
ENHANCING SOYBEAN THRESHER PERFORMANCE: A TAGUCHI DESIGN OF EXPERIMENTS APPROACH TO MODELING THRESHING AND CLEANING EFFICIENCIES

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ABSTRACT

Optimizing agricultural processing is critical to meeting the rising global demand for plant-based proteins. This study optimizes the threshing efficiency (TE) and cleaning efficiency (CE) of a modified soybean thresher using the Taguchi Design of Experiments (DOE). An L-9 orthogonal array evaluated cylinder speed (500, 600, 700 rpm), feed rate (3, 4, 5 kg/h), and concave clearance (10, 13, 16 mm). Signal-to-noise (S/N) analysis identified concave clearance as the most sensitive parameter for both metrics. Maximum TE required 13 mm clearance, 600 rpm, and 5 kg/h feed rate. Conversely, maximum CE was achieved at 13 mm clearance, 500 rpm, and 3 kg/h, minimizing excess biomass during separation. Analysis of Variance (ANOVA) revealed that cylinder speed and feed rate were significant linear predictors of TE. While concave clearance dictated overall variance via a highly sensitive non-linear "sweet spot," it lacked linear significance. Furthermore, the linear model was inadequate for CE, indicating that cleaning relies heavily on unaccounted aerodynamic properties like fan speed. Ultimately, these findings provide a resource-efficient framework for optimizing post-harvest machinery.

Keywords: Soybean thresher; Taguchi method; Threshing efficiency; Cleaning efficiency; Parameter optimization

1 INTRODUCTION

As a global community, we face the daunting task of ensuring sufficient nourishment for a rapidly expanding population, projected to reach 10 billion by 2050. Concurrently, the demand for proteins derived from renewable and sustainable sources is rising. However, agricultural and natural resources are finite, necessitating highly efficient food production and processing systems (Kumar et al., 2021; Yuliarti et al., 2021; Kumar et al., 2024). This backdrop underscores the critical importance of optimizing post-harvest crop processing, particularly for high-yield crops that offer a potential solution to protein-based malnutrition.

Soybean (*Glycine max* L.) is a globally cultivated oilseed crop renowned for its rich nutritional profile. It contains over 40% protein and 20% oil (Das et al., 2024). In addition to these macronutrients, soybeans provide essential amino acids, omega-3 fatty acids, and therapeutic compounds, including folic acid, vitamin B-complex, lactose-free fatty acids, and free-radical scavenging components. Furthermore, soybean meal, the primary by-product of soybean oil processing, has significant potential to combat protein-energy malnutrition worldwide (Das et al., 2024).

Despite the crop's immense value, threshing is a critical step in soybean processing, one that often relies on traditional, manual techniques. These rudimentary methods include pounding crops in a mortar with a pestle, beating them with sticks, or cracking them between stones (Alonge et al., 2017). While used for generations, these practices are time-consuming, labor-intensive, and inherently prone to crop loss (Alonge et al., 2017). Although numerous efforts have been made to design and develop mechanical threshers for local farmers, many of these machines operate without optimized parameters, failing to achieve maximum output. Employing optimization and modeling techniques, such as the Taguchi method or response surface methodology (RSM), can assist engineers in understanding process dynamics, managing resources, and effectively scaling up agricultural systems.

The Taguchi Design of Experiments (DOE) is a robust statistical approach developed by Genichi Taguchi, primarily designed to improve process quality by minimizing the effects of uncontrollable noise factors on system performance. This methodology is widely adopted because it facilitates the creation of a balanced and robust experimental design requiring a minimal number of experimental runs (Oemar & Chang, 2020). Implementing the Taguchi approach guarantees efficient resource utilization, thereby minimizing consumption and reducing overall production costs (Kundu et al., 2015). Consequently, this study utilizes the Taguchi method to model and optimize an existing, modified soybean thresher. The investigation focuses on three critical operating factors: cylinder speed, feed rate, and concave clearance, evaluating their specific impacts on two primary response variables: threshing efficiency (TE) and cleaning efficiency (CE).

2 MATERIALS AND METHODS

2.1 Machine description and operation

The modified soybean thresher used in this study is designed for single-operator use (Figure 1). The operational mechanism begins by feeding soybean pods into the intake hopper, where they move into the threshing chamber. This chamber houses a threshing cylinder equipped with beaters. The rotating beaters primarily thresh the crop through impact. Subsequently, the threshed mixture of grain and chaff descends into the cleaning unit. A centrifugal fan in the cleaning unit generates a targeted airstream that pneumatically separates the lighter chaff from the heavier grains, blowing the chaff out of the machine while channeling the clean grains into a collection chute.

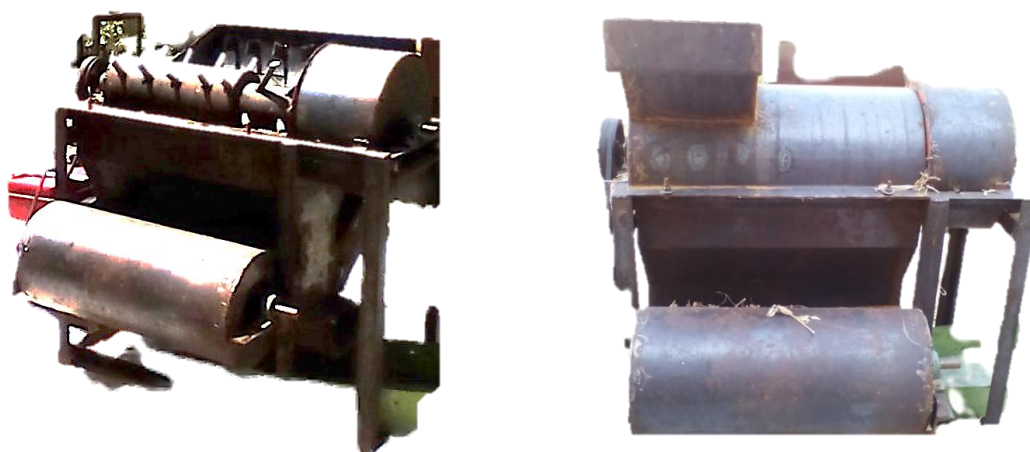


Figure 1: Pictorial presentation of the soybean thresher viewed from two different angles.

2.2 Experimental material and thresher performance test

Performance testing of the modified thresher was conducted using the TGX 1448-2E soybean variety, sourced from the Institute for Agricultural Research (I.A.R), Ahmadu Bello University, Zaria, Nigeria. Prior to the experiments, the moisture content of the soybeans was determined and standardized to 12% dry basis (d.b.) to ensure uniformity. To evaluate the machine's performance, three independent operating variables were tested at three levels each: cylinder speed (500, 600, and 700 rpm), feed rate (3, 4, and 5 kg/h), and concave clearance (10, 13, and 16 mm). All experimental runs were conducted in triplicate to guarantee reliability.

2.3 Performance evaluation indices

The machine's performance was evaluated based on four primary indices: threshing efficiency (TE), cleaning efficiency (CE), scatter loss (SL), and output capacity (Cp). These indices were calculated using the following relationships (Equations 1–4):

$$TE(\%) = \left(1 - \frac{A}{T_G}\right) \times 100 \quad (1)$$

$$CE(\%) = \left(\frac{B}{D}\right) \times 100 \quad (2)$$

$$SL(\%) = \left(\frac{E}{T_G}\right) \times 100 \quad (3)$$

$$Cp(kg/h) = \frac{Q}{t} \quad (4)$$

Where:

A = Weight of un-threshed grain collected per unit time (kg), T_G = Total grain input per unit time (kg), B = Weight of cleaned grain in the sample from the main outlet (kg), D = Total weight of material (grain + chaff) collected from the main outlet (kg), E = Weight of scattered grain collected per unit time (kg), Q = Total weight of threshed grain collected per unit time (kg), and t = Threshing time (h). For modeling and optimization in this study, TE and CE were selected as the primary response variables. TE is the primary indicator of the machine's core functional capability, measuring its effectiveness at detaching soybean grains from pods to minimize unthreshed crop losses (Aseffa, 2024; Powar et al., 2019). Conversely, CE determines the market quality and purity of the final agricultural output by evaluating the system's ability to separate threshed grains from chaff and other impurities (Dangora et al., 2024). Consequently, prioritizing the simultaneous maximization of these two parameters is critical for minimizing post-harvest wastage and ensuring the overall economic and operational viability of the thresher (Aseffa, 2024).

2.4 Experimental design

The Taguchi Design of Experiments (DOE), coupled with multiple regression analysis, was employed to develop a robust experimental design and determine the optimal settings of control parameters (El-Deen, 2024). Using an orthogonal array, the Taguchi method enables a balanced, comprehensive analysis while minimizing the total number of experimental runs, reducing experimental error and enhancing repeatability (Sahu et al., 2024).

An L-9 orthogonal array was used in this study (Tables 1 and 2). In accordance with standard Taguchi L-9 design principles, this modeling approach assumes that interaction effects among the three independent factors (cylinder speed, feed rate, and concave clearance) are negligible, allowing a focused evaluation of their main effects. We evaluated response-variable optimization using the signal-to-noise (S/N) ratio. Depending on the desired outcome, S/N ratios are typically categorized into three standard algorithms: smaller-the-better (Equation 5), larger-the-better (Equation 6), and nominal-the-best (Equation 7) (Kundu et al., 2015). Because this study aimed to maximize both threshing and cleaning efficiencies, the larger-the-better algorithm was selected.

$$S/N = -10 \log\left(\frac{1}{n} \sum X^2\right) \quad (5)$$

$$S/N = -10 \log\left(\frac{1}{n} \sum \frac{1}{X^2}\right) \quad (6)$$

$$S/N = -10 \log\left(\frac{1}{n} \sum \frac{\bar{X}^2}{s^2}\right) \quad (7)$$

Where X represents the responses and n is the number of replications. The algorithms for larger-the-better were selected because our goal was to maximize the threshing and the cleaning efficiency of

the thresher. Table 1 shows the selected variables with their respective levels, and Table 2 presents the Taguchi design based on L-9 orthogonal array design.

Table 1: Presentation of the variables and their levels

Parameter	Level		
	1	2	3
Cylinder speed (rpm)	500	600	700
Feed rate (kg/h)	3	4	5
Concave clearance (mm)	10	13	16

Table 2: Taguchi orthogonal array design based on L-9 with responses

Cylinder speed (rpm)	Feed rate (kg/h)	Concave clearance (mm)	Threshing efficiency (%)	Cleaning efficiency (%)
500	3	10	90.00 ± 0.85	85.00 ± 1.10
500	4	13	92.70 ± 0.64	86.10 ± 0.95
500	5	16	92.00 ± 1.05	85.80 ± 0.80
600	3	13	92.50 ± 0.72	86.70 ± 0.65
600	4	16	93.60 ± 0.55	85.40 ± 1.20
600	5	10	93.80 ± 0.90	84.60 ± 0.75
700	3	16	93.20 ± 0.82	85.10 ± 0.88
700	4	10	93.24 ± 0.68	83.30 ± 1.02
700	5	13	95.12 ± 0.45	85.20 ± 0.70

2.5 Statistical Analysis

The experimental data were structured and analyzed according to the Taguchi L-9 orthogonal array design. We used Minitab 2021 to perform the Taguchi analysis, compute the signal-to-noise (S/N) ratios using the larger-the-better algorithm, and generate the corresponding main effects plots to identify the optimal parameter combinations. We conducted an Analysis of Variance (ANOVA) for multiple linear regression. This regression ANOVA was evaluated at a 95% confidence interval ($\alpha = 0.05$) to test the significance of the linear models.

3 RESULTS AND DISCUSSION

3.1 Taguchi analysis and parameter optimization

The threshing and cleaning efficiencies of the modified soybean thresher were evaluated under varying conditions of cylinder speed (500, 600, and 700 rpm), feed rate (3, 4, and 5 kg/h), and concave clearance (10, 13, and 16 mm). To maximize both output responses, the larger-the-better Signal-to-Noise (S/N) ratio algorithm was utilized for optimization (Equation 6). To address the distinct operational dynamics of these two processes, the Taguchi analysis was performed and evaluated separately for threshing efficiency (TE) and cleaning efficiency (CE).

3.1.1 Threshing Efficiency (TE) Optimization

Taguchi analysis ranks the operating variables by their S/N ratios to determine their relative influence on machine performance. As presented in Table 3, the optimal S/N ratio for cylinder speed (39.00) was achieved at the second level (600 rpm). Similarly, the highest values for feed rate (39.00) and concave clearance (39.03) were observed at level 3 (5 kg/h) and level 2 (13 mm), respectively. By comparing the delta values of the S/N ratios, concave clearance emerged as the most influential factor dictating TE performance (Rank 1), followed closely by cylinder speed (Rank 2) and feed rate (Rank 3).

These numerical findings are directly corroborated by the analysis of means (Table 4), which follows the exact same ranking hierarchy. Furthermore, the main effects plots for the means (Figure 2) and S/N ratios (Figure 3) visually confirm this parameter hierarchy. The peak of each plotted line clearly identifies the parameter combination required for maximum threshing efficiency. Consequently, the optimal operational setting for maximizing TE is a concave clearance of 13 mm, a cylinder speed of 600 rpm, and a feed rate of 5 kg/h. This hierarchy aligns with crop threshing mechanics; studies by Ponican et al. (2009) and Adewumi (2007) found that concave clearance and cylinder speed are crucial for performance and control impact forces. Based on Tables 3 and 4 and Figure 3, optimal settings for threshing and cleaning are 13 mm concave clearance, 600 rpm cylinder speed, and 5 kg/h feed rate. The 600 rpm speed is noteworthy, as higher speeds increase grain detachment but exceeding thresholds (e.g., >700 rpm) can cause more damage and scatter loss, reducing efficiency (Aseffa, 2024; Powar et al., 2019).

Table 3: Response for signal-to-noise ratios, TE (Larger-is-better)

Level	Cylinder speed (rpm)	Feed rate (kg/h)	Concave clearance (mm)
1	38.93	38.95	38.89
2	39.00	38.96	39.03
3	38.97	39.00	38.98
Delta	0.07	0.05	0.14
Rank	2	3	1

Table 4: Response for means TE

Level	Cylinder speed (rpm)	Feed rate (kg/h)	Concave clearance (mm)
1	88.60	88.75	88.32
2	89.43	89.06	89.72
3	89.19	89.42	89.18
Delta	0.83	0.67	1.40
Rank	2	3	1

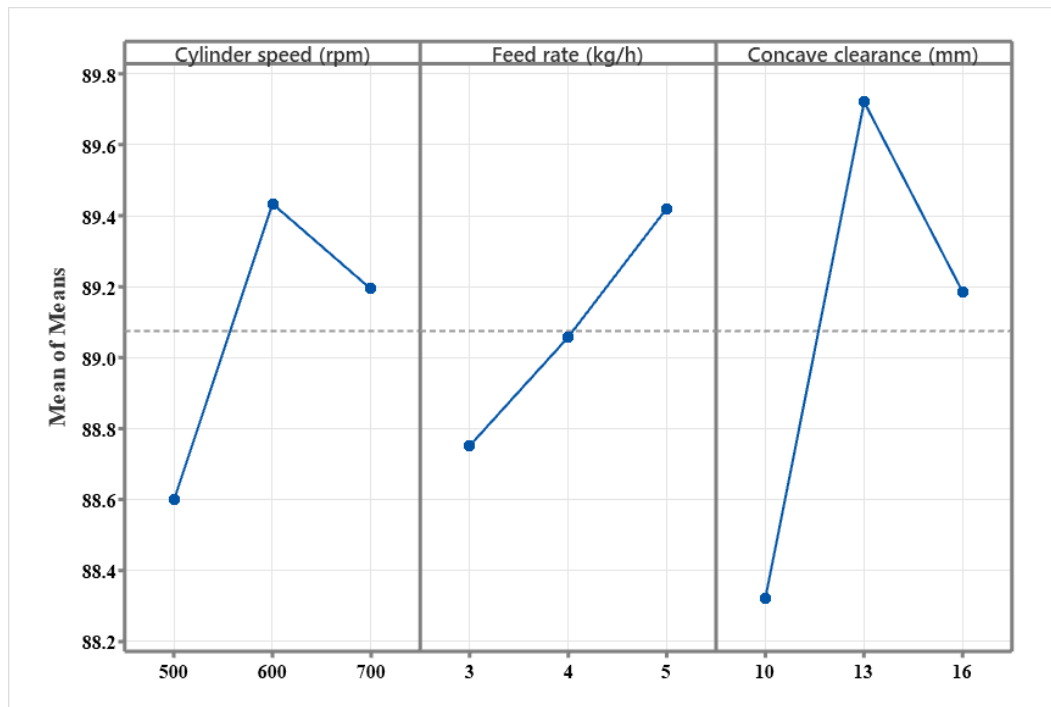


Figure 2: Main effects plot for means (TE)



Figure 3: Main effects plot for signal-to-noise ratio (TE)

3.1.2 Cleaning Efficiency (CE) Optimization

Table 5 and Table 6 detail the response S/N ratios and means specifically for cleaning efficiency. The Taguchi analysis shows that concave clearance is the most influential factor in cleaning performance (Rank 1, Delta = 0.17), followed by cylinder speed (Rank 2, Delta = 0.11) and feed rate (Rank 3, Delta = 0.07). Figure 4 and Figure 5 visually confirm these parameter hierarchies through the CE main effects plots.

The plotted data indicates that the optimal parameter combination for maximizing cleaning efficiency differs slightly from threshing efficiency. The highest S/N ratio for concave clearance was achieved at the second level (13 mm), identical to the TE optimization. However, cleaning efficiency is maximized at a lower feed rate of 3 kg/h (level 1) and a lower cylinder speed of 500 rpm (level 1). A reduced feed rate introduces less total biomass into the separation zone at any given moment, allowing the constant airflow from the centrifugal fan to separate the chaff more thoroughly. Similarly, a lower cylinder speed prevents excessive mechanical pulverization of the soybean pods, reducing the volume of fine debris that typically evades pneumatic separation.

Table 5: Response for Means for CE

Level	Cylinder speed (rpm)	Feed rate (kg/h)	Concave clearance (mm)
1	85.63	85.60	84.30
2	85.57	84.93	86.00
3	84.53	85.20	85.43
Delta	1.10	0.67	1.70
Rank	2	3	1

Table 6: Response for Signal-to-Noise Ratios for CE

Level	Cylinder speed (rpm)	Feed rate (kg/h)	Concave clearance (mm)
1	38.65	38.65	38.52
2	38.65	38.58	38.69
3	38.54	38.61	38.63
Delta	0.11	0.07	0.17
Rank	2	3	1

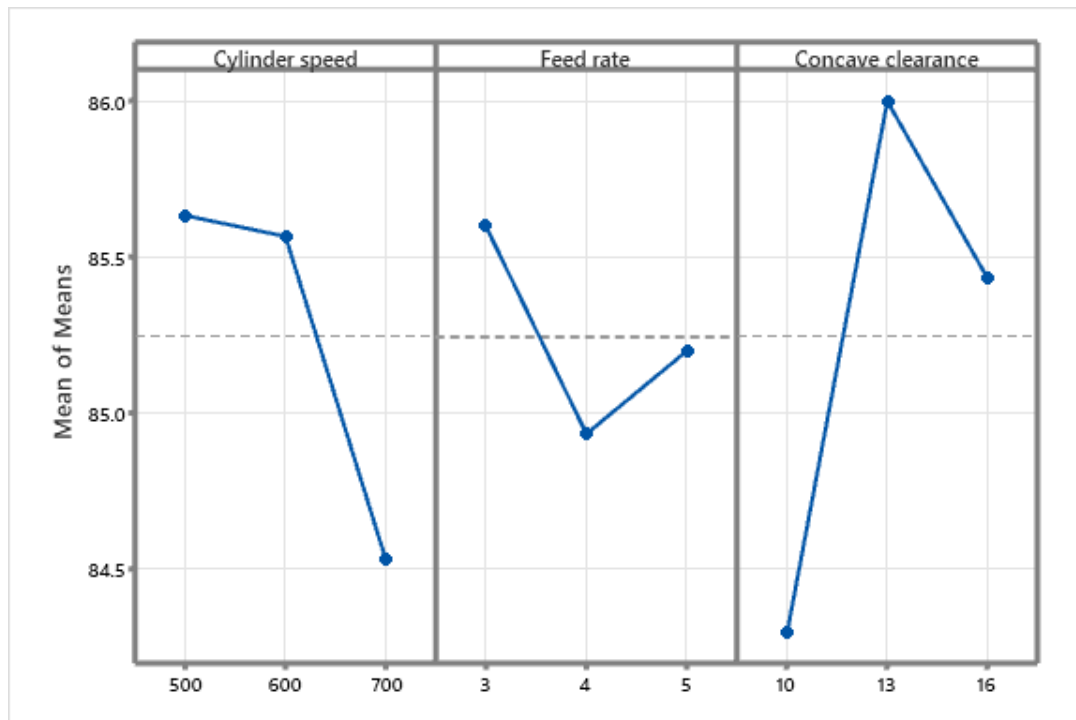


Figure 4: Main effects plot for mean (CE)

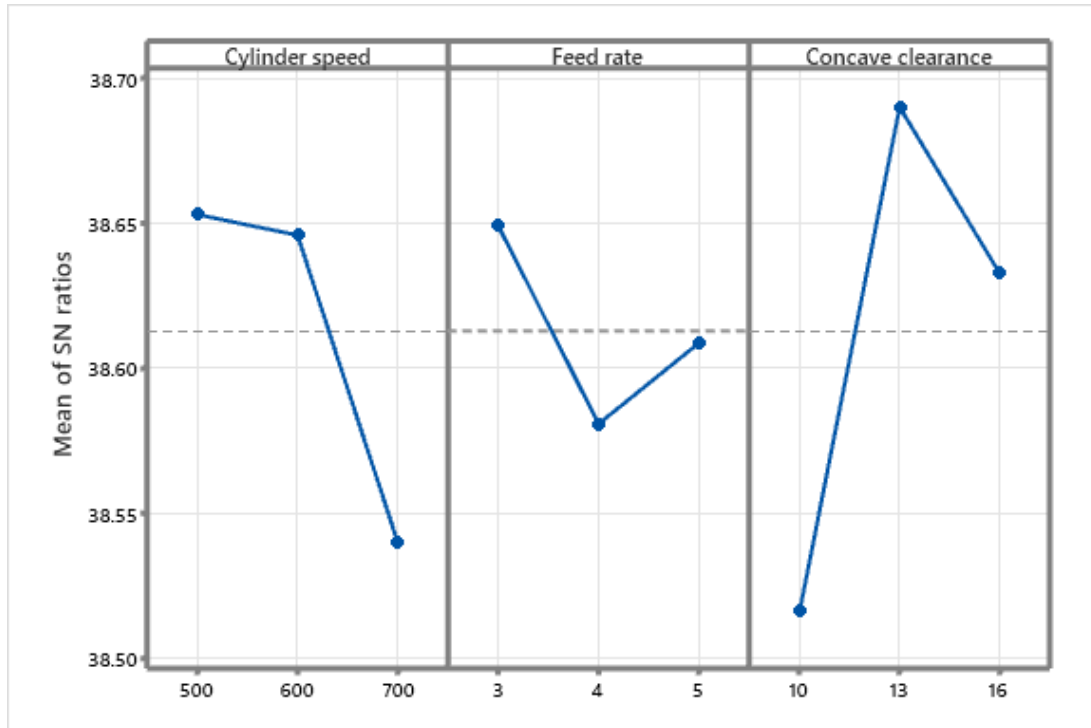


Figure 5: Main effects plot for signal-to-noise ratio (CE)

3.2 Regression analysis of response variables

Regression analysis quantified the relationship between the independent operational parameters and the dependent performance efficiencies, providing predictive insights to minimize grain loss.

3.2.1 Threshing efficiency (TE)

The Analysis of Variance (ANOVA) for threshing efficiency (Table 7) demonstrated a statistically significant linear relationship between TE and the tested parameters. The overall regression model was significant at a 95% confidence interval ($p = 0.028$). Analysis of the individual factors showed that both cylinder speed ($p = 0.015$) and feed rate ($p = 0.039$) significantly influenced TE. The linear regression model for predicting Threshing Efficiency is expressed as:

$$TE(\%) = 81.30 + 0.01143 \text{cylinder speed}(rpm) + 0.87 \text{feed rate}(Kg/h) + 0.098 \text{concave clearance}(mm) \quad (8)$$

The Pareto chart of standardized effects (Figure 6) visually confirms the statistical significance of these parameters. In this chart, the bars representing cylinder speed and feed rate extend beyond the critical reference line ($\alpha = 0.05$), indicating their significant linear impact on threshing efficiency. This aligns with the findings by Desta and Mishra (1990) and Sharma and Devnani (1980), who observed that increasing the peripheral speed of the threshing drum systematically enhances the impact force required to shatter pods and detach grains. Furthermore, the residual plots for threshing efficiency (Figure 7) demonstrate a normal distribution of data points, validating the adequacy of the linear model.

Interestingly, while concave clearance was ranked as the most influential factor in the overarching Taguchi optimization (Table 3), the ANOVA (Table 7) shows it was not statistically significant ($p = 0.393$) as a standalone linear predictor. This is visually reaffirmed in the Pareto chart (Figure 6), where the bar for concave clearance falls well short of the significance reference line. This suggests that the influence of concave clearance on TE is inherently non-linear, operating optimally only within a specific "sweet spot" (e.g., 13 mm) rather than scaling linearly.

Table 7: Analysis of variance for TE

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	12.9009	4.3003	7.28	0.028
Cylinder speed (rpm)	1	7.8433	7.8433	13.28	0.015
Feed rate (kg/h)	1	4.5414	4.5414	7.69	0.039
Concave clearance (mm)	1	0.5163	0.5163	0.87	0.393
Error	5	2.9527	0.5905		
Total	8	15.8536			

At first glance, a discrepancy appears to exist between the Taguchi signal-to-noise (S/N) ratio analysis, which ranks concave clearance as the most influential parameter (Rank 1), and the Analysis of Variance (ANOVA), which identifies it as a non-significant linear predictor ($p = 0.393$). These are distinct statistical constructs that measure different aspects of response variability. The Taguchi S/N sensitivity analysis evaluates absolute deviation and overall variance across discrete experimental levels, effectively capturing non-linear impacts—such as the pronounced optimal "sweet spot" at 13 mm. Conversely, the ANOVA used in this study assesses only the statistical significance of *linear* trends. Therefore, while concave clearance is highly sensitive and strongly dictates overall threshing efficiency, its influence does not scale linearly, which explains its non-significance in the linear regression model.

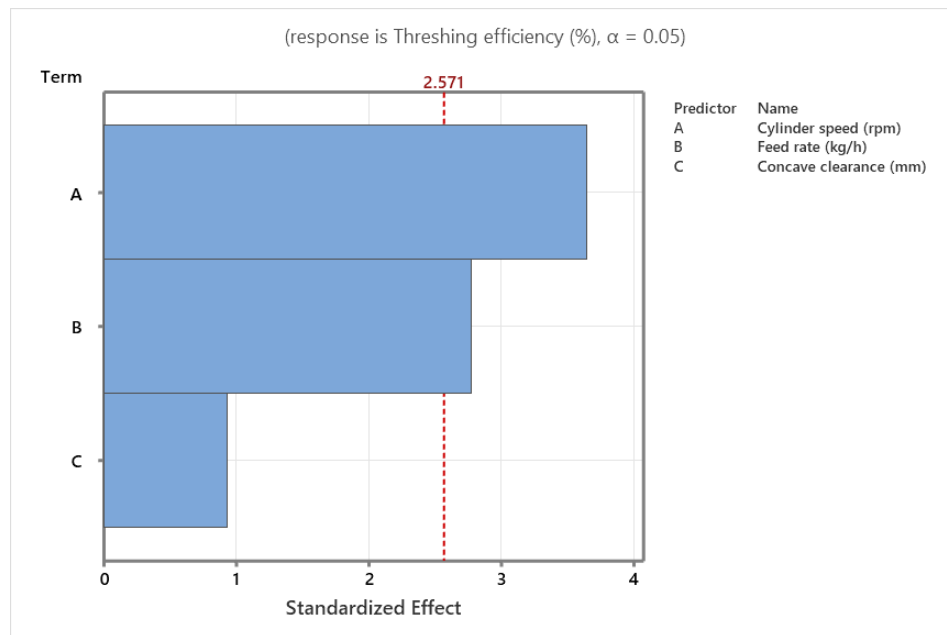


Figure 6: Pareto Chart of the standardized effects, TE (%)

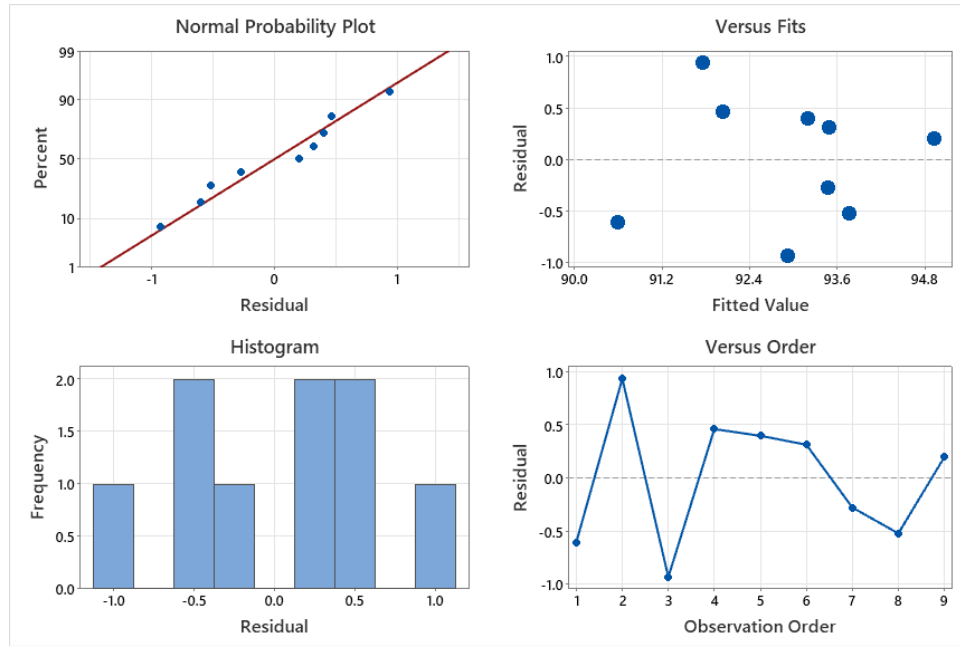


Figure 7: Residual plots for threshing efficiency (%)

3.2.2 Cleaning efficiency (CE)

We conducted a similar regression analysis for CE. The linear model equation is represented as:

$$CE(\%) = 86.89 - 0.0055 \text{cylinder speed}(rpm) - 0.2 \text{feed rate}(Kg/h) + 0.189 \text{concave clearance}(mm) \quad (9)$$

In stark contrast to the threshing model, the ANOVA results for CE (Table 8) indicated that the overall linear regression model for cleaning efficiency was not statistically significant ($p = 0.247$). Furthermore, none of the independent operational parameters (speed, feed rate, or clearance) were statistically significant linear predictors of CE within the tested ranges ($p > 0.05$). The Pareto chart of standardized effects for cleaning efficiency (Figure 8) visually corroborates this lack of linear significance. As shown in the chart, none of the bars representing the tested parameters cross the critical reference line, confirming that cylinder speed, feed rate, and concave clearance do not have a statistically significant linear effect on the cleaning process.

Recent agricultural engineering literature strongly supports the inadequacy of a simple linear model for predicting cleaning efficiency. Cleaning mechanisms in harvesters and threshers rely on complex aerodynamic properties rather than pure mechanical impact. Studies evaluating thresher cleaning systems show that cleaning efficiency is largely governed by non-linear fluid dynamics, such as fan speed, airflow distribution, and sieve oscillation, which often exhibit complex non-linear couplings with feed rate (Badretdinov et al., 2019; Dauda et al., 2024). Because aerodynamic variables like fan speed were held constant or were not the primary focus of this specific linear matrix, the model in Table 6 could not fully capture the cleaning dynamics. Therefore, predicting CE accurately in future iterations will require higher-order (e.g., quadratic) models that directly incorporate fan speed and airflow parameters alongside mechanical variables.

Table 8: Analysis of Variance for CE

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	3.9817	1.3272	1.91	0.247
Cylinder speed (rpm)	1	1.8150	1.8150	2.61	0.167
Feed rate (kg/h)	1	0.2400	0.2400	0.34	0.583
Concave clearance (mm)	1	1.9267	1.9267	2.77	0.157
Error	5	3.4806	0.6961		
Total	8	7.4622			

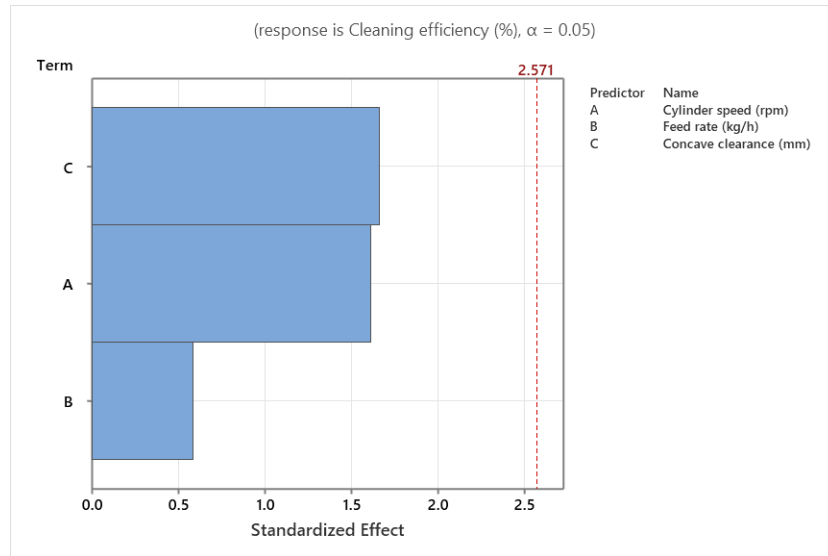


Figure 8: Pareto chart of the standardized effects CE (%)

4 CONCLUSION

This study successfully applied the Taguchi Design of Experiments (DOE) and multiple regression analysis to model and optimize a modified soybean thresher. The investigation demonstrated that concave clearance is the most sensitive mechanical parameter governing overall machine performance, followed by cylinder speed and feed rate. By optimizing these variables, the system can maximize grain detachment while mitigating the risk of grain damage and scatter loss associated with excessive mechanical force. While the analysis revealed a statistically significant linear relationship between the mechanical parameters and threshing efficiency, the linear model proved inadequate for predicting cleaning efficiency. This contrast highlights a vital synthesis in agricultural machinery evaluation: threshing is fundamentally a mechanical impact process, whereas cleaning is heavily governed by unmeasured aerodynamic fluid dynamics. Ultimately, the Taguchi method proved highly effective at establishing a resource-efficient baseline for local machinery manufacturers to maximize processing throughput and combat protein-based malnutrition.

FUTURE WORK

To build upon these findings, future research must transition beyond linear mechanical models to fully optimize the cleaning unit. Subsequent studies will incorporate aerodynamic variables—such as fan speed, air velocity, and airflow distribution—into higher-order mathematical models or utilize computational fluid dynamics (CFD). This approach is necessary to capture the complex, multi-field coupling required to achieve perfect grain separation.

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