Structural design optimization for pedal operated paddy thresher using response surface methodology

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Abstract: Paddy is the main crop in India grown in about 44 million ha area. Threshing of paddy is one of the most widely used practices in India. Traditional methods of threshing are still prevalent in most of the parts of North-Eastern region. The farming community of the North-Eastern region faces some difficulties in adoption due to low productivity, inadequate design, and injuries during threshing. This study attempted to optimize the most significant design parameter of pedal operated paddy thresher (POPT) such as loop spacing, tip height, drum peripheral speed and number of strips in the periphery of drum to achieve the optimum threshing capacity using Response surface methodology (RSM) in Design Expert tool. From the analysis of variance (ANOVA), results indicated that the linear term of loop spacing and tip height; interaction term of drum peripheral speed and number of strips and the quadratic term of loop spacing and drum peripheral speed have more influence on the response (P<0.05). The coefficient of determination (R^2) of the model was 0.95 which indicate a good fit between the predicted value and the experimental value. For machine parameter, optimize design dimensions are-loop spacing 3.99 cm, tip height 5.09 cm, drum peripheral speed 398.215 r min^{-1}. and number of strips 13.9421(~14). At optimum condition of machine parameters, the threshing capacity was found approximately 53.0127 kg h^{-1} with minimal worker's discomfort.

Keywords: paddy, threshing, POPT, machine parameters, RSM, optimize

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1 Introduction

Rice (*Oryza sativa* L.) is the main crop in India grown in about 44.01 million ha area produces 105.30 million tonnes in 2011-2012 (Anonymous, 2015). India is one of the world's largest producers accounting for 20% of global rice production. The North-East (NE) regions with rich bio-diversity and varying agro-climatic conditions have tremendous potential to increase the productivity of rice. In the NE, 75% farmers are small and marginal farm holder (<2 ha) (Birthal et al., 2006) are not capable of purchasing higher machinery like power thresher, instead of its, farmers used to hire the machinery but which still not meeting the needs of the farmer. The land-to-person ratio for the NE region (0.68 ha person^{-1}) is much higher than the national average (0.32 ha person^{-1}) (Anonymous, 2011). Although NE continues to be a net importer of food grains as despite covering 8.8% of the country's total geographical area, it produces only 1.5% of the country's total food grain production (Patel et al., 2013). At present, it is estimated that farm power availability in the North-East region is 0.67 kW ha^{-1} which is much lower than the national average of 1.15 kW ha^{-1} (Kaul, 2001).

The traditional rice threshing performed by hand; bunches of panicles are beaten against a hard element (e.g., bamboo table, a wooden bar or stone) or with a flail. The outputs are 10 to 30 kg of grain per man-hour according to the variety of rice. This method leads to the grain loss amount is around 1% to 4% (Paulsen et al., 2015) when threshing is performed excessively late; some unthreshed grains can also be lost over the threshing area.

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Traditional threshing methods trampling with humans and animals incur enormous losses (Belay et al., 2013). Increased rice production, the inefficiency of manual threshing, seasonal drudgeries of women worker and children, and subsequent losses require the implementation of improved threshing machines (Azouma et al., 2009). Farmers of NE mostly prefer to carry machine like the thresher by a single man for which machine weight should be less than 35 kg (Singh et al., 2008). Existing thresher available from this region (power as well as manual thresher) is not comfortable to fulfil the needs of NE farm workers. Due to non-availability of power thresher to every corner of NE area; threshing is still practised by pedal operated paddy thresher (POPT). However, many studies revealed that the threshing machine was responsible for severe injuries due to inadequate design. Many researchers have reported that threshing machines caused 2% of total agricultural injuries (Mohan et al., 1992) and the accident caused by threshers in four regions of India is about 14.6% (Nag et al., 2004) in a survey conducted in India. It was reported that more than 20% of the energy utilized for threshing activity alone (Satapathy and Sahay, 1998). Traditional methods of threshing require manpower input in the range of 80-120 man-h ha^{-1} whereas pedal paddy thresher requires about 35-40 man-h ha^{-1}, which means considerable savings in time and cost (Agrawal, 2008). The existing paddy thresher encountered problems of wrapping of paddy stalks due to the clearance between the drum and concave, inadequate threshing due to fewer numbers of strips on the periphery of the thresher drum. Thus, the objective of the present study is to optimize structural machine parameters to enhance maximum threshing capacity using response surface methodology (RSM) and central composite rotatable design (CCRD) techniques.

2 Materials and methods

A single variety of paddy was used to thresh in the nearest village, Harmuti, North Lakhimpur District, Assam. The moisture content of paddy during threshing was 20±2% (w.b.), and it was determined by universal moisture testing machine.

2.1 A brief description and measurement of existing thresher

Several pedal operated paddy threshers are available in the Department of Agricultural Engineering, North Eastern Regional Institute of Science and Technology (NERIST), Arunachal Pradesh, India.

Table 1 Various dimensions of existing POPT

Parameter	Dimension
Loop Spacing	4.5-5.5
Tip Height	5.5-6.5
Number of strips on drum periphery (nos)	12-14
Number of loop in each bar (nos)	12

Note: All the dimensions are in cm except otherwise mentioned.

The most important machine parameter which mostly influenced in paddy threshing along with their various dimensions is listed in Table 1. Although POPT is used in some part of NE region, however, the threshing output is not up to the mark as compared to traditional practice. Therefore, further modification is required for maximizing threshing output by changing the machine parameter through optimization considering threshing capacity as an output variable.

2.2 Central composite rotatable experiment design

A central composite design (CCD) with four independent variables, viz., loop spacing (X_1), tip height (X_2), drum peripheral speed (X_3) and number of the horizontal bar in the periphery of the thresher drum (X_4) at three levels was performed by applying the Stat-Ease Design Expert v7.0.0 software. For this study, RSM, using a CCRD (Hunter, 1959; Rastogi et al., 1998; Das, 2005; and Myers, 1971) to fit a 2nd order polynomial equation, was employed. The CCRD of RSM is employed to fit 2nd order polynomial equation for a desirable and optimum solution among the four independent and one dependent variable (Singh et al., 2008). The values of loop spacing (X_1) ranged from 3.5 to 5.5 cm, tip height (X_2) ranged from 4 to 6 cm, drum peripheral speed (X_3) ranged from 300 to 500 r min^{-1} (Patel, 2015) and number of strips (X_4) ranged from 12 to 14 as shown in Table 2. The limiting value of the independent variable was taken from the survey of the existing thresher and literature study. With the help of limiting values of independent variables, three different coded values viz. -1, 0 and +1 were selected. For analyzing data statistically, the variables were coded as given below (Sampaio et al., 2006).

$$x_i = \frac{X_i - X_m}{\Delta X_D}; \quad i = 1, 2, 3 \tag{1}$$

where, X_i is the uncoded value of the i^{th} test variable; x_i is the coded value of the i^{th} variable; X_m is the uncoded value of the i^{th} test variable at the center point and ΔX_D is the step change value (Singh et al., 2008).

Table 2 Experimental design for conducting the study

Sl. No.	Variable	Unit	Level 1(–1)	Level 2(0)	Level 3(+1)
1	Loop Spacing (X_1)	cm	3.5	4.5	5.5
2	Tip height (X_2)	cm	4	5	6
3	drum peripheral speed (X_3)	r min^{-1}	300	400	500
4	No of strips (X_4)	-	12	13	14

Table 3 Design of experiment using CCRD

Std	Run	Block	F1: Loop spacing (cm)	F2: Tip Height (cm)	F3: Speed (r min^{-1})	F4: No of Strips	Response (kg h^{-1})
13	1	Block 1	3.5(–1)	4(–1)	500(+1)	14(+1)	44.2
27	2	Block 1	4.5(0)	5(0)	400(0)	13(0)	49.5
24	3	Block 1	4.5(0)	5(0)	400(0)	14(+1)	53
30	4	Block 1	4.5(0)	5(0)	400(0)	13(0)	50
22	5	Block 1	4.5(0)	5(0)	500(+1)	13(0)	44
11	6	Block 1	3.5(–1)	6(+1)	300(–1)	14(+1)	47.5
19	7	Block 1	4.5(0)	4(–1)	400(0)	13(0)	50.5
25	8	Block 1	4.5(0)	5(0)	400(0)	13(0)	51.5
20	9	Block 1	4.5(0)	6(+1)	400(0)	13(0)	48.8
18	10	Block 1	5.5(+1)	5(0)	400(0)	13(0)	45.5
23	11	Block 1	4.5(0)	5(0)	400(0)	12(–1)	51
7	12	Block 1	3.5(–1)	6(+1)	500(+1)	12(–1)	45.8
3	13	Block 1	3.5(–1)	6(+1)	300(–1)	12(–1)	44
4	14	Block 1	5.5(+1)	6(+1)	300(–1)	12(–1)	42.6
26	15	Block 1	4.5(0)	5(0)	400(0)	13(0)	52
10	16	Block 1	5.5(+1)	4(–1)	300(–1)	14(+1)	40.6
1	17	Block 1	3.5(–1)	4(–1)	300(–1)	12(–1)	40.6
16	18	Block 1	5.5(+1)	6(+1)	500(+1)	14(+1)	41.6
17	19	Block 1	3.5(–1)	5(0)	400(0)	13(0)	52.4
29	20	Block 1	4.5(0)	5(0)	400(0)	13(0)	52
15	21	Block 1	3.5(–1)	6(+1)	500(+1)	14(+1)	44.5
2	22	Block 1	5.5(+1)	4(–1)	300(–1)	12(–1)	39.6
12	23	Block 1	5.5(+1)	6(+1)	300(–1)	14(+1)	44.2
28	24	Block 1	4.5(0)	5(0)	400(0)	13(0)	51.5
5	25	Block 1	3.5(–1)	4(–1)	500(+1)	12(–1)	44
6	26	Block 1	5.5(+1)	4(–1)	500(+1)	12(–1)	42.6
8	27	Block 1	5.5(+1)	6(+1)	500(+1)	12(–1)	42.4
9	28	Block 1	3.5(–1)	4(–1)	300(–1)	14(+1)	44.2
21	29	Block 1	4.5(0)	5(0)	300(–1)	13(0)	45.5
14	30	Block 1	5.5(+1)	4(–1)	500(+1)	14(+1)	40.1

Note: F1, F2, F3 and F4 represent the independent factors.

The loop spacing, tip height and number of strips with three levels of coded value were fabricated in the Department of Agricultural Engineering, NERIST, Arunachal Pradesh. For optimization of the machine parameters, a 2nd order polynomial equation (Equation (2)) was developed as a response (threshing capacity) for the coded value of independent parameters (Chen et al., 2012).

$$Y = \beta_0 + \sum_{i=1}^{n}\beta_i X_i + \sum_{i=1}^{n}\beta_{ii} X_i^2 + \sum_i\sum_j \beta_{ij} x_i x_j + \varepsilon \qquad (2)$$

The goodness of fit of the developed non-linear equations tested by F- value for lack of fit (LoF). The independent variables have fixed at three levels as per CCRD type experimental design, and a total number of 30 experiments were carried out as shown in Table 3.

3 Results and discussion

The investigation was carried out for threshing of paddy with different drum peripheral speed with a combination of tip height, loop spacing and strips to obtain the response against the independent variable. Response surface analysis applied to 30 experimental runs, and 2nd order polynomial response surface model (Equation (3)) fitted to response variables (threshing capacity). Regression analysis and ANOVA were carried out for fitting the model equation to examine the statistical significance of model terms. From the model summary statistics of the experiment, quadratic model was showing the R^2 value of 0.953 a better one along with adjusted R^2 of 0.910 and predicted R^2 of 0.819 and the quadratic model was significant (p<0.001) as shown in Table 4. Lack of fit having F-value of 1.62 was insignificant as the p>0.05 imply that the quadratic model was found significant and this model was sufficiently accurate for predicting the response (Table 5). From the ANOVA analysis, the linear term of loop spacing (A) and tip height (B); interaction term of drum peripheral speed (C) and number of strips (D), and the quadratic term of spacing (A^2) and drum peripheral speed (C^2) has more influence on the response. The coefficient of determination (R^2) of the model was 0.953, which indicates a good fit between the predicted value and the experimental value. Further, it also implies that the independent variable explains 95.33% of the variation for threshing capacity. The mathematical expression in a change of the threshing capacity with different variables A, B, C and D were well fitted to the 2nd order polynomial equation as shown in Equation 3 with R^2 of 0.953 as given below:

$$Threshing\ Capacity = 50.95 - 1.56 \times A + 0.83 \times B + 0.022 \times C + 0.41 \times D - 0.056 \times A \times B - 0.16 \times A \times C - 0.42 \times A \times D - 0.62 \times B \times C + 0.044 \times B \times D - 0.88 \times C \times D - 1.87 \times A^2 - 1.17 \times B^2 - 6.07 \times C^2 + 1.18 \times D^2 \quad (3)$$

Table 4 Model summary statistics

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	4.29	0.113	–0.0281	–0.2427	645.00	
2FI	4.80	0.155	–0.2885	–1.9032	1506.8	
Quadratic	1.27	0.953	0.9097	0.8192	93.82	Suggested
Cubic	0.95	0.987	0.9494	0.7447	132.51	Aliased

Note: PRESS stands for predicted residual error sum of squares.

Table 5 ANOVA for response surface quadratic model

Source	Sum of Square	df	Mean Square	F value	p-value Prob>F	
Model	494.76	14	35.34	21.86	<0.0001	Significant
A- loop spacing	43.56	1	43.56	26.94	0.0001	
B-tip height	12.50	1	12.50	7.73	0.014	
C-drum peripheral speed	0.0089	1	0.008889	0.005499	0.9419	
D- No of strips	2.96	1	2.96	1.83	0.1960	
AB	0.051	1	0.051	0.031	0.8619	
AC	0.39	1	0.39	0.24	0.6301	
AD	2.81	1	2.81	1.74	0.2075	
BC	6.13	1	6.13	3.79	0.0706	
BD	0.031	1	0.031	0.019	0.8924	
CD	12.43	1	12.43	7.69	0.0142	
A^2	9.08	1	9.08	5.62	0.0316	
B^2	3.56	1	3.56	2.20	0.1586	
C^2	95.52	1	95.52	59.09	<0.0001	
D^2	3.60	1	3.60	2.22	0.1566	
Residual	24.25	15	1.62			
Lack of Fit	18.54	10	1.85	1.62	0.3086	Insignificant
Pure Error	5.71	5	1.14			
Total	519.01	29				

3.1 Variation of threshing capacity with independent variables

From the above relation between the response and independent variable, it clearly shows that threshing capacity (Response) was directly related to every independent parameter. It observed from the Figure 1 that at fixed value of speed (400 r min^{-1}) and number of strips (13), threshing capacity increased slowly with loop spacing up to 4 cm (approx.) and decreasing thereafter, achieving the maximum response of capacity at about 52.6 kg h^{-1}. Similarly, at same condition, it increased with tip height up to 5.3 cm (approx.) and reduced thereafter. At a fixed value of tip height (5 cm) and number of strips (13), threshing capacity was slightly increased with loop spacing up to 4 cm but decreased abruptly thereafter with increasing the spacing (Figure 2), and at this stage, maximum capacity with peripheral speed was observed at around 390 r min^{-1}. and decreased thereafter. Again at fixed value of loop spacing (4.5 cm) and number of strips (13), threshing capacity increased gradually with tip height up to 5.8 cm (approx.) and decreased gradually. At same condition, it increased with drum peripheral speed up to 400 r min^{-1}. (approx.) and reduced thereafter (Figure 3). At fixed value of loop spacing (4.5 cm) and tip height (5 cm), threshing capacity increased gradually with drum peripheral speed 400 r min^{-1}. (approx.) and decreased thereafter, and it decreased with number of strips up to 13 r min^{-1}. (approx.) and increased thereafter (Figure 4). Threshing capacity is maximum at loop spacing of 4 cm (approx.) with the number of strips in between 13 and 14 when other two parameters are in constant (i.e. tip height = 5 cm and drum peripheral speed = 400 r min^{-1}) and decreases gradually (Figure 5). Similarly, threshing capacity found maximum around tip height of 5.5 cm with 14 numbers of strips (approx.) at a constant spacing of 4.5 cm and drum peripheral speed of 400 r min^{-1}. and decreases slowly with varying the tip height and number of strips (Figure 6). These were the probable findings towards the best optimal condition for the existing pedal thresher.

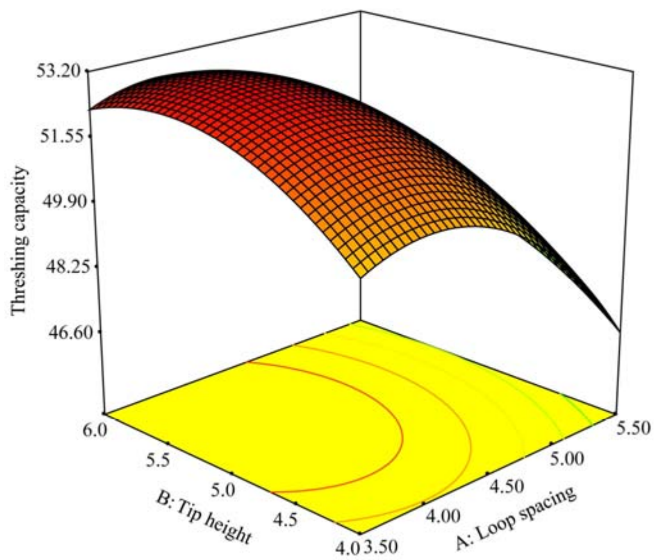


Figure 1 Effect of loop spacing (cm) and tip height (cm) on threshing capacity at optimum drum peripheral speed (400 r min^{-1}) and No of strips (13)

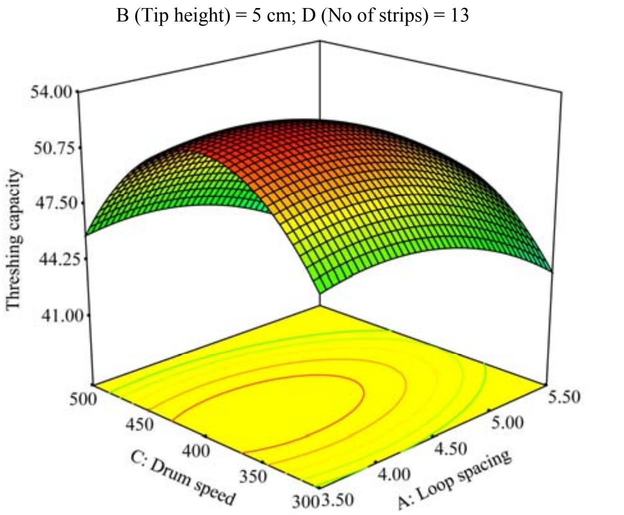


Figure 2 Effect of loop spacing (cm) and drum peripheral speed (r min^{-1}) on threshing capacity at optimum height (5 cm) and No of strips (13)

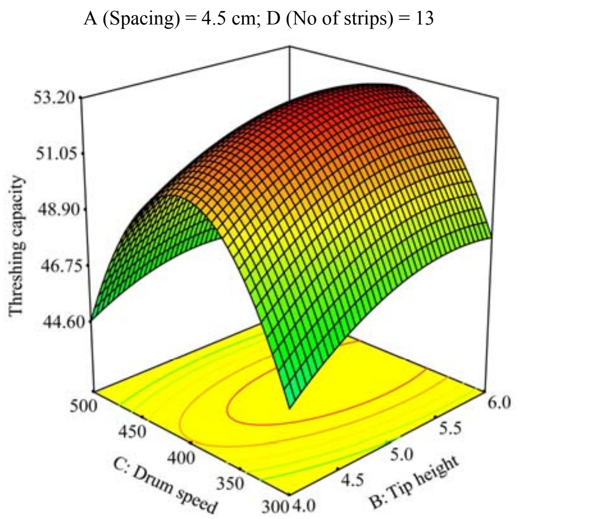


Figure 3 Effect of tip height (cm) and drum peripheral speed (r min^{-1}) on threshing capacity at optimum loop spacing (4.5 cm) and No of strips (13)

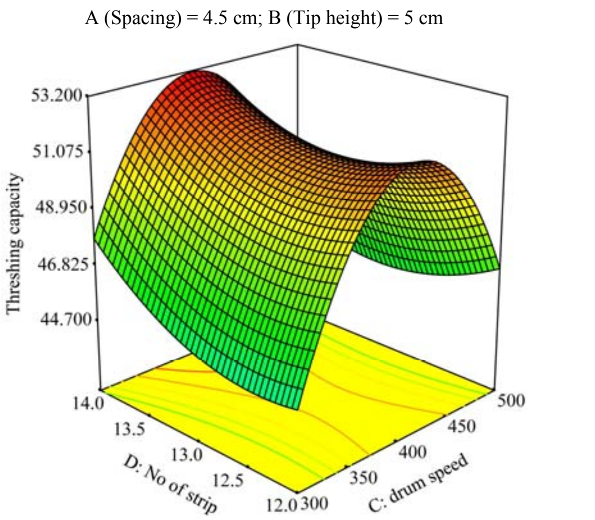


Figure 4 Effect of No of strips and drum peripheral speed (r min^{-1}) on threshing capacity at optimum height (5 cm) and loop spacing (4.5 cm)

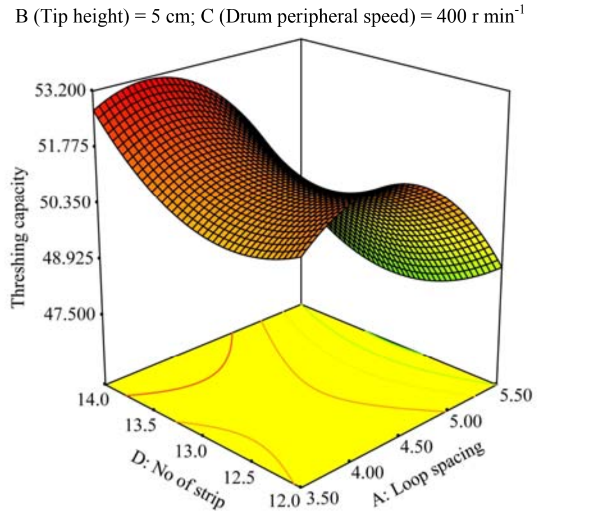


Figure 5 Effect of loop spacing (cm) and No of strips on threshing capacity at optimum height (5 cm) and drum peripheral speed (400 r min^{-1})

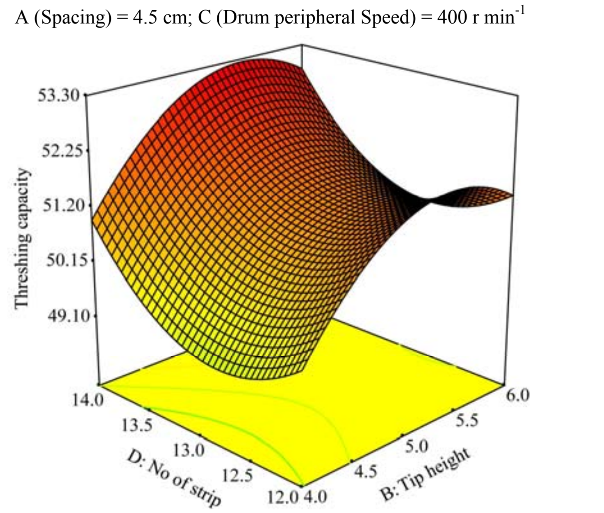


Figure 6 Effect of No of strips and tip height (cm) on threshing capacity at optimum drum peripheral speed (400 r min^{-1}) and loop spacing (4.5 cm)

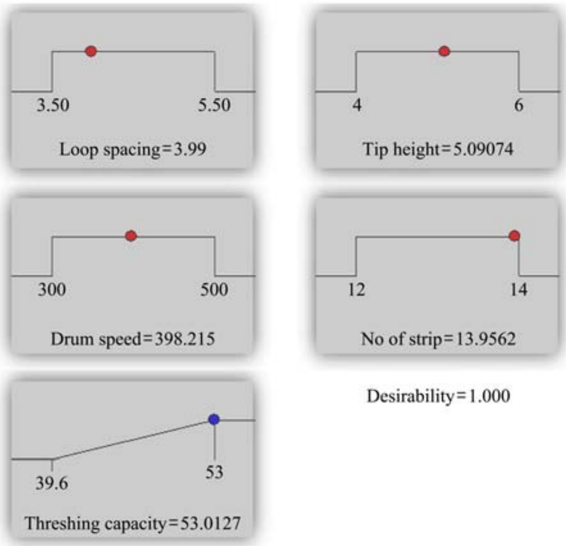
3.2 Desirability function approach towards the optimum response

The desirability function approach is a technique for simultaneous determination of optimum settings of input variables that can determine optimum performance levels for one or more responses. It was introduced by Harrington (1965).

The general approach is to first convert each response (y_i) into an individual desirability function (d_i) over the range.

$$0 \le d_i \le 1$$

From the Design Expert analysis for optimization, the tool suggests 25 numbers of optimizing solution for threshing capacity which having suitable desirability. Among the results, the best optimizing condition for threshing capacity with respect to four independent variables having a maximum desirable value of 1.0 as shown in Figure 7.



(Unit of parameter: loop spacing in cm; tip height in cm; drum speed in r min^{-1})

Figure 7 Desirability ramp for optimization

3.3 Optimization of design parameter

From the selected design parameters, optimize dimensions are loop spacing = 3.99 cm, tip height = 5.09 cm, drum peripheral speed = 398.215 r min^{-1} and number of strips = 14. The maximum threshing capacity for optimize independent variables was found 53.0127 kg h^{-1} (Figure 8). The findings of the optimization study i.e. threshing capacity and developed model was found comparable with work carried out by other researchers in agriculture and allied science (Goyal et al., 2008; Zhang et al., 2007; Mangaraj et al., 2011; Pratape et al., 2004; and Rastogi et al., 1998). Further, similar approach was also carried out for paddy thresher by Singh et al. (2008) and inferred that wire loop geometry and speed of the drum have a significant effect on the threshing efficiency.

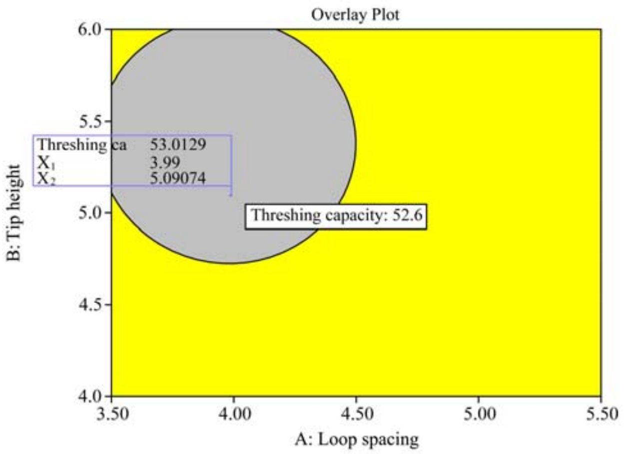


Figure 8 Overlay plot for optimizing threshing capacity

4 Conclusions

This paper presents the application of response surface methodology for optimizing the most significant design parameters of pedal operated paddy thresher. The experiment investigated into the effect of loop spacing, tip height, drum peripheral speed and number of the strips in the periphery of the drum on the threshing capacity of POPT. The outcome of the investigation revealed that loop spacing = 3.99 cm, tip height = 5.09 cm, peripheral drum speed = 398.215 r min^{-1} and number of strips on the periphery of the rotating drum =13.9421(~14) were the significant factors influencing the threshing capacity investigated. Among the four independent parameters, most considerable influence on threshing capacity was a linear term of loop spacing (A) and tip height (B); the quadratic term of spacing (A^2) and speed of the drum (C^2) and an interaction term of drum peripheral speed and number of strips (CD). The quadratic models developed using RSM were reasonably accurate and can be used for prediction within the limits of the factors considered for investigation.

Nomenclature

ha	hectare
kW ha^{-1}	Kilowatt/hectare
w.b.	Wet basis
No	number
cm	centimeter
F-test	Fisher test
df	Degree of freedom
X_i	Uncoded value
x_i	Coded value
X_m	Uncoded value at center point
X_D	Steep change
Y	Threshing capacity
v7	Version 7
Kg h^{-1}	Kilogram/hour
β_o	Constant coefficient
β_i	Linear coefficient
β_{ij}	Interaction coefficient
X_i	Coded value of independent parameter
X_{ii}	Quadratic term of independent parameter
X_{ij}	Interaction term of independent parameter
ε	Experimental error
r min^{-1}	Revolution per minute
NE	North-East
Eqn	Equation
h	Hour
p	Probability

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