Optimization of indented cylinder rice separator parameters using RSM for enhanced sorting efficiency and reduced loss

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Abstract: This research aimed to optimize the configuration of an indented cylinder rice separator using response surface methodology (RSM). The study employed the Box-Behnken design (BBD) with three center points to investigate the impact of sieve slope, trough angle, and sorting duration on efficiency and loss. The results demonstrated that all three factors significantly influenced the performance of the machine. By increasing the sieve slope and sorting duration while adjusting the trough angle closely to zero, the loss percentage decreased significantly, leading to improved sorting efficiency. A quadratic model was employed to determine the optimal conditions for the studied factors. The analysis revealed that a 2-degree sieve slope, a -0.1 scale of the trough angle, and a sorting duration of 120 seconds achieved a minimum loss of 0.42% and a maximum efficiency of 97.29%. Validation experiments confirmed that the actual performance closely matched the predicted values. This optimized condition provides practical guidelines for implementing the studied factors in a continuous type of indented cylinder rice separator.

Keywords: Indented cylinder, rice separator, sorting efficiency, response surface methodology, optimization

Citation: Sokudlor, N., K. Laloon, C. Junsiri, and S. Sudajan. 2024. Optimization of indented cylinder rice separator parameters using RSM for enhanced sorting efficiency and reduced loss. Agricultural Engineering International: CIGR Journal, 26 (2):196-206.

1 Introduction

Randomly sampling paddy to test for hulling and polishing is a method to analyze the quality of rice using small devices that simulate the actual working process of a rice mill. The milled rice obtained from these processes was separated into whole grain and head rice and then calculated as a percentage of rice milling quality (Thai Agricultural Standard, 2017). The paddy with a high milling quality is considered a fine-quality paddy for milling because there will be more whole grain and head rice compared to the paddy with a low rice gram percentage (Bodie et al., 2019). A rice separator is a machine used in the last step of analyzing the rice milling quality that serves to separate broken kernels from whole kernels. If the machine is not properly used, the ability to separate rice is lower, and the resultant data will be inaccurate. Several studies have investigated the efficiency of rice separators, with Lee et al. (2009) identifying optimal ranges for cylinder speed, receiving trough angle, and feed rate (30-35 rpm, 30 °-40 °, and 6 kg h^{-1}, respectively). Tawfik et al. (2011) found optimal performance within similar ranges (30–35 rpm, 30 °–

Received date: 2023-07-04 **Accepted date:** 2023-10-19

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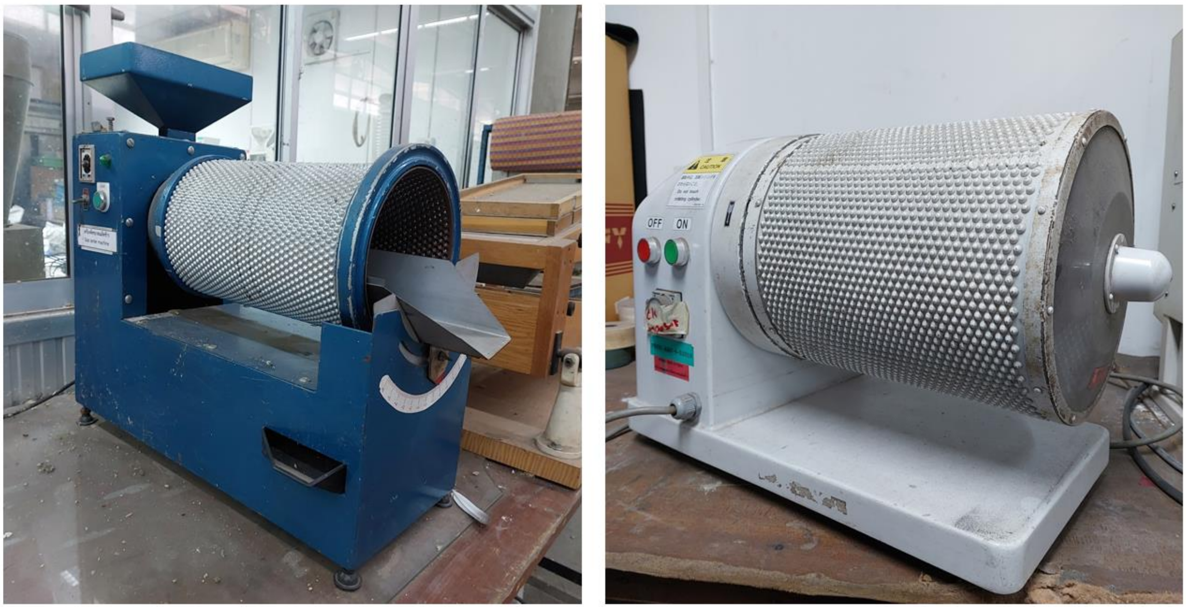
40°, and 6 kg h^{-1}). Kim and Park (2013) highlight the significant impact of trough angle and cylinder speed on separation efficiency. Meng et al. (2019) determined optimal operating conditions and trough position for rice separation using the discrete element method and then addressed low separation efficiency through baffle simulations and the intercriteria correlation (CRITIC) method (Meng et al., 2022). Hao et al. (2023) investigated radial segregation of rice and explored multi-component mixture segregation, and Yu et al. (2023) studied motion characteristics of rice particles and determined optimum parameters for indented cylinder separators. The above research indicated that the efficiency of rice separators depended on many factors. Therefore, setting the separator at optimum conditions must be adjusted for rice varieties and types of separators. In Thailand, there are two main types of small rice indented cylinder separators used for testing the quality of milled rice: continuous separators (Figure 1a) and non-continuous separators (Figure 1b). The non-continuous type is the most common, particularly in experimental research. As a result, there is a wealth of literature and information available that provides guidance on configuring the machine to achieve optimal efficiency. On the other hand, the efficiency of continuous rice separators has not been extensively studied. However, these separators are widely employed by paddy merchants across the country to assess the milling quality due to their simple and straightforward operation. The configuration of these separators varies based on the user's experience and understanding. Consequently, government offices responsible for ensuring rice quality face challenges related to the accuracy of rice quality assessment and a lack of confidence in the capabilities of the machines. This research focuses on investigating and determining the optimal conditions for continuous rice separators, aiming to establish a standardized configuration applicable to the commercial rice trading process.



(a) continuous type (b) non-continuous type

Figure 1 The indented cylinder separator cylinder commonly used in Thailand for the quality analysis of milled rice is of two types

2 Materials and methods

2.1 The continuous-indented cylinder separator

This separator is a machine for separating broken milled rice from whole rice grain in the final step of calculating milling quality, especially in the commercial rice trading process. The separator specification is shown in Figure 2 and contains the key components of the machine, which consist of a feed hopper, a cylinder sieve, a broken-rice receiver, a whole rice container, an electric motor, a machine leveling point to adjust the slope of the separator, and an operational timer. An unremovable cylinder sieve is 470 millimeters long with a 200 mm diameter and 5.7 mm sieve holes. Operational time can be set for the separator to operate for a maximum of 3 minutes. During operation, the sieve will rotate at a constant speed of 28.4 rpm (0.29 m s^{-1}). The slope of the machine and sieve can be adjusted by about 1-2 degrees. The angle of the broken rice receiver can be adjusted at 11 levels on a -5 to +5 scale. By adjusting the scale by +/-1, the angle of the broken rice receiver will incline by +/-5 degrees (Figure 3). To be operational, the slopes of the sieve and broken-rice receiver must be set first. After switching on, the electric motor will supply power to drive the separating sieve to rotate, and then paddy in the feed hopper will flow through the sieve. Whole rice grains will flow through the sieve and fall into the container, while broken rice will get stuck in the holes of the sieve. When the sieve rotates to the point that the angles of the holes reach an optimum angle, broken rice will fall from the holes to the broken rice receiver and flow to the outlet. Figure 4 illustrates the operation of the separator.

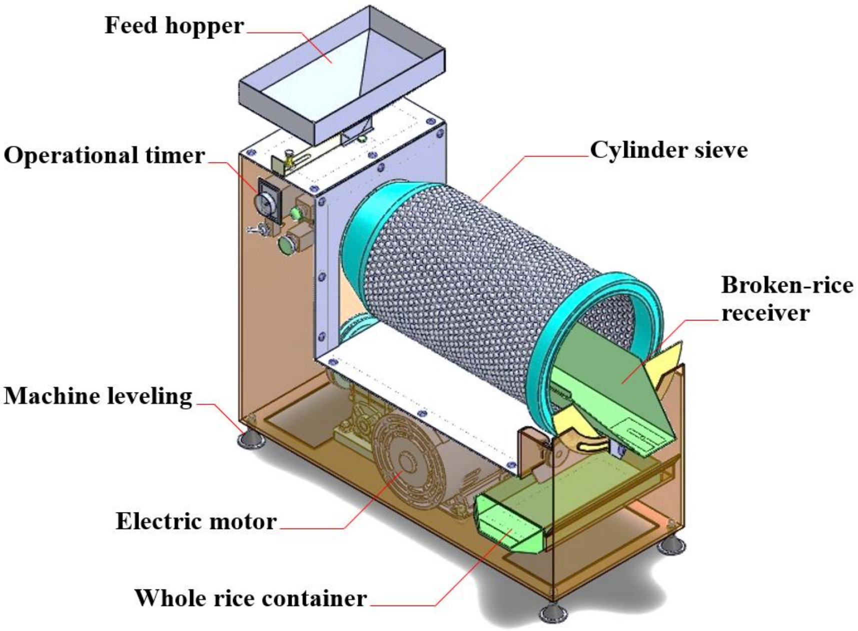
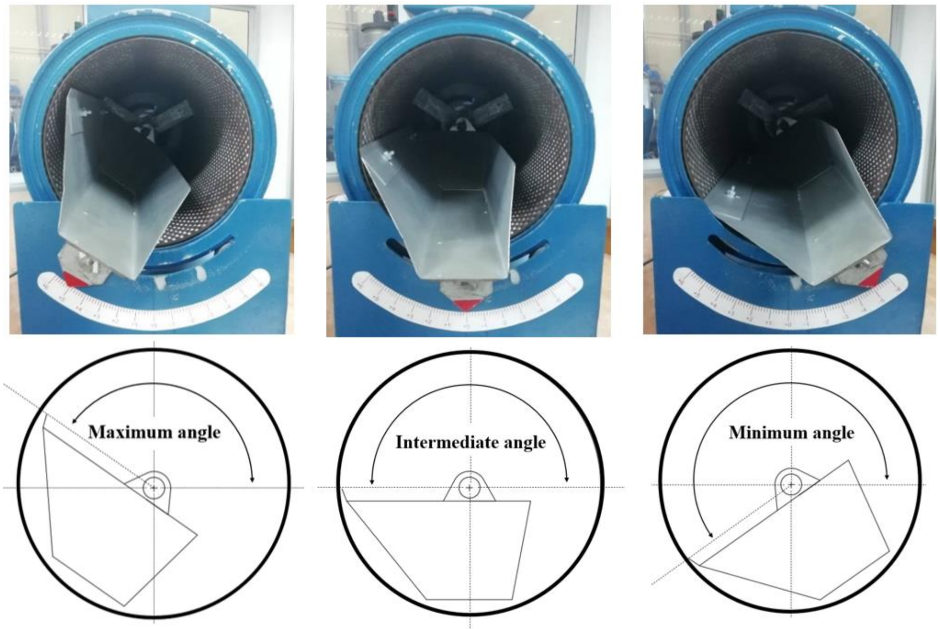


Figure 2 The main components of a continuous rice separator



Adjust the angle to the "+" direction.
Maximum scale: +5

Intermediate scale: 0

Adjust the angle to the "-" direction.
Minimum scale: -5

Figure 3 The angle of the broken-rice receiver from the highest to the lowest position

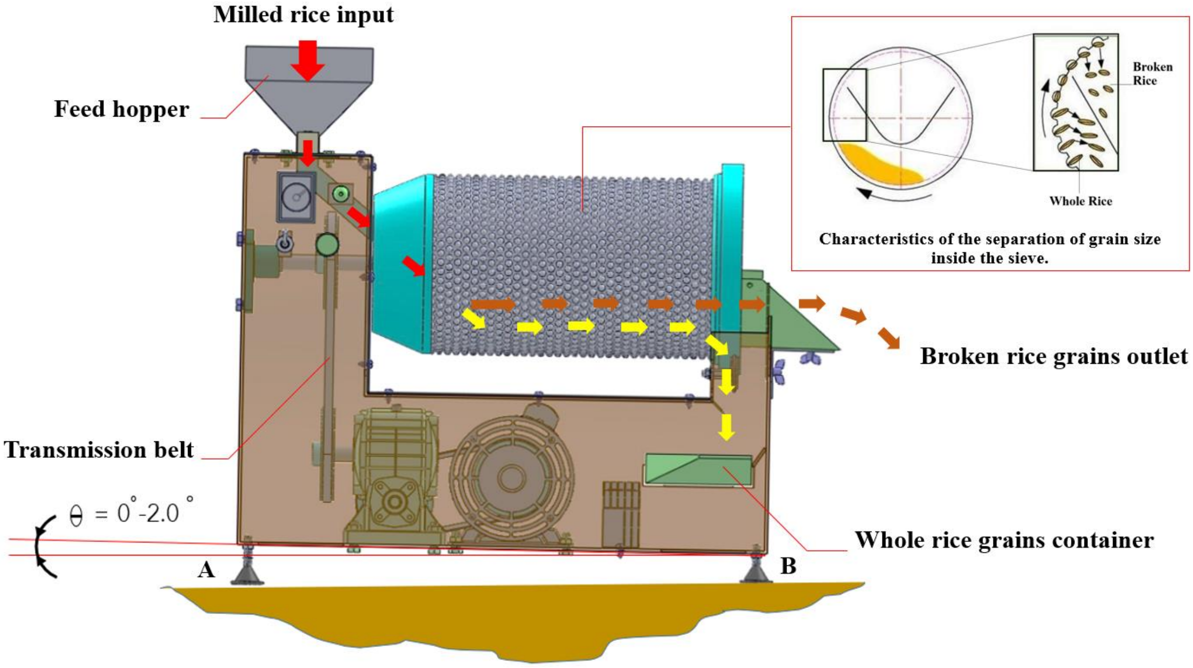


Figure 4 The operational principle of the studied continuous rice separator

2.2 Experimental design

This research utilized a Box-Behnken design (BBD) with three center points to investigate the relationship between machine settings and sorting efficiency. The key factors examined in relation to machine performance were the sieve slope, the angle of the broken-rice receiver (or trough angle), and sorting duration. Each of these factors was tested at three different levels. The slope of the sieve was tested at three angles: 1, 1.5, and 2 degrees. Trough angle was tested at +5, 0, and -5 levels. The sorting duration was tested for three different durations (60, 90, and 120 seconds). To represent the varying levels of each factor, variable codes were assigned. The codes +1, 0, and -1 were used to denote the maximum, medium, and minimum values of each studied factor, respectively. Table 1 shows a detailed overview of the variable codes and their corresponding factor levels.

Table 1 Variable code and actual value of the studied factors

Studied factors	Variable	Level and value codes		
		Minimum (-1)	Medium (0)	Maximum (+1)
Sieve slope (degree)	A	1	1.5	2
Trough angle (scale)	B	-5	0	+5
Sorting duration (seconds)	C	60	90	120

2.3 Material preparation

A rice of the Khao Dawk Mali 105 variety (KDML105), obtained from the Rice Research Center under the Ministry of Agriculture and Co-operatives and the Rice Science Center at Khon Kaen Province, was used as a sample in this research. The rice samples were analyzed for moisture at 103±1 degrees Celsius for 72 hours (Attaviroj and Noomhorm, 2014). The average moisture content was found to be 13.7% (wet basis). The rice samples were then separated from adulteration matter and husked by husking rollers (THU-35B, Satake Engineering Co., Ltd., Tokyo, Japan), with a distance between the rollers set at 0.7 mm. The husked rice was then milled by a milling machine (TM05C, Satake Engineering Co., Ltd., Tokyo, Japan) for 150 seconds. The milled rice was then separated by a rice separating machine, as shown in Figure 5. A sieve with a hole size of 6.0 mm was used to separate the rice into two parts. The first part was full-grained rice with at least 6.0 mm of length, and the other was broken rice, which was shorter than 6.0 mm (Rerkasem, 2017; Sreethong et al., 2018). Both types of rice were then weighted for 50 grams and mixed as a sample of 100 grams for further study. A total of 15 samples were prepared for studying the optimum condition of the rice separator, and another 10 samples of 100 g rice were also prepared with the same method to confirm the study results.

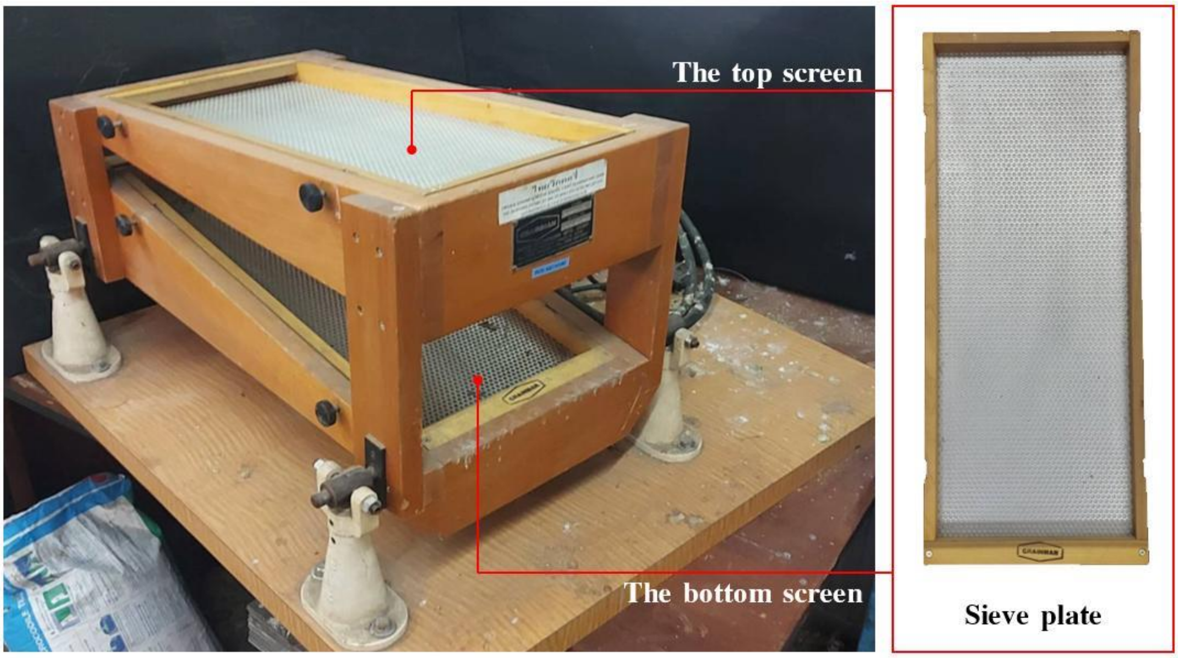


Figure 5 Rice sizing device

2.4 Methods

The separator was set according to the experimental design. After running, a sample of milled rice was poured into the feed hopper while the machine was operating. When the separation process was finished, the milled rice was separated into whole rice and broken rice. The separated rice was weighed and checked. The whole rice and broken rice were manually separated once again. After removing the broken rice from the obtained whole rice, the remaining whole rice was weighed, and the data was recoded. Likewise, after removing the whole rice, the remaining broken rice was weighted, and the data was recorded. The data was calculated for responsive indicators, namely loss and sorting efficiency, from Equations 1 and 2, respectively (Kim and Park, 2013; Meng et al., 2022; Tawfik et al., 2011).

$$Loss = \frac{(W_{in} + B_{in}) - (W_{out} + B_{out})}{W_{in} + B_{in}} \times 100 \qquad (1)$$

$$Sorting\ efficiency = \left(\frac{W_{out}}{W_{in}} \times \frac{B_{out}}{B_{in}} \times \frac{W_{net}}{W_{in}} \times \frac{B_{net}}{B_{in}} \right) \qquad (2)$$

Where, W_{in} is the initial weight of whole rice in the sample (g). W_{out} is the total weight of rice in the outlet of whole rice. W_{net} is the net weight of whole rice after removing the broken rice. B_{in} is the initial weight of broken rice in a sample. B_{out} is the total weight of rice in the outlet of broken rice. B_{net} is the net weight of the broken rice outlet after removing the whole rice.

The experimental results were analyzed for correlation between the factors that responded to indicators through a regression model. The relationship between the factors and indicators was presented in a quadratic equation given by Tran and Nguyen (2023), as shown in Equation 3. The regression model was then analyzed to identify the optimal condition of each factor using the response surface method (RSM). After the optimum conditions were identified, the test was repeated with ten new samples of rice to confirm the result by adjusting the separator to the optimum conditions. Then the data from the new sample experiment was compared with the predicted results with a t-test.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_{jj}^{2} + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} X_i X_j \qquad (3)$$

Where, Y is the predicted indicator. X_i and X_j represent the factors that were tested. β_0 is the constant term, β_i represents the coefficient of linear regression term, β_{ii} represents the coefficient of quadratic regression term, and β_{ij} represents the coefficient of the interaction between factors. The variable *k* represents the number of factors that were tested.

3 Results and discussion

3.1 The results and normality test

In an experiment with a rice separator with BBD, there were 15 treatments with two responsive values, namely loss and sorting efficiency. Results indicated that loss in separation ranged between 0.52% and 11.08%, while sorting efficiency was 72.85% to 97.25% (Table 2). The normality testing results of the experimental model, considering the normal probability plot, residual versus order plot, and residual versus fits plot as shown in Figure 6, showed that the distribution of the sorting loss and sorting efficiency data tends to be linear, so the data is normally distributed. The residual was pattern-less, which indicated that the data were freely distributed. As for variance stability, it is characterized by a balance above and below the zero line, which indicates that the data is stable (Shrivastava and Singh, 2021; Sultana et al., 2020) . From the above information, it can be concluded that the data is normally distributed, independent, and stable, which will have a positive effect on regression modeling with high testing authority (Purnomo et al., 2023).

Table 2 Experimental results

Run	Sieve slope (A) (degree)		Trough angle (B) (scale)		Sorting duration (C) (second)		Loss (%)	Sorting efficiency (%)
	Actual	Code	Actual	Code	Actual	Code		
1	1.5	0	-5	-1	120	1	6.35	82.78
2	2.0	1	-5	-1	90	0	2.63	83.25
3	2.0	1	0	0	120	1	0.52	97.25
4	1.0	-1	0	0	60	-1	9.75	79.05
5	2.0	1	0	0	60	-1	0.75	89.38
6	1.5	0	0	0	90	0	2.05	82.75
7	1.0	-1	-5	-1	90	0	11.08	72.85
8	1.0	-1	5	1	90	0	10.72	74.35
9	2.0	1	5	1	90	0	3.75	90.51
10	1.5	0	5	1	120	1	7.75	86.46
11	1.0	-1	0	0	120	1	7.01	81.72
12	1.5	0	0	0	90	0	1.86	84.85
13	1.5	0	0	0	90	0	1.55	84.15
14	1.5	0	-5	-1	60	-1	8.44	77.36
15	1.5	0	5	1	60	-1	9.16	79.44

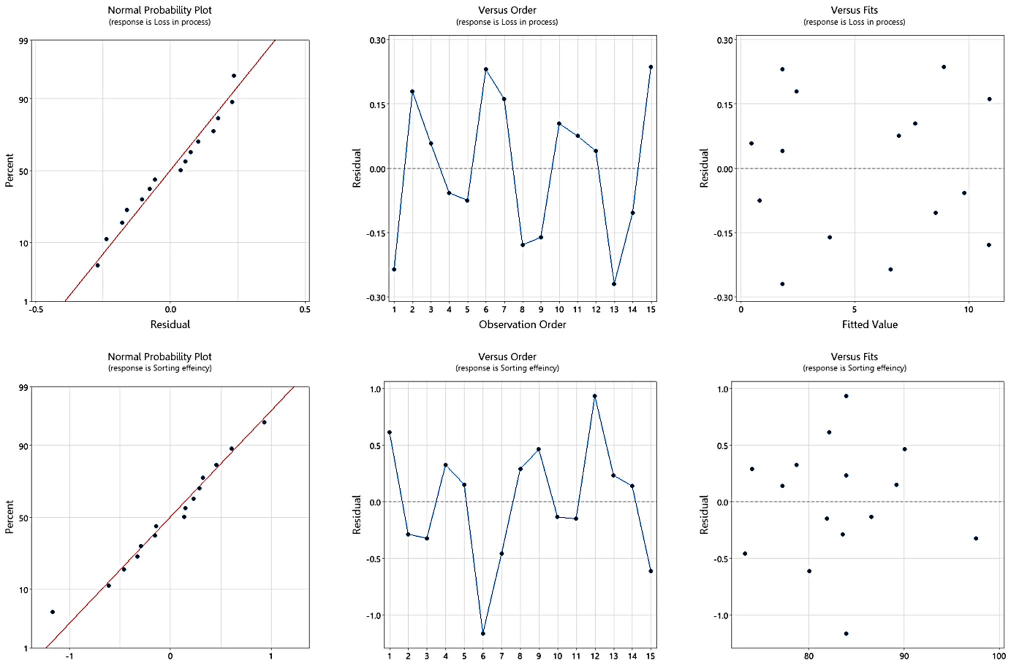


Figure 6 The results of evaluating the validity of the experimental design

3.2 Regression models and reliability

Regression analysis was employed to examine the relationship between the three factors under study and the two response indicators, with a confidence level of 95%. The results of this analysis are presented in Table 3. Based on the analysis results, quadratic equations (Equations 4 and 5) can be employed to model this relationship in terms of factor codes. The determination coefficient (R^2) and adjusted determination coefficient (Adj. R^2) of both equations were found to be close to 1, indicating a strong fit between the model and the data. The predictive determination coefficient (Pred. R^2) of both equations shows a minor difference from the Adj. R^2 value, suggesting that the mathematical model is adequate, and the data supports its sufficiency (Mueanmas, 2022). These indicate that the model can effectively estimate the values of the response indicators (Qu et al., 2020; Sakthivel et al., 2019).

Table 3 Analysis of the regression model of loss percentage and sorting efficiency

Term	Loss (%)				Sorting efficiency (%)			
	Coeff	SE Coeff	T-Value	P-Value	Coeff	SE Coeff	T-Value	P-Value
Constant	1.820	0.162	11.230	0.000	83.917	0.511	164.160	0.000
Sieve Slope (A)	-3.864	0.099	-38.910	0.000	6.552	0.313	20.930	0.000
Trough Angle (B)	0.360	0.099	3.630	0.015	1.814	0.313	5.800	0.002
Operation Time (C)	-0.809	0.099	-8.150	0.000	2.873	0.313	9.180	0.000
A*A	0.904	0.146	6.180	0.002	0.831	0.461	1.800	0.131
B*B	4.321	0.146	29.570	0.000	-4.509	0.461	-9.790	0.000
C*C	1.784	0.146	12.210	0.000	2.102	0.461	4.560	0.006
A*B	0.370	0.140	2.640	0.046	1.439	0.443	3.250	0.023
A*C	0.628	0.140	4.470	0.007	1.300	0.443	2.940	0.032
B*C	0.170	0.140	1.210	0.280	0.400	0.443	0.900	0.408
S / R^2	0.2808/ 99.81%				0.8854/ 99.30%			
Adj. R^2 / Pred. R^2	99.46% / 97.79%				98.03%/ 94.38%			

$$Loss = 1.820 - 3.8638\,A + 0.3600\,B - 0.8088\,C + 0.904\,A\times A + 4.321\,B\times B + 1.784\,C\times C + 0.370\,A\times B + 0.628\,A\times C + 0.170\,B\times C \tag{4}$$

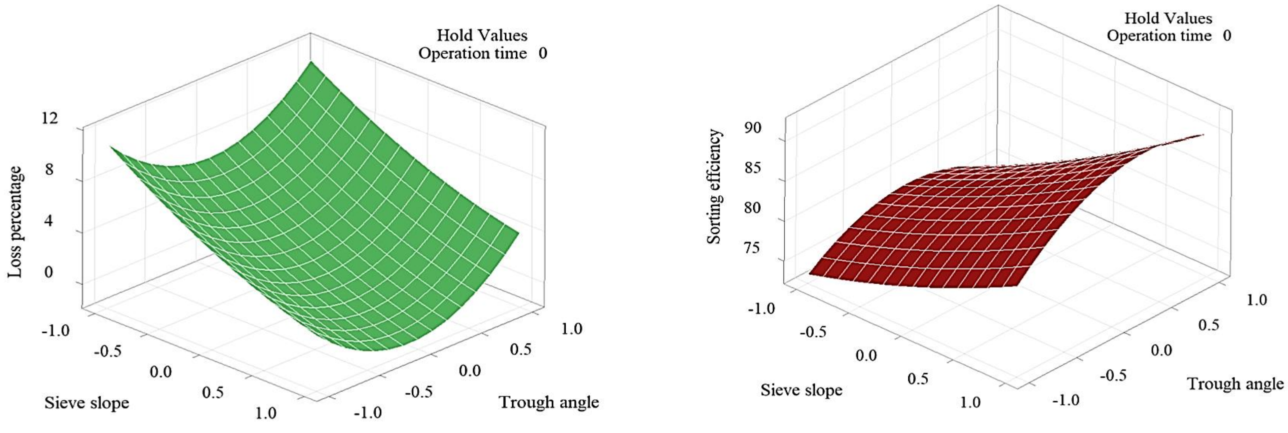
$$Sorting\ efficiency = 83.917 + 6.552\,A + 1.814\,B + 2.873\,C + 0.831\,A\times A - 4.509\,B\times B + 2.102\,C\times C + 1.439\,A\times B + 1.300\,A\times C + 0.400\,B\times C \tag{5}$$

From the variance analysis of Equations 4 and 5, whose details are shown in Table 4, it was found that the loss prediction equation and the efficiency prediction equation had a p-value of the model equal to zero, indicating that both equations ability to explain the relationship between the studied factors and the predicted outcome values was significant (Jambo et al., 2019). When considering the influence of the main variable (Linear), which consists of sieve slope (A), trough angle (B), and sorting duration (C), It was found that all variables significantly influenced the predicted values in the predicted results of both equations. In terms of squared variables, it is found that every term of the squared variable in both equations influences the predicted result value. For the interaction variable terms of both equations, only the A*B term and the A*C term significantly influence the predicted value ($p < 0.05$), but the B*C term has no influence on the predicted value. When considering the lack of fit of both equations, it was found that the p-value was 0.443 and 0.731, respectively, which shows that the lack of fit was greater than 0.05, which shows that both equations were tested appropriately and that the prediction results were reliable. It can be used to predict the sorting loss and sorting efficiency appropriately.

The response surface plot was created to illustrate the relationship between the studied factors and two respondent indicators from the equation predicting loss and sorting efficiency. The analysis of the relationship between various factors and each indicator found that higher sieve slopes, when combined with a nearest 0 angle of trough angle, resulted in a reduction in loss percentage and an increase in sorting efficiency (Figures 7a and 7b). Likewise, a high sieve slope along with a longer sorting duration (Figures 7c and 7d) contribute to a similar effect. Moreover, when the trough angle is close to zero and the sorting duration is extended (Figures 7e and 7f), the percentage of loss is further reduced, and the sorting efficiency is further improved. Another significant observation is that a very low slope of the sieve results in a slower flow of rice, causing some rice to become trapped in the sieve, leading to a higher loss percentage. On the other hand, when the trough angle is set to a very low value, a significant amount of whole rice is mixed with broken rice. Conversely, if the angle is too high, the separation of broken rice from whole rice is less effective, resulting in lower sorting efficiency. Regarding the sorting duration, the grains within the sieve are tightly packed and overlap each other at low sorting times, negatively impacting the separating efficiency. Conversely, increasing the sorting duration gives the grains more time to separate properly, leading to improved sorting efficiency and a reduced percentage of loss. In conclusion, the method for improving the efficiency of the rice separator should be to set a sorting sieve with high slopes, set the trough angle close to zero, and extend the sorting duration. This can significantly enhance rice separation by reducing loss and increasing sorting efficiency.

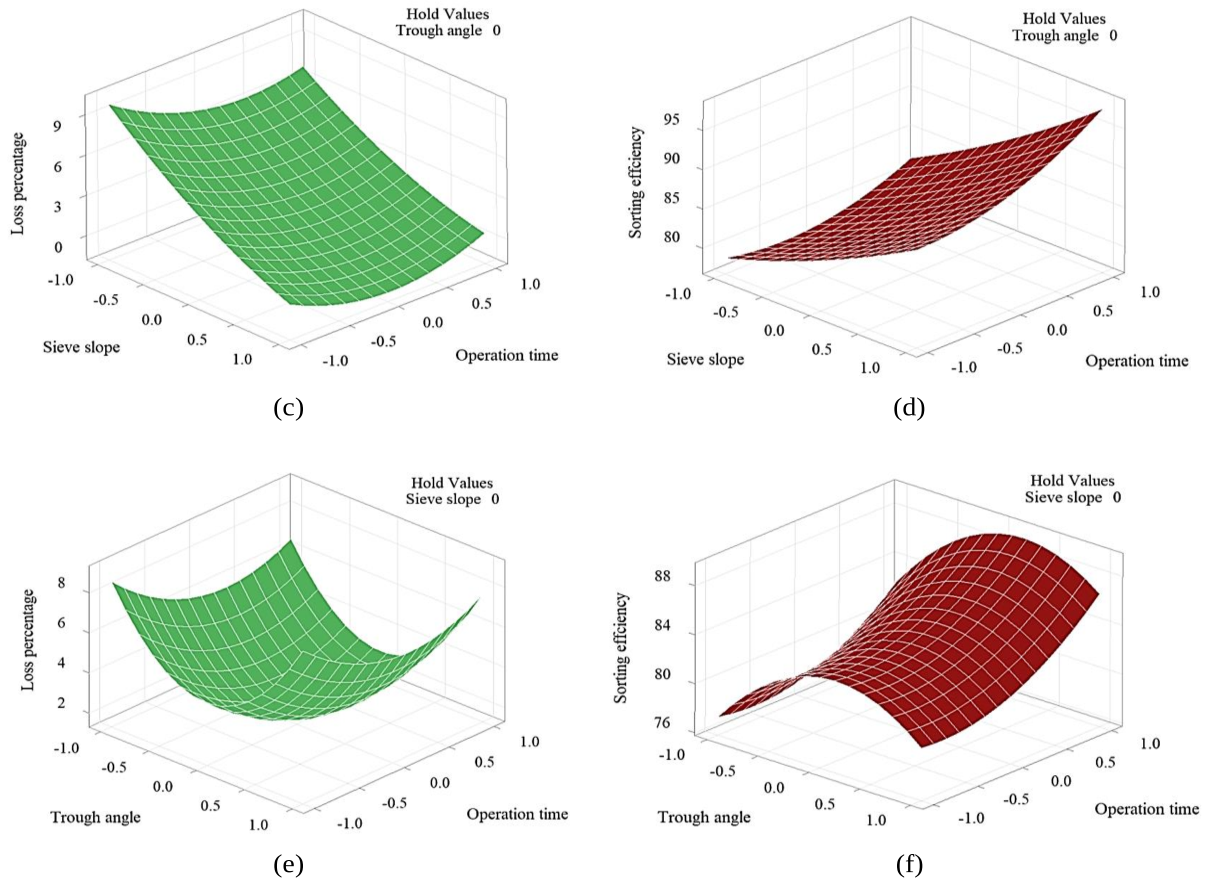
Table 4 An analysis of variance in the loss and sorting efficiency equations

Source	df	Loss (%)				Sorting efficiency (%)			
		Adj SS	Adj MS	F-Value	P-Value	Adj SS	Adj MS	F-Value	P-Value
Model	9	205.524	22.836	289.560	0.000	552.544	61.394	78.320	0.000
Linear	3	125.698	41.899	531.280	0.000	435.762	145.254	185.290	0.000
Sieve slope (A)	1	119.429	119.429	1514.340	0.000	343.417	343.417	438.080	0.000
Trough angle (B)	1	1.037	1.037	13.150	0.015	26.336	26.336	33.600	0.002
Operation time (C)	1	5.233	5.233	66.350	0.000	66.010	66.010	84.210	0.000
Square	3	77.588	25.863	327.930	0.000	101.102	33.701	42.990	0.001
A*A	1	3.016	3.016	38.240	0.002	2.550	2.550	3.250	0.131
B*A	1	68.947	68.947	874.240	0.000	75.067	75.067	95.760	0.000
C*C	1	11.748	11.748	148.960	0.000	16.319	16.319	20.820	0.006
2-Way Interaction	3	2.238	0.746	9.460	0.017	15.680	5.227	6.670	0.034
A*B	1	0.548	0.548	6.940	0.046	8.280	8.280	10.560	0.023
A*C	1	1.575	1.575	19.970	0.007	6.760	6.760	8.620	0.032
B*C	1	0.116	0.116	1.470	0.280	0.640	0.640	0.820	0.408
Error	5	0.394	0.079			3.920	0.784		
Lack-of-Fit	3	0.267	0.089	1.400	0.443	1.633	0.544	0.480	0.731
Pure Error	2	0.127	0.064			2.287	1.143		
Total	14	205.918				556.464			



(a) (b)

Figure 7 Response surface plot of the studied factors and the indicators



(c) (d)

(e) (f)

3.3 The optimum conditions

An analysis was conducted to determine the optimal conditions for the continuous-type indented cylinder separator. The objective was to identify the suitable sieve slope, trough angle, and sorting duration that would minimize the loss of rice and maximize the effectiveness of rice separation. The evaluation utilized the composite desirability score, which ranged from 0 to 1. A score of 1 indicated the optimal desired outcome (Ozkan et al., 2023). The analysis was conducted using Minitab's version 20 and the "Response Optimizer" function. Based on the analysis results (Table 5), it was determined that a specific condition yielded a composite desirability of 1.00, indicating the highest level of desirability. This condition involved a sieve slope at level +1 (equivalent to a 2-degree slope), a trough angle at a scale of -0.1 (corresponding to the -0.5 scale of the broken rice receiver), and a sorting duration at level +1 (equivalent to 120 seconds). This optimized condition resulted in a low loss rate of 0.42% and a sorting efficiency of 97.29%.

Table 5 The results of the optimum condition analysis

Response	Goal	Lower	Target	Upper	Weight	Importance
Sorting efficiency	Maximum	72.85	97.25		1	1
Loss	Minimum		0.52	11.08	1	1
		Code	Actual			
Solution	A=Sieve slope	1.0	2.0	degree		
	B=Trough angle	-0.1	-0.5	scale		
	C=Operation time	1.0	120.0	second		
Predicted response	Separation efficiency	97.29	Desirability	1		
	Loss in process	0.42	Desirability	1		
Composite desirability	1					

3.4 Validation of the optimal condition

To validate the results obtained from the optimization analysis, the indented cylinder separator was adjusted to the optimum condition, and 10 sets of rice samples were subjected to separation tests. A t-test was conducted to compare the actual results with the predictions. The hypothesis (H_0) was formulated for the predicted value of sorting efficiency from the optimization analysis, assuming a mean of 97.29% (μ = 97.29), and another hypothesis (H_0) was established for the predicted loss, assuming a mean of 0.42% (μ = 0.42). The validation process revealed that the average sorting efficiency during validation was determined to be 97.10%±0.53%, deviating from the predicted value by 0.19% with a *p*-value of 0.307. Similarly, the mean loss was calculated as 0.41%±0.18%, differing from the predicted value by 0.01% with a p-value of 0.922. In both cases, the *p*-values exceeded 0.05, indicating that the hypotheses were acceptable. These results suggest that, at a 95% confidence interval, the results obtained from the actual experiment did not significantly deviate from the results predicted by the regression models. Consequently, the optimum condition derived from this study can be practically implemented in continuous-type indented cylinder separator.

4 Conclusions

A study was conducted to determine the optimal settings for a continuous type of indented cylinder rice separator. The study involved testing rice separation using different levels of sieve slope, trough angle, and sorting duration. The results showed that a loss of 0.52%-11.08% of rice occurred during the process, resulting in a sorting efficiency range of 72.85%-97.25%. To analyze the data, a regression equation was developed, and the response surface technique was used to determine the optimum conditions for each factor. The analysis revealed that the sieve slope should be set at 2 degrees, the trough angle should be adjusted to -0.1, and the sorting duration should be 120 seconds. These settings were found to minimize loss at 0.42% and maximize efficiency at 97.29%. To validate the findings, the machine was configured according to the suggested optimal conditions from the analysis. The results of the validation experiment closely matched the predicted values, confirming that the optimum conditions identified in this study can be effectively applied to a continuous type of indented cylinder rice separator.

Acknowledgements

This research was supported by the Fundamental Fund of Khon Kean University, under the National Science, Research and Innovation Fund (NSRF), and the authors gratefully acknowledge the Postharvest Technology Innovation Center, Science Research and Innovation Promotion and Utilization Division, Office of the Ministry of Higher Education, Thailand. The Agricultural Machinery and Postharvest Technology Center and Department of Agricultural Engineering, Khon Kaen University, Thailand, provided support for all the facilitation in this study.

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