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Research Article
Design, Development and Evaluation of a Tangential-flow Paddy Thresher: A Response Surface Analysis

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Abstract

Background and Objective: Traditional paddy threshing is still usually carried out by women and children in the rural village. The aim of this study was to design and develop a tangential thresher, optimize the conditions necessary for threshing paddy using a response surface modeling methodology. **Materials and Methods:** Paddy straw (Faro 44 variety) was used for this study. Moisture contents at three levels between 14.50 and 25.10% and threshing drum speed between 398 and 565 rpm. The response surface of desirability function was used for the numerical optimization. **Results:** Some of the performance efficiencies (cleaning efficiency, threshing recovery, threshing efficiency, percentage loss and percentage blown grain) which was evaluated were significantly ($p<0.05$) affected by moisture content and threshing drum speed. **Conclusion:** The effects of the moisture content, threshing drum speed and its optimization were regarded as very useful to ascertain the performance efficiency of the developed tangential flow threshing machine.

Key words: Paddy threshing, threshing recovery, tangential-flow, threshing drum, cleaning efficiency, tangential thresher

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Rice (*Oryza sativa*) has been classified as a cereal belonging to the group Gramineae, a wide monocotyledonous family of 600 genera and at about 10000 species[1]. Rice is a cereal crop with wide acceptability in West Africa because it serves as a staple food of virtually all ethnic groups. Its level of demand exceeds current production output with the deficit been offset from importation[2]. Rice is consider as essential food for human consumption because of its rich nutrient constituting about 23% of human per capita energy and 16% of per capita protein[3]. Despite increasing output in rice production as a result of Government policies in Nigeria, a little pocket of importation, especially from Asia, still thrive to meet the ever increasing demand for this essential commodity[4]. In Nigeria, rice stands as the 4th most important grains crops following sorghum, millet and maize in terms of cultivated land mass and productivity due to its high nutritional value and consumption[5]. Rice is of two species, namely; *Oryza sativa* and *Oryza glaberrima*, with which *Oryza sativa* is more widely consumed[1]. India as one of the leading rice producing country, gained its food surpluses in the last four decades by engaging 42.41 million ha into paddy cultivation sharing about 28% of the world's total area of 151 million ha under paddy cultivation[6].

Threshing as an integral part of the unit operations involved in rice processing[7]. Traditional paddy threshing is usually carried out by women and children in the rural village. The techniques used include beating the straw with a wooden rod to detach the paddy, rubbing out under feet on a platform or spread out mat[7]. The output from this process is low and poor in term of quantity and quality, stress and injuries to the processors[7-9]. The low output capacity per man hour ranging from 0.001-30 kg has compelled a large population of the rural farmers to migrate to the usage of mechanical threshers which are most times difficult to access because of the absence of locally manufactured threshers[10]. Singh *et al.*[11] reported that mechanization of the threshing operation improves the quality of product and reduces the drudgery impose on farm women. Apart from the harvesting technique, the threshing technique adopted also affects the quantitative and qualitative losses of rice[12]. Based on flow mechanism, threshers can be classified as axial and tangential. In the axial flow thresher type, paddy stalks rotate spirally between the threshing drum and concave in several runs causing longer threshing duration[13]. Asli-Ardeh and Abbaspour-Gilandeh[14] reported that the axial flow thresher type does not have the capability to thresh harvested wet paddy having long stalks due to its lack of an auto-heed threshing unit. These observed shortcomings of both the manual thresher and the axial flow thresher type led to the development of the mechanical tangential-flow paddy thresher. This study was undertaken to design and construct a tangential-flow paddy thresher and also to investigate the effect of threshing drum speed and paddy moisture content on the performance efficiency of the constructed machine.

MATERIALS AND METHODS

Materials: This study was conducted in Agricultural and Biosystems Engineering workshop, Landmark University (latitude 8°9°0"N, longitude 5°61°0"E), Omu-Aran, Kwara State, Nigeria, between the period of July-October, 2018. Some freshly harvested paddy straw (Faro 44 variety) from the university farm was used in evaluating the constructed tangential-flow paddy thresher in term of the efficiencies investigated.

Methods: Three levels of moisture content (MC) (25.10, 18.10 and 14.5%) were used in the evaluation. The threshing process was accomplished with the aid of anti-clockwise revolving threshing cylinder carrying spike tooth beaters and radial fan blades arranged concentrically.

Machine component parts: The paddy rice tangential flow thresher is made up of different parts as shown in Fig. 1 and 2 comprises of the hopper for feeding, threshing drum; where paddy are detached from their straws, cylinder concave, where the detached paddy exits from, straw outlet for exit of the empty straws, paddy collector for collecting detached paddy, frame for holding all other components in position during threshing, electric motor for driving the moving parts.

Machine analysis

Threshing drum diameter: Equation 1 was used for determining the diameter of a threshing drum[15]:

$$D = \sqrt{\frac{4V}{\pi l}} \tag{1}$$

where, V is the drum volume [m^3], l is the cylinder length [m], D is the cylinder diameter [m].

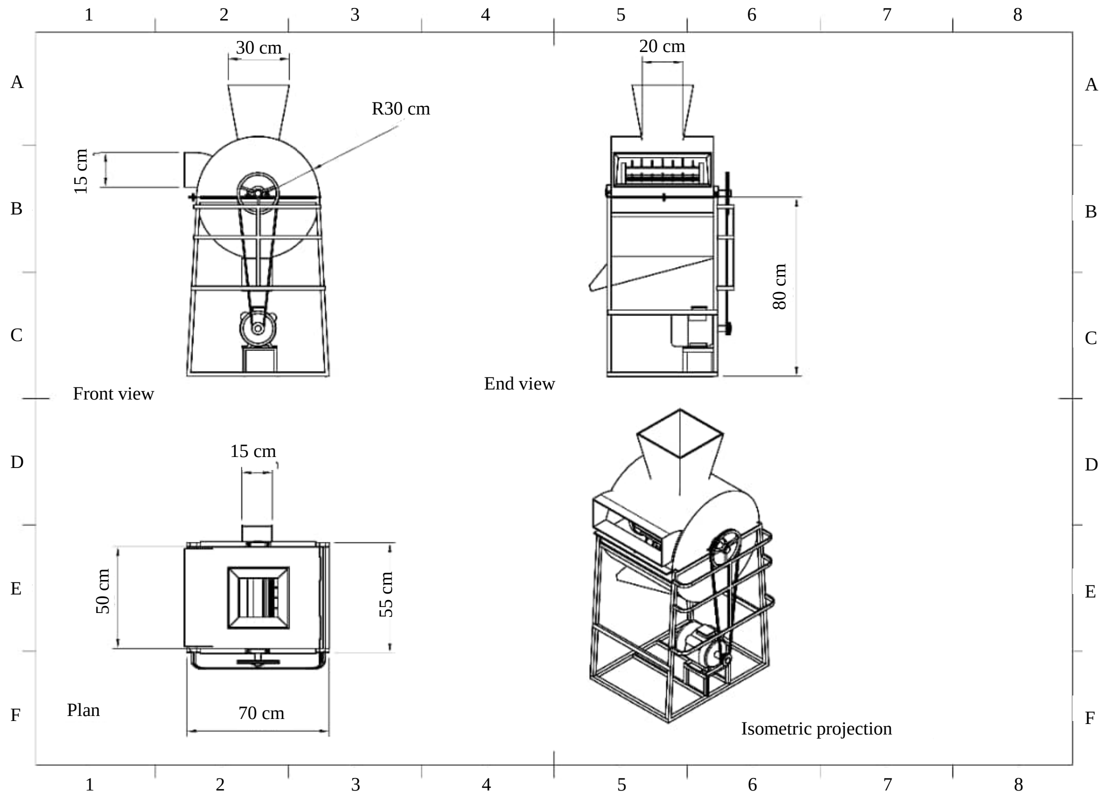

Fig. 1: Developed tangential flow paddy thresher (Orthographic view of the tangential flow paddy thresher)

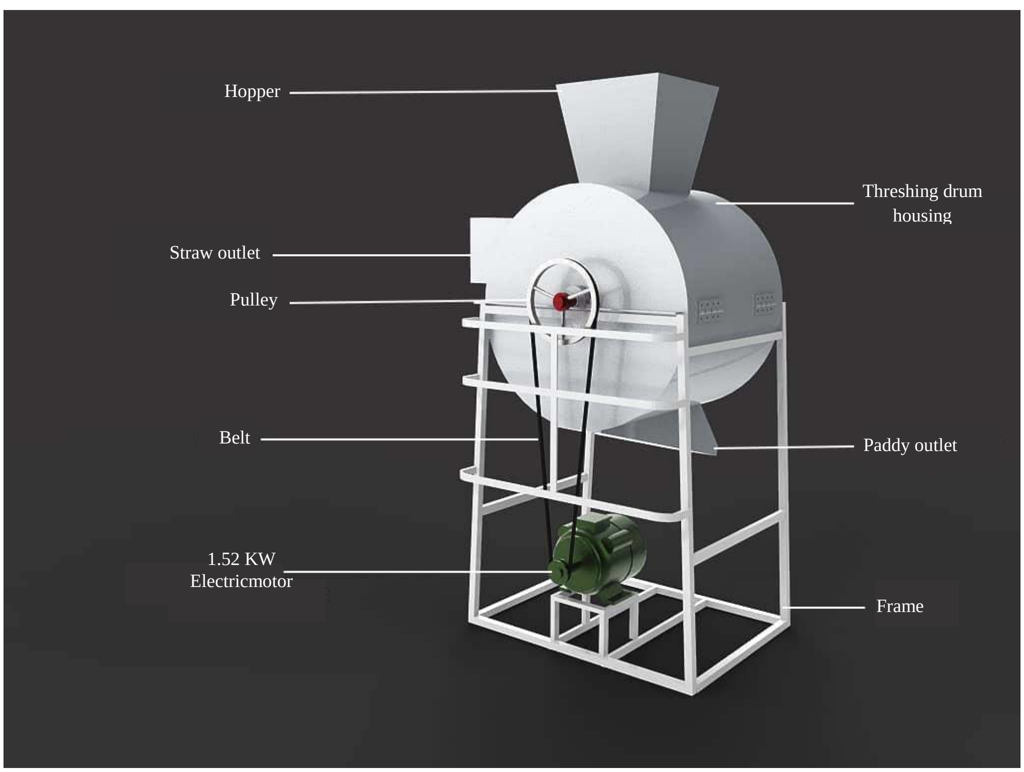

Fig. 2: Developed tangential flow paddy thresher (3-D view of the tangential flow paddy thresher)

Weight of the threshing drum: The weight of the threshing drum was computed using Eq. 2 and 3[15]:

$$W = mg \tag{2}$$

$$m = \rho V \tag{3}$$

where, W is the threshing drum weight [N], m is the mass of the threshing drum [kg], ρ is the density of the mild steel material [kg m^{-3}], g is the gravitational acceleration [m sec^{-2}].

Belt length: According to Okonkwo *et al.*[16], Fadele and Aremu[17] and Gbabo *et al.*[15], the nominal pitch length was calculated using Eq. 4 to know the actual belt length required to transfer the speed from the electric motor to the threshing unit:

$$L = 2C + \frac{\pi}{2}(D_1 + D_2) + \frac{(D_2 - D_1)^2}{2C} \tag{4}$$

where, D_1 and D_2 are the diameter of the driving and driven pulley, respectively [m], C is the distance between the centers of the driving and driven pulley [m].

Power requirement: The total power needed to thresh the paddy rice from its straw was computed[18] using Eq. 5-9:

$$\text{Total power} = P_S + P_T \tag{5}$$

where, P_S, as stated by Owolarafe *et al.*[18] is given as follows:

$$P_T = T_\omega \tag{6}$$

$$T = \frac{\pi D^3 t}{12} \tag{7}$$

$$\omega = \frac{\pi DN}{60} \tag{8}$$

$$P_S = (T_1 - T_2)V \tag{9}$$

The power rating of the electric motor used was 1.52 kw. Where, P_S is the power required to drive the threshing drum, P_T power required to detach paddy rice from it straw, T is the torque [Nm], ω is the angular speed, N speed in revolution/minute, T_1 tension of the belt on the tight side [N], T_2 tension of the belt on the slack side [N].

Determination of the threshing drum shaft: Equation 10 was used for determining the diameter of the shaft welded to the threshing cylinder[19,20]:

$$d^3 = \frac{16}{\pi S_s}\sqrt{(M_t K_t)^2 + (M_b K_b)^2} \tag{10}$$

where, S_s is the allowable shear stress, M_t is the torsional moment [Nm], K_t is the combined shock and fatigue factor applied to the torsional moment, M_b is the bending moment [Nm], K_b is the combined shock and fatigue factor applied to bending moment

The diameter of the threshing drum shaft used was 0.025 m.

Speed determination: As suggested by Sobowale *et al.*[19], Eq. 11 was used for calculating the speed of the threshing drum is as follows:

$$N_1 D_1 = N_2 D_2 \tag{11}$$

where, N_1 speed of the driving pulley [rpm], D_1 diameter of driving pulley [m], N_2 speed of driven pulley [rpm], D_2 diameter of the driven pulley [m].

Three different threshing drum speed was used; 398, 487 and 565 rpm.

Velocity of belt drive: The velocity of the belt drive (V) of the threshing drum was computed[21] using Eq. 12:

$$V = \frac{\pi DN}{60} \tag{12}$$

Determination of the shaft angle of twist: It was determined to know if the shaft size selected was safe to carry the applied load. This was calculated[15,22] by using Eq. 13:

$$\theta = \frac{584 M_t l}{G d^4} \tag{13}$$

where, θ is the angle of twist of the shaft [degrees], M_t is the twisting moment [Nm], l is the length of the shaft [m], G is the torsional modulus of elasticity [N/m^2], d is the shaft diameter of the threshing drum [m].

Machine evaluation: In the machine evaluation, crop moisture content (MC) and threshing drum speed (TDS) was varied, keeping constant the feed rate and cylinder concave clearance.

Three different paddy straws MC levels were used simultaneously with three levels of TDS (398, 487, 565 rpm). The experimental design was a central composite design with three replicates. Data collected were analyzed for its threshing efficiency, cleaning efficiency, threshing recovery, percentage loss and percentage of blown grain. Effect of threshing drum speed and moisture content levels on the performance efficiency of the machine was studied.

Cleaning efficiency: The expression given by Olaye *et al.*[2] was used to obtain the machine cleaning efficiency (CE) Eq. 14:

$$CE = \frac{W_G}{W_M} \tag{14}$$

Threshing recovery: The threshing recovery (TR) was computed using Eq. 15:

$$TR = \frac{W_T}{W} \tag{15}$$

Threshing efficiency: The threshing efficiency (TE) was calculated using Eq. 16 and 17 stated by Olaye *et al.*[2]:

$$TE = 100\text{-\% Unthreshed} \tag{16}$$

$$\text{Unthreshed (\%)} = \frac{W_U}{W} \tag{17}$$

Percentage loss: The percentage loss (PL) was calculated using a formula as expressed in Eq. 18:

$$PL = \frac{S}{W} \tag{18}$$

Percentage blown grain: The percentage of blown grain (PBG) was computed using the formula of Eq. 19:

$$PBG = \frac{Ws}{W} \tag{19}$$

where, W_g weight of the whole grain at main grain outlet per time [kg], W_M weight of the whole material at main outlet per time [kg], W_T is the weight of threshed paddy (damaged and whole) at the main grain outlet [kg], W is the total grain input per time [kg], W_U is the weight of unthreshed grain at all outlet [kg], S is the weight of whole, damaged, un-threshed and scattered grain at the straw outlet [kg], W_S is the quantity of whole grain collected at the straw outlet [kg].

Statistical analyses: The experimental design is a 3×3 factorial design. Each measurement was replicated three times and the data obtained was analyzed using IBM SPSS Statistics 22. Means, standard deviation and one-way analysis of variance (ANOVA) were conducted ($p \leq 0.05$). The data was further analyzed using Design expert software 11 (Statease) to study the responses of the various performance efficiencies on moisture content and threshing drum speed. Responses obtained as a result of the proposed experimental design were subjected to regression analysis. A polynomial regression model for the dependent variables was established to fit experimental data for each response[23] as shown in Eq. 20:

$$y_i = a_0 + \sum_{i=1}^{b} a_i x_i + \sum_{i=1}^{b} a_{ii} x_{i^2} + \sum_{i=1}^{b} \sum_{i=1}^{b} a_{ij} x_i x_j \tag{20}$$

where, x_i (i = 1, 2) are the independent variables (MC and TDS) and a_0, a_i, a_{ii} and a_{ij} are coefficient for intercept, linear, quadratic and interactive effect, respectively. Statistical analysis of the 3D surface plot was designed using Design expert software 11 (Statease), the adequacy of the regression model was checked by correlation coefficient R^2 and the p-value. To aid the visualization of the variation in responses with respect to the straw MC and TDS were drawn[23].

Optimization: The CE, TR, TE, PL and PBG are some of the parameters that determine the performance efficiency of the tangential paddy thresher. Therefore, optimal conditions were determined for the operation of the paddy thresher based on these parameters. The targeted optimal values for CE, TR, TE, PL and PBG were 63.76, 58.86, 95.27, 5.76 and 3.73%, respectively. The response surface of desirability function was used for the numerical optimization[23].

RESULTS AND DISCUSSION

Machine parameters: The analysis of variance (ANOVA) of the effect of paddy MC and TDS on the CE, TE, TR, PL and PBG were significant ($p \leq 0.05$) as presented in Table 1. The first order polynomial model for CE, TR, TE, PL and PBG were well correlated with the measured data because none of the models showed a significant lack of fit. The predicted R^2 for the responses were in reasonable agreement with the adjusted R^2 i.e., the difference was less than 0.2. The adequate precision values were >4 indicating an adequate signal (i.e., adequate model discrimination) as shown in Table 2.

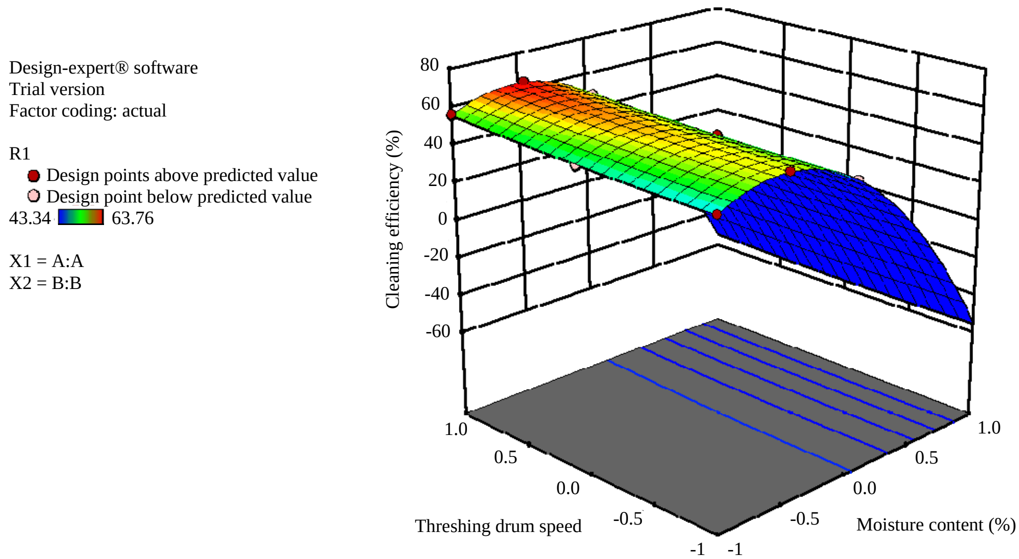

Fig. 3: Effects of moisture content (MC) and threshing drum speed (TDS) on cleaning efficiency

Table 1: Effect of moisture content and threshing drum speed on the performance efficiency of the developed tangential thresher with its coded values

MC (%)	TDS (rpm)	α CE (%)	β TR (%)	$ TE (%)	∞ PL (%)	Ω PBG (%)
14.50(-1)	398(-1)	49.29 ± 0.29^{a}	40.03 ± 0.08^{a}	90.59 ± 0.04^{b}	6.42 ± 0.02^{a}	3.73 ± 0.03^{a}
	487(0)	50.91 ± 0.11^{a}	46.62 ± 0.01^{b}	88.31 ± 0.03^{c}	8.39 ± 0.06^{b}	6.79 ± 0.02^{b}
	565(1)	56.13 ± 0.02^{b}	52.40 ± 0.05^{c}	85.30 ± 0.04^{a}	9.20 ± 0.03^{a}	8.40 ± 0.02^{c}
18.01(-0.5)	398(-1)	58.24 ± 0.05^{a}	41.32 ± 0.02^{a}	92.82 ± 0.01^{b}	5.76 ± 0.01^{c}	4.68 ± 0.01^{a}
	487(0)	59.63 ± 0.03^{a}	58.45 ± 0.02^{b}	89.71 ± 0.01^{c}	7.44 ± 0.01^{b}	6.25 ± 0.01^{b}
	565(1)	63.76 ± 0.03^{b}	58.86 ± 0.03^{b}	88.66 ± 0.01^{c}	9.18 ± 0.02^{a}	6.88 ± 0.01^{b}
25.10(0)	398(-1)	43.34 ± 0.01^{a}	41.56 ± 0.01^{a}	93.47 ± 0.02^{a}	8.36 ± 0.01^{b}	7.83 ± 0.03^{a}
	487(0)	45.47 ± 0.01^{b}	53.82 ± 0.02^{b}	95.27 ± 0.01^{b}	8.98 ± 0.01^{b}	8.14 ± 0.03^{a}
	565(1)	47.88 ± 0.01^{c}	54.09 ± 0.02^{b}	95.16 ± 0.01^{b}	9.09 ± 0.01^{b}	8.94 ± 0.01^{a}

$^{\alpha}$MC×TDS ($p\leq0.05$) = Significant, $^{\beta}$MC×TDS ($p\leq0.05$) = Significant, $^{\$}$MC×TDS ($p\leq0.05$) = Significant, $^{\infty}$MC×TDS ($p\leq0.05$) = Significant, $^{\Omega}$MC×TDS ($p\leq0.05$) = Significant, Means followed by different superscripts are significantly different ($p<0.05$) along column according to Duncan multiple range test

Table 2: Analysis of variance and model statistics for performance efficiency of the developed tangential paddy thresher

Product response	Term CE (%)	TR (%)	TE (%)	PL (%)	PBG (%)
F-value	234.010	7.630	28.520	6.680	28.690
P>F	0.0004	0.0225	0.0014	0.0298	0.0098
Mean	52.740	49.680	91.030	8.090	6.850
SD	0.577	4.570	1.010	0.8201	0.407
CV	1.090	9.190	1.110	10.140	5.940
R^2	0.997	0.718	0.945	0.690	0.980
Adjusted R^2	0.993	0.624	0.912	0.587	0.945
Predicted R^2	0.970	0.4681	0.840	0.275	0.755
Adequate precision	42.523	6.681	14.968	6.583	14.028

CE: Cleaning efficiency, TR: Threshing recovery, TE: Threshing efficiency, PL: Percentage loss, PBG: Percentage blown grain, SD: Standard deviation, CV: Coefficient of variation, R^2: Coefficient of determination

Cleaning efficiency: Response surface plot of the CE with the two independent variables (MC and TDS) is as shown in Fig. 3.

In the response surface plot it was observed that the cleaning efficiency increased with a decrease on the moisture content of the paddy, but was not appreciably affected by threshing drum speed. A similar increase was reported by Olaye *et al.*[2] where they evaluated an axial thresher at constant paddy MC of 18%, but at the variable speeds for *orylux* 6 paddy varieties. The results reported by Singh *et al.*[11] was similar to the result obtained, where it was noticed that the CE of multi-millet thresher increased with a simultaneous increase in the MC and TDS. Gbabo *et al.*[15] reported a result for the CE of a millet thresher which was in concomitance with this result, stating that CE increased with increase in speed and a decrease in MC of straw.

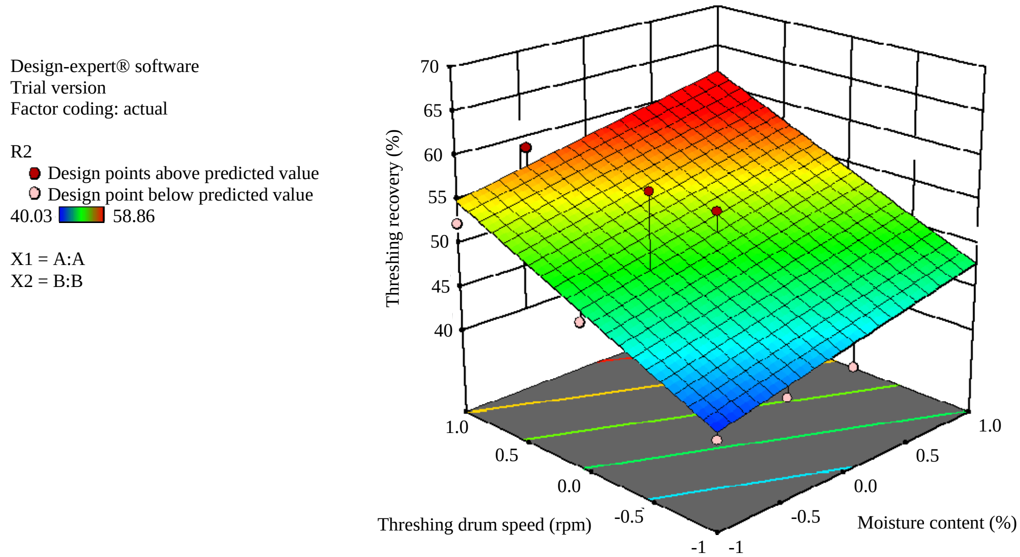

Fig. 4: Effects of moisture content (MC) and threshing drum speed (TDS) on threshing recovery

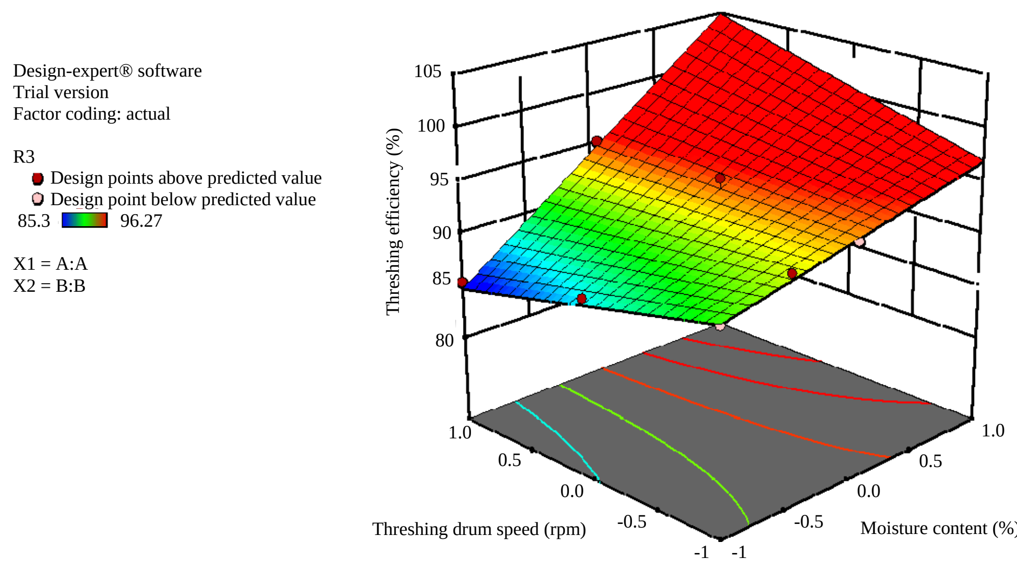

Fig. 5: Effects of moisture content (MC) and threshing drum speed (TDS) on threshing efficiency

Threshing recovery: The response surface plot for the TR with the two independent variables illustrated that it increased with an increase in the MC and TDS, this is as shown in Fig. 4. Weerasooriya *et al.*[24] reported that TR was affected negatively by MC and crop feeding rate, although the interactive effect of the TDS and MC on TR was not examined.

Threshing efficiency: The response surface plot for the TE with the two independent variables illustrated that it increased with increase in the MC and a decrease in TDS as shown in Fig. 5. The result was similar to the result reported by Olaye *et al.*[2] where an axial-flow thresher was evaluated at constant paddy MC of 18%, but at the variable speed of 600, 800, 1000 and 1200 rpm of *orylux* 6 paddy varieties. It was reported that the TE was 100% at all TDS levels. These result was not in agreement with Gbabo *et al.*[15], it was reported that TE of their millet thresher increased with an increase in speed and a decrease in MC. Singh *et al.*[11] in their report on the development of a multi-millet thresher, optimized four independent variables; MC, TDS, feed gate and sieve size and noticed that optimization with the lowest TDS gave the maximum TE of 95.13% at 7.79% MC.

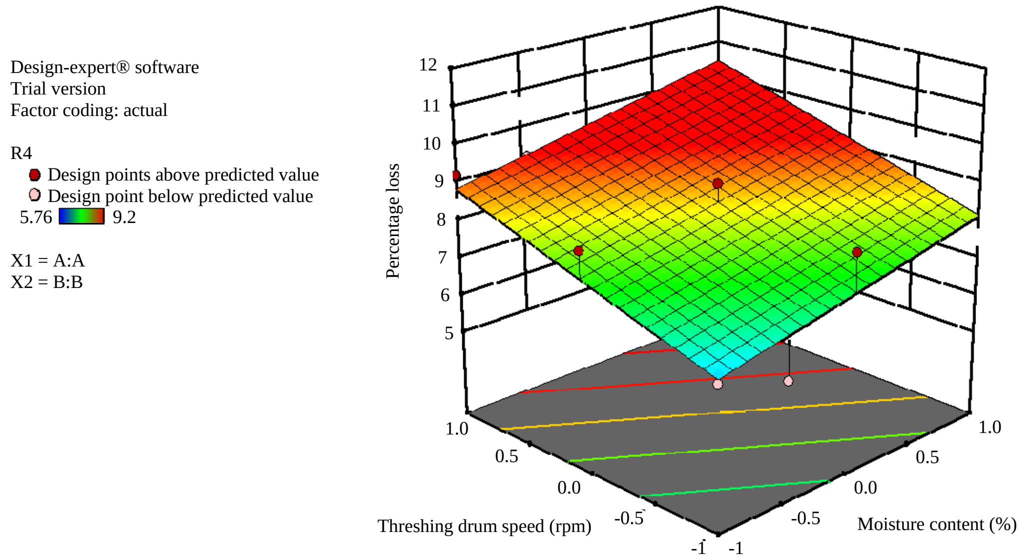

Fig. 6: Effects of moisture content (MC) and threshing drum speed (TDS) on percentage loss

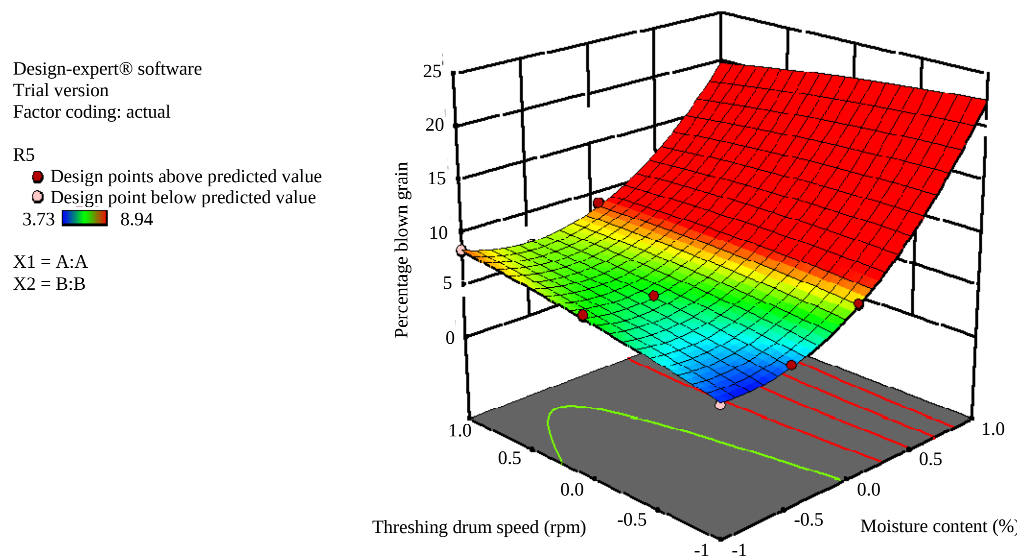

Fig. 7: Effects of moisture content (MC) and threshing drum speed (TDS) on percentage blown grain

Table 3: Predicted response versus actual response

Responses	Predicted	Actual	Variation (%)
Cleaning efficiency	43.34	63.76	32.03
Threshing recovery	40.03	58.86	31.99
Threshing efficiency	85.30	95.27	10.47
Percentage loss	5.76	9.20	37.39
Percentage blown grain	3.73	8.94	58.28

Percentage loss and percentage blown grain: The response surface plot for the PL and PBG with the two independent variables illustrated that PL and PBG increased with an increase in the MC and TDS used as shown in Fig. 6 and 7. These results were not in total agreement with the result reported by Alizadeh and Khodabakhshipour[12]. It was reported that a higher PL was recorded as the paddy MC decreased from 23-17% with an increase in the TDS from 450-850 rpm.

Optimization: The optimal performance efficiencies were obtained using the desirability function method[23]. The desirability value obtained was 0.554 as shown in Fig. 8. A MC of 19.16% wb and TDS of 446 rpm was predicted by the response surface methodology to be the optimal conditions for threshing paddy using the developed tangential flow paddy thresher. The variation between actual response and the predicted response were within the range of 10-58% as shown in Table 3. The results of all polynomial regression equation for the dependent variables are shown in Table 4.

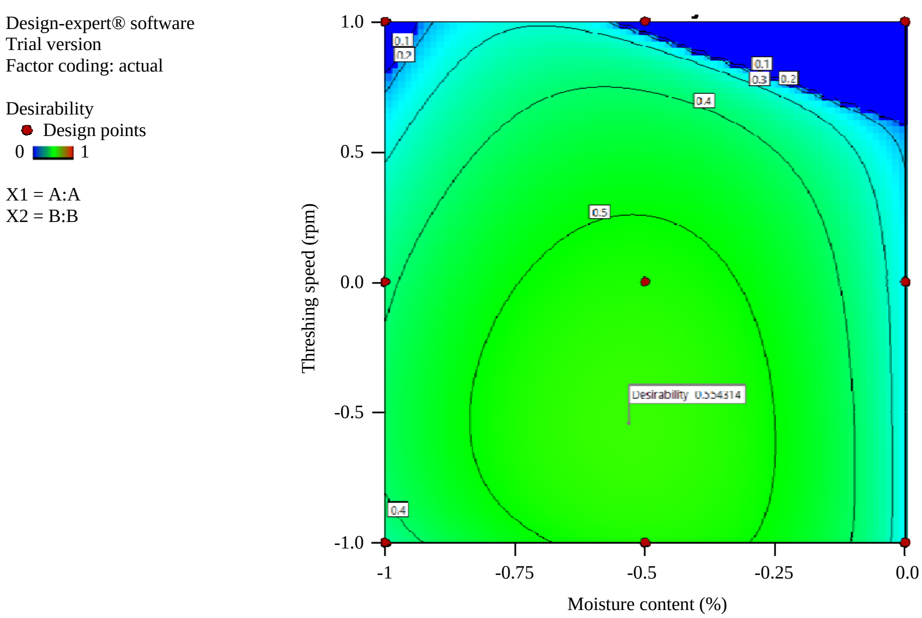

Fig. 8: Desirability function response surface for performance efficiency of the developed tangential flow paddy thresher

Table 4: Fitted regression equations

Regression models	Findings	R^2
$CE = 44.8-53.4MC+2.2TDS-1.2MC\times TDS-46.8MC^2+1.1TDS^2$	Positive and negative coefficient for the linear terms of the TDS and MC indicates that the CE increased with decrease in the MC and an increase in TDS	0.997
$TR = 51.42+3.47MC+7.07TDS$	Positive coefficient of MC and TDS in the fitted regression model suggests that the TR increased with an increase in the MC and TDS	0.718
$TE = 94.31+6.57MC+0.45TDS+3.49MC\times TDS$	Positive coefficient of MC and TDS in the fitted regression model suggests that the TE increased with an increase in the MC and TDS	0.945
$PL = 8.49+0.81MC+1.155TDS$	Positive coefficient of MC and TDS in the fitted regression model suggests that PL increased with an increase in the MC and TDS	0.690
$PBG = 8.51+7.47MC+0.44-1.78MC\times TDS+5.47MC^2-0.32TDS^2$	Positive coefficient of MC in the fitted regression model suggests that PBG increased with an increase in the MC	0.980

CONCLUSION

The traditional threshing of paddy is laborious, time-consuming and cost-intensive and of low efficiency with high PL as compared to the tangential thresher developed in the present study. The response surface modeling revealed the significant effect of the two threshing parameters (MC and TDS) on performance efficiency of the developed tangential flow thresher. Within the range of this experiment, MC of the input was found to have the greatest impact on the performance efficiency of the developed thresher. Effect of MC on TR, TE and PL were linear, but for the CE and PBG it was quadratic. The optimum operating condition was deduced to be 19.16% MC wet basis and 446 rpm TDS.

SIGNIFICANCE STATEMENT

This study provides a new design of paddy thresher (known as tangential-flow), optimizes some of the conditions necessary for threshing paddy (straw moisture content and threshing speed) and studied some of the responses of performance efficiency parameters like; threshing efficiency, threshing recovery, cleaning efficiency, performance blown grain and percentage loss to the above mentioned variables. These new design offers the rural farmers an alternative thresher which can handle wet paddy having long stalks due to it auto-heed threshing unit also the optimum threshing condition was also established.

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