



Direct threshing of paddy (*Oryza sativa*) ear-head with reduced straw and optimized grain throughput rate

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ABSTRACT

Reduction of the straw intake is a new harvesting technique that reduces energy and input costs. In existing combine harvesters, the cutter bar of the standard header is set at an increased height, or the stripper header combine harvester is used to minimize the straw intake. The thresher was developed and tested in the year 2018 and 2019, at Indian Institute of Technology, Kharagpur, West Bengal to reduce the straw intake by direct ear head threshing of standing plants. It reduces energy consumption compared to some common existing harvesting methods. The specially designed plant guiding plates were accommodated before the threshing cylinder to achieve this. The set of two guiding plates passes over the plant's row and converges the panicle portion of plants by bending them gradually. The rice (*Oryza sativa* L.) panicles were placed over the rotating cylinder and the stem portion remains in a standing posture. Thus, only 4.16% of total straw available on the plants was fed, and about 23 times straw intake was reduced. RSM-based response surface methodology was used to design the experiment. During the experiment, the grain throughput rate (GTR) was varied by changing the speed of plant feeding. To measure the cylinder speed, threshing torque, and plant feed speed the laboratory model thresher was equipped with rotary encoder, torque transducer and proximity sensors, respectively. The collected threshed mixture was analyzed to determine threshing performance. The optimized GTR and cylinder speed were 180 kg/h and 17.55 m/sec at which the threshing efficiency, total grain loss, and specific energy were 98.36%, 4.67%, and 1.1 kWh/t of grain, respectively.

Keywords: Cylinder length, Cylinder speed, Gradual threshing, Grain throughput rate, Reduced straw intake

The threshing of crops containing low straw reduces the cylinder effort as compared to the threshing of the whole plant (Miu and Kutzbach 2007). In conventional and stripper combine harvesters, the increased height of the cutter bar and stripping of the panicles, respectively, are done to reduce the straw intake (Miu and Kutzbach 2008). These are classic examples of high-cutting technology and low straw intake. In both harvesters, separation of panicles before threshing is common. It consumes energy and the associated components increase the cost of the machine. Listner and Axmann (1993), reported that in a stripper header, the straw intake can be reduced up to 50–70% which can increase the throughput rate by 50–90%. For a given throughput capacity, the size, weight, and cost of the machine can be minimized with less feeding of straw. Kalsirisilp and Singh (2001) reported that the average power consumed in threshing of stripped panicles in rice was 11.6 kW (20%) and the stripper rotor itself consumed 16.9 kW which was 29% of the total power consumption.

By eliminating the role of header, power requirement and associated grain loss can be minimized (Tado *et al.* 1998). The traditional cutting-threshing and new stripping-threshing technologies were compared by Straksas (2006) in wheat and barley crops. It was reported that the throughput rate can be doubled in stripping-threshing and 40% fuel and energy can also be saved. The energy required for threshing through hand beating, pedal-operated, and power threshing methods was 1.85, 0.78, and 4.16 to 9.9 kWh/t, respectively (Varshney *et al.* 2004, Agrawal *et al.* 2013). The difference in energy consumption was due to panicle and whole crop threshing.

Despite extensive research on stripping, there have been a very few success and have not been commercialized, primarily due to high shatter losses and poor performance in severely lodged crops. Another attempt at crop harvesting with low straw was made through this research. The straw intake was reduced by direct feeding of ear-heads into the thresher. The direct ear-head paddy thresher was developed and tested at various cylinder speeds and throughput rates.

MATERIALS AND METHODS

Laboratory setup for direct ear head threshing: The setup was developed and tested in the year 2018 and 2019 at

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the Indian Institute of Technology, Kharagpur, West Bengal. The arrangement of experimental laboratory setup is shown in Fig. 1(A). The setup consisted of a thresher, plant feed unit, and data acquisition systems (DAS). The wire-loop threshing cylinder was used for threshing the paddy crop. The cylinder was mounted on a frame and rotated about the axis parallel to the crop row. The panicle portion of standing plants was fed tangentially to the rotating cylinder. In the laboratory setup, the row of plants was moved forward to feed them in the thresher. The plants were clamped firmly on holders longitudinally spaced at 150 mm. Each holder carries 20 tillers that represent average plant population per hill. The paddy crop variety IR-36 was cultivated and used for experiments. It is one of the popular varieties in West Bengal. During threshing, the plant row was passed through the guiding plates. The portion of the plant above 60 cm height gets bent through the plates and fed to the cylinder. This height characterizes the minimum height of the panicle base from the ground. After threshing of panicles, the straw remains in standing posture and escapes from the rear end of the cylinder. The thresher and plant-feeding units were operated through separate motors and their speeds were controlled using separate variable frequency drives (VFDs). The DAS consisted of torque sensor, rotary encoder, proximity sensor, data logger, and laptop. These sensors were used to measure the torque, cylinder speed, and plant feeding speed, respectively. The arrangement of sensors is shown in Fig. 1(B). The output of sensors was connected to the different channels of data logger. The data logger was connected to the laptop to record the data given by the sensor.

Reduction of straw intake: The plant portion above 60 cm height was fed to the cylinder in direct ear head thresher. The weight of straws of full length and above 60 cm height was measured, respectively, to know the difference in straw intake. For this, the plants of the harvesting stage were cut from 1 m² area leaving no stubbles on the field. The grains were separated manually and the weight of the grains and full-length straw was measured. The straws were cut above 60 cm height from the base and weighed. The grain-to-straw ratio was determined for the straw of full length and above 60 cm height, respectively.

Grain throughput rate (GTR): The GTR is the ratio of weight of grain fed to the thresher per unit time. The grain fed to thresher was determined by taking the summation of weight of grains collected from all sources after threshing. It includes the grain collected from the collecting tray, grain shattered on the ground and grain that remained on

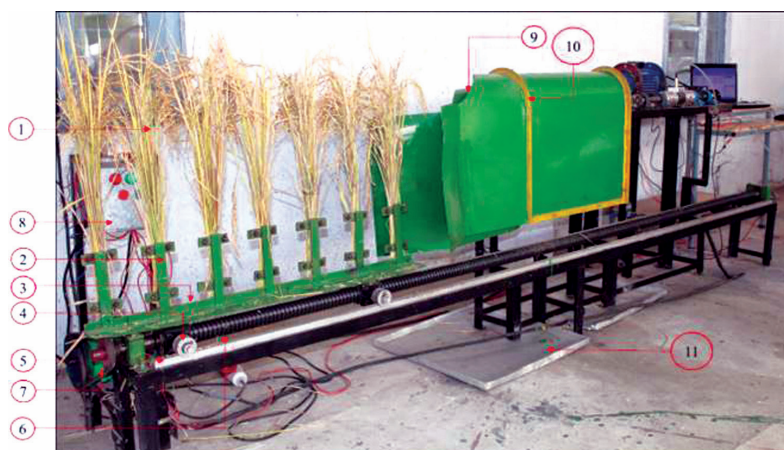


Fig. 1(A) Laboratory experimental setup for direct ear-head paddy thresher.

1. Paddy plants; 2. Plant holder; 3. Plant holding platform; 4. Roller wheel;
5. Track; 6. Belt-pulley transmission; 8. Motor starter; 9. Crop guiding plate;
10. Stiffener; 11. Trays.

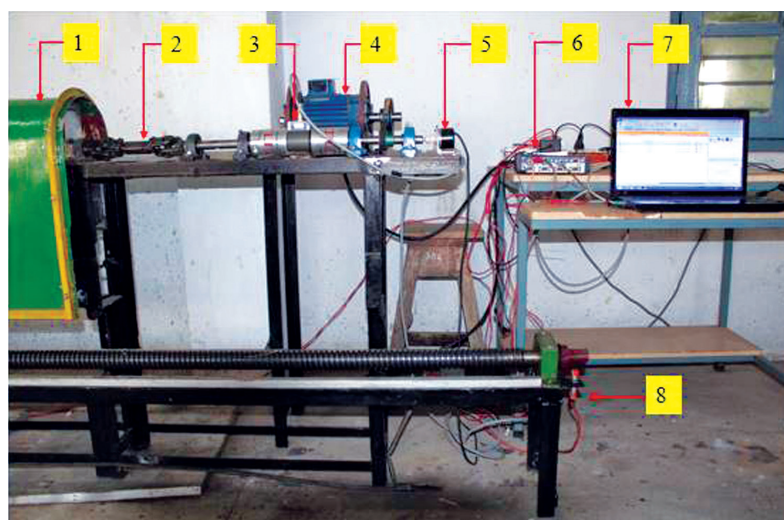


Fig. 1(B) Direct ear head thresher setup equipped with torque sensor, rotary encoder and proximity sensor.

1. Threshing cylinder; 2. Universal shaft coupling; 3. Torque sensor; 4.
- Motor; 5. Rotary encoder; 6. Data logger; 7. Laptop.

the plant after threshing. The GTR depends on the weight of grains available on the plant and speed of feeding. In the suggested threshing method, the GTR was varied by varying the speed of plant feeding during threshing. The weight of grains for 20 tillers was not possible to keep constant for each replication. Therefore, the GTR was different even when the speed of feeding was the same. Contrariwise, it could have been same for different feed speeds due to the plants having different numbers of grain.

RESULTS AND DISCUSSION

Reduction of straw intake: The average weight of different parts of plants collected from in 1 m² area is given in Table 1. The straw intake during threshing was 164 g, which was only 4.16% of the total straw available on the plant. The remaining 95.84% of plant straw remains in standing posture. However, the straw intake may vary

according to the plant height depending on crop variety. The average grain-to-straw ratio for full-length straw and straw above 60 cm was 0.19 and 4.62, respectively. The average moisture content (wb) of grain and straw was 28.48 and 45.90%, respectively.

Grain throughput rate (GTR): The GTR was calculated by taking the ratio of weight of grains fed and time consumed at uniform feed rate. A replication at which cylinder speed (V_p) and plant feed speed (V_F) were 1910 rpm and 0.60 km/h, respectively, were selected to explain the different threshing periods that occur in a complete run. A typical real-time curve in which torque was plotted against time during threshing is shown in Fig. 2. The total duration of a complete run was divided into five periods, viz. T_0 – T_1 ; No load; T_1 – T_2 , Increasing load; T_2 – T_3 , Uniform load; T_3 – T_4 , Decreasing load; and T_4 – T_5 , No load.

At no load period (T_0 – T_1), no crop was fed to the thresher and the cylinder rotates idly. This occurs twice in a run, before feeding of plants and when the plants completely exit from the thresher. During increasing feed rate (T_1 – T_2) the plants enter and started to occupy the cylinder length progressively. Torque increased gradually as the number of plants interacting with the cylinder increased (A–B, Fig. 2). The uniform feed rate (T_2 – T_3) appears when full length of the threshing cylinder was engaged with the plants (B–C). After this, the number of plants interacting with the cylinder decreased gradually and decreasing feed rate (T_3 – T_4) comes. This was the period of decreasing feed rate (C–D). At point D, the plants completely exited. The period OE was the time of completing a run and A to D was the time of threshing period. The GTR varies throughout the run as explained above. In the beginning, the GTR started from 0 at time T_1 , it became q in time T_{AB} , continues at this level in time T_{BC} , and ended at 0 in time T_{CD} . The rate of change from A to B

and from C to D are assumed to be linear. Out of three phases of threshing, the GTR (q) was estimated for the uniform feed rate T_{BC} .

From the Fig. 2,

$$W_{gf} = \left(\frac{0+q}{2} \right) \times t_{AB} + q \times t_{BC} + \left(\frac{q+0}{2} \right) \times t_{CD} \quad (\text{Eq. 1})$$

where W_{gf} , Weight of grain threshed during the test run (g); and q , Grain throughput rate during uniform feed rate.

$$W_{gf} = q \times \left(\frac{T_{AB} + T_{CD}}{2} \right) + q \times T_{BC} \quad (\text{Eq. 2})$$

$$q = \frac{W_{gf}}{\left(\frac{T_{AB} + T_{CD}}{2} \right) + T_{BC}} \quad (\text{Eq. 3})$$

The values of W_{gf} , T_{AB} , T_{BC} , and T_{CD} for different runs are 203.6 g, 0.87, 7.75, and 0.99 s for the selected replication (e.g. $V_p = 18$ m/s and $V_F = 0.6$ km/h). The GTR, after putting these values was $q = 23.45$ g/s or 84.42 kg/h. The weight of grains fed to cylinder for different runs is given in Table 2.

Torque (T_{th}), power (P_{th}), and specific energy consumption (E_{th}): The average power, GTR, and E_{th}

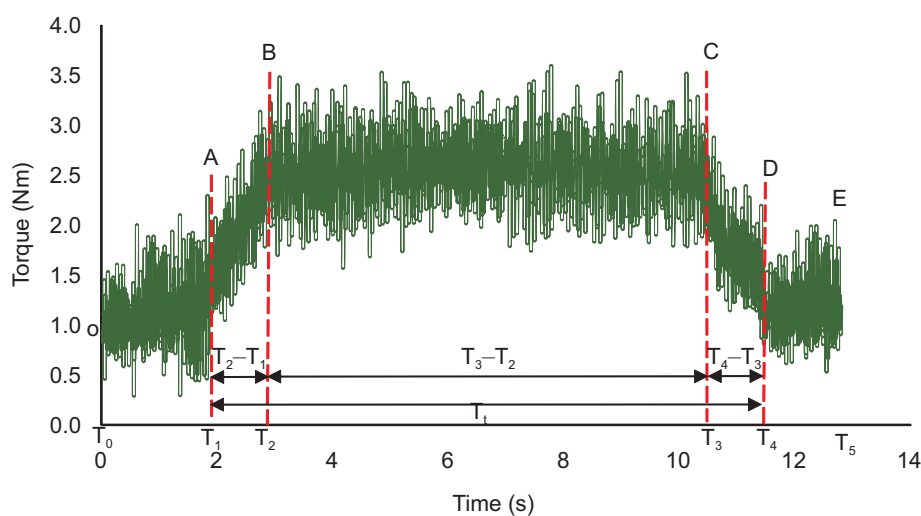


Fig. 2 A typical curve showing the variation of torque with time during different threshing periods of the plant row at V_p and V_F of 18 m/s and 0.60 km/h, respectively.

Table 1 Weight of plants, grain, full-length straw, straw above and below 60 cm height, at 1 m² area, percentage of reduced straw intake and grain to straw ratio

Sample no.	Weight (g/m ²)					Percentage of reduced straw intake (%)	Grain: straw	
	Plant bundle	Grain	Full-length straw	Straw above 60 cm	Straw up to 60 cm		Full-length straw	Straw above 60 cm
1	5085.8	738.1	4347.7	147.4	4200.3	96.61	0.17	5.01
2	5381.0	700.2	4680.8	142.5	4538.3	96.96	0.15	4.91
3	4122.6	677.9	3444.7	182.6	3262.1	94.70	0.20	3.71
4	4461.3	825.8	3635.5	172.9	3462.6	95.24	0.23	4.78
5	4844.9	818.3	4026.6	173.6	3853.0	95.69	0.20	4.71
Avg.	4779.1	752.0	4027.0	163.8	3863.3	95.84	0.19	4.62

were calculated for the uniform feed rate. The periods of increasing feed rate at the beginning and decreasing feed rate at the end are considered negligible for the condition of field having long row. The average torque required for threshing ($T_{q_{th}}$) was calculated by subtracting the no-load torque ($T_{q_{nl}}$) from the torque at uniform feed rate or load (T_{q_l}) (Table 2).

$$T_{q_{th}} = T_{q_l} - T_{q_{nl}} \quad (\text{Eq. 4})$$

$$T_{q_{th}} = 2.55 - 1.11 = 1.44 \text{ Nm.}$$

The average cylinder speed (N_{avg}) at the period of uniform feed rate BC was 1767 rpm or $\omega_{avg} = 185.0 \text{ rad/s}$. Therefore, the power required for threshing,

$$P_{th} = \tau_{th} \times \omega_{avg} \quad (\text{Eq. 5})$$

$$P_{th} = 1.44 \times 185.0 = 267 \text{ Watt}$$

The specific energy consumption (E_{th}) is the ratio of power consumed in threshing to the GTR. It was expressed in kWh/tonnes of grain.

$$E_{th} = \frac{P_{th}}{q} \quad (\text{Eq. 6})$$

$$E_{th} = 0.267/84.42 = 3.16 \text{ kWh/t of grain.}$$

The response surface plot for the threshing efficiency, specific energy consumption and total grain loss were drawn concerning GTR and cylinder speed and are explained below.

Effect of grain throughput rate on threshing performance:

The two factors i.e. cylinder speed and GTR were taken as sources of variation. The analysis of variance was carried out at 1% level of significance using values of performance parameters (Table 3). The *F*-value for each response was determined and given in Table 3, which shows the individual, quadratic, and interaction effects of factors on the response.

Table 2 Threshing efficiency, torque, power, specific energy consumption, and total grain loss at different cylinder speeds and GTR

V_p , m/s	W_{gt} , g	V_F , km/h	q , kg/h	η_{th} , %	T_{th} , Nm	P_{th} , kW	E_{th} , kWh/t	L_{gt} , %
10.00	181.74	0.6	75.96	96.48	1.80	0.20	2.58	5.93
	217.49	0.6	88.78	96.1	1.62	0.18	2.00	6.1
	219.68	0.6	93.06	96.45	1.67	0.18	1.95	5.21
12.34	202.40	0.32	48.92	97.49	1.30	0.16	3.30	4.49
	204.03	0.32	51.37	97.34	1.20	0.15	2.97	5.42
	268.58	0.22	58.32	98.35	1.60	0.21	3.65	3.28
	197.08	0.88	133.31	96.34	1.13	0.14	1.04	6.01
	215.51	0.88	136.91	97.1	1.12	0.14	1.00	6.05
	265.09	0.88	152.35	96.91	1.25	0.15	1.00	5.3
	191.80	0.2	27.86	99.37	1.25	0.19	6.71	4.8
18.00	244.88	0.2	32.83	99.39	0.83	0.14	4.36	3.73
	234.23	0.2	34.85	99.66	1.31	0.19	5.49	4.26
	190.97	0.6	79.16	98.99	1.09	0.21	2.64	5.47
	212.53	0.6	82.15	99.19	0.82	0.16	1.92	4.12
	203.58	0.6	84.42	98.97	1.44	0.27	3.16	4.93
	255.30	0.6	96.44	98.76	1.39	0.25	2.63	5.33
	271.02	0.6	112.50	99.19	1.09	0.19	1.69	4.15
	203.33	1.0	143.50	98.31	1.03	0.17	1.19	5.17
	257.69	1.0	180.36	98.1	1.34	0.25	1.37	5.47
	267.70	1.0	197.06	98.97	1.05	0.17	0.87	3.88
23.66	218.28	0.32	46.08	99.61	0.92	0.21	4.58	7.47
	232.6	0.32	51.95	99.6	1.21	0.28	5.36	6.87
	267.47	0.32	58.03	99.8	0.97	0.24	4.15	6.25
	236.03	0.88	145.30	99.58	1.05	0.24	1.66	5.82
	288.51	0.88	173.45	99.55	1.05	0.23	1.32	5.66
	288.05	0.88	196.52	99.55	1.17	0.27	1.40	4.85
	218.83	0.6	92.48	99.98	0.90	0.23	2.45	8.22
26.66	262.02	0.6	120.96	99.97	0.94	0.25	2.10	7.76
	281.80	0.6	122.83	100	1.32	0.35	2.82	6.75

V_p , Peripheral speed of cylinder; W_{gt} , Weight of grain threshed in single test run; V_F , Speed of plant feeding; q , Grain throughput rate; η_{th} , Threshing efficiency; T_{th} , Torque consumption; P_{th} , Power consumption; E_{th} , Specific energy consumption; L_{gt} , Total grain loss.

Table 3 Combined ANOVA for performance parameters of paddy thresher tested using central composite experiment design

Source of variation	df	F-value				
		η_{th}	T_{th}	P_{th}	E_{th}	L_{gt}
Model	5	82.89**	4.65**	6.16 **	43.53**	15.79**
A-Peripheral speed of cylinder, m/s	1	20.93**	0.17 ns	0.04 ns	193.09**	0.43 ns
B-Grain throughput rate, kg/h	1	370.48**	13.95**	26.75**	15.71**	17.76**
A $\times$ B	1	5.58 ns	2.02 ns	2.12 ns	1.08 ns	11.82**
A ²	1	0.14 ns	0.01 ns	1.01 ns	23.34**	1.46 ns
B ²	1	25.99**	2.26 ns	0.49 ns	0.01 ns	34.32**
Residual	7					
Total	12					

Df, Degrees of freedom; **, highly significant at the 1% level; ns, Non-significant.

Threshing efficiency (η_{th}): The ANOVA (Table 3) shows that there was a significant effect of GTR (q) and cylinder speed (V_p) on threshing efficiency (η_{th}) at 1% level of significance. As stated earlier the high GTR was obtained at the increased speed of plant feeding. At high feed speed, the retention period of plants in the threshing chamber was low. Consequently, the cylinder gets less time to impact the plants. Therefore, the separation was reduced for all levels of cylinder speed. This relation is depicted through the response surface shown in Fig. 3(A). This trend was in line with the results reported by Price (1993). Exceptionally, the η_{th} was reported high at some high levels of q. It might be due to the plants adhering to fewer grains but fed at high-speed or plants adhere more grains but fed at low speed. From Fig. 3(A), it can also be observed that the threshing efficiency was low at low cylinder speed.

Specific energy consumption (E_{th}): ANOVA (Table 3) represented that there was a significant effect of q and V_p on E_{th} at 1% level of significance. It is already explained through Eq. 6 that there is an inverse relationship between E_{th} and q. The response surface of E_{th} was plotted against q and V_p and is shown in Fig. 3(B). It is depicted that the

E_{th} decreased with the increase in q for all levels of the V_p . It can also be observed that the E_{th} was high for high V_p could be due to the high threshing rate.

Total grain loss (L_{gt}): The un-threshed grain, broken grain, shattered grain, and the grain that remains on the plant after threshing collectively represent total grain loss (L_{gt}). ANOVA (Table 3) shows that there was a significant effect of V_p on L_{gt} . The response surface plot shown in Fig. 3(C).

It depicts that L_{gt} possesses negative correlation with the q. The high feed speed accounted for the high GTR and low retention time. Consequently, the number of impacts of threshing elements on the plant was reduced and therefore, the grain damage. Another possible reason might be the cushioning due to the thick layer of plants which reduces the impact of threshing elements. And so, the breakage and shattering of grains were reduced. Although, due to the same reason, un-threshed grain was increased which increases the total grain loss. It can also be depicted that the grain loss was more at the highest and lowest levels of cylinder speed i.e. 26 and 10 m/s, respectively. It might be due to more breakage of grains at high speed and the production of un-threshed grains at low speed. The interaction of grain

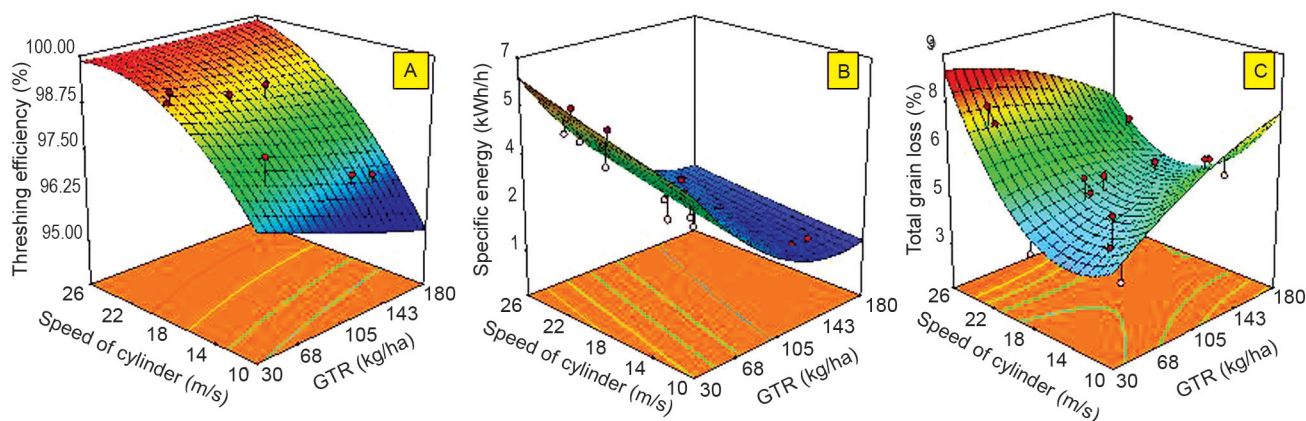


Fig. 3 Response surfaces showing the effect of grain throughput rate (GTR) and cylinder speed (V_p) on threshing efficiency (A); Specific energy consumption (B); and total grain loss (C).

throughput and cylinder speed was also significant.

Optimization of the throughput rate and cylinder speed: The numerical optimization was carried out using Design-Expert software. During the optimization, the goal opted for maximizing the GTR and threshing efficiency. On the other hand, the cylinder speed, total grain loss, and E_{th} were chosen for minimization. The optimized values of GTR and cylinder speed were obtained as 180 kg/h and 17.55 m/s at which the threshing efficiency, total grain loss, and E_{th} were reported as 98.36, 4.67%, and 1.1 kW/t of grain, respectively, with overall desirability of 0.712.

The direct threshing of grain bearing portion of standing plants is a unique method of separating the grains. Only 4.16% of the total straw available on the plants was fed, and about 23 times straw intake was reduced. There was a significant effect of GTR and cylinder speed on threshing efficiency, E_{th} and grain loss. The optimized GTR and cylinder speed were 180 kg/h and 17.55 m/s these were reported as 98.36%, 1.1 kWh/t of grain, and 4.67%, respectively, with overall desirability of 0.712. The energy consumption was lower by 1.68 and 3.78 to 8.72 times in developed direct ear head thresher as compared to manual and power threshing. Thus, it can be stated that energy consumption can be saved using developed direct ear head paddy thresher.

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