Optimization of Operational Parameters for Axial Flow Paddy Thresher using RSM

ABSTRACT

Post-harvest practices remains significant qualitative and quantitative throughout the paddy value chain despite rising agricultural productivity. When it comes to rice, most losses occur during the harvesting and threshing operations. In optimizing operating variables, the use of response surface methodology (RSM) and complete randomized design (CRD) is effective. This research discusses the application of these approaches to determine the impact of various operational factors on the performance of an axial flow paddy threshers. Three major operating variables, feeding rate, cylinder speed, moisture content, were changed during the paddy threshing. The machine was evaluated using feed rates in the range of 1700 to 1900 kg/h, threshing cylinder speed from 400 to 650 rpm, and crop moisture content 12 to 16% for the crop. Algebraic models were created in Design-Expert software using computer simulation by the least-squares method to optimize the variables. Models for fuel consumption and torque requirement for threshing were developed and represented the three operational parameters. The study found that all three parameters significantly affected fuel consumption and torque requirement at the linear and quadratic levels. Furthermore, the optimum the torque requirement and fuel consumption was 1152.78 Nm and 2.51 l/h, respectively at 12 % moisture content of paddy, Which was recorded at feed rate (1703.92kg/h), cylinder speed (400 rpm). However, no significant change was observed at the level of the interactions.

Keywords:- Axial flow thresher, Fuel consumption, Response surface methodology, Torque requirement

1. Introduction

India has 43.7 Million hectare (Mha) area under paddy cultivation with the 118.4 Metric Tonne (MT) production and the productivity was recorded about 2.7 tonne/hectare [1]. A total of 4.8 MT paddy is produced in an area of 1.98 Mha in Madhya Pradesh. The paddy production in the state increased by 4.43% annually from 4.23 MT to 4.8 MT [2]. Combine harvesters are well adapted for harvesting paddy by farmers in Madhya Pradesh. However, in many parts of the states, the threshing is done manually or with reaper. Manual harvesting of paddy is tedious, time-consuming and costly operation, it needs about 100-150 man-hour labour to harvest one hectare of paddy farm [3]. The manual method is labour intensive and often leads to low-quality paddy and a substantial grain losses. It is estimated that 30% of paddy is lost through physical losses along the cultivation chain [4]. As paddy production is increased, the manual threshing becomes unproductive and burdensome. Manual threshing is still customary used in India due to its low cost; however, theoretical and practical losses could be as considerable as 20-30%. This is particularly true for panicles that are either too dry or too wet [5]. Bora and Hansen conducted a field experiment to compare the losses in reaper and manual method of paddy harvesting. They found that grain loss was 2.3% and 1% for reaper and manual harvesting, respectively [6].

Rice quality can be improved and the threshing process made easier by using an appropriate threshing method. Due to low capacity and higher grain losses in conventional threshers, the axial flow threshing mechanism is proposed [7]. Compared to conventional spike tooth threshers, axial flow threshers may save 50% labour and 54% operating costs [8]. Axial flow threshing technologies have been applied in grain threshing systems widely. It was observed that as compared to conventional threshers, axial flow threshers are used to increase threshing quality significantly reduced grain loss and damage up to 2-5 % [9] [10].

The axial flow approach was a significant shift from the threshing mechanisms applied in threshers and combine harvesters across the world. In an axial flow machine, the crop circulates spirally between the threshing drum and concave for several rounds. As a result of the repetitive impact of threshing pegs, the crop is threshed for a more extended [11]. This approach enables multi-stage crushing and grain straw extraction, increasing threshing and cleaning efficiency [12]. The crop retention period within the threshing unit was increased from 3.0 to 7.5 seconds [13]. However, the challenge in using the threshing machines is knowing the correct threshing cylinder speed to thresh the paddy to minimize the economy of operation. Several researchers have been conducted studies regarding fuel consumption and torque requirement shown in table 1.

Table 1: Torque requirement and fuel consumption of threshers at their cylinder size and respected cylinder speeds

Researcher	Cylinder size (Diameter × Length) m	Cylinder speed (rpm)	Torque requirement (Nm)	Fuel consumption (l/h)
[14]	0.067×0.117	500-630	15000-20000	3.16
[15]	0.4×1.12	-	880-1030	-
[16]	0.3×1.1	600-1200	16422	1-1.7
[17]	0.5×1.0	550-650	4000	0.37-0.47
[18]	0.46×1.24	250 -350	148-336	-
[19]	-	398-565	1520	-
[20]	0.37×1.36	1100-1500	5430-10630	-
[21]	0.8×1.77	143 - 417	-	2.75

Currently, very few studies have addressed the economy of operation regarding fuel consumption and torque requirement for threshing of paddy with axial flow paddy thresher. This raises the question of identifying the best parameters in crop feed rate, threshing cylinder speed, optimum crop moisture content, and suitable variety recommended to paddy farmers. Thus, this study aimed to evaluate the effect of feed rate, cylinder speed, and crop moisture content for an axial flow thresher.

2. Materials and Methods

2.1 Study location and description of the machine

The study was carried out at the departmental farm of the Department of Farm Machinery and Power Engineering, College of Agricultural Engineering, Jawaharlal Nehru Krishi Vishwavidyalaya Jabalpur, Madhya Pradesh, during the period of 2018-2019. To achieve the study's objectives, PTO operated Onkar Paddy thresher (Hadamba) was used. The prevalent variety of paddy in Madhya Pradesh Kranti was used for the study.

The selected thresher is consists of an axial-flow peg and rasp bar type threshing cylinder, a manual throw-in feeding chute, and a straw blowing mechanism at the end of the cylinder (Fig 1). Generally, in an axial flow thresher, 80% of the grains are separated in the first half of the threshing cylinder, while only 20% of the grains are separated in the second half of the rotor [22] [23]. A semi-hexagonal threshing drum is covered with spiral louvers that promote axial crop movement inside the threshing unit in the thrasher. Table 2 shows the technical characteristics of the thresher adopted in this study.

Table 2. Brief specification of the axial flow paddy thresher

S. No.	Particulars	Dimensions/ Details
1	Type of thresher	Axial flow
2	Crop	Paddy
3	Method of feeding	Manual
4	Type of feeding system	Feeding chute
5	Size of feeding chute opening, mm	382×262
6	Type of threshing drum	Peg and Rasp bar type
7	Drum diameter (mm)	815
8	Drum length (mm)	1805
9	Threshing cylinder speed, rpm	550-600
10	Distance between two peg tooth, mm	212
11	Size of pegs, mm	80-90
12	Optimum feed rate	1800 kg/h
13	Concave type	Semi-circular, Open
14	Concave clearance (mm)	11
15	Type of bar used	Square bars
16	Net weight (kg)	1460
17	Power (hp)	50-60

The variety selected for the experiment was Kranti, which is quite popular among the farmers of Jabalpur and Madhya Pradesh. The crop was manually harvested, 10-15 cm above the ground, and collected for the experiment. The harvested crop was laid in the open field to dry up to the desired moisture content level. At the time of harvesting, the crop's moisture content was 18-20 %. Table 2 shows the physical properties of a chosen paddy variety.

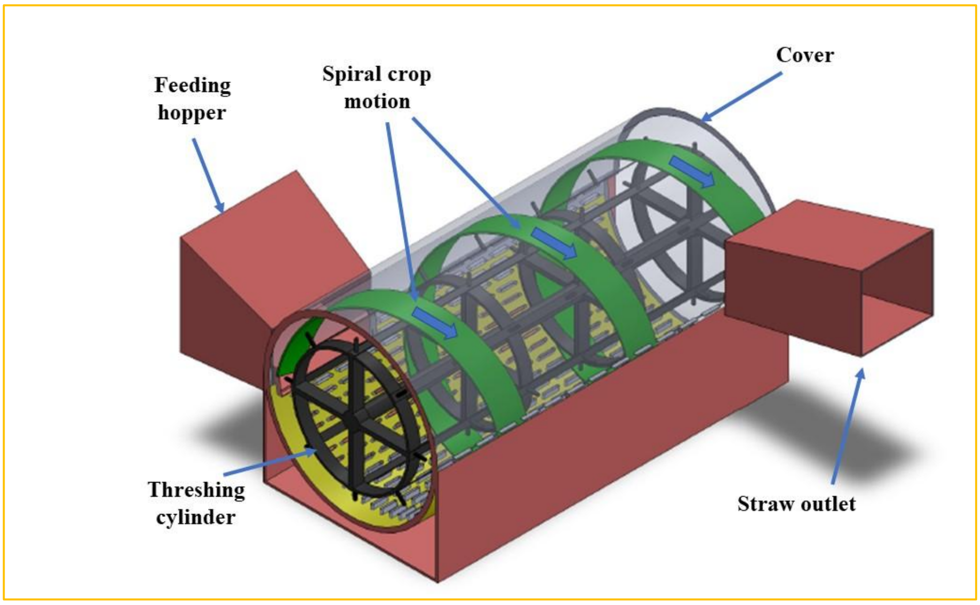

Figure 1 A view of the crop flow in axial flow paddy thresher

Table 3: Physical characteristics of selected paddy variety

S. No.	Characteristics	Description
1	Maturity period, days	118-122
2	Plant height (cm)	95-100

3	1000 grains mass (g)	31-35
4	Length of panicle (mm)	18-21
5	Length of grain (mm)	7-11
6	Straw grain ratio	1:1-1:1.3
7	Paddy grain yield (ton/ha)	58-62

2.2 Methodology

Bundles of the harvested crop were manually fed into the threshing chamber at a consistent pace for each experimental run, and the time needed for threshing was recorded. Testing of axial flow paddy thresher was carried out on known yield and quality of the threshed seed on a mass basis. The machine was evaluated using different feed rates (from 1700 to 1900 kg/h), threshing cylinder speeds (400 to 650 rpm), and crop moisture content (12 to 16 %). For measuring cylinder speed (rpm) and PTO torque (Nm), a no contact-type digital laser tachometer and a digital in-line in-line torque sensor (Fig 2) were used, respectively. The experiment was replicated three times. Torque requirement (Nm) and fuel consumption (l/h) were determined for each treatment. Analysis of variance (ANOVA) was performed using Stat-Ease Design-Expert (V 13.0) software, and separation of treatment means was done using the LSD at a 5% level of significance.

Figure 2 A view of in-line torque sensor

2.3 Experimental design and analysis

Three independent variables, viz., feed rate (A), cylinder speed (B), and moisture content (C) were considered for optimization of paddy crop threshing. The experimental plan for optimization consisted of two dependent variables, viz., torque requirement (TR) and fuel consumption (FC). Response surface methodology (RSM) was used to fit a second-order polynomial equation using a completely randomized design (CRD) [24]. Feed rate values vary from 1700 to 1900 Kg/h, Cylinder speed from 400 to 650 rpm, and Moisture content from 12 to 16 % (Table 4). The limiting values of the independent parameter were based on the test code for power thresher (IS: 6284-1985) [25].

Table 4 Study variables and their levels for analysis

Name	Units	Minimum	Maximum	Coded Low	Coded High	Mean	Std. Dev.
Feed rate	Kg/h	1631.82	1968.18	-1 ↔ 1700	+1 ↔ 1900	1800	84.78
Cylinder speed	RPM	314.78	735.22	-1 ↔ 400	+1 ↔ 650	525	105.98
Moisture content	%	10.64	17.36	-1 ↔ 12	+1 ↔ 16	14	1.70

Five potential levels of coded values, namely – β, − α, 0, + α, and + β were chosen using the limiting values of independent variables [24]. These were then used to calculate the actual variable levels for each of the 57 trials (Table 6). Table 4 shows the calculated values of the coded variable levels for CRD.

Table 5 Relationship between coded and actual values of a variable [26]

Code	Actual Value of Variable (V)
- β	V_{min}
− α	$[(V_{max}+V_{min})^2]-[(V_{max}-V_{min})/2\rho]$
0	$(V_{max}+V_{min})/2$
+ α	$[(V_{max}+V_{min})^2]+[(V_{max}-V_{min})/2\rho]$
+ β	V_{max}

Note: Vmax and Vmin = maximum and minimum values of x respectively; $\rho=2^{k/4}$; k = number of variables (in this study; $\rho = 2^{34} = 1.68$)

Table 6 Central randomized design with trials for the analysis of three experimental variables in coded and actual levels, with observed findings

Run	Coded variables			Actual variables			Responses	
	V1	V2	V3	A	B	C	TR (Nm)	FC (l/h)
1	0	0	β	1800	525	17	1270.5	4.75
2	0	0	−β	1800	525	11	1195.6	3.08
3	0	0	0	1800	525	14	1248.3	3.19
4	0	0	0	1800	525	14	1241.5	3.18
5	0	0	0	1800	525	14	1243.2	3.11
6	**-α**	**-α**	**-α**	**1700**	**400**	**12**	**1155.7**	**2.65**
7	0	β	0	1800	735	14	1300	5.04
8	β	0	0	1968	525	14	1334.2	5.22
9	0	0	0	1800	525	14	1241.5	3.18
10	-α	α	α	1700	650	16	1323.9	4.33
11	−β	0	0	1632	525	14	1185.7	2.89
12	0	−β	0	1800	315	14	1205.2	2.98
13	0	0	0	1800	525	14	1248.3	3.19
14	-α	-α	α	1700	400	16	1235.8	3.41
15	α	α	α	1900	650	16	1353.6	4.75
16	α	α	-α	1900	650	12	1285.4	3.64
17	α	-α	α	1900	400	16	1275.6	4
18	α	-α	-α	1900	400	12	1202.7	3.76
19	-α	α	-α	1700	650	12	1240.8	3.48

20	0	0	0	1800	525	14	1244.3	3.24

Fig. 3 Evaluation of axial flow paddy thresher

The intended objectives (maximize or minimize) for each variable and response were selected, and different weights (a value between 0.1 and 1.0 indicating the relevance of the preferred outcome) were applied to each target to adapt the form of its specific desirability function. The values given in table 5 were grouped, and the optimized values of variables such as Feed rate (1700.00 kg/h), cylinder speed (400 rpm), moisture content (12 %), TR (1155.7 Nm), and FC (2.65 l/h) were determined. The numerical optimization approach yielded results closer to those generated by the graphical optimization method.

The Stat-Ease Design-Expert (V 13.0) software package was used to optimize various solutions simultaneously. The response functions representing TR and FC may be written as a function of the three operational parameters of an axial flow paddy thresher, namely, feed rate, cylinder speed, and crop moisture content, based on the experimental data shown in Table 5. For the coded unit, the equations (1) and (2) between responses and operational parameters were found as follows:

$$\boldsymbol{TR = 1244.18 + 30.08A + 36.12B + 31.50C - 1.56AB - 2.76AC - 0.21BC + 7.65338\,A^2 + 5.05B^2 - 1.85C^2} \quad \textbf{...(1)}$$

$$\boldsymbol{FC = 3.19103 + 0.45A + 0.42B + 0.422C - 0.14\,AB - 0.03AC + 0.12BC + 0.24A^2 + 0.23B^2 + 0.19C^2} \quad \textbf{...(2)}$$

Where,

TR = Torque requirement (Nm)
FC = Fuel consumption (l/h)
A = feed rate (kg/h)
B = cylinder speed (rpm)
C = crop moisture content (%)

3. Results and discussion

3.1 Torque requirement

According to the F-values in Table 7, the linear term of cylinder speed has a more significant effect on torque requirement than other independent variables. All three factors impact the torque required at the linear levels, but there is no substantial effect at the interactions level. The numerical representation of the torque requirement in variation with variables A, B, and C was composed of a polynomial equation with a coefficient of determination R^2 of 0. 7361. The regression equation was obtained for the response torque requirement with three independent variables presented in equation 1.

Table 7 ANOVA for the torque requirement using the Response Surface Model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	45062.50	9	5006.94	13.37	0.0002	Significant
A-Feed Rate	12359.70	1	12359.70	33.00	0.0002	
B-Cylinder Speed	17820.97	1	17820.97	47.58	< 0.0001	
C-Moisture Content	13555.76	1	13555.76	36.19	0.0001	
AB	19.53	1	19.53	0.0521	0.8240	
AC	61.05	1	61.05	0.1630	0.6949	
BC	0.3613	1	0.3613	0.0010	0.9758	
A^2	844.13	1	844.13	2.25	0.1642	
B^2	368.22	1	368.22	0.9831	0.3448	
C^2	49.71	1	49.71	0.1327	0.7232	

Response surface plots and contours of torque requirement and fuel consumption as a function of feed rate, cylinder speed and moisture content are shown in Fig 4 a, b, c, d, e and f. Torque requirement of the thresher is affected by feed rate, It can be observed from figure 4a that, as we increase the feed rate from 1700 to 1900 kg/h the torque is also increased, this may be due to a higher feed rate, more material to be handled by the cylinder at a particular time. Similarly, Tewari et al. 2013 also came to similar conclusions [8]. The lowest torque (value) was observed at 400 rpm cylinder speed. As we increase the threshing cylinder speed, the torque requirement increases gradually (Fig 4b). This may be because the cylinder speed is directly proportional to the torque requirement of the thresher. Comparable results of increasing cylinder speed on torque requirement were observed by Ahuja et al. 2017 [18]. Torque requirement was highly influenced by the moisture content of the paddy crop. The f value of torque requirement and analysis of variance are presented in Table 6. It can be observed that 12 % moisture content (lowest) and 1700 kg/h feed rate provide minimum torque requirement (Fig 4c); however, an increase in moisture content also increases the torque requirement. The results of [27] are similar.

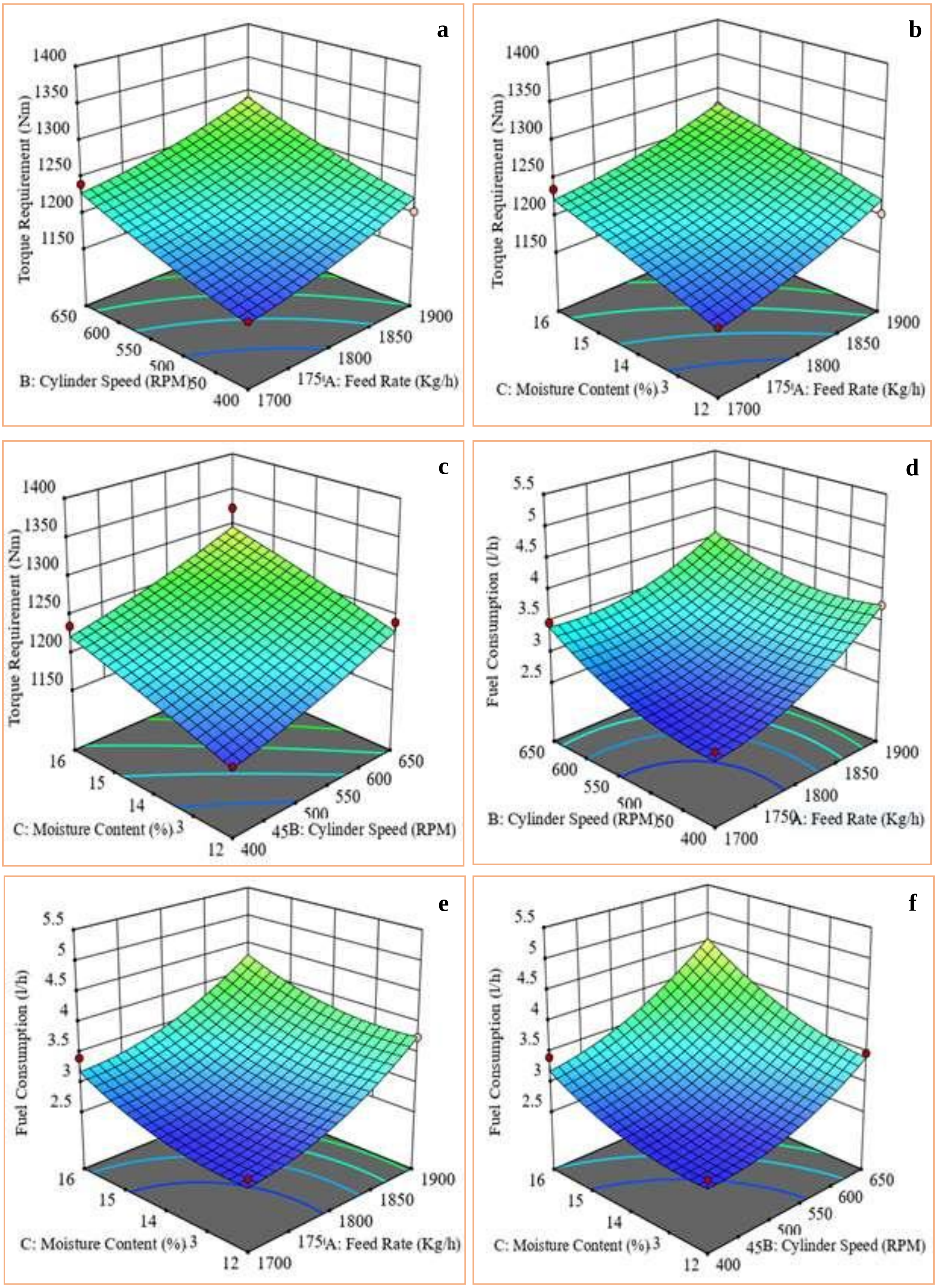

Figure 4 Effect of different levels of feed rates, cylinder speed and moisture content on torque requirement (a, b, c) and fuel consumption (d, e, f)

3.2 Fuel consumption

According to the F-values in Table 7, the linear term of cylinder speed has a more significant effect on torque demand than other independent components. All three factors influenced fuel consumption at the linear and quadratic levels, but no significant effect was found at the interactions level. The numerical representation of fuel consumption fluctuation with variables A, B, and C was successfully fitted in a polynomial equation (Equation 2) with a determination coefficient of determination $R^2 = 0.\ 7076$.

Table 7 ANOVA for the fuel consumption using the Response Surface Model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9.89	9	1.10	8.55	0.0012	Significant
A-Feed Rate	2.81	1	2.81	21.88	0.0009	
B-Cylinder Speed	2.50	1	2.50	19.45	0.0013	
C-Moisture Content	2.44	1	2.44	18.95	0.0014	
AB	0.1568	1	0.1568	1.22	0.2954	
AC	0.0084	1	0.0084	0.0657	0.8029	
BC	0.1152	1	0.1152	0.8958	0.3662	
A^2	0.8832	1	0.8832	6.87	0.0256	
B^2	0.7733	1	0.7733	6.01	0.0341	
C^2	0.5653	1	0.5653	4.40	0.0624	

Fuel consumption was highly influenced by the crop's moisture content and the cylinder speed of the thresher. The crop's feeding rate also significantly influences the fuel consumption of the thresher. It can be observed from figure 4d that the fuel consumption increase as we increase the feed rate from 1700 to 1900 kg/h; this may be due to a higher feed rate, more power being required for handling crop inside the cylinder. A similar finding was also reported by Khan (1986) [7]. Proportional relation was found between threshing cylinder speed and fuel consumption; as we increase cylinder speed from 400 to 610 rpm, the fuel consumption increases from 2.65 to 5.22 l/h (Fig 4e). This is also because of the relationship between power consumption and speed [28]. The feeding material's moisture content also influences the fuel requirement for threshing (fig 4f). The higher crop moisture content of the crop requires a higher amount of fuel to process because moisture in the crop makes it bulky to process inside the threshing cylinder [29].

4. Optimization of design parameters

Numerical values and graphical optimization algorithms were used to forecast the optimal level of independent variables for the axial flow paddy thresher's torque requirement and fuel consumption. For a visual comprehension of independent variable interactions, an overlay plot of the regression model has been highly recommended [8]. The range of optimal conditions may be shown by superimposing the contours for the different response surfaces in an overlay plot, establishing a zone in which all responses have optimum values. The RSM package's response optimizer determined the overall optimum region. Figure 5, yellow shaded area, depicts the optimum findings and the overlaying contour plot for the dependent variables as feed rate, cylinder speed, and crop moisture content.

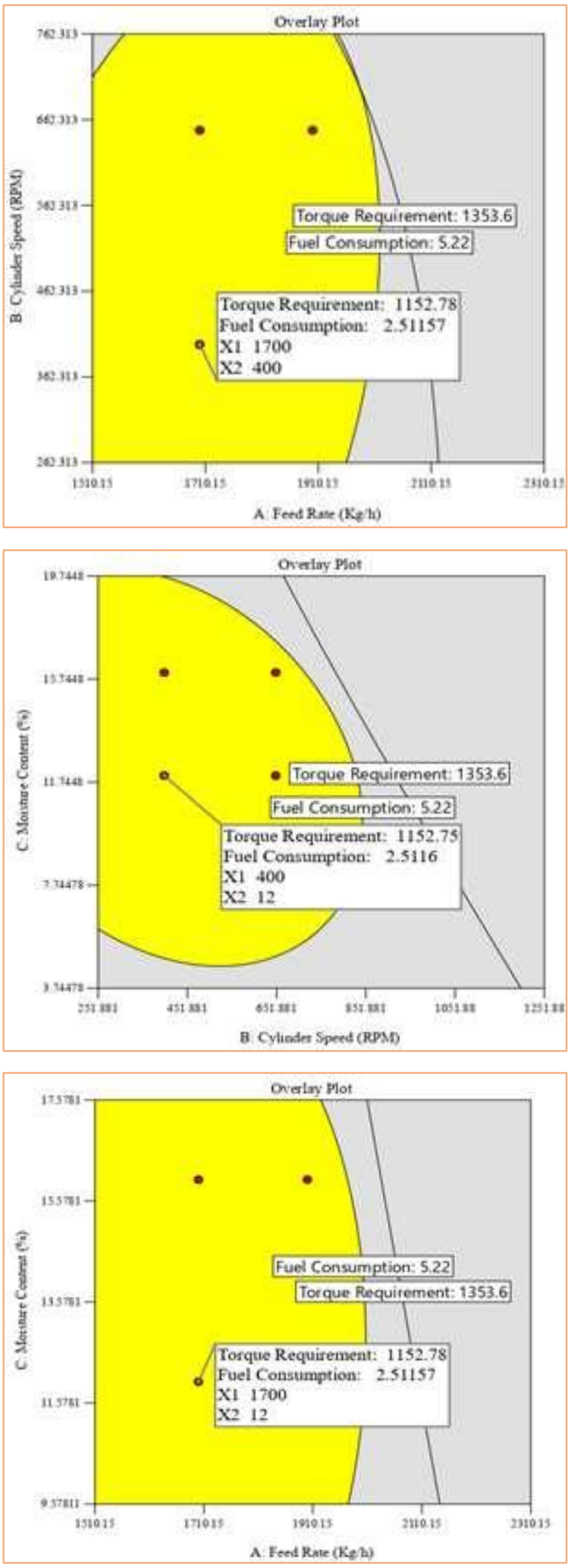

Figure 7 Superimposed contours for torque requirement and fuel consumption at varying feed rate, cylinder rpm, and crop moisture content

The flagged point in the figure shows the optimum point at which the minimum torque requirement (1152.78 Nm) and fuel consumption (2.51 l/h) can be achieved at three different independent parameters. It may be observed in this figure that the corresponding predicted response values under the optimum conditions for axial flow paddy thresher were feed rate (1703.92kg/h), cylinder speed (400 rpm), moisture content (12 %), TR (1152.78 Nm) and FC (2.51 l/h).

5. Conclusion

In this study, a tractor-operated axial flow paddy thresher was tested at different feed rates (from 1700 to 1900 kg/h), threshing cylinder speeds (400 to 650 rpm), and crop moisture content (12 to 16 %) corresponding to these parameters, its performance was evaluated. The use of Response Surface Methodology in combination with CRD to simulate and optimize the performance of axial flow paddy threshers worked effectively. The models provide accurate performance forecasting by interpolating over the database's given range. All three parameters significantly affect the torque requirement and fuel consumption. An increase in feed rate and cylinder speed increases the torque required to rotate the threshing cylinder; hence, fuel consumption also increases. Furthermore, the minimum fuel consumption (2.51 l/h) and torque requirement (1152.78 Nm) can be achieved at 400 cylinder rpm and 1703 kg/h feed rate at 12 % moisture content.

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