Response surface methodology optimization of solar powered thresher on soybean

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Abstract: Considering the need for threshing, the current energy crisis, the power potential of solar energy, especially, many stand-alone solar installations in rural areas, and their use, a study was undertaken to develop and evaluate a solar-powered multi-crop thresher on soybean. The study was conducted in IARI- Pusa Campus, New Delhi, India aiming to assess the seasonal suitability of the solar operated thresher. The devolved prototype was evaluated on soybean crop and the operational and machine parameters were optimized by response surface methodology (RSM), with central composite design (CCD). Four independent parameters, each at three levels, were taken viz, feed rate, cylinder speed, concave clearance, and spike types to evaluate their effects on three response variables, namely, threshing efficiency, cleaning efficiency, and energy consumption. The response variables ranged from 96.3% to 99.9%, 86.68% to 93.05%, and 1.12 kWh q^{-1} to 1.74 kWh q^{-1}, respectively, for threshing efficiency, cleaning efficiency, and energy consumption. The cylinder speed significantly affected all response variables. The optimization showed that the best operational and machine settings were 13.62 m s^{-1} cylinder peripheral speed, 4.3 kg min^{-1}, feed rate, 20 mm concave clearance, and spike type 3 giving the desirability of 0.799 and the threshing of 116.64 kg hr^{-1} capacity. However, the season-based optimization with lower feed rates was found advantageous to increase the duration of up to 5 hours of thresher operation in thresher direct coupling mode. Hence it is recommended to adopt the lower feed rate in seasons with reduced insolation.

Keywords: response surface methodology, threshing efficiency, cleaning efficiency, threshing Energy consumption, thresher optimization

Citation: Harerimana, L., I. Mani, P. K. Sharma, R. A. Parray, S. D. Lande, K. Bandyopdhayaya, and S. K. Sarkar. 2024. Response surface methodology optimization of solar powered thresher on soybean. Agricultural Engineering International: CIGR Journal, 26(1): 115-127.

1 Introduction

Soybean (*Glycine max L.*) occupies a preponderant role among oil seed crops for human and animal nutrition (Adekanye et al., 2016). Dry grains are highly rich in proteins (36%), carbohydrates (35%), and cholesterol-free oil (19%). Soybean protein is almost similar to that of animal protein; it contains most of the essential amino acids required for human and animal

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Received date: 2023-07-05 **Accepted date:** 2023-09-15

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nutrition (Hassan, 2013). Given the utility and role played by soybean, its production needs to be streamlined at all points of the value chain. It is opined that production is not complete without appropriate threshing tools among production machines (Adekanye and Olaoye, 2013). Threshing is the process of removal and separation of grains from the pod or from the ear. It is done manually or mechanically. There are four grain threshing principles: impact, rubbing, pre-cut combing and grinding (Fu et al., 2018). The threshing machine designer thrives on having the highest threshing and cleaning efficiency while reducing the losses and damages of grains at the minimum energy consumption.

The mechanical power thresher become in vogue; threshers are powered by 3.7-11.2 kW engines, electric motors, and tractors' power take-off (PTO) with capacity ranging from 1.5-2.0 tonnes per hour. More than 80% of wheat, barley, gram, soybean, sorghum, and pearl millet crops are estimated to be threshed by mechanical power thresher (Tiwari et al., 2018).

Qabaradin and Tsegaye (Qabaradin and Tsegaye, 2021) conducted an evaluation of soybean thresher with the goal to optimize critical operational and crop parameters that affect the threshing capacity. The independent parameters were drum speed and feed rate, whereas the dependent factors were threshing efficiency, mechanical grain damage, and cleaning efficiency. The most important element impacting threshing efficiency, cleaning efficiency and evident seed damage was found to be the drum speed. Threshing efficiency increased with the cylinder speed from 83.95% to 93.54% cleaning efficiency increased from 69.21% to 79.93%, and grain damage increased from 2.35% to 2.9%.

The lack of a steady supply and unavailability of electricity, the high cost of conventional fossil fuel used to operate the threshers in rural and remote regions hampers the rural farmers to embrace the technology. As a result, modern threshers with an engine or an electric motor are not fitting to many smallholder farmers in rural and isolated locations (Sahu and Raheman, 2020). A major factor in achieving higher yields, higher incomes, reduced losses, and more climate resilience is energizing the agri-food system (Acosta-silva et al., 2019; Rathore et al., 2018). Thus, sustainable energy accessibility for primary production, post-harvest processing is a prior requirement. The current pattern of energy use in agri-food systems, however, is characterized by regional inequalities, a lack of access to modern energy technology, particularly in the developing world, and a continued reliance on fossil fuels (IRENA and FAO, 2021; Liu et al., 2018). The use of renewable energy sources especially solar in the farm shows a prospect for the future (Sahu and Raheman, 2020). Small-scale farmers find costly the conventional source of farm energy (Benghanem et al., 2018). Compared to the solar photovoltaic source of electricity, the operating cost of other sources is many times higher. Energy consumption as well as the energy source is now the constraints in the contest of pollution, energy cost and availability. The threshing operation is the most time and energy consuming activity that constrains the farmers (Devnani and Ojha, 2016). The clean energy needs to be optimally infused in the farming system at various levels to cope with the conventional energy crisis and cost (Liu et al., 2018). The response surface method (RSM) design, central composite design (CCD) is suited for fitting a quadratic surface. This method helps to optimize the effective parameters with a minimum number of experiments, as well as to analyses the interaction effect between those parameters.

The multi-crop threshers are popular in India many farming systems with the main use on paddy, soybean, sorghum, sunflower and maize. These threshers use, mostly, electric motors in the place where the electric grid is accessed otherwise, they IC engine is used. However, the running cost of these conventional energy sources. The recourse to solar energy is a plausible solution, which also runs the inconveniency of instability of the power supply radiation. The machinery that was reportedly powered by solar energy used solar photovoltaic systems with storage backup power because the solar intensity wasn't constant during the operational hours (Garbin et al., 2019; Ibrahim et al., 2020; Sahu and Raheman, 2020). But so far limited literature has been reported related to the optimum utilization of solar powered threshers for various harvesting seasons on the concerned crops. A study was undertaken aiming at the development of solar powered multi-crop threshers with direct coupling options and optimization of its operation in the seasons of harvesting of the soybean crop. Hence, an attempt was made to design a solar energy system operating the axial multi-crop thresher for small scale farmers where soybean was used as a test crop. ARSM experiment was conducted with CCD to evaluate the performance and optimize the best option to utilize solar energy for Delhi conditions in times of soybean harvesting.

2 Materials and methods

A solar-operated multi-crop thresher was developed and evaluated in the ICAR-IARI, Division of Agricultural Engineering, Pusa campus (28.633^o N, 77.153^{o}E) located in New Delhi, India during the months of October and November 2021. The longitudinal axial thresher was designed and manufactured in the division of Agricultural Engineering and soybean crop material varieties of PS-1347and SL 958 were used to test the thresher. The data were collected according to the experimental design with 31treatments/runs in 3 replications. The relationship between independent parameters and objectives was established after the analysis of data using the Minitab 19 software. The optimal values of the process parameters were obtained as constrained by the response parameters such as threshing efficiency, cleaning efficiency, and energy consumption.

2.1 Description of thresher and solar array

Targeting a small-scale farmer, a spike tooth axial multi-crop thresher with the reduced size of machine that threshes cereals, oilseed, and pulse crops satisfactorily at low cost was designed and developed with the salient specifications shown in Table 1. The machine was operated by a 1500 W, 48 V blushless DC motor powered by solar energy from a solar array rated 2400 W, which was used basically for solar pumping.

Table 1 salient specification of the machine

Sr. No.	Parts, units	Dimension, Numbers
1	Diameter of the cylinder, mm	380
2	Length of the cylinder, mm	580
3	Number of spikes rows	6
4	Length of the exit shoes, mm	140
5	Diameter of the blower, mm	380
6	Width and length, mm	160
7	Blower blades, numbers	4
8	Size of the sieve, mm	760 × 460
9	Solar array rated power, W	2400
10	Solar panel open voltage	45 V
11	DC to DC convertor,	1800W 40A
12	BLDC Motor power	1500 W, 48 V
13	Speed of the motor	2200 rpm

The solar panel array is coupled to the load directly or through a battery through a DC to DC convertor to match the source voltage and required load voltages. The thresher's power requirement was derived by calculating the torque and speed data required for threshing. A solar panel array was used to produce the power and supplied the latter through a DC to DC convertor, connected directly to the brushless DC motor controllers and then to 1.5 kW BLDC motor to run the thresher. A CY-Gold 1528 BLDC motor and its controller were used as the prime mover to operate the thresher. The motor speed was controlled using a potentiometer. The power transmission to the thresher drum and other driven parts was achieved through Vbelt and pulley systems as shown in Figure1.

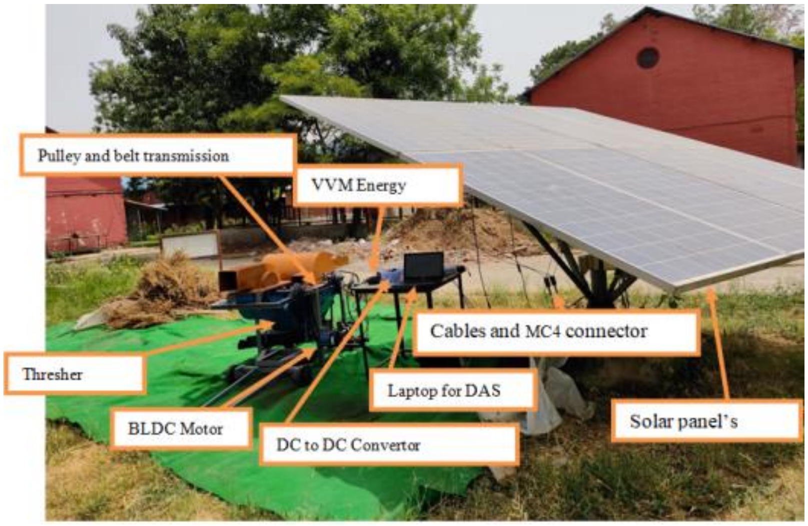


Figure 1 Direct connection of solar array and thresher

The soybean crop was harvested, dried, and then threshed using a solar-powered spike-tooth thresher. The experiment was conducted with the crop material at 10.6% moisture content at wet basis. An inclined chute was used to feed plant materials into the thresher. After threshing, the grains were gravity fed to the seed sieve (screen). The clean seeds were collected at the seed's outlet at the end of the sieve, which oscillates back and forth while the chaff materials are being blown by the air stream from the blower.

2.2 Experiment statistical design

Four independent variables were considered for optimization through a CCD experiment. The experiment was set to evaluate the effect of the operating parameters (feed rate and cylinder speed) and machine parameters (concave clearance and spike types) on the threshing responses viz. threshing efficiency, cleaning efficiency, and energy consumption. Among the four factors, there were three continuous factors, namely, feeding rate, cylinder speed, and concave clearance, while the spike type is a categorical factor. All factors were taken at Three levels and with feed rates (X_1) of 3, 4.5, and 6 kg min^{-1}, the cylinder peripheral speed (X_2) of 7.95, 10.94, and 13.92 m s^{-1} of peripheral speed and the concave clearance (X_3) with three levels of 10, 15 and 20 mm and three types of spikes were taken. The fourth factor, which was a categorical factor of spike type (X_4), had three types (round spikes length 80 mm from the drum, spaced of 80 mm with 17. 2 kg weight, rectangular spikes of 80 mm height, space of 80 mm with 19.6 kg weight, and rectangular spikes of 80mm height, space of 50mm with 21.7 kg weight). An experiment set-up of 31 runs was created using Minitab 19 software and conducted with 3 replications. Threshing efficiency (%), cleaning efficiency (%), and energy consumption (kWh) were the three dependent variables in the optimization experiment. The experiment was designed using RSM-CCD with 31 runs.

The experiments occurred in random order and three replications were done to calculate the sum of squared error and lack of fitness for the proposed regression equation between the dependent and independent variables (Myres et al., 2009). The analysis was done using Minitab 19 software. The effects of the independent variables on various responses were illustrated, the mean and standard deviation were calculated, and the analysis of variance and mean separation and grouping were performed by Tukey's method (honestly significant difference, HSD) test at 0.05 probability.

2.3 Evaluation procedure

The thresher's performance was assessed at three different levels of each independent parameter on the thresher after it was adjusted and installed on a hard surface. The experiments evaluated the effects of these independent factors on threshing efficiency, cleaning efficiency, and energy consumption. To obtain the thresher performance indices, samples of unthreshed crops were randomly prepared and fed to the thresher. The speed of the motor was controlled by the help of the potentiometer connected to the BLDC motor controller. The crop materials to be fed at various machine loading levels were measured using the weighing balance. The stability of cylinder speed was ensured using the tachometer and the feeding was done regularly for the period of 1 minute for each treatment. Three dependent variables were determined at various treatments. The threshing efficiency is the percentage of threshed grains calculated on the basis total grains entering the threshing cylinder. The cleaning efficiency is the percentage of clean grain on the total grain sample. The energy consumption, in kWhq^{-1} is the quantity of energy required for the threshing operation for one quintal of grains.

The samples of threshed grains and material other than grains were collected from the seed outlet, straw outlet, and chaff outlet. They were separated into total seeds received at the main outlet (*W*), total seed (*ST*), unthreshed seeds (*Su*), and material other than grains at the main outlet (*MoG*). The performance with respect to threshing efficiency (*TE, %*), and cleaning efficiency (*CE, %*) were calculated using the following relationships:

$$TE = 100 - \left(\frac{Su}{ST}\right) x\ 100 \quad (1)$$

$$CE = \frac{\mathrm{W - MoG}}{\mathrm{W}}\ x100 \quad (2)$$

The energy consumption measuring device is VVM digital voltmeter ammeter provided with a WCS1600 hall sensor, and the microcontroller board and a display. The module was connected to the Arduino board to record the power consumption data continuously. The Atmega 2560 R3 model was used to collect the energy data readings and store them, Figure 2. The hourly solar irradiation in the months of soybean harvesting was measured and used to assess and optimize the approaches to adopt for an effective and efficient use of directly connected solar powered thresher.

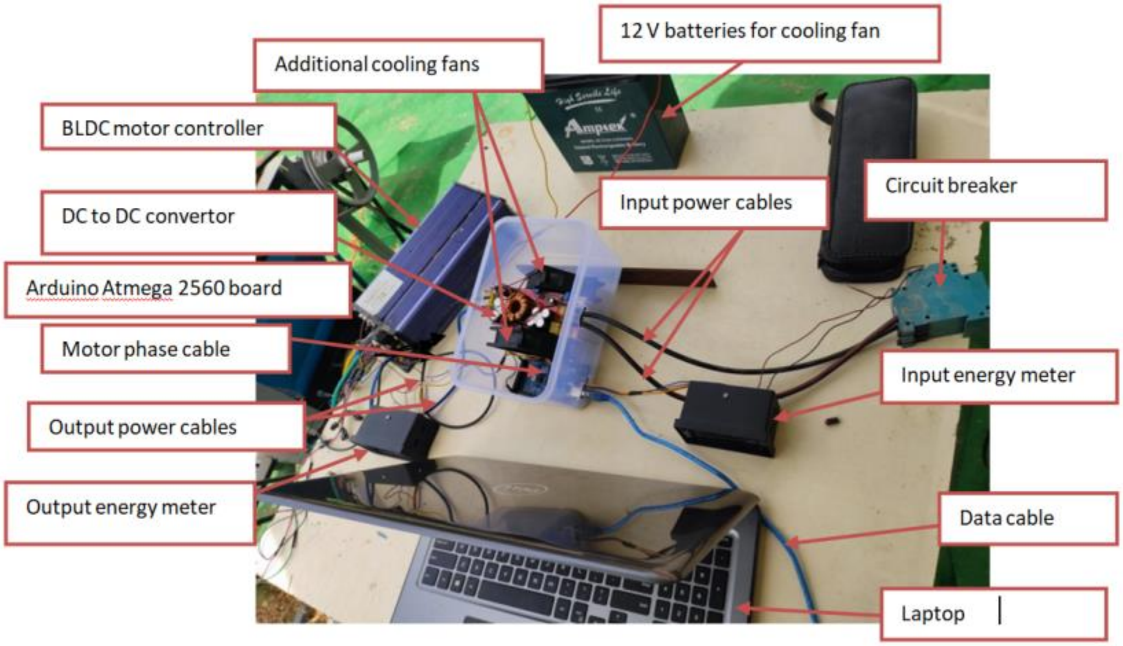


Figure 2 Direct connection of the multi-crop thresher’s motor to the solar panels

2.4 Optimization of independent parameters

Optimization of independent parameters, i.e., feeding rate, cylinder speed, and concave clearance, was done by a numerical optimization technique using Minitab 19 software. For the numerical optimization, lower and upper limits of independent parameters were set ‘In Range’ to get the desired optimum values of dependent parameters viz, threshing efficiency, cleaning efficiency, and energy consumption. The primary goal for the optimization of parameters was to maximize the threshing efficiency and cleaning efficiency while the energy consumption was to be minimized. Table 2 shows the desired goal for optimization of each parameter.

Table 2 Criteria to optimize the thresher’s parameters

	Parameters	Target/Goal
Constraints parameters	Feed rate (A)	In range
	Speed of drum (B)	In range
	Clearance (C)	In range
	Type of spikes (D)	Categorical factor
Objective parameters /response optimizer	Threshing efficiency,%	Maximize
	Cleaning efficiency,%	Maximize
	Energy consumption, kWh q^{-1}	Minimize

The cost of operation for the optimum machine setting was calculated and compared to the cost of existing thresher using conventional sources of the power.

3 Results

Four independent parameters were considered for evaluating the performance of the solar operated multi-crop thresher. The analysis of variance has shown the effect of the independent parameters and their interaction on the performance parameters. The results of the ANOVA are shown in Table 3 while the mean separation using Tukey’s HSD is shown in Table 4.

3.1 Threshing efficiency

The results of the experiment showed the threshing efficiency between 96.3% and 99.9% with an overall average of 98.47% and a standard deviation of 0.842%. The threshing efficiency was found to be highly influenced by the cylinder speed and the type of spikes at 1% level of significance, Table 3. Figure 3 shows the effect of cylinder speed and feed rate on the threshing efficiency.

It can be noticed that the threshing efficiency increases tremendously with the cylinder speed and the mid values of feed rate (around 4.5 kg min^{-1}) have the higher threshing efficiency. At a feed rate of 4.5 kg min^{-1} on spike 3 type, with increasing cylinder speed from 7.95 to 13.92 m s^{-1} the threshing efficiency increased from 97.81% to 99.8%. The threshing efficiency decreases with the increased concave clearance (Figures 3a. and 3b). With the increase in concave clearance from 10 to 20 mm at the cylinder speed of 13.92 m s^{-1}, the threshing efficiency dropped from 99.8% to 99.6%, while at the cylinder speed of 7.95 m s^{-1} decreased from 99.5% to 99.1%. Comparatively, concave clearance has a lower effect on the threshing than the speed of spike.

Higher threshing efficiency at the higher cylinder speed and at spike 3 was due to the increase in impact effect. The lowest threshing efficiency was found at the higher concave clearance. The optimal feed rate maximizes the impact and rubbing parts' contact with the pods, resulting in increased threshing. The interactions between spike types and all other parameters had a substantial effect on threshing efficiency at the 1% confidence level. Among the first-order interactions, it was noticed that the order of importance as cylinder speed × spike type, concave clearance × spike type, feed rate × spike type came at the top of the interaction effects as shown in Table 3, while other interactions did not show a significant effect. The quadratic effect was found to be significant for the feed rate and the cylinder speed (Table 3). The separation of means shows that spike 3 is significantly different from the other spike types, similarly level 2 feed rates (4.5 kg min^{-1}) and level 3 of cylinder speed (13.92 m s^{-1}) as they form separate groups, Table 4.

The individual mean comparison showed that spike type has significant effect on the threshing efficiency with averages of 97.95%, 98.23%, and 99.25%, for spike type 1, type 2, and type 3, respectively, as shown in Table 4. With spike 3 making a separate group.

Table 3 ANOVA for soybean threshing using response surface quadratic model.

		Threshing efficiency ,%		Cleaning efficiency,%		Energy consumption	
Source	DF	F-Value	P-Value	F-Value	P-Value	F-Value	P-Value
Model	17	41.17	0.000**	48.49	0.000**	17.80	0.000**
Linear	5	93.88	0.000**	67.97	0.000**	25.25	0.000**
X_1	1	0.00	0.982NS	5.04	0.028*	9.48	0.003**
X_2	1	185.37	0.000**	290.38	0.000**	33.48	0.000**
X_3	1	0.05	0.828NS	41.85	0.000**	23.39	0.000**
X_4	2	142.00	0.000**	1.31	0.277NS	29.95	0.000**
Quadatic	3	19.25	0.000**	21.09	0.000**	5.96	0.001**
X_1*X_1	1	45.14	0.000**	18.61	0.000**	11.06	0.001**
X_2*X_2	1	23.80	0.000**	0.40	0.530NS	2.05	0.157NS
X_3*X_3	1	0.71	0.403NS	17.55	0.000**	2.15	0.146NS
2-Way Interaction	9	6.69	0.000**	4.90	0.000**	8.81	0.000**
X_1*X_2	1	0.49	0.488NS	3.85	0.053NS	3.99	0.049*
X_1*X_3	1	2.85	0.096NS	4.41	0.039*	2.28	0.135NS
X_1*X_4	2	6.44	0.003**	0.22	0.801NS	2.65	0.077NS
X_2*X_3	1	2.10	0.151NS	11.72	0.001**	32.96	0.000**
X_2*X_4	2	7.34	0.001**	10.54	0.000**	16.10	0.000**
X_3*X_4	2	13.62	0.000**	1.30	0.280NS	1.29	0.280NS
Error	75						
Lack-of-Fit	7	0.51	0.093NS	3.32	0.064NS	4.93	0.000**
Pure error	68						
Total	92						

Note: *: significant at 5% level, **: significant difference at 1%, NS: No significant difference

X_1: Feed rate, X_2: Cylinder speed, X_3: Concave clearance, X_4: Spike type

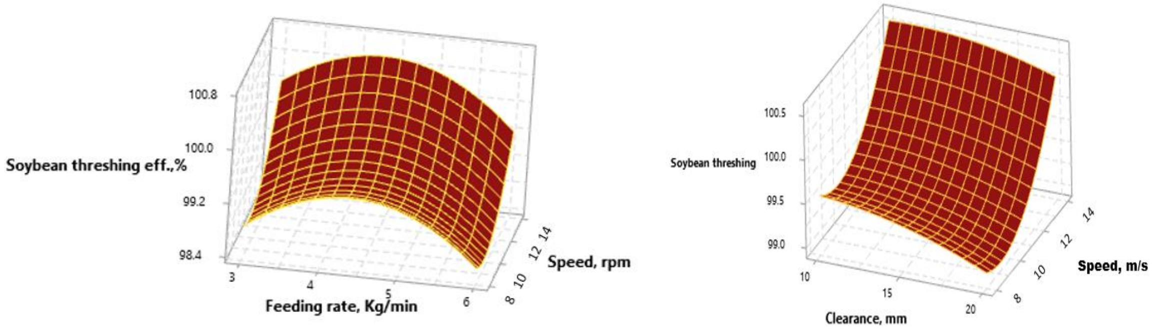
3.2 Cleaning efficiency

The cleaning efficiency ranged from 86.68% to 93.05% with an average of 90.9% and a standard deviation of 1.03%. The ANOVA for response of cleaning efficiency showed that the linear effects of independent variables had significant effect, feed rate at 5% level and the speed and concave clearance at 1% level of significance and the type of spikes showed no significant effect. The interactions with significant effect were the feed rate x concave clearance at 5% level, the cylinder speed x concave clearance, and the cylinder speed x spike types at 1%, Table 4. The response surface plot of cleaning efficiency as a function of feed rate, cylinder speed and concave clearance is shown in Figures 4a and 4b. The cleaning efficiency was found to highly, increase with speed and mildly increase with the concave clearance at 4.5 feeding rate, the cleaning increase from 89.7% to 92.4% at the speed of 7.95 to13.92 respectively (Figure 4b). This increase is mainly due to the speed of the blower, responsible for cleaning of the grains, which was directly proportional to the speed of the cylinder. Cleaning efficiency was slowly increasing with the increase of feed rate up to the mid values, and then it started to reduce Figure 4 a. In general, the cleaning and threshing changed in the same direction. Cleaning efficiency increased with cylinder speed at all values of concave clearance. The feed rate effect on the cleaning efficiency was in a similar trend as on the threshing efficiency as the separation and cleaning happen only after threshing. The spike type has no significant effect on the clearing efficiency as they fall in the same group with averages of 90.65%, 9124%, and 90.75% for spike type 1, type 2, and type 3, respectively, Table 4.

Table 4 Mean separation for threshing efficiency, cleaning efficiency and energy consumption

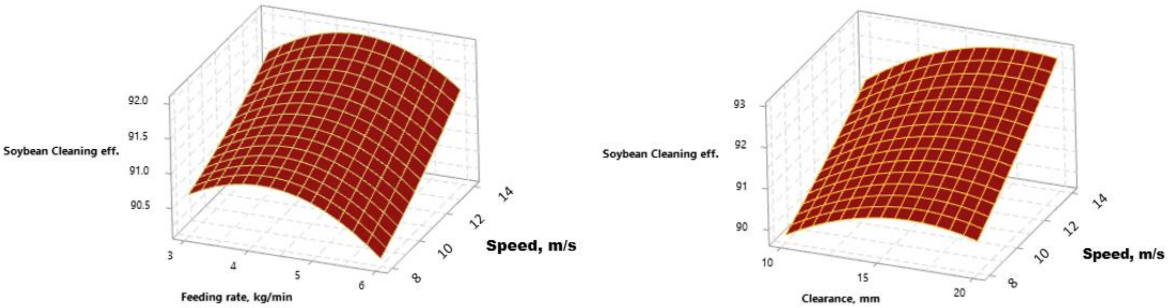
	Threshing efficiency mean,%				Cleaning efficiency mean,%				Threshing energy consumption, kWh-q^{-1}			
	X1	X2	X3	X4	X1	X2	X3	X4	X1	X2	X3	X4
Level 1	98.26^{b}	97.96^{b}	98.43^{a}	97.95^{b}	90.81^{b}	89.82^{c}	90.30^{b}	90.65^{a}	1.43^{b}	1.42^{b}	1.53^{a}	1.41^{b}
Level 2	98.9^{a}	98.14^{b}	98.54^{a}	98.23^{b}	91.20^{a}	90.81^{b}	91.19^{a}	91.24^{a}	1.49^{ab}	1.46^{b}	1.51^{a}	1.49^{b}
Level 3	98.23^{b}	99.33^{a}	98.46^{a}	99.25^{a}	90.58^{b}	91.96^{a}	91.09^{a}	90.75^{a}	1.54^{a}	1.58^{a}	1.42^{b}	1.55^{a}

Note: Means that do not share a letter in a column are significantly different at the 5% level.



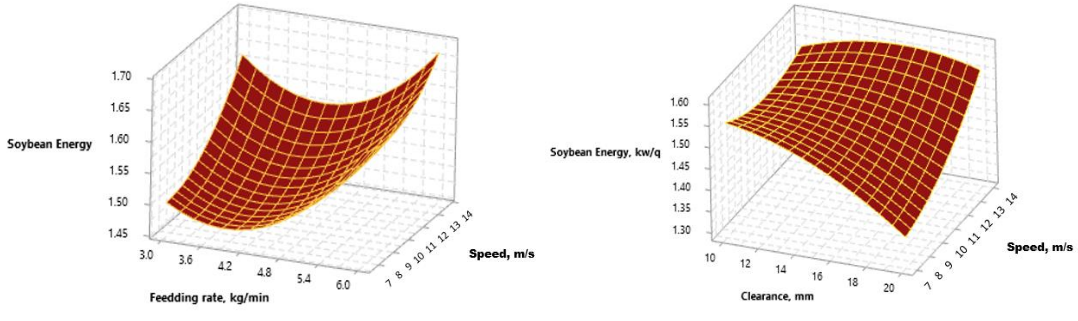
(a) cylinder speed and feed rate and (b) cylinder speed and concave clearance

Figure 3 Surface plot for soybean threshing efficiency



(a) cylinder speed and feed rate and (b) cylinder speed and concave clearance

Figure 4 Surface plot for soybean cleaning efficiency



(a) cylinder speed and feed rate and (b) cylinder speed and concave clearance

Figure 5 Surface plot for soybean threshing energy consumption

3.3 Threshing energy consumption

The threshing energy consumption is an important variable especially for the solar powered thresher. The former varied between 1.12 and 1.74 kWh q^{-1}with an overall average of 1.48 and a standard deviation of 0.113 kWh q^{-1}. The energy consumption was highly influenced by all variables at 1% level of significance. All first-order interactions with the cylinder speed were with significant effects; the feed rate x speed of cylinder at 5%, the cylinder speed x concave clearance, and the cylinder speed x spike type at 1%, Table 4. Figures 5a and 5b present the effect of cylinder speed and feed rate on power consumption. The threshing energy consumption increased significantly with increasing cylinder speed and feeding rate and the decreasing of concave clearance. A similar trend is observed in cylinder speed; where the increasing cylinder speed from 3 to 4 kg min^{-1}, the energy consumption increase rate was modest and it got a sharp rise from 4.5 to 6 kg min^{-1}. However, energy consumption decreases with the increase in concave clearance at all cylinder speeds. The negative relationship is observed with the concave clearance and energy consumption where a mild fall was noticed at the clearance of 10 to 15 mm and a sharp decrease of energy consumption achieved the minimum value (Figure 5. b). These facts were also illustrated by the mean separation and groups where levels 1 and 2 are having the common group and level 3 is set in a distinct group. The spike types 3 was found to consume more energy consuming; with average energy consumption of 1.55 kWh q^{-1} against 1.41, and 1.49 kWh q^{-1} for spike types 1 and 2, respectively, as shown in Table 4. The spike type 3 showed higher energy consumption statistically significant at 1% level.

3.4 Optimization

The independent parameters were numerically optimized for desirability with equal importance on the threshing efficiency and cleaning efficiency maximization and threshing energy consumption minimization. A multifactor optimization technique was used to find the optimum operating condition for threshing soybean crop. It was found that the best performance results were obtained at 13.62 m s^{-1} cylinder peripheral speed, 4.3 kg min^{-1} feed rate, 20mm concave clearance, and spike type 3. At this condition, the desirability factor is 0.799 and the performance for threshing efficiency, cleaning efficiency, and energy consumption were 99.99%, 92.72%, and 1.45 kWh q^{-1}, Table 5. They result in optimal threshing capacity of 116 kg per hour. The cost of threshing at optimal setting of the machine was US$ 12.27 per 1000kg of grain which is competitively good in comparison to US$ 12.43 per 1000kg and US$ 17.26 per 1000kg, for the electric motor operated multi-crop thresher and diesel engine operated multi-crop thresher making a cost reduction of 1.34% and 28.9%, respectively.

These operating and machine setting conditions were recommended for the prototype in normal usage condition with sufficient solar radiation or in battery connected mode. Given the harvest period of the soybean crop, the optimal performance solutions show the average energy consumption which does not guarantee the leverage of maximum time of thresher operation. However, the lower feed rate can help to use the thresher for longer period in direct connection mode. Hence, the solar power thersher would be operated at the usefull speed and opt for lower feed rate and options with lower energy consumption. The alternative machines and operating parameter settings for lower threshing energy consumption on soybean crop using solar powered threshers show various levels of energy consumption as shown by Table 5. The solution with energy consumption of 1.25 kWh q^{-1} was used for fitting the threshing and solar energy, Figure 6. The setting 85.8 kg h^{-1} feed rate, 10.89 m s^{-1} of ccylinder peripheral speed, 20 mm concave clearance, and spike type 3 were the least energy consuming with 0.57 desirability factor.

Hence, in the period of less solar energy with direct connection of the solar system to the threshers, the capacity of the threshers would be reduced to lower feeding and so that the thresher can work.

Taking the lower energy consumption option, the thresher can be operated for an average period of 5 and 4 hours, respectively, in the months October and November of 2021 while in the optimal machine settings the duration was hardly 2 hours in October and no clear time was possible in November of 2021, in the conditions of use in Delhi, as shown in Figure 6. The further increase in duration can be supplemented by the battery storage, charged in duration when the solar radiation produces less than the minimum usable power.

Table 5 Five optimal solutions

Solution	X1	X2	X3	X4	Threshing energy consumption, kWh q^{-1}	Soybean Cleaning	Soybean threshing	Composite Desirability	Grain feed capacity, kg h^{-1}
Optimal solutions	4.32	13.62	20	Spike 3	1.54	92.72	99.99	0.799	116.64
	5.47	13.92	20	Spike 3	1.59	92.53	99.91	0.722	147.69
	4.00	12.59	20	Spike 3	1.49	92.25	99.61	0.710	108
Least feed rate solutions	3.18	10.89	20	Spike 3	1.25	91.34	98.69	0.57	85.83
	3.27	10.40	20	Spike 3	1.26	91.19	98.67	0.57	88.26
	3.75	7.95	20	Spike 2	1.36	90.54	97.88	0.58	101.30

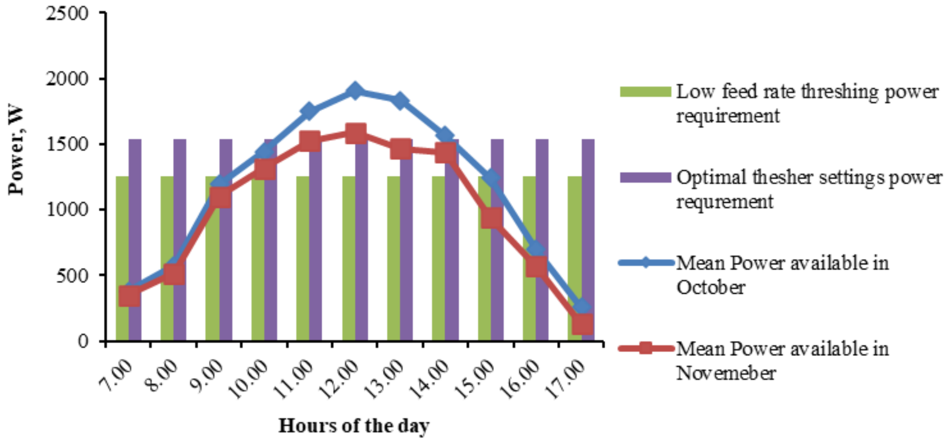


Figure 6 Mean hourly solar power availability and power requirement for threshing soybean in Delhi conditions

4 Discussion

4.1 Threshing and cleaning efficiency

The threshing and cleaning efficiencies were significantly influenced by the speed of the cylinder, concave clearance, and feed rate.

The increased cylinder speed had the highest effect on the TE. The direct and positive effect of speed on the threshing is caused by the increase in friction and abrasion between the cylinder and the concave resulting in higher impact to the crop material and leading to more pod opening and seed detachment. In a similar way the spike type had a significant effect on the TE. This could be attributed to the higher impulse force and contact area with the crop material in the threshing process. In fact, the highest TE was noticed on the rectangular spike with more spike density while the lowest threshing was noted to the round spikes with widely spaced spike.

The feed rate showed a contrasted effect on the threshing efficiency and cleaning efficiency; it was found that, taking all the other parameters constant, the threshing and cleaning increase with the feed rate up to mid values of the feed rate which showed the highest performance, then it dropped with further increase in feed rate. This is probably due to the distribution pattern of crop material coupled with the effectiveness of compression and rubbing force on threshing action, beside the impact action. At lower feed rate the rotating spikes drive the thin layer of material quickly; these crop materials are not sufficiently compressed leading to less and late threshing. By increasing the feed rate, the threshing and separation improves. However, feed rate higher than the optimal gave rise to the denser layer of crop material within the concave clearance, this has an effect of damping to the beating energy provided by spikes and negatively affect the threshing and cleaning performance; therefore, the feed rate should be kept to the optimal value. The feed rate effect on the CE was in the similar trend as on the threshing efficiency. This happened because the separation and cleaning happen only after the threshing. The faster and higher the threshing led to the higher CE and the cleaning process was endowed with longer time. The results are in congruence with those found by Pawar (2018) on finger millet, for soybean (Adekanye et al., 2016; Vejasit and Salokhe, 2004) and for green gram (Bansal and Lohan, 2009).

4.2 Energy consumption and cost analysis

The statistical analysis showed that TEC significantly increased with the increase in rotational speed and feed rate and the decreased in the concave clearance. This may be due to a high load on the thresher because more stalk quantity is passing through the threshing gap (Abdeen et al., 2021; Ezzatollah et al., 2009; Pawar, 2018). The increase in power consumption with the cylinder speed was expected to happen due to the increased application of energy on the crop material because the input energy release to the threshed crop is proportional to the kinetic energy of the threshing element. The feed rate direct and positive effect was related to the resistance or obstruction to the movement of the threshing elements which become higher as the feed rate increased and clearance between the drum and the concave was more congested. Therefore, more energy is required to overcome it. The same rationale perfectly applied also to concave clearance which had a reversed effect on the energy consumption. These observed results agreed with those obtained in similar studies (Abdeen et al., 2021; Bansal and Lohan, 2009; Bedada, 2018; Karagiannakis, 2020; Sahu and Raheman, 2020; Salari et al., 2013; Sale, 2015). The spike type 3 showed higher energy consumption and is statistically significant at 1% level. This was due to the pull and push force of the spike tooth cylinder which increased with the number of spikes in contact with crop mat increases (Devnani and Ojha, 2016; Minin et al., 2020). The higher energy consumption was observed to be for spike 3 as evidenced by the higher overall mass developing more the inertia to be overcome by the prime mover.

4.3 Optimum performance

The mid values of feeding rate and concave clearance were more beneficial to the performance level with respect to threshing and cleaning and the higher values of the speed and spike type 3 were more advantageous. The duration of use can be increased by operating the thresher at the reduced feed rate during the crops harvesting months.

The solar powered thresher had lower operating cost because the fuel or electricity bill cost was cut and replaced by the solar panel. In addition to the operating cost, the environment friendliness constitutes an advantage of the solar powered thresher. Carbon footprint reduction of 25 kg of CO_2 per 1000kg of threshed seeds is credited the designed solar power.

5 Conclusion

In conclusion, the cylinder speed has significant affect all the observed parameters. The the solar operated multi-crop thresher will be beneficial for farmers saving time and cost with precise threshing of the crops while increasing the options of solar system utilization for maximization of return on the investment made. Farmers can save the fuel and electricity cost incurred in conventional threshers and contribute to the contemporary issue of environment protection. This solution fits well in the current scenario where multiple installations of solar arrays for water pumping purposes in an isolated places are noticed, which are mostly underutilized in periods of the year with reduced irrigation requirements. Therefore, the maximum use of these resources needs to devise tools and systems to diversify their use; this threshing system will be one of those solutions and to the benefit of the small-scale farmers. The optimum combination of the machine and operating parameter would produce the maximum threshing capacity and would be used in period of high insolation. However, it is recommended to adopt the options reduced feed which consume less energy in period of limited insolation. This optimization study has not elaborated on the case of battery storage and integration with direct connection. Future studies should integrate and optimize the two modes in different climatic conditions throughout the year.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgement

The authors acknowledge the scientists from Indian Agricultural Research Institute (New Delhi – 110012, India)-Division of agronomy and Division Plant Genetics, namely Dr. Anchel Das, Dr. S.P. Singh, Dr. Hegde, for providing the crop material from their projects’plots to be used in the evaluation of the thresher experiments to be conducted.

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