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ORIGINAL ARTICLE

Optimizing operational parameters of finger millet threshing drum using RSM

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Abstract The operational parameters of threshing drum play a dominant role in the design and development of the finger millet thresher-cum-pearler. The finger millet threshing drum was developed and effects of operational parameters such as feed rate, drum speed and concave clearance on threshing efficiency, pearling efficiency and grain damage were individually studied using response surface method. A statistical tool of the central composite rotatable design was used for analysis. It was found that the maximum threshing efficiency, maximum pearling efficiency and minimum grain damage were 98%, 85% and 0.086%, respectively at the feed rate 36 kg/h, drum peripheral speed 7.12 m/s and concave clearance 5 mm. The performance evaluation of the drum was validated by setting above condition in the threshing drum. It was found that the maximum threshing efficiency 99% against predicted 98%, maximum pearling efficiency 86% against predicted 85% and 0.1% grain damage was found against predicted 0.086%.

Keywords Finger millet threshing · Pearling · CCRD · RSM

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Introduction

Finger millet (*Eleusine coracana (L.) Gaertn*) commonly known as *Ragi*, is one of the important small millet crops grown in the red soil areas of India and it is popularly called as *Nachni* (dancer) in the Western Ghats of Maharashtra. The finger millet crop has a unique property to grow in rainfed and slightly drought tolerated area. Due to its high nutritional and medicinal value, its popularity increased day by day (Pradhan et al. 2010). The crop occupied an area of 2.5 million ha and contributed 2.6 million tons of grain production. The average yield of the crop under rainfed condition was 1000 kg/ha and under irrigated conditions, it was 2500 kg/ha. The low yield per ha (1062 kg/ha) in Maharashtra and lack of mechanization in the cultivation and processing practices are the main reasons behind to decrease the % area under cultivation of finger millet (Kumar et al. 2013).

The manual harvesting of finger millet crop is done at physiological maturity (16–20% (db.) moisture content), then the crop is sun-dried to reduce moisture content up to 10–12% and then staked for 1–1.5 month to lose the grains and glumes from crop panicles easily (Singh et al. 2015). Traditionally, the threshing of finger millet is performed by different methods viz, beating with sticks, Bullock and tractor-drawn stone rollers. These methods are characterized as laborious, low output, uneconomical, substandard products, a hygienic operation, low germination percentage and poor quality of seed. The output capacity of manual threshing, animal and tractor-drawn stone roller crushing ranges in between 4–8, 25–29 and 55–60 kg/h with threshing efficiencies 100, 65–70 and 80–90%, respectively (Kumar et al. 2013). Similarly, the pearling operation of finger millet is performed by three different methods viz rubbing grains in the gunny bag, leg pounding and stone grinding (*Jatta*). In leg pounding method, grains are filled in the hole made in a stone block and the impact force is applied by the leg to grain. The third indigenous method of pearling is the use of *Jatta*. It consists of two round stone plates i.e. top and bottom plate. The top plate having a hole for the feeding the grains and a bottom plate having the facility to guide top plate. The bottom plate is fixed on the ground by using cement mortal and the top plate placed on the bottom plate. At the time of operation, top plate rotates on bottom plate manually. The feeding of grains is done simultaneously. The contact surface between the top plate and bottom plate is rough. The rough surface created friction force is responsible for the pearling. These methods are time-consuming and laborious (Joshi et al. 2015; Pradhan et al. 2010). In India, few attempts have been made on design and development of finger millet thresher both pedal and operated. The thresher with spike tooth drum and open bar concave showed lower threshing and cleaning efficiency and there was an absence of pearling operation (Parmanand 2015; Kumar et al. 2013; Gbabo et al. 2013; Pradhan et al. 2010; Chandrakanthappa et al. 2001). The thresher developed by Vivekananda Parvatiya Krishi Anusandhan (VPKAS), Almora is a promising option showing higher threshing and pealing efficiency but it needed the double pass to complete threshing and pearling. Therefore, it was decided to develop a machine to thresh and perform pearling operation in a single pass.

Response Surface Methodology (RSM) is a mathematical and statistical tool for the collection of data and empirical model building. Myers et al. (2009) reported that the RSM helps to reduce the number of expensive experimental analysis and involved associated noise in it. Similar technique was used by many researchers viz., Singh et al. (2008) for optimizing machine parameters of paddy thresher, Salari et al. (2013) for optimization of operational parameters of chickpea thresher, Singh and Deepa (2014) for optimizing machine parameters of parvatiya Sugam motorized thresher, Tewari et al. (2013) for performances modeling of ground nut stripper and Pishgar-Komleh et al. (2012) for optimizing seed corn harvesting losses. To achieve maximum threshing efficiency, pearling efficiency and minimum grain damage there is need to maintain optimum operating parameters of the threshing drum. Hence, operational parameters of threshing drum viz. peripheral speed, concave clearance and feed rate were optimized using response surface methodology with central composite rotatable design technique.

Materials and methods

The details of the threshing drum, testing procedure and testing parameters were given in following sub-points.

Raw material

The finger millet (variety: Dapoli-1) panicles were separated from straw and used in the present experiment. After harvesting, the panicles were sun-dried to reduce moisture content up to 12% (db.). Then it was used for measurements. The grain moisture at the time of threshing was 9.9% (db.).

Size of threshing drum

The diameter of the threshing drum was calculated by using Eq. (1).

$$\vartheta = \frac{\pi \times D_c \times N_c}{60} \tag{1}$$

The speed of threshing cylinder as (N_c) 750 rpm was considered economical from the energy consumption point of view (Varshney et al. 2004). Singh et al. (2010) found that the peripheral speed (ϑ) of 8 m/s was optimum for the threshing operation. Substituting the values of N_c and ϑ in the Eq. (1), the diameter of the threshing drum was calculated as 200 mm. The length of the threshing drum was assumed 1.5 times diameter of the drum (Aware 2012). Therefore, the length of the drum was 300 mm.

Development of drum

The threshing drum was rasp bar type of 300 mm length and 200 mm diameter made with 16-gauge Milled Steel (M.S) sheet. Eight MS strips, 25 mm wide and 300 mm long, were welded on the threshing drum lengthwise. To provide impact and rubbing forces simultaneously, the circular closed concave covering 220° of cylinder circumference was fabricated with 6 mm M.S round bar. The possibility of grains damage due to direct contact between metal rasp bar plates and grain was avoided using a canvas belt, which was fitted on rasp bar. Threshing sieve was provided at the bottom section of the drum. It increased the residence period of crop inside the drum. Therefore, it permitting repeated impact and rubbing force on the finger millet panicles. The threshing sieve opening 2 mm was selected based on the mean diameter of finger millet grain; which was in the range of 1.2–1.8 mm (Powar et al. 2018). The sieve was made up of the 16-gauge M.S sheet. The shaft of the drum was made of a round bar 25 mm diameter and 690 mm length fitted in universal ball bearing. The machine was operated by 1 hp single phase D.C electrical motor. A belt pulley arrangement was used for transmitting power from the motor to the threshing drum. The motor placed on the metal frame with belt-tightening adjustment. To change the speed of the motor, a variable frequency distributor was used. To adjust concave clearances, the sufficient space was provided between the threshing drum and concave. The duct was provided at bottom of the drum to collect threshed grain. The threshing drum was shown in Fig. 1.

Central composite rotatable experiment design (CCRD)

The various nomenclatures used in the optimization of operational parameters are as given below

Abbreviations			
a_d	Accuracy of variable	x_i	Coded value of the ith variable
a_m	Extreme coded value (maximum = + a_m; minimum = − a_m)	X_i	The actual value of the ith variable
b_0	Constant	Y_{ai}	The experimental value of the ith response
b_i	Linear regression coefficient	Y_{ci}	The calculated value of the ith response
b_{ii}	Quadratic regression coefficient	Y_{av}	The average of actual values of responses
b_{ij}	Interaction regression coefficient	η_λ	Threshing efficiency, %
CCRD	Central composite rotatable design	GD_λ	Grain damage in threshing operation, %
F_{loc}	F-value for lack of fit	P_λ	Pearling efficiency in threshing operation, %
K	Number of independent variables considered for optimization	D_c	The diameter of the threshing drum
N	Total number of experiments	N_c	rpm of the threshing drum
n_c	Number of central experiments	RMSE	Root mean squared error
RSM	Response surface methodology	MAE	Mean absolute error
F_R	Feed rate, kg/h	MSE	Mean square error
ϑ	Drum speed, m/s	q^2	Cross-validated correlation coefficient
C_C	Concave clearances, mm	r^2	Correlation coefficient
X_{min}	The minimum value of independent variables	y_i^p	Experimental values
X_{max}	The maximum value of independent variables	y_i^m	Predicted values
x_1	Coded value of F_R	y_i^{-m}	Mean experimental values
x_2	Coded value of ϑ		

Fig. 1 Threshing drum

The optimization was carried out by using RSM with a second order polynomial equation in Central Composite Rotatable Experiment Design (CCRD) (Myers et al. 2009; Singh et al. 2008; Tewari et al. 2013). 'Design expert 10' software was used. The optimization was carried out with three independent variables, viz., feed rate (F_R), drum speed (ϑ) and concave clearance (C_C) with three dependent variables viz., threshing efficiency, pearling efficiency and grain damage. The values of independent variables (natural variables) were varied in the range 20–40 kg/h, 3–15 mm and 5–10 m/s respectively, for F_R, ϑ and C_C. Those natural variables were needed to convert in coded variables; which were dimensionless. The selected 5 different levels of coded independent variables were + 1.682, + 1, 0, − 1 and − 1.682 (Myers et al. 2009). The conversion of natural values to coded values was accomplished by Eqs. (2)–(5) (Myers et al. 2009; Singh et al. 2010; Tewari et al. 2013). The details of converted CCRD experimental levels are given in Table 1.

$$x_i = \frac{X_i - X_m}{X_D} \quad (2)$$

here i = 1, 2 and 3

$$X_D = \frac{X_{max} - X_m}{a_m} \quad (3)$$

Table 1 CCRD experimental levels for conducting the threshing study

Sl. no.	Variable	Level 1 (− 1.68)	Level 2 (− 1)	Level 3 (0)	Level 4 (1)	Level 5 (+ 1.68)
1	Feed rate (X_1), kg/h	20	24	30	36	40
2	Concave Clearances (X_3), mm	3	5	9	13	15
3	Drum Speed (X_2), m/s	5	6	7.5	9	10

$$x_m = \frac{X_{max} - X_{min}}{2} \quad (4)$$

$$a_m = 2^{0.25k} \quad (5)$$

The general form of nonlinear second-order regression Eq. (6) was developed for independent parameters in coded values to optimize the threshing efficiency, pearling efficiency and grain damage (Myers et al. 2009; Singh et al. 2010; Tewari et al. 2013).

$$Y = b_0 + \sum_{i=0}^{3} b_i x_i + \sum_{i=1}^{3} b_{ii} x_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{3} b_{ij} x_i x_j \quad (6)$$

The goodness of fit of the developed nonlinear equations was tested by F-value for lack of fit (F_{lof}) (Myers et al. 2009; Singh et al. 2010; Tewari et al. 2013). The value of F_{lof} was calculated by Eq. (7).

$$F_{lof} = \frac{\sum_{i=1}^{N} (Y_{ai} - Y_{ci})^2 - \sum_{i=1}^{n_c} (Y_{ai} - Y_{av})^2}{N - \text{no.of coefficients in regression equation} - N_c + 1} \quad (7)$$

The experimental and predicted values of responses were compared by the values of errors and correlation coefficients. The validation of the model was done by the root mean square error (RMSE), mean absolute error (MAE), cross-validated correlation coefficient (q^2) and correlation coefficient (r^2). The mean absolute error (MAE) is a quantity used to measure how close predicted values to the experimental values. The respective values represented an average value of the absolute error. The values MSE, MAE and q^2 were found by Eqs. (8)–(11), respectively (Savic et al. 2015, 2016).

$$RMSE = \sqrt{\frac{\sum \left(y_i^p - y_i^m\right)^2}{N}} \quad (8)$$

$$MSE = \frac{\sum \left(y_i^p - y_i^m\right)^2}{N} \quad (9)$$

$$MAE = \frac{\left|\left(y_i^p - y_i^m\right)^2\right|}{N} \quad (10)$$

$$q^2 = 1 - \frac{\sum_{i=1}^{n} \left(y_i^p - y_i^m\right)^2}{\sum \left(y_i^m - y_i^{-m}\right)^2} \quad (11)$$

Model is considered acceptable when q^2 is higher than 0.5. As per the CCRD experiment, the five levels of the independent variables were fixed to get 20 experiments. The details of the experiment are furnished in Table 2. Accordingly, performance evaluation of the drum was carried out in the random order. To calculate error sum of squares and the lack of fit of the developed regression equation, six replicated experiments were conducted at the central points of the coded variables (Singh et al. 2008; Tewari et al. 2013). The numbers 15–20 in Table 2 are six replicated experiments at the central point of coded variables.

Results and discussion

The laboratory testing of the threshing drum was carried out as per CCRD experimental design. The performance was evaluated in randomized order and noted in Table 2. The numerical and graphical optimization of data (Table 2) was carried out using response surface method.

Effect of operational parameters on the performance of threshing drum

The effect of operational parameters on the performance of the threshing drum was studied. The optimized levels of the variables viz. feed rate, concave clearance and drum speed were 36 kg/h, 5 mm and 7.12 m/s, respectively. The effects of independent parameters on dependent parameters were individually studied.

Effect on threshing efficiency

The Fig. 2a–c were prepared at the optimum level of feed rate 36 kg/h, concave clearance 5 mm and drum speed 7.12 m/s. Figure 2a indicated that the threshing efficiency increased with the decrease in concave clearance and an increase in feed rate. The maximum threshing efficiency 98.7% was found at 3 mm concave clearance with 40 kg/h feed rate. It can be observed from Fig. 2b that the threshing efficiency increased with increase in drum speed and feed rate. The maximum threshing efficiency (η_λ, 99.7%) was

Table 2 Performances evaluation of threshing drum according to CCRD experiments design

Expt. No	Feed rate (kg/h)	Drum speed (m/s)	Concave clearance (mm)	Threshing efficiency (%)	Pearling efficiency (%)	Grain damage (%)
1	24	6	5	96.0	76	0
2	36	6	5	97.0	80	0
3	24	6	13	94.0	60.66	0
4	36	6	13	95.0	65	0
5	24	9	5	96.7	82.33	0.6
6	36	9	5	98.5	85	0.5
7	24	9	13	96.5	78.33	0.4
8	36	9	13	97.8	83.33	0.1
9	20	7.5	9	96.1	75	0.2
10	40	7.5	9	98.7	84	0
11	30	7.5	3	97.5	85	0.2
12	30	7.5	15	94.7	70	0
13	30	5	9	95.1	60.33	0
14	30	10	9	98.3	82.66	0.8
15	30	7.5	9	97.0	79.33	0
16	30	7.5	9	97.7	80.66	0.1
17	30	7.5	9	96.0	78	0
18	30	7.5	9	97.3	79	0
19	30	7.5	9	96.5	78	0.1
20	30	7.5	9	96.3	78.33	0

found at 40 kg/h of feed rate with 10 m/s drum speed. Similarly, the threshing efficiency increased with increase in drum speed and the decrease in concave clearance. It was attained maxima (η_λ, 99%) at 10 m/s of drum speed with 3 mm concave clearance (Fig. 2c). The decrease in a concave clearance between canvas strip and concave bar increased the rubbing force between canvas-grain and grain-concave, resulted in more the threshing efficiency. Similarly, threshing efficiency was increased with increase in drum speed, as the speed that is more peripheral was responsible for higher acceleration and impact force on the panicles. As feed rate increased, the threshing efficiency increased due to an intensification of friction between the finger millet panicles. Similar trends were observed by Kamble et al. (2003) for pearl millet thresher and Sudajan et al. (2002) for sunflower thresher.

The ANOVA shown in Table 3 indicated that, the high value of model F (19.81) suggesting a quadratic model could be successfully used to fit experimental data ($p < 0.001$). As per F-values indicated in Table 3, the linear term of feed rate, concave clearance and drum speed had a significant effect on the threshing efficiency at 1% level of significance. Similarly, the interaction terms of drum speed × concave clearances and quadratic term of drum speed had a significant effect on the threshing efficiency at 5% level of significance. The remaining terms of interaction and quadratic had no significant effect on threshing efficiency even at a 10% level of significance. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Here the ratio became 16.577 indicates an adequate signal. This model can be used to navigate the design space (Savic et al. 2015, 2016; Savic-Gajic et al. 2018). The predicated R^2 (0.81) for this model was agreed with adjusted R^2 (0.89).

The regression equation representing the variation of the threshing efficiency (η_λ, %) with different independent parameters F_R, ϑ and C_C were fitted in polynomial form (Eq. 12). The insignificant terms were excluded from the quadratic model in order to obtain the reduced polynomial model (Savic et al. 2014a, b).

$$\eta_\lambda = 96.64 - 0.71F_R - 0.70C_c - 0.96\vartheta + 0.39C_c\vartheta - 0.24\vartheta^2 \quad (12)$$
$$R^2 = 0.94$$

Effect on pearling efficiency

The Fig. 2d–f were prepared at optimum levels of feed rate 36 kg/h, concave clearance 5 mm and drum speed 7.12 m/s, respectively. It was observed in Fig. 2d that the pearling efficiency increased with the decrease in concave clearance

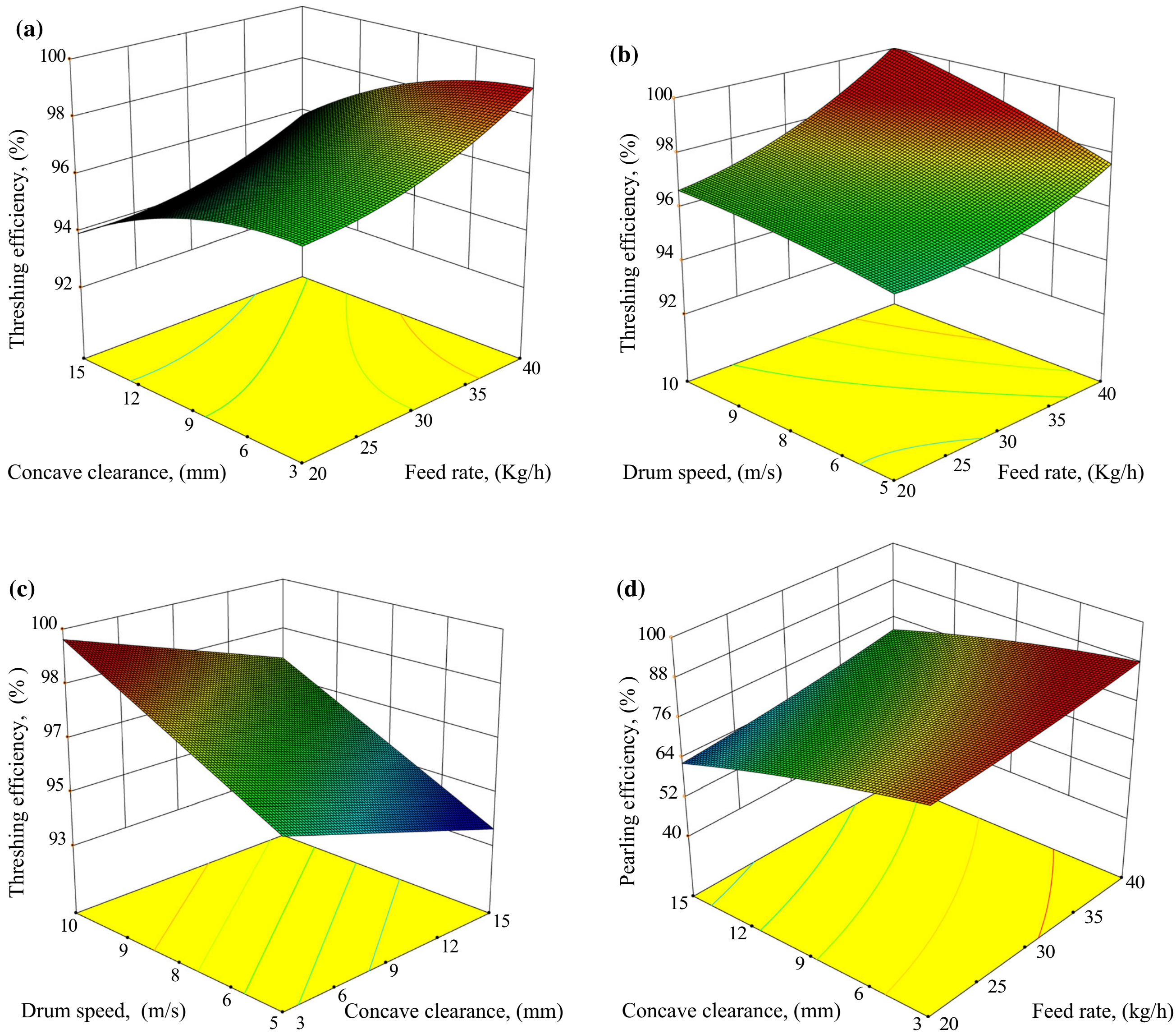

Fig. 2 Combined effects of operational parameters of threshing drum on its performance. **a** Effect of concave clearance and feed rate on the threshing efficiency. **b** Effect of drum speed and feed rate on the threshing efficiency. **c** Effect of drum speed and concave clearance on the threshing efficiency. **d** Effect of concave clearance and feed rate on the pearling efficiency. **e** Effect of drum speed and feed rate on the pearling efficiency. **f** Effect of drum speed and concave clearance on the pearling efficiency. **g** Effect of concave clearance and feed rate on the grain damage. **h** Effect of drum speed and feed rate on the grain damage. **i** Effect of drum speed and concave clearance on the grain damage

and increased in feed rate. The maximum pearling efficiency (87.5%) was found at 3 mm concave clearance with 40 kg/h feed rate. Figure 2e indicated that the pearling efficiency increased with increase in drum speed as well as feed rate. The maximum pearling efficiency 86% was found at feed rate 40 kg/h and drum speed 10 m/s. Similarly, the pearling efficiency increased with increase in drum speed and the decrease in concave clearance. The maximum pearling efficiency 84% was observed at drum speed 10 m/s with 3 mm concave clearance (Fig. 2f).

The decrease in concave clearance led to increasing the rubbing forces imparted on the cobs of finger millet; ultimately, the pearling efficiency was increased. The pearling efficiency increased with feed rate; as due to maximum intensification, the friction between the canvas strip and grains, between grains and grains to concave increased. The similar trends were also observed by Singh et al. (2011) for the Barnyard millet dehuller and Verma et al. 2014 for finger millet dehuller-cum-pearler.

The high value of model F (124.92) given in ANOVA Table 3 indicated that the quadratic model could be

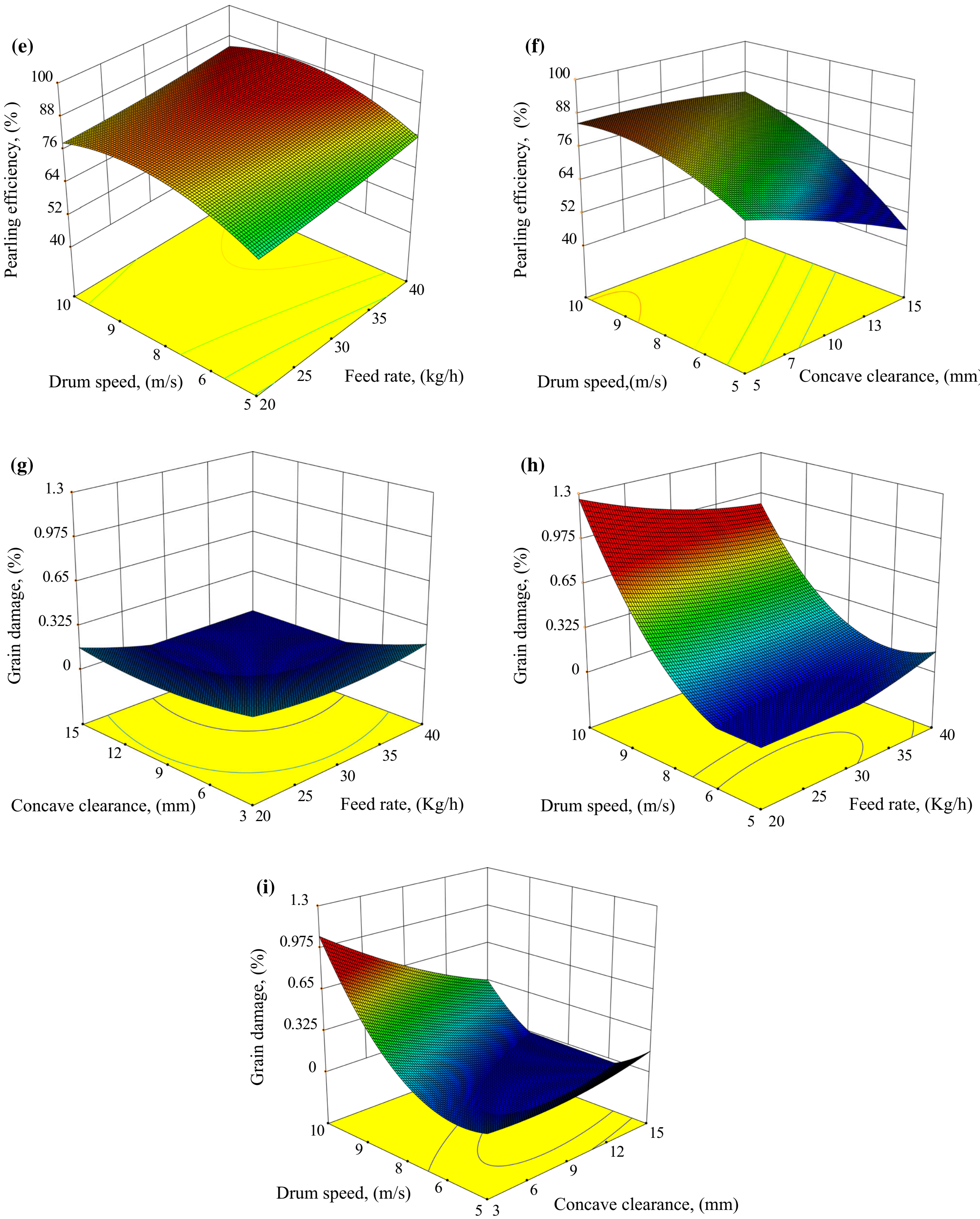

Fig. 2 continued

Table 3 ANOVA for study effect of feed rate, concave clearance and drum speed on threshing efficiency, pearling efficiency and grain damage

Source of variation	Degree of freedom	F Value		
		Threshing efficiency	Pearling efficiency	Grain damage
Model	9	19.81	124.92	47.41
F_R	1	41.79*	76.17*	16.20*
ϑ	1	41.52*	294.46*	26.20*
C_C	1	76.57*	565.79*	259.27*
$F_R\vartheta$	1	0.19^{ns}	0.96^{ns}	2.04^{ns}
F_RC_C	1	0.93^{ns}	0.060^{ns}	8.16**
ϑC_C	1	7.38**	81.58*	18.37*
F_R^2	1	3.44^{ns}	1.27^{ns}	2.70^{ns}
ϑ^2	1	5.30**	2.73^{ns}	2.70^{ns}
C_C2	1	0.22^{ns}	99.98*	95.62*
Lack of Fit	5	0.46^{ns}	0.78^{ns}	0.84^{ns}
Residual	10			
Pure Error	5			
Cor Total	19			

* Significant at 1% level, ** significant at 5% level, *ns* non-significant

successfully used to fit experimental data. The linear terms viz. feed rate, concave clearances, drum speed, interaction term concave clearance × drum speed (X_2X_3) and quadratic term of concave clearance had a significant effect on the pearling efficiency at 1% level of significance. Interaction terms viz. feed rate × concave clearance (X_1X_2), feed rate × drum speed (X_1X_3) and quadratic terms feed rate and concave clearance hadn't a significant effect on the pearling efficiency even at the 10% level of significance. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Here the ratio became 38.019 indicates an adequate signal. This model can be used to navigate the design space (Savic et al. 2015, 2016; Savic-Gajic et al. 2018). The predicated R^2 (0.96) for this model had an agreement with adjusted R^2 (0.98).

The regression equation representing the variation in pearling efficiency (η_λ, %) with different independent variables F_R, ϑ and C_C were fitted in polynomial form (Eq. 13). The insignificant terms were excluded from the quadratic model in order to obtain the reduced polynomial model (Savic et al. 2014a, b).

$$P_\lambda = 78.88 + 2.28F_R - 4.48C_c + 6.22\vartheta + 3.08\vartheta C_c - 0.42C_c^2 \quad R^2 = 0.99 \tag{13}$$

Effect on grain damage

The Fig. 2g–i were prepared at optimum condition of feed rate 36 kg/h, concave clearance of 5 mm and the drum speed of 7.12 m/s. The Fig. 2g indicated that the maximum grain damage was observed at 3–5 mm concave clearance all feed rates from 20 to 25 kg/h. Grain damage was not found in the range of 6–15 mm concave clearance with 25–40 kg/h feed rate. The maximum grain damage found to be 0.5%, at 3 mm concave clearances with 26 kg/h feed rate. Figure 2h indicated that the grain damage increased with increase in drum speed and feed rate. The maximum grain damage of 1.3% was found at feed rate 20 kg/h with drum speed 10 m/s. Similarly, the grains damage was increased with increase in drum speed and the decrease in concave clearance. The maximum grain damage of 0.8% was observed at a drum speed of 10 m/s with 3 mm concave clearance (Fig. 2i). Similar trends were also observed by Singh et al. 2011 for barnyard millet dehuller and Kamble et al. (2003) for pearl millet thresher.

The decrease in concave clearance increased the rubbing forces between canvas strip and grains were responsible for grains damage. It also happened due to the increase in direct contact between canvas strip and grains as well as grains and concave bars of the drum. Dominating impact forces were observed at a higher speed of the drum. Those maximum impact forces were responsible for the maximum grain damage.

The decrease in concave clearances that increases the rubbing forces between the canvas strip and grain are responsible for grains damage. It also happens due to the increase in direct contact between canvas strip and grain as well as grain and concave bars of the drum. Dominating impact forces were observed at the higher speed of the drum. These maximum impact forces are responsible for the maximum grain damage vice versa observed at lower drum speed. At a higher feed rate, lower grain damage was

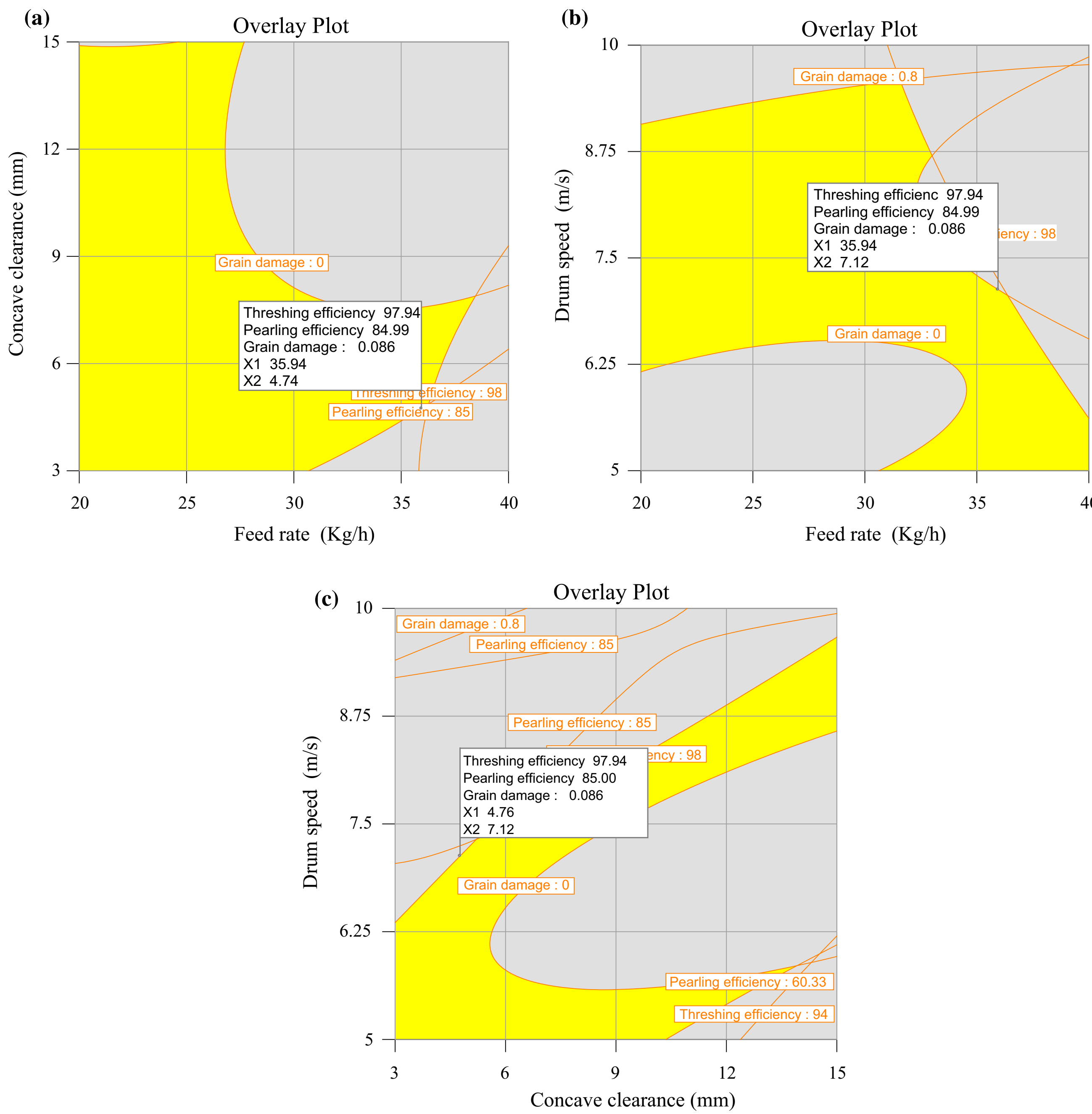

Fig. 3 Graphical optimization of operational parameters of threshing drum. **a** Superimposed contours for threshing efficiency, pearling efficiency and grain damage at varying feed rate and concave clearance. **b** Superimposed contours for threshing efficiency, pearling efficiency and grain damage at varying feed rate and drum speed. **c** Superimposed contours for threshing efficiency, pearling efficiency and grain damage at varying concave clearance and drum speed

found because the maximum feed rate shares the impact and rubbing force imparted by rotating drum, it did not happen in minimum feed rate because minimum grain handles the maximum impact and rubbing force is responsible for maximum grain damage. Similar trends were also observed by Singh et al. (2011) for barnyard millet dehuller and Kamble et al. (2003) for pearl millet thresher. At a higher feed rate, the less grain damage was found because the more quantity of feed shared the impact and rubbing force imparted by rotating drum.

The ANOVA shown in Table 3 was prepared to study the effect of feed rate (F_R, kg/h), drum speed (ϑ, m/s), and concave clearance (Cc, mm) on the grains damage. The high value of model F (47.41) suggesting a quadratic model could be successfully used to fit experimental data ($p < 0.001$). As per F-values indicated in Table 3, the linear terms feed rate, drum speed, concave clearances, and interaction term concave clearance × drum speed and quadratic term concave clearance had a significant effect on grains damage at 1% level of significance. The interaction term feed rate × drum speed had also the significant effect on the grains damage at 5% level of significance. Interaction terms viz. feed rate × concave clearance and quadratic terms of feed rate and concave clearance variables hadn't a significant effect on the grains damage even at the 10% level of significance ($p < 0.1$). Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Here the ratio became 22.74 indicates an adequate signal. This model can be used to navigate the design space. (Savic et al. 2015, 2016; Savic-Gajic et al. 2018). The predicated R^2 (0.89) for this model was agreed with adjusted R^2 (0.95).

The regression equation representing the variation of the pearling efficiency (GD_λ, %) with different variables F_R, ϑ and C_C were fitted in polynomial form (Eq. 14). The insignificant terms were excluded from the quadratic model in order to obtain the reduced polynomial model (Savic et al. 2014a, b).

$$GD_\lambda = 0.034 - 0.054F_R - 0.069C_c + 0.22\vartheta - 0.025F_RC_c - 0.075\vartheta C_c + 0.021C_c^2$$
$$R^2 = 0.97 \quad (14)$$

Optimization of operational parameters of threshing drum

The software generated numerical optimum conditions of the independent variables such as feed rate, concave clearance and drum speed were 36 kg/h, 5 mm and 7.12 m/s, respectively. It predicted the responses such as threshing efficiency, pearling efficiency and grain damage were 97.94%, 85% and 0.086%, respectively. In graphical optimization, the values shown in the flagged area of Fig. 2a–c were grouped together and the optimized values of variables such as feed rate 36 kg/h, drum speed 7.12 m/s, concave clearances 4.76 ≈ 5 mm with threshing efficiency 97.94%, pearling efficiency 85% and grain damage 0.086% were determined. The values obtained by numerical and graphical optimization method were the same (Singh et al. 2008; Tewari et al. 2013). Based on those optimized values, the development of the drum was finalized. To validate the optimized parameters, the performance of the drum was carried out. It was found that threshing efficiency was 99% against predicted 97.94%, pearling efficiency was 86% against predicted 85%, while grain damage was 0.1% against predicted 0.086% (Fig. 3).

Effect of double pass on the performance of threshing drum

In the "Effect of operational parameters on the performance of threshing drum" and "Optimization of operational parameters of threshing drum" sections the detail performance of threshing drum for the single pass was discussed. The effect of double pass on the performance of threshing drum was studied. It was found that threshing efficiency, pearling efficiency and grain damage were 99.75%, 99% and 1.3%, respectively at same condition of single pass. The performance of threshing drum in single pass were compared to double pass, it was found that the threshing efficiency pearling efficiency and grain damage was increased by 0.75%, 13.13% and 92.83%, respectively.

Conclusion

The threshing drum is one of important part of finger millet thresher cum pearler. The performance of the threshing drum is depending on its operating parameters. Therefore, the optimization of operational parameters of the threshing drum was carried out. The optimized machine operational parameters viz. feed rate, concave clearance and drum speed were 36 kg/h, 5 mm and 7.12 m/s, respectively with predicted performance parameters viz. threshing efficiency (η_λ), pearling efficiency (P_λ) and grains damage (GD_λ) were 97.94%, 85% and 0.1%, respectively. The predicted performance of the drum was validated at optimized parameters of threshing drum. It was found that the threshing efficiency (η_λ), pearling efficiency (P_λ) and grain damage (GD_λ) were 99%, 86% and 0.086%, respectively. The satisfactory pearling efficiency was found for the double pass.

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