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ORIGINAL PAPER

Optimization of Machine Parameters for Milling of Pigeon Pea Using RSM

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Abstract Optimization of machine parameters using response surface methodology (RSM) greatly overcomes the numbers of experimental trials generally undertaken for milling study of pigeon pea apart from maximizing the output of the system. The independent milling parameters for Central Institute of Agricultural Engineering dal mill viz., roller speed, emery grit size, and feed rates were optimized for pigeon pea dehulling using RSM. The roller peripheral speed of 9.6 m/s, emery grit size 1 mm, and feed rate 111 kg/h were found optimal. The dal recovery and milling efficiency at optimized independent parameters were 75% and 80%, respectively.

Keywords Pigeon pea · Milling efficiency · Dal recovery · Emery grit size · Response surface methodology

Introduction

India is the largest producer of pulses in the world. The Annual production of pulses in the world in 2006–2007 is 54.4 million tonnes and in India is around 13.2 million tonnes from 22.5 million hectares area (Anon 2007a, b). India ranks first by contributing about 22.52% to the global pulse production and 35.2% area of global production area (Anon. 2007a). Pulses along with cereals play a vital role in human nutrition (Tiwari et al. 2007). Pigeon pea (*Cajanus cajan*) is the most commonly used pulse in the Indian subcontinent. Pulses are also referred to as a source of "Poor man's Protein." It is more popular in vegetarian diet especially for the poor socio-economic group. The per capita availability of pulses is around 30 g as against the requirement of 40 g per day (Indian Council of Medical Research) for an optimal diet (Anon. 2007b).

In India, about 80% of the pulse production is consumed in the form of dal or powder and remaining 20% as the whole seed and other forms (Chacko et al. 2001; Mangaraj et al. 2005). Whole pulses are milled into split dal by various methods/processes. The recovery of dal varies from 60% to 75%, depending upon the type of pulses and techniques adopted by the millers such as methods of pretreatment and milling machinery used (Sahay and Bisht 1988; Mangaraj et al. 2005). Generally, the husk is tightly attached to the cotyledons in pulses (Chakravarty 1988). In most pulses, husks are attached with cotyledons through a layer of gums (Kurien and Parpia 1968). Hence, a pretreatment of pulse grain for loosening of the husk prior to milling is desirable as it increases the recovery of dal (Sahay et al. 1985; Mangaraj et al. 2004). Kurien (1981) reported that dehulling of pigeon pea can be rendered easier by prolonged soaking in water for 12 h or more, but the dal so obtained remains uncooked and tough even with prolonged boiling (Singh 1995). The maximum dehulling efficiency for pigeon pea was obtained at 10.1% moisture content (db), dehulling time 12.3 s (with closed outlet) and mustered oil treatment 0.3% (Goyal et al. 2008). Tiwari et al. (2007) studied application of oil and subsequent heating of black gram as a premilling treatment on the removal of husk and observed that 85.5% of dehusking was obtained at 0.8% oil and at drying temperature of 90°C for 30 min.

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Dehulling is the most important operation of post harvest handling of pulses. The removal of seed coat is very important because it is indigestible and bitter. At present, loss of about 10–12% (as broken grain) edible portion takes place during milling operation due to improper milling practices, uncontrolled operational parameters, and lack of knowledge about the appropriate emery/carborundum grit size for different pulses and operations (Chacko et al. 2001). Ehiwe and Reichert (1986) studied the dehulling quality of cowpea, pigeon pea, and green gram cultivars with the tangential abrasive dehulling device and reported that seed size was the most important factor affecting the dehulling process. Seed size affected both efficiency of dehulling and splitting of cotyledons (Erskine et al. 1991). Some work has been done in identification of emery/carborundum grade and few for milling studies (Sahay and Bisht 1988; Kulkarni 1989; Mangaraj et al. 2004). Other researchers have worked on the optimization of process parameter for milling of various pulses (Singh et al. 2004; Tiwari et al. 2007). Response surface methodology has been successfully employed for the optimization of pulse milling operation (Khuri and Cornell 1987; Mandhyan and Jain 1993; Phirke et al. 1996; Goyal et al. 2008). Also, Ribott et al. (2008) determined the influence of sodium stearoyl-2-lactylate, transglutaminase, and xylanase on soy-wheat dough and bread properties, modeled by response surface methodology. Therefore, the machine parameters of Central Institute of Agricultural Engineering (CIAE) dal mill was optimized using response surface methodology for milling of pigeon pea.

Materials and Methods

Raw Material Pigeon pea (*C. cajan*, cv. ICPL-87) was obtained from CIAE farm.

Machine The CIAE dal mill (Fig. 1, manufactured by Central Institute of Agricultural Engineering, Nabibagh, Berasia Road, Bhopal, India) with overall dimensions of 770×630×1,020 mm, total weight 90 kg (without motor), capacity 100 kg/h, power unit 2 hp electric motor, labor requirement two (one to operate and another to load/unload grains) was used for all the milling studies. It consists of a feed hopper, feed screw, shaft, pulley, frame, and abrasive roller cylinder. The abrasive roller rotated inside the perforated screen cage. Dehulling took place due to friction between grain and abrasive surface. Scratching of raw grain and milling of pretreated grains was also done in the same mill (Sahay and Bisht 1988; Mangaraj et al. 2004).

Fig. 1 CIAE dal mill in operation

Fabrication of Carborundum Roller The roller was a main component in CIAE dal mill and basically consisted of a cylinder of 2 mm thick mild steel, 250 mm diameter with 10 mm mild steel end plates. It was coated first with emery of grade number 30 by mixing of two parts (by volume) of emery and one part of special cement (magnesium oxide, MgO) with hot salted water prepared into a paste of desired consistency and then pasted in the roller. Finally, it was coated with a working outer layer of desired carborundum grits, which were thoroughly mixed with white cement and magnesium chloride salt in a proportion of 6:1 (Sahay et al. 1985; Mangaraj and Kapur 2005). Separate roller was made for each grit size (Mangaraj et al. 2004).

Pretreatment Method The CIAE premilling treatment method was used for the milling study (Mangaraj et al. 2004) and the details are given in Fig. 2.

Drying The pretreated pigeon pea grains were dried in open sunlight to a desired moisture content of 9–10% (db) (Sahay et al. 1985; Mangaraj et al. 2004; Goyal et al. 2008).

Design of Experiment

Central Composite Rotatable Design Central composite rotatable design (CCRD; Hunter 1959; Rastogi et al. 1998; Condon et al. 2001; Manickavasagan et al. 2008) with three independent machine parameters viz., drum peripheral speed (d_{ps}), emery grit size (e_{gs}), and feed rate (f_r) was considered for optimization (Cochran and Cox 1957). Experimental plan for optimization constituted two responses viz., dal recovery (r) and milling efficiency (γ). For this purpose, response surface methodology (RSM) was employed to fit a second-order polynomial equation (Onwubolu 2006; Tiwari et al. 2008) for dehulling of pigeon pea. Value of d_{ps} varies from 7.85 to 13.09 m/s, e_{gs} between 0.18 and 4.24 mm, and f_r between 80 and 120 kg/h. Nonlinear second-order regression equation of the form Eq. 1 for the responses as function of coded value of the independent parameters were developed, and machine

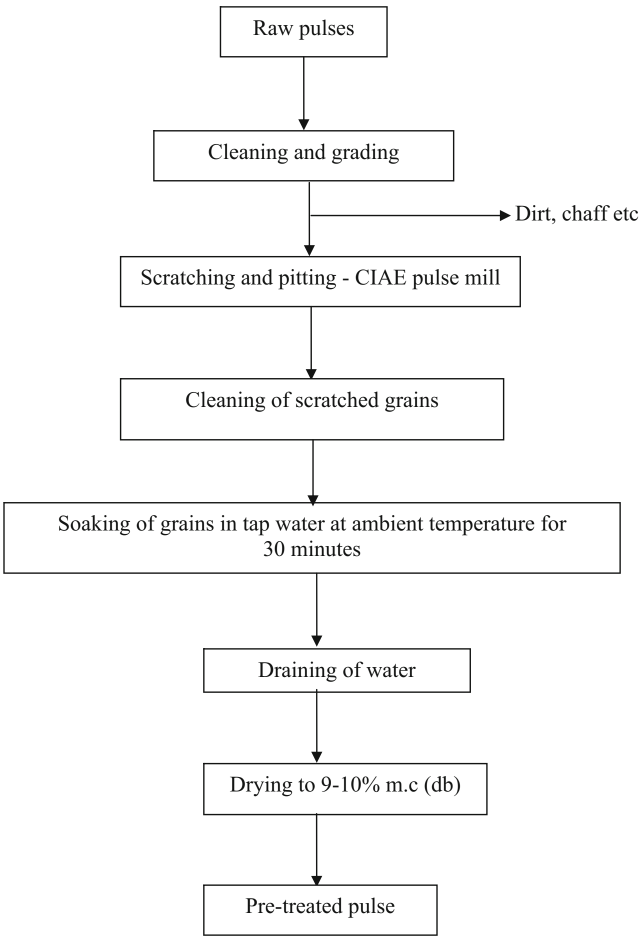

Fig. 2 CIAE method of premilling treatment of pulses

parameters were optimized for maximizing the r and γ using design expert 7.0.0 (Design Expert 2002).

$$Y_p = a_0 + a_1 d_{ps} + a_2 e_{gs} + a_3 f_r + a_{11} d_{ps}^2 + a_{22} e_{gs}^2 + a_{33} f_r^2 + a_{12} d_{ps} e_{gs} + a_{23} e_{gs} f_r + a_{13} d_{ps} f \quad (1)$$

The independent variables were fixed at five levels as per CCRD type experimental design, and a total number of 20 experiments were carried out as evident from Table 1. The experiments were conducted in random order. Five repeated experiments were conducted at the central points of the coded variables to calculate the error sum of squares and the lack of fit of the developed regression equation between the responses and independent variables (Myres 1971).

Milling Operation The experiments were conducted at different roller speed and feed rates and with different grade of carborundum rollers. The samples of milled product were taken for determination of dal recovery and dehulling efficiency. The milling efficiency and dal recovery was calculated as per the following formulae given by Kuprits (1967).

$$\gamma = E_h \times E_{wk} \times 100 \quad (2)$$

$$E_h = 1 - \frac{n_2}{n_1} \quad (3)$$

$$E_{wk} = \sim \frac{(k_2 - k_1)}{(k_2 - k_1) + (d_2 - d_1) + (m_2 - m_1)} \quad (4)$$

$$r = \frac{d_d}{(t_g - u_g)} \times 100 \quad (5)$$

Results and Discussion

Response surface analysis was applied to the experimental data (Table 1), and the second-order polynomial response surface model (Eq. 1) was fitted to each of the response variables (r and γ). Regression analysis and analysis of variance (ANOVA) were conducted for fitting the model and to examine the statistical significance of the model terms. The estimated regression coefficients of the quadratic polynomial models for the response variables, along with the corresponding R^2 and coefficient of variation (CV) values, are given in Table 2. Analysis of variance showed that all the models were significant ($p<0.05$) for all the responses (Table 2). The lack of fit (Table 2), which measures the fitness of the model, did not result in a significant F value for pigeon pea dal recovery and milling efficiencies, indicating that these models are sufficiently accurate for predicting those responses.

Pigeon Pea Dal Recovery

It was observed from ANOVA (Table 2) that roller peripheral speed, emery grit size, and feed rate are not significantly affecting the dal recovery of pigeon pea at linear level ($p \geq 0.05$), while quadratic term of roller peripheral speed is a more significant ($p \leq 0.01$) parameter affecting the dal recovery of pigeon pea. Figure 3 shows that at fixed value of emery grit size (2.21 mm), the dal recovery of pigeon pea (r) gradually increased with roller speed up to 10.47 m/s and reduced thereafter. Similarly, with increase of feed rate, it is decreased gradually. At fixed value of roller speed (10.60 m/s) the dal recovery decreased with feed rate up to 105.95 kg/h and increased thereafter up to 111.89 kg/h. Similarly the maximum dal recovery was observed at 1 mm grit size and decreased thereafter. At

Table 1 Treatment combinations for pulse milling with three variable second-order RSM design

Experiment number	d_{ps} (m/s)	e_{gs} (mm)	f_r (kg/h)	r (%)	γ (%)
1	10.47 (0)	0.18 (−1.68)	100.00 (0)	76	81.4
2	8.91 (−1)	3.42 (+1)	112 (+1)	68.7	74
3	12.03 (+1)	3.42 (+1)	88.11 (−1)	72	77
4	13.09 (+1.68)	2.21 (0)	100.00 (0)	66	74
5	12.03 (+1)	1.00 (−1)	88 (−1)	74.5	80.3
6	8.91 (−1)	1.00 (−1)	112 (+1)	74.9	81.5
7	10.47 (0)	2.21 (0)	100.00 (0)	75.5	80
8	12.03 (+1)	1.00 (−1)	112 (+1)	71	74
9	10.47 (0)	2.21 (0)	80.00 ((−1.68)	75.3	80
10	10.47 (0)	2.21 (0)	100.00 (0)	72	78
11	7.85 (−1.68)	2.21 (0)	100.00 (0)	69	76
12	8.91 (−1)	3.42 (+1)	88 (−1)	73	73
13	10.47 (0)	2.21 (0)	100.00 (0)	75.5	80
14	10.47 (0)	2.21 (0)	100.00 (0)	76	81.4
15	8.91 (−1)	1.00 (−1)	88 (−1)	76	81
16	10.47 (0)	4.24 (+1.68)	100.00 (0)	74	81
17	10.47 (0)	2.21 (0)	120.00 (+1.68)	73	76
18	10.47 (0)	2.21 (0)	100.00 (0)	72	78
19	10.47 (0)	2.21 (0)	100.00 (0)	76	81.4
20	12.03 (+1)	3.42 (+1)	112 (+1)	73	80.5

fixed feed rate (102 kg/h), the dal recovery increased with roller speed up to 10.47 m/s and decreased thereafter up to 12.03 m/s at all emery grit sizes. The pigeon pea dal recovery was found to be maximum at roller speed 10.6 m/s, emery grit size 2.21 mm, and feed rate 102 kg/h. The second-order polynomial equation for pigeon pea pulse recovery is shown in Eq. 6 as follows.

Table 2 Analysis of variance and regression coefficients of the second-order polynomial model for the response variables (in coded units)

Variables	DF	Estimated coefficients r	Estimated coefficients γ	F values r	F values γ
		74.47	79.81	4.22*	4.11*
d_{ps1}	1	−0.52	−0.08	1.19	0.23
e_{gs2}	1	−0.96	−0.95	3.98	3.47
f_{r3}	1	−0.86	−0.59	3.23	1.33
$d_{ps}e_{gs}$	1	1.09	2.34	3.01	12.31**
$d_{ps}f_r$	1	0.36	−0.54	0.33	0.65
$e_{gs}f_r$	1	0.16	1.29	0.07	3.73
${d_{ps}}^2$	1	−2.30	−1.76	24.38**	12.57**
${e_{gs}}^2$	1	0.53	0.43	0.55	0.76
f_r^2	1	0.047	−0.70	0.01	1.99
Lack of fit	5			0.58	2.83
R^2		0.79	0.79		
$R^2\text{v}_{ad}$		0.60	0.60		
CV %		2.4	2.42		

*p<0.05, significant; **p<0.01, significant; ***p<0.001, significant

$$r = 74.47 - 0.52d_{ps} - 0.96e_{gs} - 0.86f_r - 2.3d_{ps}^2 + 0.53e_{gs}^2 + 0.047f_r^2 + 1.09d_{ps}e_{gs} + 0.16e_{gs}f_r + 0.36d_{ps}f_r \quad (6)$$

Pigeon Pea Milling Efficiency

The quadratic term of roller peripheral speed and interaction term of roller speed and emery grit size are more significant ($p \leq 0.01$) parameters affecting the milling efficiency of pigeon pea (γ) (Table 2). Figure 4 shows that at fixed value of emery grit size (2.21 mm), the milling efficiency of pigeon pea (γ) gradually increased with roller speed up to 11.25 m/s and reduced thereafter up to 12.03 m/s. Similarly, with increase of feed rate, it is increased up to 105.95 kg/h and reduced thereafter. At fixed value of roller speed (10.47 m/s), milling efficiency gradually decreased with feed rate up to 106 kg/h and increased thereafter up to 112 kg/h. Similarly, the maximum milling efficiency was observed at 1 mm grit size and decreased thereafter. At fixed feed rate (101 kg/h), the milling efficiency was maximum at roller speed of 8.91 m/s and decreased thereafter up to 12.03 m/s at grit size 1 mm.

However, the reverse effect was observed at emery grit size of 3.42. The pigeon pea milling efficiency was found to be maximum at roller speed 10.47 m/s, emery grit size 2.21 mm, and federate 101 kg/h. The second-order

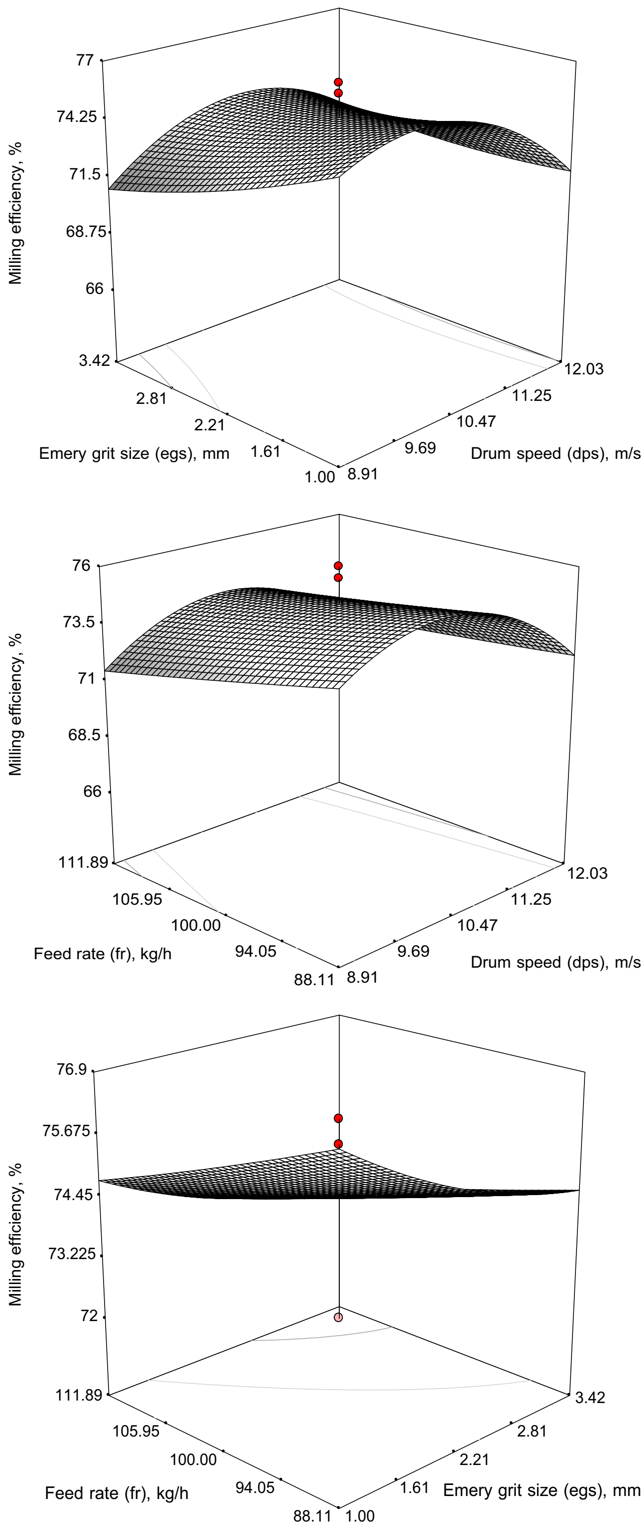

Fig. 3 Response surface and contour plots for pulse recovery of pigeon pea as a function of roller speed, emery grit size, and feed rate. For each plot, the third machine parameter is fixed at "0" level

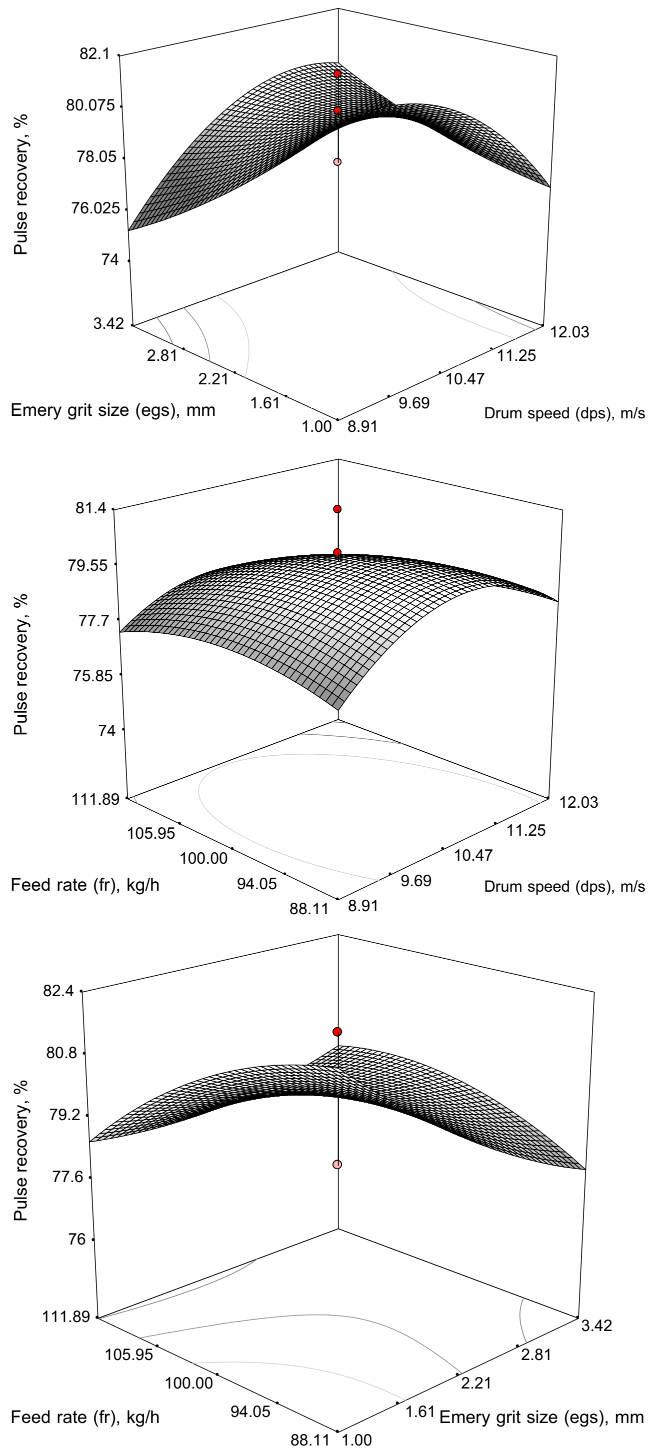

Fig. 4 Response surface and contour plots for milling efficiency of pigeon pea as a function of roller speed, emery grit size, and feed rate. For each plot, the third machine parameter is fixed at "0" level

Table 3 Solutions for optimal conditions

Number	d_{ps} (m/s)	e_{gs} (mm)	f_r (kg/h)	r (%)	γ (%)	Desirability
1	9.65	1	111.14	74.89	79.87	0.92
2	9.65	1	111.34	74.87	79.82	0.92
3	9.66	1	110.92	74.91	79.92	0.92
4	9.66	1	111.10	74.90	79.87	0.92
5	9.66	1	111.69	74.85	79.73	0.92
6	9.72	1	110.76	74.97	79.91	0.92
7	9.68	1	111.89	74.84	79.66	0.92
8	9.65	1	110.32	74.97	80.07	0.92

polynomial equation for milling efficiency of pigeon pea is shown in Eq. 7.

$$\gamma = 79.81 - 0.08d_{ps} - 0.95e_{gs} - 0.59f_r - 1.76d_{ps}^2 + 0.43e_{gs}^2 - 0.70f_r^2 + 2.34d_{ps}e_{gs} - 0.54e_{gs}f_r + 1.29d_{ps}f_r \quad (7)$$

Optimization of Machine Parameters for Development of Appropriate Milling Machine

The pulse recovery (r, kg/h) and milling efficiency (γ, %) were taken as responses in order to optimize the machine parameters. The optimization was carried out using response surface methodology (Design Expert 7.0.0). The optimized values of roller peripheral speed, emery grit size, and feed rate were taken in CIAE pulse mill for further study. Numerical (Table 3) and graphical optimizations (Fig. 5) were carried out for obtaining the appropriate design parameter of the machine for obtaining optimum pulse recovery and efficiency. Design expert program of the STATEASE software was utilized (Design Expert 7.0.0) for simultaneous optimization of the multiple regressions, and responses were chosen and different weights (0.9 for dal recovery and 0.8 for milling efficiency) assigned to each goal to adjust the shape of its particular desirability function.

The roller peripheral speed of 9.65 m/s, emery grit size 1 mm, and feed rate 111.2 kg/h for the CIAE dal mill were found optimal for the milling of pigeon pea. At this optimized condition, the dal recovery and milling efficiency were 74.89% and 79.87%, respectively (Table 3). The milling experiment results were in close agreement with the dal recovery and milling efficiency values at optimized independent parameters. The findings of the optimization study, viz., the dal recovery and milling efficiency of pigeon pea, and developed models were compared with the work carried out by Hunter (1959), Sahay and Bisht (1988), Rastogi et al. (1998), Mangaraj et al. (2004), Pratape et al. (2004), Zhang et al. (2007), and Goyal et al. (2008) and were found to be comparable. The dal recovery and milling efficiency of pigeon pea were obtained as 74–76% and 79–81% at 9–10 moisture content (% db) using CIAE methods of pretreatments and 32 grades of rollers (Sahay and Bisht 1988; Mangaraj et al. 2004). Pratape et al. (2004) designed and developed a mini dal mill at Central Food Technological Research Institute, Mysore (India) with a dal recovery of 75–77% as compared to 55–60% dal recovery for traditional chakki and 75–78% for commercials dal mills.

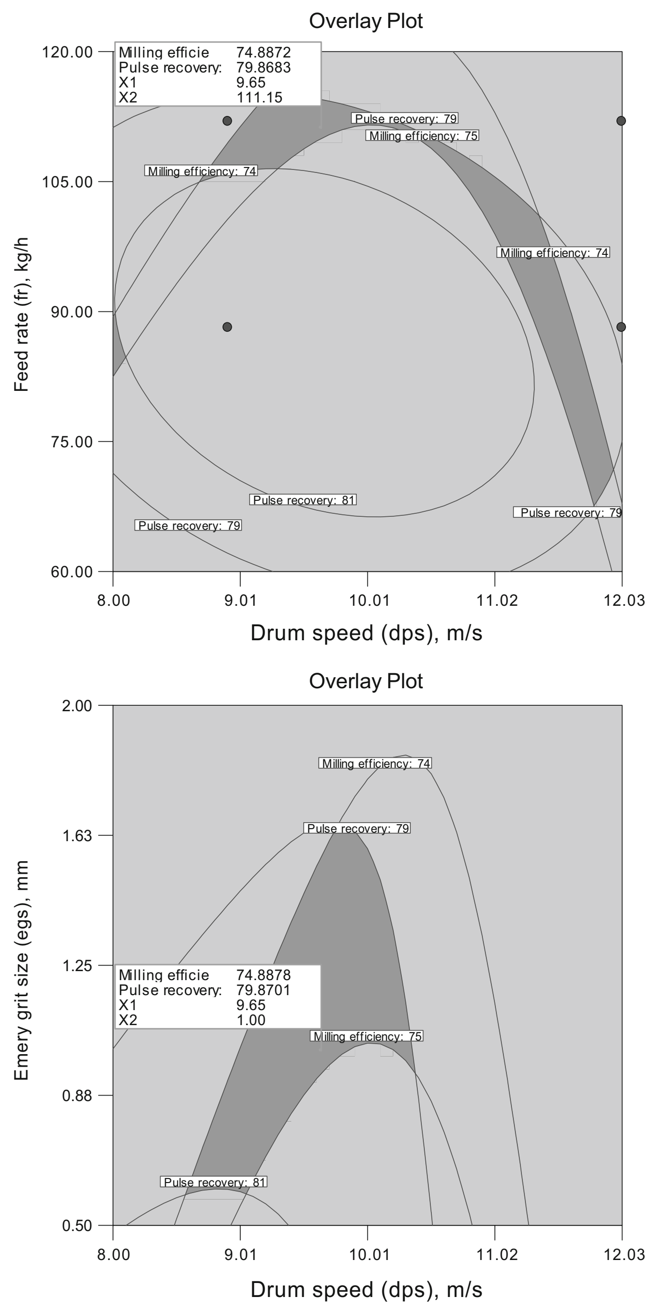

Fig. 5 Optimization of independent parameters of CIAE dal mill

Conclusions

The roller peripheral speed of 9.6 m/s, emery grit size 1 mm, and feed rate 111 kg/h were found optimal for CIAE pulse mill for higher pulse recovery and milling efficiency of pigeon pea. The dal recovery and milling efficiency on the optimized independent parameters were 75% and 80%, respectively. The calculated *F* value for lack of fit for dal recovery and milling efficiency of pigeon pea was found to be less than tabular values, which indicates that the regression equation obtained though RSM are in close agreement with the experimental values.

Nomenclature

a_0, a_1, a_2, a_3, a_{11}, a_{22}, a_{33}, a_{12}, a_{23}, and a_{13}	Regression coefficients
d_1	Fraction of crushed kernels before hulling
d_2	Fraction of crushed kernels after hulling
E_h	Effectiveness of hulling
E_{wk}	Effectiveness of wholeness of kernels
k_1	Amount of whole kernels before hulling, kg
k_2	Amount of whole kernels after hulling, kg
m_1	Content of mealy waste in the product before hulling, %
m_2	Content of mealy waste in the product after hulling, %
n_1	Amount of unhulled grains before hulling, kg
n_2	Amount of unhulled grains after hulling, kg
N	Total number of experiments
r	Dal recovery of pigeon pea, %
d_{ps}	Drum peripheral speed, ms^{-1}
e_{gs}	Emery grit size, mm
f_r	Feed rate, kg h^{-1}
d_d	Amount of desirable fraction after hulling, kg
x_1, x_2, and x_3	Coded values of the independent variables X_1, X_2, and X_3, respectively
Y_p	Predicted value of the responses from the developed models
γ	Milling efficiency of pigeon pea, %
t_g	Amount of grain fed to the dal mill for hulling, kg
u_g	Amount of unhulled grain after hulling, kg

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