Modeling and optimization of finger millet pearling process by using RSM

Ranjit Powar¹ · Vijay Aware² · Prashant Shahare²

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Abstract Finger millet pearling process involves so many drudgery prone operations that specify the need for the development of finger millet pearling drum. The performance of pearling drum depends on its operational parameters. Therefore, this study aims to optimize the operational parameters of the pearling drum such as drum speed, concave clearance and pearling sieve size to obtain maximum pearling efficiency and minimum grain damage. The analysis was carried out using Response Surface Method along with the Box–Behnken Design tool. The optimum operational parameters were found as drum speed 7.25 m/s, concave clearance 3 mm and pearling sieve size 2 mm that predicts the maximum pearling efficiency of 98.95% and minimum grain damage of 0.73%. Finally, the performance of the pearling drum was validated setting optimum conditions. It results pearling efficiency of 99% along with 0.5% grain damage. Above results indicates that

the validated pearling drum performance was better than predicted.

Keywords Finger millet · Pearling · Grain damage · RSM · BBD

List of symbols

b_0	Constant
b_i	Linear regression coefficient
b_{ii}	Quadratic regression coefficient
b_{ij}	Interaction regression coefficient
BBD	Box–Behnken Design
F_{loc}	F-value for lack of fit
K	Number of independent variables considered for optimization
N	Total number of experiments
n_c	Number of central experiments
RSM	Response surface methodology
ϑ	Drum speed (m/s)
C_C	Concave clearances (mm)
P_{SS}	Pearling sieve size (mm)
X_i	Actual value of the i th variable
X_o	Actual value of an independent variable at center point
ΔX	Step change value of an independent variable
x_1	Coded value of ϑ
x_2	Coded value of C_C
x_3	Coded value of P_{SS}
x_i	Coded value of the i th variable
Y_{ai}	Experimental value of the i th response
Y_{ci}	Calculated value of the i th response
Y_{av}	Average of actual values of responses
η_p	Pearling efficiency (%)
GD_p	Grain damage in pearling operation (%)
ϑ_p	Peripheral velocity of pearling drum (m/s)

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✉ Ranjit Powar
 ranjitpowar56@gmail.com
 Vijay Aware
 vijayaware.2000@gmail.com
 Prashant Shahare
 pushahare@yahoo.co.in

¹ Department of Farm machinery and Power Engineering, Dr. D. Y. Patil College of Agricultural Engineering and Technology Talsande, Kolhapur 416 112, India

² Department of Farm Machinery and Power Engineering, College of Agricultural Engineering and Technology, Dapoli, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli 415 712, India

D_p Diameter of the pearling drum (mm)
 N_p RPM of the pearling drum

Introduction

Finger millet (Ragi or Nachani) is an ancient crop grown in hilly areas. It is nutritional source of an amino acid, calcium, iron, sulfur, and fibers. Also, it helps to control weight, strengthening the bones, bringing down the cholesterol level and maintaining blood pressure (Shobana et al. 2011; Gull et al. 2016; Ushakumari 2009). However, the utilization of finger millet in daily dietary is restricted mainly due to its low production, an unwillingness of farmer towards cultivation due to lack of mechanization and unavailability of processed food products.

Finger millet grains are tiny in size and its diameter ranges between 1.2 and 1.7 mm. The color of pericarp of the finger millet varies from dark red to purple. The varieties with yellow, white, tan, red, brown, or violet colors are available among red-colored are widely cultivated (Powar et al. 2018). The endosperm and pericarp accounting for about 85% and 13% of seed mass, respectively, whereas the embryo forms 1–2% of it (Patel and Verma 2015; Shobana et al. 2011). The pericarp contains five layers tightly bound on endosperm and it has little nutritional significance compare with endosperm. Besides, it is unattractive and difficult to digest (Ushakumari 2009). Therefore, it needs to be removing from the kernel before further processing (Shobana et al. 2011). It improves the quality of byproducts in terms of color, texture and taste (Patel and Verma 2015; Verma et al. 2014).

Finger millet grains are challenge to the mill, due to its small size, and the nature of pericarp that tightly bounded to the endosperm. Moreover, the grains are so soft and friable; therefore, the conventional milling equipment is unable to remove the pericarp without crushing the grains (Verma et al. 2014). In traditional pearling practices, the conditioning of finger millet grains are done by mixing grains with water and allowed to stand for 5 min. Afterward, it pound with a wooden pestle for 10–15 min to detach the husk from the grains. Hereafter, the husk from the grains is removed by drying and winnowing operations (Verma et al. 2014). These operations are time-consuming, labour intensive and uneconomical to the farmers.

Traditionally, the finger millet grains are pearled by three different methods such as rubbing grains in gunny bags, leg pounding and stone grinding (*Jatta*). Rubbing grains in a gunny bag method, the threshed finger millet grains are filled into gunny bags, then rubbed by hand or leg. In leg pounding method, the grains are filled into a hole made on the surface of the stone, and with the help of leg-operated pestle, the impact force is applied to the grains.

The third indigenous method of pearling is the use of *Jatta*. It consists of two stone plates are placed above to each other. The lower plate is fixed and the upper plate is continuously rotated over it to get the pearled grains. All these above-discussed traditional methods are characterized as low output, drudgery prone and poor pearling efficiency (Joshi et al. 2015; Pradhan et al. 2010; Singh et al. 2002). The mechanical pearler works on the principle that the hulls of the grains are scraped away by the grinding and friction action of whirling stones and the friction with each other. This pearler has more grain damage than traditional method (Verma et al. 2014). Summing up these challenges while designing a finger millet pearling drum, the design development and optimization work done are presented in this paper.

RSM is a critical tool in the design, development, and formulation of new products. It also mostly preferred and used in the improvement of the existing design. Box–Behnken Design (BBD) is a popular experiment design method of RSM play an essential role in the design of 3 levels and 3 to 21 factors. The actual variables in RSM are called as natural variables; it contains its unit. BBD considering three levels of the variable, three factorial experiment designs required which feet the quadratic model best for analysis; beyond quadratic model, the other model is aliased (Myers et al. 2009; Bazaria and Kumar 2016). Many researchers used this method for analysis and optimization as; Bazaria and Kumar (2016) used for optimization of spray drying parameters for beetroots juice powder, Verma et al. (2014) used for studying some machine parameters of finger millet dehuller, Pasma et al. (2013) for optimization of glucose production from oil palm empty fruit bunch cellulose and many others. Effective design of pearler requires optimum operational parameters such as peripheral speed of the drum, concave clearance, and pearling sieve size to achieve maximum pearling efficiency and minimum grain damage. Keeping these requirements in mind, the optimization of operational parameters of the pearling drum was carried out using RSM with BBD techniques. With the help of these optimized parameters, the further design and development of finger millet thresher cum pearler will be carried out.

Materials and methods

Pearling drum

Pearling drum is a design part of finger millet thresher cum pearler (Fig. 1e). The output capacity of the threshing drum (36 kg/h) was used same as the input of the pearling drum (Powar 2018). Therefore, the input of the pearling (36 kg/h) drum was kept constant throughout the experiment.

Fig. 1 Components of Finger millet thresher cum pearler. **a** Pearling drum. **b** Schematic view of pearling cylinder. **c** Pearling drum upper cover. **d** Pearling drum lower cover. **e** Finger millet thresher cum pearler

Pearling drum consists of pearling cylinder, concave, pearling sieve size and the outer casing (Fig. 1a). The diameter of the pearling cylinder was calculated by using Eq. (1).

$$g = \frac{\pi \times D_c \times N_c}{60} \quad (1)$$

The speed of the pearling cylinder was considered as (N_c) 750 rpm. It is economical speed from the energy consumption point of view (Varshney et al. 2004). Singh et al. (2010) concluded that the peripheral speed (v) of 8 m/s was optimum for better performance of pearling drum. Considering above parameters, the diameter of the

Fig. 1 continued

pearling drum was calculated as 200 mm. Arnold et al. (1964) and Devnani et al. (2016) concluded that the change in diameter of the drum does not have any significant effect on output capacity, but the change in length has a significant effect on the output capacity of pearling drum at a diminishing rate. Singh et al. (2010) reported that the capacity of the pearling operation was twice that of the threshing operation by using the same drum dimensions. Therefore, to meet the capacity of threshing drum (36 kg/h) the length of a pearling drum was considered as half that of

threshing drum. Finally, the length of the pearling drum was taken as 180 mm considering 20% allowance.

Pearling cylinder made of mild steel (M.S.) sheet of 16 gauge with the size 409×180 mm was rolled to get a cylinder of diameter 130 mm and 180 mm length. On both, the sides of the drum a circular plate of 130 mm diameter, 5 mm thickness with a 30 mm diameter hole in the center were welded. M.S. shaft of 30 mm diameter and 578 mm length was inserted into the drum center and welded to the two end plates of pearling cylinder. On the periphery of the pearling cylinder eight strips of M.S., 25 mm wide and

180 mm long were welded along the length. On these M.S. flats, canvas flats of 35 mm wide and 180 mm long were fitted such that some width of canvas remained exposed to the grains that provides abrasive and soft impact action for removing the husk from the grains. In this way, the required diameter of the pearling cylinder (200 mm) was achieved by the combination of the round cylinder and metal strips with canvas (Fig. 1b). The concave was fabricated to the same curvature as that of pearling drum. The concave has 230 mm length and 110 mm peripheral diameter. The unit was fabricated by fixing 6 mm diameter M.S. rods along its length. The clearance between concave and the tip of the canvas strip should be made adjustable up to 15 mm. To select the optimum size of pearling sieve three different hole size of sieve viz. 2, 3 and 4 mm was fabricated the same curvature as that of pearling drum. The overall dimension of each pearling sieve is 70 × 241 mm. Outer drum consists of two parts such as the upper part and lower parts. Both upper and lower parts made of M.S. sheet of 16 gauge with the size 700 × 240 mm was rolled to get a cylinder of size 224 mm diameter and 240 mm length. On both, the sides of the drum half circular plate of 224 mm diameter, 5 mm thickness with a 30 mm diameter hole in the center were welded. The drum was divided into half-section along the diameter of the side plates. Two openings one at the upper and another at lower section (60 × 224 mm) of drum were provided for inlet and outlet of the drum. The opening of lower part accommodates space for pearling sieve and upper part for intermediate feeding duct (threshing drum to pearling drum). The details of the upper drum and the lower drum are given in Fig. 1c, d. 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 pearling drum (Fig. 1e). To change the speed of the motor variable frequency distributor was used. To adjust concave clearance, the sufficient space was provided in between pearling cylinder and concave. The duct was provided at the bottom of the pearling drum to collect pearled grain. To simulate optimum operational condition the concave clearance, drum speed and pearling sieve were selected in the range of 3–15, 5–10 m/s and 2–4 mm, respectively based on the reviews.

Preparation of sample

The finger millet (Variety: Dapoli-1) panicles used in this experiment were procured from Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth Dapoli, Maharashtra, India. After harvesting, the panicles were sun-dried to reduce its moisture content below 12% (db) and then it was used for further analysis. The moisture content of the panicles at the time of threshing was determined using oven-dry method,

and it was found to be 10% (db). The output of threshing drum was used the same as input of pearling drum, therefore; samples were prepared by threshing finger millet panicles at optimized levels of threshing drum and as it is used for pearling drum experiments.

Experiment design

The analysis was carried out by using RSM with fitting second order polynomial equation in BBD (Myers et al. 2009; Verma et al. 2014). The ‘Design Expert 10’ software was used for optimization and analysis process. BBD based on the construction of balanced incomplete block design, which has better prediction precision in the center of the factor space (Myers et al. 2009). The 3-factor-3-level BBD with five replicates at the center point was used for optimizing operational parameters of the pearling drum. Three independent variable viz. drum speed (m/s), concave clearance (mm) and pearling sieve size were designed as η , C_C , and P_{SS} and converted into coded variables x_1, x_2 and x_3 by using Eq. (2) for optimizing two dependent variables were maximum pearling efficiency and minimum grain damage (Pasma et al. 2013). The codes assigned for respective variables were $-1, 0$ and 1 for low, intermediate and high value, respectively. Table 1 shows the levels and coded variables selected for the BBD.

$$x_i = \frac{X_i - X_o}{\Delta X} \quad i = 1, 2, 3 \quad (2)$$

Nonlinear second-order regression Eqs. (3) and (4) were developed to optimize the pearling efficiency and grain damage for the response as functions of the coded value of the independent parameters of pearling drum (Singh et al. 2010; Verma et al. 2014).

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

$$GD_p = b_0 + \sum_{i=1}^3 b_i x_i + \sum_{i=1}^3 b_{ii} x_i^2 + \sum_{i=1}^2 \sum_{j=i+1}^3 b_{ij} x_i x_j \quad (4)$$

The goodness of fit of the developed nonlinear equations was tested by F-value for lack of fit (F_{lof}). The value of F_{lof} was calculated by Eq. (5)

$$F_{lof} = \frac{\sum_{i=1}^N (Y_{ai} - Y_{ci})^2 - \sum_{i=1}^{n_c} (Y_{ai} - Y_{av})^2}{N - \text{no. of coefficients in regression equation} - N_c + 1} \quad (5)$$

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

Table 1 BBD experimental design for conducting the pearling study

Sl. no.	Variable	Level 1 (− 1)	Level 2 (0)	Level 3 (1)
1	Drum speed (9) [m/s]	5	7.5	10
2	Concave clearances (C _C) [mm]	3	9	15
3	Pearling sieve size (P _{SS}) [mm]	2	3	4

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. (6), (7), (8) and (9), respectively (Savic et al. 2015, 2016).

$$RMSE = \sqrt{\frac{\sum (y_i^p - y_i^m)^2}{N}} \quad (6)$$

$$MSE = \frac{\sum (y_i^p - y_i^m)^2}{N} \quad (7)$$

$$MAE = \frac{|(y_i^p - y_i^m)|}{N} \quad (8)$$

$$q^2 = 1 - \frac{\sum_{i=1}^n (y_i^p - y_i^m)^2}{\sum (y_i^m - y_i^{-m})^2} \quad (9)$$

The independent variables were fixed at three levels as per the BBD, and a total number of 17 experiments were carried out as evident from Table 2. The experiments were conducted in random order. To calculate the error sum of squares and the lack of fit of the developed regression equation between the responses and independent variables,

five replicated experiments were conducted at the central points of the coded variables (Myers et al. 2009).

Results and discussion

Laboratory testing of the pearling drum was done as per BBD, and evaluated results were presented in Table 2.

Optimization

The numerical and graphical optimization of operational parameters viz. drum speed, concave clearance, and pearling sieve were carried out for maximum pearling efficiency and minimum grain damage. The software generated optimum conditions of the independent variables were drum speed 7.25 m/s, concave clearance 3 mm and pearling sieve size 2 mm with predicted optimum values of response were pearling efficiency of 98.95% and 0.73% grain damage. The values given in the flagged area of Fig. 2a–c were grouped and the optimized values of parameters such as drum speed 7.25 m/s, concave clearance 3 mm and pearling sieve size 2 mm with predicted pearling efficiency of 98.95% and 0.73% grain damage

Table 2 Performances evaluation of pearling drum according to BBD

Expt. No.	Drum speed [m/s]	Concave clearance [mm]	Pearling sieve size [mm]	Pearling efficiency [%]	Grain damage [%]
1	5	3	3	96	0.1
2	10	3	3	98	1.2
3	5	15	3	95	0
4	10	15	3	97	0.9
5	5	9	2	97	0.4
6	10	9	2	99	1.5
7	5	9	4	93	0
8	10	9	4	97	0.8
9	7.5	3	2	99	0.8
10	7.5	15	2	97	0.6
11	7.5	3	4	96	0.3
12	7.5	15	4	92	0
13	7.5	9	3	96	0.2
14	7.5	9	3	96.5	0.2
15	7.5	9	3	97	0.1
16	7.5	9	3	96	0.2
17	7.5	9	3	96	0.2

Fig. 2 Graphical optimization of operational parameters of pearling drum. **a** Superimposed contours for pearling efficiency (%) and grain damage (%) at varying pearling sieve size (mm) and drum speed (m/s) at optimum concave clearance 3 mm. **b** Superimposed contours for pearling efficiency (%) and grain damage (%) at varying concave clearance (mm) and drum speed (m/s) at optimum pearling sieve size 2 mm. **c** Superimposed contours for pearling efficiency (%) and grain damage (%) at varying concave clearance (mm) and pearling sieve size (mm) at optimum drum speed 7.25 m/s

(Singh et al. 2010; Tewari et al. 2013). The values obtained in the numerical optimization method were found closer to the values obtained in the graphical optimization method. Based on these optimized values the modification in the drum was carried out. To validate the optimized parameters, the performance evaluation of the drum was carried out with optimum values of the independent variables. It was found that the pearling efficiency was 99% against predicted 98% and 0.5% grain damage was found against predicted 0.73%, respectively. The effects of operational parameters on the performance of the pearling drum were studied at their optimum level. This study was discussed in following sub-points.

Pearling efficiency

The Fig. 3a–c shows the effect of operational parameters on pearling efficiency at the set level of pearling sieve size (2 mm), drum speed (7.25 m/s) and concave clearance (3 mm), respectively. It was observed in Fig. 3a that, the pearling efficiency increased with the decrease in concave clearance and increase in drum speed. The maximum pearling efficiency (99.9%) was found at 3 mm concave clearance with 10 m/s drum speed. Figure 3b indicated that the pearling efficiency increased with the decrease in concave clearance and pearling sieve size. The maximum pearling efficiency (98%) was observed at 3 mm concave clearance with 2 mm pearling sieve size. It can be observed from Fig. 3c that the pearling efficiency increased with increase in drum speed and decreased in pearling sieve size. The maximum pearling efficiency of 99.9% was found at 10 m/s of drum speed and 2 mm pearling sieve size.

The decrease in two variables, i.e., concave space and pearling sieve size and increase in the drum speed is responsible for repeated impact and rubbing force on the finger millet grains, which thereby increase the pearling efficiency. Similar trends were also observed in Barnyard millet dehuller by Singh et al. (2011) and finger millet dehuller-cum-pearler by Verma et al. (2014).

The ANOVA shown in Table S1 (Supplementary 1) indicated that, the high value of model F (30.14) suggesting that the linear model can be successfully used to fit

Fig. 3 Combined effects of operational parameters of pearling drum on its performance. **a** Effect of concave clearance and drum speed on the pearling efficiency. **b** Effect of concave clearance and pearling sieve size on the pearling efficiency. **c** Effect of drum speed and pearling sieve size on the pearling efficiency. **d** Effect of concave clearance and drum speed on the grain damage. **e** Effect of drum speed and pearling sieve size on the grain damage. **f** Effect of concave clearance and pearling sieve size on the grain damage

experimental data ($p < 0.0001$). As per F-values indicated in Table S1 (Supplementary 1), the linear term of pearling sieve size ($p < 0.0001$), drum speed ($p < 0.001$) and concave clearance ($p > 0.01$) has a significant effect on the pearling efficiency at 1% level of significance. The predicated R^2 (0.75) for these model was also in agreement with adjusted R^2 (0.84). Adequate precision measures the signal to noise ratio and the ratio greater than four is desirable. Here the ratio became 17.53 indicates an adequate signal. This model can be used to navigate the design space. The regression equation in a variation of the pearling efficiency (η_p , %) with different independent variables ϑ , C_C and P_{SS} were fitted well in polynomial Eq. (10) with a coefficient of determination (R^2) 0.87 as given below:

$$\eta_p = 96.32 + 1.25\vartheta - 1C_C - 1.75P_{SS} \quad (10)$$

Grain damage

The effect of operational parameters on grain damage was studied at the set level of optimum pearling sieve size (2 mm), concave clearance (3 mm) and drum speed (7.25 m/s), respectively. By setting these optimum conditions, the graphs should be prepared and presented in Fig. 3d–f, respectively. The grain damage was increased with increase in drum speed and the decrease in concave clearance. The maximum grain damage 1.6% found at 3 mm concave clearance with 10 m/s drum speed (Fig. 3d). Figure 3e indicated that the grain damage increased with increase drum speed and decrease in pearling sieve size. The maximum grain damage was found to be 1.6%, at 2 mm pearling sieve size with 10 m/s drum speed. It can be observed from Fig. 3f that the grain damage increased with the decrease in concave clearance and pearling sieve size. It was attaining maxima 0.5% at a concave clearance of 3 mm with 2 mm pearling sieve size.

The decrease in concave clearance that increases the rubbing force between the canvas strip and grains are responsible for grain damage. It also happens due to the increase in direct contact between canvas strip-grain and grain-concave bars of the drum. Dominating impact force was observed at a higher speed of the drum. This maximum impact force is responsible for the maximum grain damage vice versa found at lower drum speed. Pearling sieve size

decreases, it increases the grain damage due to the maximum resident time of grains inside the pearling drum, ultimately it increases repeated impact and rubbing force on the finger millet grains. Similar trends were observed by Singh et al. (2011) for barnyard millet dehuller, Verma et al. (2014) for finger millet dehuller and Kamble et al. (2003) for pearl millet thresher.

The high F value of the model (240.79) shown in ANOVA Table S1 (Supplementary 1) was suggesting a quadratic model can be successfully used to fit experimental data ($p < 0.0001$). As per F-values indicated in Table S1 (Supplementary 1), the linear term of drum speed ($p < 0.0001$), concave clearance ($p < 0.0001$) and pearling sieve size ($p < 0.0001$), quadratic term of drum speed ($p < 0.0001$), pearling sieve size ($p < 0.0001$) and interaction term of concave clearance $\times$ pearling sieve size ($p < 0.0061$) has a significant effect on the grain damage at 1% level of significance. The interactions terms of drum speed $\times$ concave clearance ($p < 0.036$) and quadratic term of concave clearance ($p < 0.015$) has a significant effect on grain damage at 5% level of significance. Interaction terms of pearling sieve size and concave clearance did not have a significant effect on the grain damage even at the 10% level of significance ($p < 0.1$). The predicated R^2 (0.98) for these model was also in agreement with adjusted R^2 (0.99). Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Here the ratio became 51.33 indicates an adequate signal. This model can be used to navigate the design space.

The numerical presentation in a variation of the pearling efficiency (GD_p , %) with different variables ϑ , C_C and P_{SS} were fitted well in polynomial equation (Eq. 11) with a coefficient of determination (R^2) 0.97 as given below:

$$\begin{aligned} GD_p = & 0.18 + 0.49\vartheta - 0.11C_C \\ & - 0.28P_{SS} - 0.0509C_C - 0.0759P_{SS} \\ & - 0.025C_C P_{SS} + 0.31\vartheta^2 + 0.060C_C^2 + 0.18P_{SS}^2 \end{aligned} \quad (11)$$

Conclusion

As the developed pearling drum is a part of finger millet thresher cum pearler. The operating parameters as drum speed, concave clearance, and pearling sieve size play an important role in the performance of pearling drum. Therefore, the optimization of operational parameters of the pearling drum was carried out. The machine performance was found optimum on drum speed 7.25 m/s, concave clearance 3 mm and pearling sieve size 2 mm. The corresponding pearling efficiency was 99% against

predicted 98.95% and 0.5% grain damage against predicted 0.73%, respectively.

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