 2.22 m s^{-1} harrowing

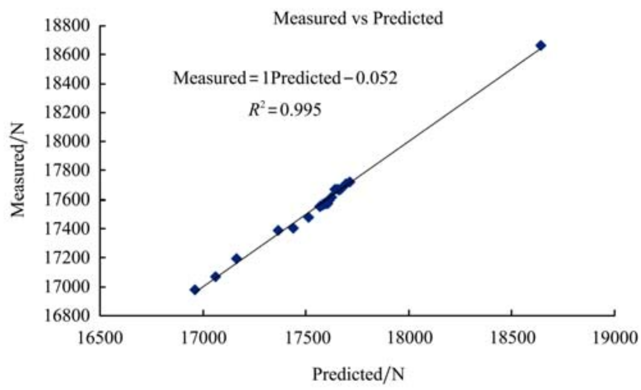

Figure 5 A plot of relationship between measured and predicted tractive force, N at tillage speed of 2.5 m s^{-1} harrowing

5 Conclusion

The sensitivity coefficients of the tractive force models parameters for disc harrowing at tillage speeds of 1.94 m s^{-1}, 2.22 m s^{-1} and 2.5 m s^{-1} showed negligible changes. The highest sensitivity coefficient value of 0.3041 for draw-bar pull was obtained at 2.5 m s^{-1} tillage speed. This indicates the best tillage speed operation for harrowing. The developed predicted equations gave results similar to the measured data. To design simple tractive devices for tillage operations, these models developed in this study can be utilized.

Appendix

Theory

The developed tractive force models for harrowing at different tillage speeds after appropriate substitutions are;

For harrowing at 1.94 m s^{-1} (Equation (1))

$$F = 12674.26 + 1.0154 F_{P\mu} + 0.0000432 F_P \frac{F_R b \mu^2}{P_c} - 0.077580 F_p \mu^2 \qquad (1)$$

For harrowing at 2.22 m s^{-1} (Equation (2))

$$F = 13241.76 + 0.889 F_{P\mu} + 0.783 F_P \frac{F_R b \mu^2}{P_c} - 0.0000774 F_p \mu^2 \qquad (2)$$

For harrowing at 2.5 m s^{-1} (Equation (3))

$$F = 12795.46 + 1.010067 F_{P\mu} + 0.184820 F_P \frac{F_R b \mu}{P_c} - 0.039298 F_p \mu^2 \qquad (3)$$

Sensitivity measured parameter is defined as the rate of change in the output of the model with respect to the change in the value of the parameter while keeping other parameters constant. Sensitivity equation (error equation) is developed for a function using (Equation (4))

$$N = f(U_1, U_2 \ldots U_n) \quad (4)$$

Sensitivity analysis was done by mathematically differentiating the developed models (1,2 and 3) using error equation in the form (Equation (5))

$$N = f(U_1, U_2, U_n) \quad (5)$$

where, N = dependent variable; (U_1, U_2, ..., U_n) independent variables.

Using Taylor's expansion

We differentiate the independent function

$$N + \Delta N = f(U_1 + \Delta U_1, U_2 + \Delta U_2, \ldots U_n + \Delta U_n)$$

Taylor's series expansion, neglecting higher orders gives

$$f(a) = f(a) + hf^1(a)$$

Thus in this case we have,

$$f(N) = f(U_1, U_2 \ldots U_n) + hf^1(U_1, U_2 \ldots U_n)$$

Application of complete derivatives formula gives Equation (6)

$$\Delta Nj = \frac{\partial Nj}{\partial U_1}\Delta U_1 + \frac{\partial Nj}{\partial U_2}\Delta U_2 + \ldots + \frac{\partial Nj}{\partial Um}\Delta Um \quad (6)$$

This equation (6) can be written as (Equation (7))

$$\Delta Nj = \sum_{i=1}^{m} \frac{\partial Nj}{\partial Ui}\Delta Ui \quad (7)$$

Then applying Taylor's theorem and neglecting squares, products, higher powers and also not considering other variables when discussing one variable causes other variables to be zero, hence,

$$\Delta N = \frac{\partial N}{\partial u_1}\Delta U_1 + \frac{\partial N}{\partial U_2}\Delta U_2 . \quad (8)$$

Relative changes or errors are defined as follows (Equation (9) and Equation (10))

$$N\xi = \frac{\Delta N}{N} \quad (9)$$

$$u\xi = \frac{\Delta u}{U} \quad (10)$$

Putting Equation (8) into Equation (9), we get Equation (11)

$$N\xi = \frac{\frac{\partial N}{\partial u_1}\Delta U_1 + \frac{\partial N}{\partial U_2}\Delta U_2}{N}$$

$$N\xi = \frac{\partial N}{\partial u_1}\cdot\frac{\Delta U_1}{N} + \frac{\partial N}{\partial U_2}\frac{\Delta U_2}{N} \quad (11)$$

from (10)

$$U\xi = \frac{\Delta u}{U}$$

$$\Delta_u = U\xi u$$

hence

$$\Delta U_1 = U_1\,\xi U_1, \quad \Delta U_2 = U_2\,\xi U_2 \quad (12)$$

as was the case with the following.

$$\Delta N = \sum_{i=1}^{n} \Delta Ni$$

$$\Delta_u = \sum_{i=1}^{n} \Delta u_i$$

Introducing (12) into (11) we obtain Equation (13):

$$N\xi = \left(\frac{\partial N}{\partial u_1} . \frac{\Delta U_1}{N}\right) + \left(\frac{\partial N}{\partial u_2} . \frac{\Delta U_2}{N}\right)$$

$$N\xi = \frac{\partial N}{\partial u_1} . \frac{U_1\,\xi U_1}{N_x} + \frac{\partial N}{\partial u_2} . \frac{U_2\xi}{N} U_2$$

$$N\xi = \left(\frac{\partial N}{\partial u_1} . \frac{U_1}{N}\right) U_1\xi + \left(\frac{\partial N}{\partial u_2} . \frac{U_2}{N}\right) U_2\xi \quad (13)$$

Which expressed the relative changes of N with respect to the sum of the relative changes of each variable. If the error or change that occurs in only one variable is considered, all the other terms would be zero i.e. only one variable causes others to become zero.

hence, Equation (14)

$$N\xi = \left(\frac{\partial N}{\partial u_1}\cdot\frac{U_1}{N}\right) U_1\,\xi + O$$

Therefore,

$$N\xi = \left(\frac{\partial N}{\partial u_1}\cdot\frac{U_1}{N}\right) U_1\xi \quad (14)$$

The bracketed terms become dimensionless coefficient, which expresses the percentage of the independent variable change, transmitted to the relative dependent variable (Simonyon, 2006). This is the sensitivity coefficient which shows the relative importance of each of the variables to the model solution. The developed and the calculated sensitivity equations for the tractive force developed model is given below:

Harrowing at 1.94 m s^{-1}

$$F = 12674.26 + 1.0154F_p + 0.0000432F_p \frac{F_R b\mu}{P_c} - 0.07758F_p\mu$$

(1) $\frac{dF}{dF_p} = 1.0154 + 0.0000432\,\frac{F_R b\mu}{P_c} - 0.07758\mu$

(2) $\frac{dF}{dF_R} = 0.0000432\frac{F_p b\mu}{P_c}$

(3) $\frac{dF}{db} = 0.0000432\,\frac{F_p F_R \mu}{P_c}$

(4) $\frac{dF}{dP_c} = -0.0000432\,\frac{F_p F_R b\mu}{P_{c^2}}$

(5) $\frac{dF}{d\mu} = 0.0000432F_p\,\frac{F_R b\mu}{P_c} - 0.07758F_p$

Harrowing at 2.2 m s^{-1}

$$F = 1324.76 + 0.889F_p + 0.783F_p \frac{F_R b\mu}{P_c} - 0.0000774F_p\mu$$

(1) $\frac{dF}{dF_p} = 0.889 + 0.783\,\frac{F_R b\mu}{P_c} - 0.0000774\mu$

(2) $\frac{dF}{dF_R} = 0.783\frac{Fpb\mu}{P_c}$

(3) $\frac{dF}{db} = 0.783\,\frac{F_p F_R \mu}{P_c}$

(4) $\frac{dF}{dP_c} = -0.783\,\frac{F_p F_R b\mu}{P_{c^2}}$

(5) $\frac{dF}{d\mu} = 0.783F_p\,\frac{F_R b}{P_c} - 0.0000774Fp$

Harrowing at 2.5 m s^{-1}

$$F = 12795.46 + 1.010067F_p + 0.184820F_p \frac{F_R b\mu}{P_c} - 0.039298F_p\mu$$

(1) $\frac{dF}{dF_p} = 1.010067 + 0.184820\,\frac{F_R b\mu}{P_c} - 0.039298\mu$

(2) $\frac{dF}{dF_R} = 0.184820\frac{F_p b\mu}{P_c}$

(3) $\frac{dF}{db} = 0.184820\,\frac{F_p F_R \mu}{P_c}$

(4) $\frac{dF}{dP_c} = 0.184820\,\frac{F_p F_R b\mu}{P_{c^2}}$

(5) $\frac{dF}{d\mu} = 0.184820F_p\,\frac{F_R b}{P_c} - 0.039298$

Nomenclature

μ	Moisture Content (%)
a	Widths of harrow, (mm)
b	Depths of harrow, (mm)
C_2	Constants
C_3	Constants
C_4	Constants
CI	Cone index (N m^{-2})
Cn	Wheel numeric
F	Tractive force (N)
F_P	Drawbar Pull (N)
F_R	Rolling resistance (N)
N	dependent variable
P_C	Tyre Contact Pressure (ground pressure) (kPa)
S	Wheel Slip (%)
U_1	Independent variable
U_2	Independent variable
V	Tractor forward speed (m s^{-1})
Z	Wheel Sinkage (mm)

References

Afolayan, S .O., J. C. Igbeka, and O. Babalola. 2005. Tillage systems and their effect on some soil properties, crop growth and shoot yield of grain- Amaranth. *Agricultural Mechanization in Asia and Latin America,* 36(1): 46-51.

Ani, A.O., C. O. Akubuo, and E. U. Odigboh. 2004. Tractability conditions for disc ploughing on a loamy sand soil in The Ilorin Agro- Ecological Zone. Proceedings of *The 5th International Conference and 26th Annual General Meeting of The Nigerian Institution of Agricultural Engineers,* Ilorin, Volume 26, pp 33- 39.

ASAE Standard. 2002. Terminology and definition for Agricultural tillage Implements ASAE S414, pp. 303.

Goering, C. E., I. Stone, W. S. David, and K. T. Paul. 2006. Off-Road Vehicle Engineering Principles. Tractions and transport devices chapter 13, pp. 351-382, St. Joseph, Mich. ASAE Copyright American Society of Agricultural Engineers.

McCuen, R. H. 1973. The role of Sensitivity analysis in hydrologic modelling. *Journal of Hydrology,* 18(1): 37-53.

Nkakini, S. O. 2013. Modeling tractive forces of wheel tractors on tilled loamy sand soils of the Rainforest Zone of Nigeria. Unpublished PhD Thesis. Department of Agricultural and Environmental Engineering of Rivers State University of Science and Technology, Port Harcourt, Nigeria.

Nwokedi, P. M. 1992. Machinery traffic and tillage effects on yam cultivation experimental and system optimization. Unpublished PhD Thesis. Department of Agricultural Engineering University of Nigeria, Nsukka.

Simonyan, K. J. 2006. Mathematical modeling of the grain cleaning process in a stationary. Sorghum thresher. Unpublished PhD Dissertation. Ahmadu Bello University, Zaria.

Thangavadivelu, S. and T. S. Colvin. 1990. Trafficability determination using Fuzzy set Theory. For presentation at the 1990 International Winter Meeting sponsored by ASAE, Hyatt Regency Chicago, Chicago, Ilionis, Dec. 18-21, 1990. ASAE, St. Joseph, M149085, 9659, U.S.A.