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Longitudinal Axial Flow Rice Thresher Performance Optimization Using the Taguchi Technique

Mohamed Anwer Abdeen [1,2], Abouelnadar Elsayed Salem [1,3] and Guozhong Zhang [1,*]

[1] College of Engineering, Huazhong Agricultural University, Wuhan 430070, China; mohamed.anwer2010@yahoo.com (M.A.A.); abouelnadar@webmail.hzau.edu.cn (A.E.S.)
[2] Agricultural Engineering Department, Zagazig University, Zagazig 44519, Egypt
[3] Desert Research Center, Mataria 11753, Egypt
* Correspondence: zhanggz@mail.hzau.edu.cn

Abstract: Combine harvesters are widely used worldwide in harvesting many crops, and they have many functions that cover the entire harvesting process, such as cutting, threshing, separating, and cleaning. The threshing drum is the core working device of the combine harvester and plays an influential role in rice threshing efficiency, threshing power requirement, and seed loss. In this study, two structures of rice threshers (conical-shaped and cylindrical-shaped) were tested and evaluated for performance under different thresher rotating speeds of 1100, 1300, and 1500 rpm and different feeding rates of 0.8, 1.1, and 1.4 kg/s. The experiment was designed using the Taguchi method, and the obtained results were evaluated using the same technique. The thresher structure and operating parameters were assessed and optimized with reference to threshing efficiency, required power, and productivity. The obtained results revealed that increasing thresher rotating speed and the feeding rate positively related to threshing efficiency, power, and productivity. The highest efficiency of 98% and the maximum productivity of 0.64 kg/s were obtained using the conical-shaped thresher under a 1500 rpm rotating speed and a feed rate of 1.4 kg/s, whereas the minimum required power of 5.45 kW was obtained using the conical thresher under a rotating speed of 1100 rpm and a feed rate of 0.8 kg/s.

Keywords: rice threshing; rice combine; longitudinal axial flow thresher; Taguchi method

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1. Introduction

Rice is the second most important cereal after wheal, which together supply 95% of the world's population's whole staple food [1].

China is the biggest grain producer globally, with a planting area of 94,370.8 km^2 and accounting for 21.98% of the world's grain production [2].

The grain harvester is the most essential piece of agricultural machinery that improves harvesting efficiency and reduces labor costs [3–6].

Combine harvesters are widely used worldwide to harvest different crops under different environmental and operating conditions. They have many functions such as cutting, threshing, separating, cleaning, and sometimes storing crops.

Many small, medium, and giant threshers have existed for a long time, but because of their low performance compared to traditional threshing methods, they have never been adapted to a significant extent. Some of these threshers are hand-held, and others are pedal-operated [7].

Threshing is considered one of the most vital crop processing operations for separating grains from the ears and preparing them for the market [8].

Threshing is the process of separating the edible part of the cereal grain from the chaff that surrounds it, and it is done after harvesting the crop and before winnowing it [9].

The simplest threshing system is picking up rice stalks and trampling the panicles underfoot or beating them against a hard surface such as a rack, threshing board, or tub [10].

In several countries in Asia, Madagascar, and Africa, cereal crop is being trodden by humans or animals underfoot for threshing; this method results in a high loss due to grain breakage or buried under the earth [11].

Many researchers have done many experiments to examine grain threshing devices, and many kinds of grain threshers have been developed since the 1820s [12–17].

The mechanical threshing concept entails providing energy for turning materials, drawing in materials to be threshed, and creating different layers of velocity to rub grain heads together. The grain separating process directly acts on the linkage of grain and stalk. The threshing chamber is made of a drum and concave. The drum consists of a long cylinder mounted on bearings with spikes or rasp bars attached to its surface, and the concave is perforated to enable the threshed product to drop by gravity into a collector [18].

There are many types of threshing cylinders: the spike tooth, which threshes by striking action, and the rasp bar, which thresh by rubbing and friction. A spike teeth threshing drum gives higher throughput values at higher speeds than a rasp bar threshing drum due to the greater impact of the spikes against the stalk, even at lower speeds [19].

In axial flow threshers, the crop spirally moves between the concave and the rotating drum for several complete turns, which allows for multiple impacts between the concave and drum as the crop moves along the drum length [11].

In axial-flow threshers, around 80% of grains are separated in the drum's first half, whereas just 20% of grains are separated in the other half [20].

The factors influencing thresher performance are classified as crop factors (crop variety and crop moisture content), machine factors (cylinder diameter, cylinder type, feeding chute angle, spike shape, spike number and size, concave clearance, shape, and size), and operational factors (feed rate, cylinder speed, and machine adjustment) [21].

An optimum drum speed is necessary for improving thresher performance because extreme speed can cause grain crack but a low speed can result in an un-threshed head. The impact is the main threshing action for grain separating from the ear. In all threshers, this impact force is controlled by the thresher rotating speed [22].

A multi-crop thresher was developed and evaluated by Singh et al. (2015) [23], who found that increasing the drum speed highly affected the thresher threshing efficiency.

A paddy thresher was fabricated and evaluated at three threshing drum speeds (15.5, 17.3, and 19.0 m s^{-1}) and three feed rates (44, 720, and 1163 kg h^{-1}). The results revealed that the percentage of threshing efficiency and damaged grain increased with increasing drum speed for all feed rates [24]. The impact of drum speed, crop moisture content, and crop variety on grain damage, threshing loss, and power was studied. It was revealed that the increase in drum speed reduced threshing losses but increased the damaged grain due to spikes' greater impact against the crop stalks [25].

Increasing the drum speed increased the threshing efficiency because of high level of impacting to the plant spikes. The highest threshing efficiency was 99.76% at a feed rate of 15 kg/min and a drum speed of 1400 rpm (21.25 m/s) [26].

The threshing efficiency was positively affected by the cylinder speed, the concave clearance, the crop feeding rate, and the crop variety [27].

In this paper, a testing platform for a longitudinal axial flow rice thresher was constructed. Two kinds of threshers (cylindrical and conical) were tested and evaluated for performance under different rotating speeds and feeding rates using Taguchi techniques to get the highest possible threshing efficiency and productivity and the lowest required power.

2. Materials and Methods

2.1. Testing Platform

To simulate the rice threshing process, a longitudinal axial flow threshing platform was constructed in a factory. The platform comprised a conveying belt, a longitudinal axial flow thresher, a concave thresher cover, receiving boxes, a diesel engine, a feeding device, a frequency convertor, an electric motor, and a torque sensor. The platform is shown in Figure 1, and the characteristics of it are shown in Table 1.

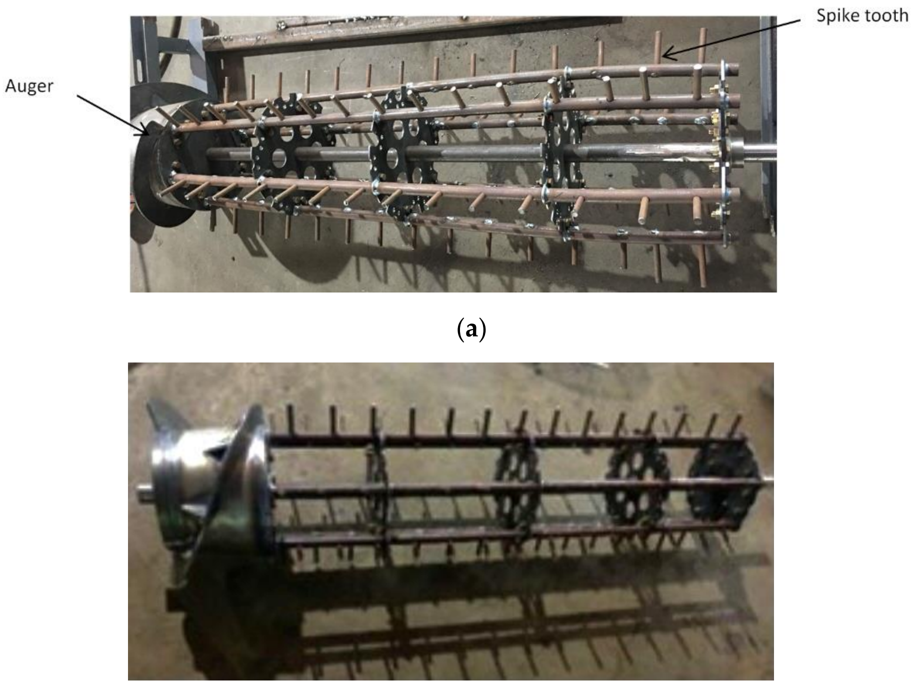
Figure 1. Testing platform.

Table 1. Characteristics of the platform.

Part	Parameters	Value
platform	Length	3700 mm
	Width	1460 mm
	Height	1540 mm
Thresher	Length	1360 mm
	Diameter	370 mm
	No. of threshing bars	6
	No. of threshing teeth	87
	Tooth height	50–70 mm
	Tooth diameter	20 mm
	Distance between two adjacent teeth	80 mm
Concave	Length	1000 mm
	Wrap angle	180°
	Meshing size	20 × 36.6 mm
	Clearance	20 mm
Top cover	Deflector helical angle	24–30°
	The gap between the two deflectors	160°
Feeding auger	Length	193 mm
	Front diameter	230 mm
	rear diameter	270 mm

The conveying mechanism composed of a rotating belt with dimensions of 6 × 0.5 m, and it was driven by an electric motor. Its speed was controlled using a frequency converter. It was used to transport rice to the feeding auger, which consisted of a rotating auger and a rotating chain with steel bars. The power was conveyed from the diesel engine to the auger using a belt and pulley. Its function was to feed the rice from the conveying mechanism to the threshing unit.

The threshing unit consisted of a longitudinal axial flow thresher with spike teeth, a thresher cover with helical blades, and a stationary concave. The thresher composed of 6 bars with spike teeth, and the rotational speed was conveyed from the engine to the thresher using a pulley and belt. Two kinds of thresher structures (cylindrical and conical), and three thresher rotating speeds of (1100, 1300, and 1500 rpm) were tested for the experiment. The threshers are shown in Figure 2.



(**a**)

(**b**)

Figure 2. Longitudinal axial flow threshers: (**a**) Conical thresher and (**b**) cylindrical thresher.

2.2. Torque Sensor

The torque sensor (Figure 3) was installed on the thresher shaft to measure thresher rotating speed, threshing torque, and required power. The torque sensor's measuring range was 0–10,000 N.m and 0–12,000 rpm.

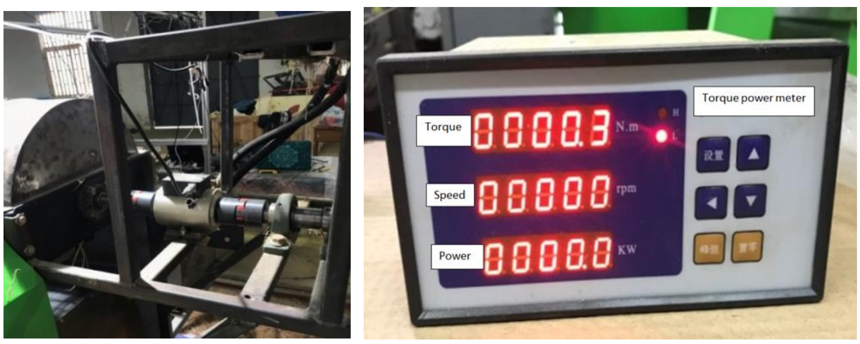


Figure 3. Torque sensor.

2.3. Testing Instruments

An TD 1001 electronic digital balance with an accuracy of 0.01 g produced by the Chengdu Cheng Sheng tools group company, LTD; an Sdh-1202 rapid halogen moisture meter produced by the same instruments company, LTD; a TMS-PRO type texture analyzer produced by the FTC USA company; an MB45 moisture meter produced by the OHAUS

USA company; an electronic digital display Vernier caliper; a tape; scissors; some sealing bags; a tachometer; and a frequency converter were used for the test.

2.4. Rice Cultivar

The Huanghuazhan rice variety was used for the experiment. It was planted in a field at Huazhong agricultural university, Wuhan, China. The planting method was artificial transplanting. Manual harvesting was used, with a stubble height of about 150 mm, and then the rice was transported to the university factory for testing.

Each rice stem was subjected to a three-point bending test and a shearing test using the TMS-PRO type texture analyzer at the engineering college's agricultural equipment laboratory, as shown in Figure 4. The properties of rice stalks and grains are shown in Table 2.

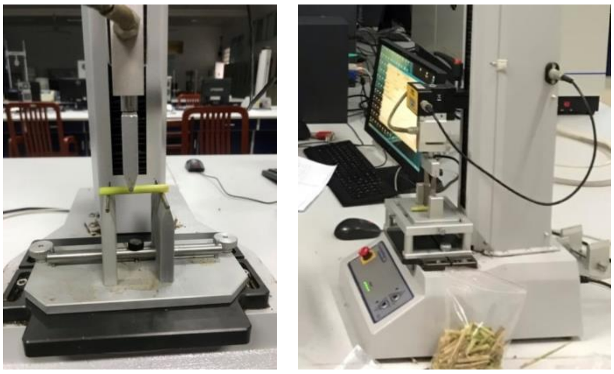


Figure 4. Bending and shearing test.

Table 2. Rice stalks and grain properties.

Properties	Value
Average Grain Length; mm	9.75
Average Grain Width; mm	2.75
Average Grain Thickness; mm	2.02
Grain Moisture Content; %	13.32
1000 Grains Weight; g	30.43
Average Stalk Length; mm	964.08
Stalk Moisture Content; %	63.21
Max Shearing Force; N	249.6
Max Bending Force; N	9

2.5. Taguchi Method and Experiment Design

The Taguchi method is used widely in engineering analysis. It is a dominant design that reduces the number of tests and minimizes the effects of factors that cannot be controlled [28,29]. It uses a loss function to calculate the deviation between the desired values and the experimental values. This loss function is converted into a signal–noise (S/N) ratio [29,30].

The S/N ratio can be divided into three categories given by Equations (1)–(3) [31]:

The nominal is the best:

$$\frac{S}{N} = 10 \log \frac{\overline{y}}{s_y^2} \tag{1}$$

The lower is better:

$$\frac{S}{N} = -10 \ \log \frac{1}{n}\left(\sum y2\right) \tag{2}$$

The higher is better:

$$\frac{S}{N} = -\log \frac{1}{n}\left(\sum \frac{1}{y2}\right) \tag{3}$$

where $\bar{y}$ is the average of observed data, s_y^2 is the variation of y, n is the number of observations, and y is the observed data or each type of the characteristics.

2.5.1. Threshing Parameters and Their Levels

For the test, we used the cylindrical and conical types of threshers (A); three rotational speeds (B) of 1100, 1300, and 1500 rpm; and three feeding rates (C) of 0.8, 1.1, and 1.4 kg/s, as shown in Table 3.

Table 3. Threshing parameters levels.

Parameters	Symbol	Level 1	Level 2	Level 3
Thresher type (T)	A	Cylindrical	Conical	
Thresher rotating speed (N), rpm	B	1100	1300	1500
Feeding rate (F), Kg/s	C	0.8	1.1	1.4

2.5.2. Taguchi Full Factorial Design L_{18} ($2^1 \times 3^2$)

In this study, the Taguchi method was used to assess threshing performance and to compare two threshers' structures (cylindrical and conical). Taguchi's L_{18} arrangement was used for experimenting. To determine the optimal threshing conditions and the best operating parameters, the S/N ratio was calculated. The lower is better was used to determine the S/N ratio for power requirement, and the higher is better was used for efficiency and productivity. The experiment results and S/N ratios are shown in Table 4.

Table 4. The results of experiment and the signal–noise (S/N) ratios.

No	Thresher Type	Thresher Speed	Feeding Rate	Threshing Efficiency	S/N Efficiency	Productivity	S/N Productivity	Power	S/N Power
1	Cylindrical	1100	0.8	96.98	39.73	0.27	−11.37	6.20	−15.85
2	Cylindrical	1100	1.1	97.77	39.80	0.30	−10.46	8.27	−18.35
3	Cylindrical	1100	1.4	98.16	39.84	0.35	−9.12	10.37	−20.32
4	Cylindrical	1300	0.8	97.07	39.74	0.33	−9.63	6.31	−16.00
5	Cylindrical	1300	1.1	97.96	39.82	0.38	−8.40	8.96	−19.05
6	Cylindrical	1300	1.4	98.28	39.85	0.39	−8.18	10.43	−20.37
7	Cylindrical	1500	0.8	97.40	39.77	0.40	−7.96	6.57	−16.35
8	Cylindrical	1500	1.1	98.05	39.83	0.45	−6.94	9.04	−19.12
9	Cylindrical	1500	1.4	98.41	39.86	0.51	−5.85	10.63	−20.53
10	Conical	1100	0.8	97.21	39.75	0.33	−9.63	5.45	−14.73
11	Conical	1100	1.1	97.90	39.82	0.38	−8.40	7.22	−17.17
12	Conical	1100	1.4	98.21	39.84	0.39	−8.18	10.06	−20.05
13	Conical	1300	0.8	97.48	39.78	0.38	−8.40	5.89	−15.40
14	Conical	1300	1.1	98.09	39.83	0.42	−7.54	7.66	−17.68
15	Conical	1300	1.4	98.34	39.85	0.44	−7.13	10.22	−20.19
16	Conical	1500	0.8	97.92	39.82	0.48	−6.38	6.44	−16.18
17	Conical	1500	1.1	98.15	39.84	0.59	−4.58	8.90	−18.99
18	Conical	1500	1.4	98.60	39.88	0.64	−3.88	10.30	−20.26

2.6. Testing Procedure

The platform of the thresher was established in the factory. The conveyor belt's total length was 6 m, the first meter was left empty, and the rice straw was evenly spread on the last 5 m to ensure that it would be fed at a stable speed. The conveyor belt's speed was kept to 1 m/s, and different feeding rates of 0.8, 1.1, and 1.4 kg/s were tested. The drum speeds were 1100, 1300, and 1500 rpm. After the experiment, the rice grains were collected from the boxes under the concave and from the straw outlet, cleaned using a cleaning machine, and then weighed to measure the threshing efficiency and productivity. Additionally, the required power was measured using the torque sensor mounted on the thresher shaft.

2.7. Threshing Performance Indicators

Performance evaluation is a scientific method of ascertaining the working conditions of a system's main components to establish how the components contribute to the system's overall efficiency [32].

The criteria for evaluating threshing mechanisms' performance include threshing efficiency, grain loss, grain damage, output capacity, cleaning efficiency, and power requirement [33].

The crop's feed rate into the thresher and operating parameters such as drum speed significantly affected the threshing performance [34].

2.7.1. Threshing Efficiency

Threshing efficiency is the ratio between the mass of threshed grains received from thresher outlets and the total grain input per time unit expressed in percentage [25].

It was calculated regarding the following equation:

$$\text{TE} = \text{weight of threshed seed (g)}/\text{total weight of seed (g)} \times 100$$

2.7.2. Thresher Productivity

The throughput of a thresher is the mass of materials passing through the thresher per time unit [35].

$$\text{Throughput} = \text{total weight of seed}/\text{threshing time}$$

2.7.3. Power Requirement

The required power was calculated after analyzing the obtained data from the torque sensor.

3. Results and Analysis

3.1. Taguchi Technique Analysis

3.1.1. Analysis of the Signal-to-Noise (S/N) Ratio

Threshing efficiency, power, and productivity were measured using Taguchi techniques, and the optimization of the control factors was provided by signal-to-noise ratios using the Minitab software. The lowest value of power was effective on threshing performance enhancing, so the lower is better equation was used to determine its S/N ratio. Additionally, the highest values of threshing efficiency and productivity were very effective on threshing performance, so the higher is better was used. The values of the S/N ratios are shown in Tables 5–7 and show the optimal levels of control factors for optimal threshing efficiency, power, and productivity. These levels are also shown in graph forms in Figures 5–7.

The optimum level for each control factor was found regarding the highest S/N ratio in the levels of that control factor. The levels of the factors giving the best efficiency and productivity were specified as $A_2B_3C_3$. This means that the optimum efficiency and productivity were obtained using the conical shaped thresher (A_2), a rotating speed of 1500 (B_3), and a feed rate of 1.8 (C_3). On the other hand, the lowest power requirement was obtained with a thresher type (A_2), at rotating speed (B_1), and feeding rate (C_1).

Table 5. Response table for signal to noise ratios for threshing efficiency (larger is better).

Level	A	B	C
1	39.81	39.80	39.77
2	39.82	39.81	39.82
3		39.83	39.85
Delta	0.02	0.03	0.09
Rank	3	2	1

Table 6. Response table for signal to noise ratios for productivity (larger is better).

Level	A	B	C
1	−8.656	−9.527	−8.895
2	−7.124	−8.214	−7.720
3		−5.930	−7.055
Delta	1.532	3.597	1.840
Rank	3	1	2

Table 7. Response table for signal to noise ratios for power (smaller is better).

Level	A	B	C
1	−18.44	−17.74	−15.75
2	−17.85	−18.11	−18.39
3		−18.57	−20.28
Delta	0.59	0.83	4.53
Rank	3	2	1

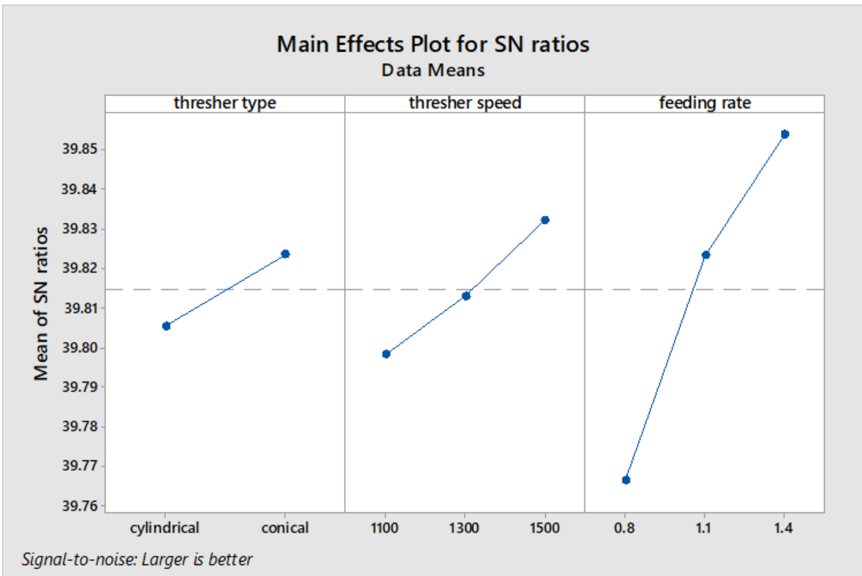


Figure 5. Effect of operating parameters on S/N ratio for threshing efficiency.

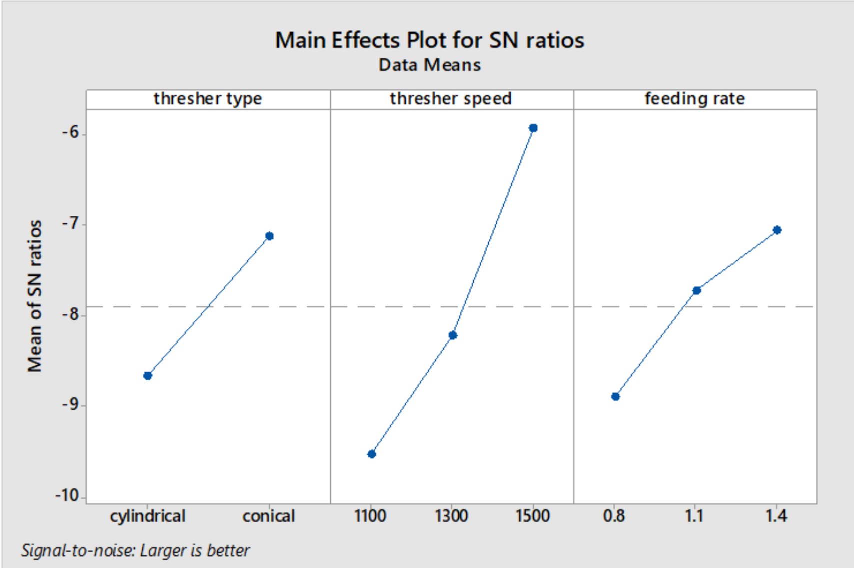


Figure 6. Effect of operating parameters on S/N ratio for productivity.

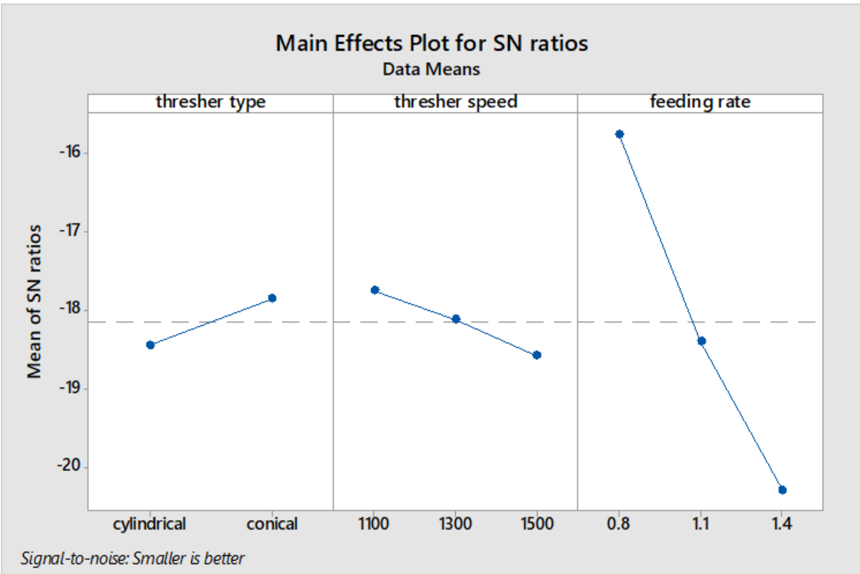


Figure 7. Effect of operating parameters on S/N ratio for power.

3.1.2. Analysis of Variance

ANOVA was used to determine the individual interaction of all of the control factors in the test. In this study, ANOVA was used to analyze the effects of thresher type, rotating speeds, and feeding rates on threshing performance. The ANOVA results are shown in Tables 7–9. This analysis was carried out at a 5% significance level and a 95% confidence level. The last column of the table shows the percentage value of each parameter contribution, which indicates the degree of influence on threshing performance.

According to Table 8, the percent contributions of the A, B, and C factors on the threshing efficiency were found to be 4.87, 11.63, and 79%, respectively. Thus, the most important factor affecting the threshing efficiency was feeding rate.

Table 8. ANOVA for threshing efficiency.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	Contribution Rate (%)
Thresher Type (A)	1	0.1860	0.18600	12.99	0.004	4.87
Thresher Speed (B)	2	0.4440	0.22200	15.50	0.000	11.63
Feeding Rate (C)	2	3.0160	1.50799	105.29	0.000	79.00
Error	12	0.1719	0.01432			4.50
Total	17	3.8178				100.00

Table 9. ANOVA for productivity.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	Contribution Rate (%)
Thresher Type (A)	1	0.024939	0.024939	33.25	0.000	16.16
Thresher Speed (B)	2	0.096544	0.048272	64.36	0.000	62.54
Feeding Rate (C)	2	0.023878	0.011939	15.92	0.000	15.47
Error	12	0.009000	0.000750			5.83
Total	17	0.154361				100.00

Referring to Table 9, the percent contributions of the A, B, and C factors in productivity were 16.16, 62.54, and 15.47%, respectively. Thus, the most effective factor on the productivity was thresher speed.

Regarding Table 10, the contributions percentage of the A, B, and C factors on the power were 2.11, 2.74, and 93.05%. Thus, the most effective factor was the feeding rate.

Table 10. ANOVA for power.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	Contribution Rate (%)
Thresher Type (A)	1	1.196	1.1961	12.04	0.005	2.11
Thresher Speed (B)	2	1.555	0.7776	7.83	0.007	2.74
Feeding Rate (C)	2	52.752	26.3761	265.61	0.000	93.05
Error	12	1.192	0.0993			2.10
Total	17	56.695				100.00

3.2. Results Evaluation and Discussion

After the test was carried out, and after the collected data were analyzed according to Taguchi techniques, some graphs were drawn using the Origin software in order to assure the former obtained results.

3.2.1. Effect of Feed Rate on Threshing Efficiency under Different Rotating Speeds for the Cylindrical and Conical Thresher

It was concluded that increasing the thresher's feeding rate and rotating speed increased the threshing efficiency from 96.98% to 98.41% for the cylindrical thresher and from 97.21 to 98.6% for the conical thresher, as shown in Figure 8. These results were in agreement with the results of Osueke, 2013 [36], and Ahuja et al., 2017 [37]. The increase in threshing efficiency with drum speed could be attributed to the high frequency of collisions and impacts between spikes and grain heads, resulting in more grain threshing and separating, and it could also be attributed to the increased friction between the concave and grain heads. The efficiency increased with the increase of feeding rate due to greater amount of mass of the crop fed to the thresher per the time unit.

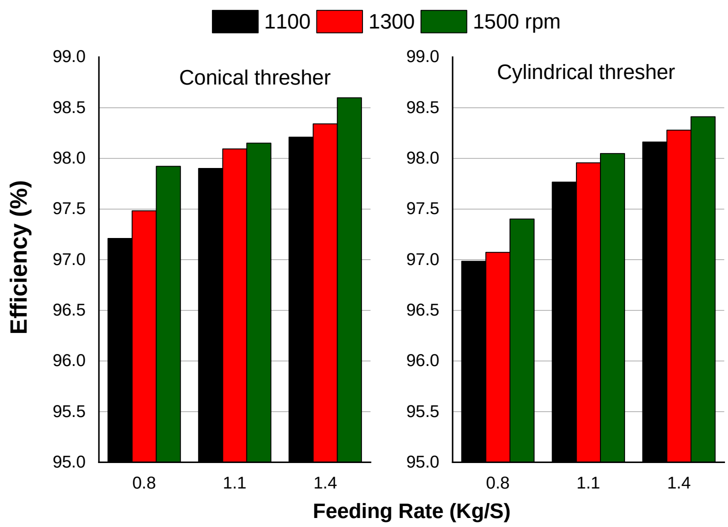


Figure 8. Effect of operating parameters on threshing efficiency.

3.2.2. Effect of Feed Rate on Power Requirement under Different Rotating Speeds for the Cylindrical and Conical Thresher

The required power increased with the increase in feeding rate and rotational speed. This may be attributed to a high load on the thresher because of the excessive stalks passing through the threshing gap. These results were the same as the obtained results by Ezzatollah et al., 2009 [8], who noticed that drum speed significantly affected the power requirements.

Using the conical-shaped thresher resulted in low power requirements when compared to the cylindrical thresher, as shown in Figure 9.

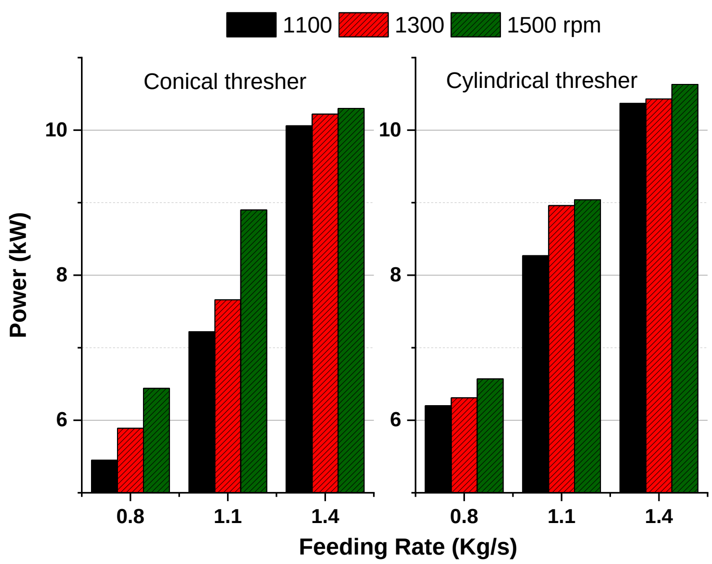


Figure 9. Effect of operating parameters on threshing power.

3.2.3. Effect of Feed Rate on Productivity under Different Rotating Speeds for the Cylindrical and Conical Thresher

Increasing the feed rate increased the productivity of the thresher from 0.27 to 0.51 kg/s for the cylindrical thresher and from 0.33 to 0.64 kg/s for the conical thresher, as illustrated in Figure 10. These results were in agreement with the work of Osueke, 2013 [36]. This may be attributed to the higher mass of rice passing through the thresher per time unit.

Additionally, the increase of the rotational speed increased productivity because the higher speed resulted in a low threshing time, which increased the threshed crop per the time unit. The conical thresher gave a higher productivity than the cylindrical thresher.

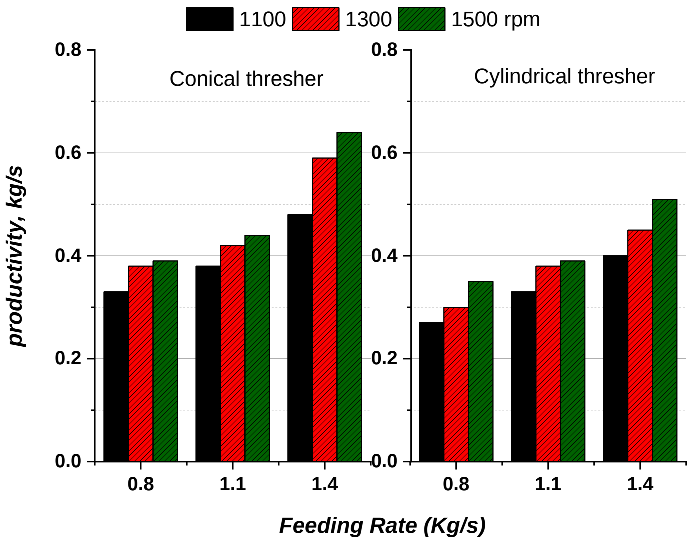


Figure 10. Effect of operating parameters on threshing productivity.

4. Conclusions

1. In this paper, two thresher structures were tested and evaluated for performance under different operating parameters such as thresher speed and feeding rate. The Taguchi technique was used to reduce the testing time and number and to analyze the data for experimental variable optimization. The obtained results revealed that increasing the feed rate and rotating speed positively correlated with threshing efficiency, productivity, and power requirements.
2. The highest threshing efficiency and highest productivity of 98.6% and 0.64 kg/s, respectively, were achieved using the conical thresher under a rotating speed of 1500 rpm and a feeding rate of 1.4 kg/s.
3. The lowest required power of 5.45 kW was obtained using the conical thresher under a rotational speed of 1100 rpm and a feeding rate of 0.8 kg/s.
4. It was concluded that the conical thresher was more effective than the cylindrical thresher because it achieved a higher efficiency, a higher productivity, and a lower power requirement.
5. This research provides a new method for assessing rice thresher performance and presents a new threshing drum structure that will be more efficient for rice threshing with a combine harvester.

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References

1. Center American Trends Panel. The forecast of world agricultural supply and demand forecast for February. *World Agric.* **2017**, *4*, 215–219.
2. Callaway, E.J.N. The birth of rice. *Nature* **2014**, *514*, S58. [CrossRef] [PubMed]
3. Qi, W. Impacts of nitrogen and zeolite managements on yield and physicochemical properties of rice grain. *Int. J. Agric. Biol. Eng.* **2016**, *9*, 93–100.
4. Cerquitelli, T.J.E.P. Predicting large scale fine grain energy consumption. *Energy Proc.* **2017**, *111*, 1079–1088. [CrossRef]
5. Zami, M.A. Performance evaluation of the BRRI reaper and Chinese reaper compared to manual harvesting of rice (Oryza sativa L.). *Agriculturists* **2014**, *12*, 142–150. [CrossRef]
6. Unakıtan, G.; Aydın, B.E.J. A comparison of energy use efficiency and economic analysis of wheat and sunflower production in Turkey: A case study in Thrace Region. *Energy* **2018**, *149*, 279–285. [CrossRef]
7. Chabrol, D. The Technical Centre for Agricultural and Rural Cooperation. *ACP-EU Lome* **1996**, *6*, 12–15.
8. Ezzatollah, A.A.-A.; Yousef, A.-G.; Saeid, A. Study of Performance Parameters of Threshing Unit in a Single Plant Thresher. *Ardabil* **2009**, *4*, 92–96.
9. Asundep, N.N. Determinants of access to antenatal care and birth outcomes in Kumasi, Ghana. *J. Epid. Glob. Health* **2013**, *3*, 279–288. [CrossRef]
10. Olayanju, T. An assessment of the status of small rice threshers in Nigeria. *J. Nat. Sci. Eng. Technol.* **2009**, *8*, 84–94.
11. Azouma, O.Y. Design of throw-in type rice thresher for small scale farmers. *Indian J. Sci. Tehnol.* **2009**, *2*, 10–14. [CrossRef]
12. Gbabo, A.; Gana, I.M.; Amoto, M.S. Design, fabrication and testing of a millet thresher. *Net J. Agric. Sci.* **2013**, *1*, 100–106.
13. Singh, B.; Linvill, D.E. Determining the effect of pod and grain moisture content on threshing loss and damage of navy beans. *Trans. ASAE* **1977**, *20*, 226–0227. [CrossRef]
14. Ndirika, V.J. A mathematical model for predicting output capacity of selected stationary spike-tooth grain threshers. *Appl. Eng. Agric.* **2006**, *22*, 195–200. [CrossRef]
15. Gang, W. Design of variable screw pitch rib snapping roller and residue cutter for corn harvesters. *Int. J. Agric. Biol. Eng.* **2016**, *9*, 27–34.
16. Li, H. CFD–DEM simulation of material motion in air-and-screen cleaning device. *Comp. Electron. Agric.* **2012**, *88*, 111–119. [CrossRef]
17. Li, Y. Development and application of mechanized maize harvesters. *Int. J. Agric. Biol. Eng.* **2016**, *9*, 15–28.
18. Tang, Z.; Li, Y.; Xu, L. Design and optimization for length of longitudinal-flow threshing cylinder of combine harvester. *Trans. Chin. Sci. Agric. Eng.* **2014**, *30*, 28–34.
19. Addo, A. Effect of different threshing cylinders on soybean quality. *J. Sci. Tehnol.* **2004**, *24*, 121–125. [CrossRef]
20. Alizadeh, M.R.; Bagheri, I. Field performance evaluation of different rice threshing methods. *Int. J. Nat. Sci. Eng.* **2009**, *3*, 139–143.
21. Osueke, C.O. Frictional impact modeling of a cereal thresher. *Am. J. Eng. Appl. Sci.* **2011**, *4*, 405–412. [CrossRef]
22. Khazaei, J. Force Requirement for Pulling off Chickpea Pods as Well as Fracture Resistance of Chickpea Pods and Grains. Ph.D. Thesis, Tehran University, Tehran, Iran, 2003.
23. Singh, K. Development and evaluation of multi millet thresher. *J. Appl. Nat. Sci.* **2015**, *7*, 939–948. [CrossRef]
24. Azhar Saeed, M. Testing and evaluation of hold-on paddy thresher. *Agric. Mech. Asia Africa* **1995**, *26*, 47.
25. Asli-Ardeh, E.A.; Abbaspour-Gilandeh, Y. Investigation of the effective factors on threshing loss, damaged grains percent and material other than grain to grain ratio on an auto head feed threshing unit. *Am. J. Agric. Biol. Sci.* **2008**, *3*, 699–705.
26. El-Haddad, W.Z. A simplified design and performance study of threshing and winnowing machine suitable for sample holdings. Master's Thesis, University Egypt, Tanta, Egypt, 2000.
27. Helmy, M.; Yousef, I.; Badawy, M.A. Performance evaluation of some sunflower threshers. *Egypt J. Agric. Res.* **2000**, *78*, 959–975.
28. Palanikumar, K.J.M. Experimental investigation and optimisation in drilling of GFRP composites. *Measurement* **2011**, *44*, 2138–2148. [CrossRef]
29. Asiltürk, I.; Akkuş, H. Determining the effect of cutting parameters on surface roughness in hard turning using the Taguchi method. *Measurement* **2011**, *44*, 1697–1704. [CrossRef]
30. Köksoy, O.; Muluk, F.Z. Solution to the taguchiâs problem with correlated responses. *Gazi Univ. J. Sci.* **2004**, *17*, 59–70.
31. Shetty, R.; Pai, R.B.; Rao, S.S.; Nayak, R. Taguchi's technique in machining of metal matrix composites. *J. Braz. Soc. Mech. Sci. Eng.* **2009**, *31*, 12–20. [CrossRef]
32. Chukwu, O. Performance evaluation of locally manufactured rice threshers in Niger state. *J. Eng. Appl. Sci.* **2008**, *3*, 602–606.

33. Behera, B.K. Development and testing of a power-operated wheat thresher. *Agric. Mech. Asia Africa Lat. Am. Jpn.* **1990**, *21*, 15–21.
34. Špokas, L.; Steponavičius, D.; Petkevičius, S. Impact of technological parameters of threshing apparatus on grain damage. *Agron. Res.* **2008**, *6*, 367–376.
35. Ndirika, V.I.O. Modeling the Performance of Selected Stationary Grain Threshers. Ph.D. Thesis, Department of Agricultural Engineering Ahmadu, Bello University, Zaria, Nigeria, 1997.
36. Osueke, E.C.O. Study of the influence of crop, machine and operating parameters on performance of cereal threshers. *Int. J. Eng. Res. Dev.* **2014**, *7*, 1–9.
37. Ahuja, M.; Dogra, B.; Narang, M.K.; Dogra, R. Development and evaluation of axial flow paddy thresher equipped with feeder chain type mechanical feeding system. *Curr. J. Appl. Sci. Technol.* **2017**, *23*, 1–10. [CrossRef]