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Optimization of Operational Parameters on Harvesting Efficiency of Lathyrus Harvester Using Response Surface Methodology

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Lathyrus crop [*Lathyrus sativus* (L.)] or grass pea is the third most important cool-season pulse crop of India, occupying an area of 0.58 million ha with an annual production of 0.43 million tonnes. The productivity is fluctuates between 369 to 605kg/ha. Traditionally, farmers harvest lathyrus by either hand-pulling or using a sickle, methods that are labor-intensive, time-consuming, and cause significant discomfort to farmers. Till date, the traditional method (manually hand plucking/sickle) is the prevailing practice in Chhattisgarh. Due to rising labor costs, labor scarcity during peak seasons, and unpredictable weather, manual harvesting has become uneconomical. There is an urgent need of introducing modern practices for harvesting of the crop. Traditional testing and statistical analysis methods used in most existing studies are limited by complex test processes,

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their time-consuming nature, high costs, and poor prediction accuracy. To address these problems Response surface methodology (RSM) was used for optimizing the performance parameters. Effects of various parameters viz. reel speed, cutter bar speed and height of cut which is considered as the heart of harvesting machine was evaluated to get optimum harvesting efficiency of developed tractor operated lathyrus harvester. The optimum harvesting efficiency of 90% was found at 30 mm height of cut, 250 rpm cutter bar speed and 12.5 rpm respectively.

Keywords: Grass pea; harvesting efficiency; mechanization; response surface methodology.

1. INTRODUCTION

The grass pea [*Lathyrus sativus* (L.)] commonly known as *khesari* and*teora* is a food and fodder crop belonging to the family Leguminosae (Fabaceae). The cultivation of grass peas dates back to about 6000 BC and It contains 31.9% protein (almost having twice the protein in wheat and thrice that of rice), 0.9% fat, 53.9% carbohydrate, 362.3 cal energy (Kuo *et al.,* 2000). Grass pea when compared to other legume crops found to have high yielding potential at low or zero levels of fertilization rate [1]. Some of the tremendous features of lathyrus crop are-high protein content, a high level of adaptation to harsh environments, are disease resistant, and require little input to grow. It does not require irrigation or the application of harmful fertilizers or pesticides. It is a self-protective crop. Grass pea is also known as the most profitable crop because it has the highest productivity of all pulses at about 2.5 tons per hectare. In comparison to all other edible pulses, it is also the cheapest pulse grown in the country. The harvesting of grass pea is done when plant gets hard and changes colour from green to brownish. Indian agriculture witnessed unprecedented growth in farm mechanization. Mechanization conjointly helps in improving the utilization efficiency of other inputs, safety and comfort of the agricultural worker, enhancement within the quality and value addition of the produce. This shortage of unskilled labour also necessitates the development of appropriate machines to reduce dependence on manual labour.

Response Surface Methodology (RSM) is statistical analysis method extensively employed for optimizing performance parameters of an agricultural machine. It serves as a valuable tool in enhancing processes and systems by systematically adjusting factors to achieve optimal outcomes. This method reduces the number of experiment to be conducted to optimize the independent variable for the optimum performance of the machine. Myers *et al.,*[2] stated that the response surface methodology (RSM) is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes. It also had important applications in the design, development, and formulation of new products, as well as in the improvement of existing product designs.

"Response surface methodology (RSM) is an advanced mathematical and statistical tool used to evaluate the relationship between the output responses and the multiple independent input variables. It can also optimize these variables to achieve the best responses" Taoufik et al. [3]. It was used successfully by many scientists for optimization of different parameters for different operations (Ushakumari *et al*., [4,1] (Tiwari *et al.,* 2013). Mechanization of grass pea harvesting using machines optimized through (RSM) will significantly improve harvesting efficiency, reduce labor requirements, and increase crop yield compared to traditional manual harvesting methods. The main objectives of this study are as follows: (1) To determine the optimized operating parameters of the header(reel and cutter bar) of the lathyrus harvester; (2) To analyze the influence of each factor and its interaction on harvesting efficiency and loss rate; (3) To develop the predicting models for the header performance of the lathyrus harvester. This study overcomes the limitations of traditional methods and can provide data and method references for the design, optimization, prediction, and intelligent fault diagnosis of the operation parameters of agricultural machinery.

2. MATERIALS AND METHODS

2.1 General Description

This section deals with the details of materials, methods employed and equipment used over the span of study. Based on the knowledge gathered from the literature cited, experiment planning, crop characteristics (structure, agronomical practices etc) and data picked during harvesting at different location of Chhattisgarh, the conceptual design of tractor operated lathyrus harvester was developed using CATIA software. The field testing of the developed machine was carried at Research cum Instructional Farm, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh. In order to optimize the crop, machine and operational parameters, Response Surface Methodology (RSM) was used.

2.2 Optimization Method using RSM

The experiment was carried out by using second order polynomial equation in Central Composite Rotatable Design (CCRD). The three independent variable were selected i.e. reel speed, cutter bar speed and height of cut with selected dependent variable harvesting efficiency. Table 1 illustrates the description of the independent variables with response.

As per the CCRD design the selected four and five levels of each independent variable needs to be converted into coded variables. The selected five levels of coded variables in the design were -1.68, -1, 0, +1 and +1.68 [2]. The conversion of natural variables to the coded values was accomplished by using equations 1 to 4. The details of converted CCRD experimental levels are presented in Table 2.

$$x_i = \frac{X_i - X_m}{X_D} \tag{1}$$

Where,

I = 1, 2, and 3

$$X_D = \frac{X_{max} - X_m}{a_m} \tag{2}$$

$$x_m = \frac{X_{max} - X_{min}}{2} \tag{3}$$

$$a_m = 2^{0.25k} \tag{4}$$

Where,

x_i = Coded value of the i[th] variable;
X_i = Actual value of the i[th]variable;
X_{max} = Maximum values of independent variables;
X_{min} = Minimum values of independent variables;
k = Number of independent variables considered for the optimization.

“Many factors affect the harvesting efficiency and loss rate of header operation. In fact, during the harvest, the operator usually controls the forward speed of the harvester and the cutting height based on their own experience, which can easily lead to broken pods, stalks of the plant and increase harvest loss. The uncut stalk is likely to wrap around the reel of harvester, resulting in blockage and increased energy consumption” Li *et al.,* [5]. This study selects the harvesting efficiency as the performance indexes of the reel, cutterbar and cutting height from ground level and the calculation method is thus:

2.3 Harvesting Efficiency

Number of lathyrus plants in 10 m length was counted before operation and the plants left in same 10 m length were counted after operation.

$$\text{Harvesting efficiency, \%} = \frac{W_1 - W_2}{W_1} \times 100 \tag{5}$$

Where,

W_1 = Number of plants before cutting; and
W_2 = Number of plants after cutting.

The following non linear second order regression equation 5 were developed for the independent variables in coded value to optimize the dependent parameter viz. harvesting efficiency.

$$\rho_e = b_0 + \sum_{i=0}^{3} b_i x_i + \sum_{i=1}^{3} b_{ii} x_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{3} b_{ij} x_i x_j \tag{6}$$

Where,
ρ= Harvesting efficiency,%

As per central composite rotatable design (CCRD), the different levels for each independent variable were fixed which gave the 20 experiments. The details of the 20 experiments are presented in Table 2.

Table 1. Details of coded and converted CCRD experimental levels

S. No.	Variables	Level 1 (-1.68)	Level 2 (-1)	Level 3 (0)	Level 4 (+1)	Level 5 (+1.68)
1.	Reel speed, rpm	10	12.5	15	17.5	-
2.	Cutter bar speed, rpm	225	250	275	300	-
3.	Height of cut, mm	10	20	30	40	50

Table 2. Experiment design for conducting the performance evaluation of the developed machine

Run	Reel speed, rpm	Cutter bar speed, rpm	Height of cut, mm
1	17.5	250	30
2	10	275	20
3	10	225	20
4	12.5	250	30
5	15	275	40
6	12.5	250	10
7	10	275	40
8	12.5	300	30
9	15	275	20
10	12.5	250	30
11	12.5	250	30
12	10	250	30
13	12.5	200	30
14	12.5	250	50
15	15	225	20
16	10	225	40
17	15	225	40
18	12.5	250	30
19	12.5	250	30
20	12.5	250	30

Fig. 1. Testing and performance evaluation of developed tractor operated lathyrus harvester at research farm, IGKV University, Raipur

3. RESULTS AND DISCUSSION

3.1 Effect of Reel Speed, Cutter Bar Speed and Height of Cut on Harvesting Efficiency

A CCRD experimental design was employed to evaluate the effects of reel speed, cutter bar speed, and height of cut on harvesting efficiency. The experimental data are tabulated in Table 3.

The analysis of variance (ANOVA) table for the effect of reel speed, cutter bar speed and height of cut on harvesting efficiency of developed harvester is represented in Table 4. The ANOVA table indicated F- value of model (56.99) suggesting the quadratic modelas well as linear model could be successfully used to fit experimental data (p <0.0001).

Table 3. Results on effect of reel speed, cutter bar speed and height of cut on harvesting efficiency

Run	Reel speed, rpm	Cutter bar speed, rpm	Height of cut, mm	Harvesting efficiency,%
1	17.5	250	30	89.45
2	10.0	275	20	92.00
3	10.0	225	20	89.60
4	12.5	250	30	90.00
5	15.0	275	40	90.84
6	12.5	250	10	91.50
7	10.0	275	40	90.25
8	12.5	300	30	92.49
9	15.0	275	20	92.54
10	12.5	250	30	90.00
11	12.5	250	30	90.00
12	10.0	250	30	89.89
13	12.5	200	30	88.95
14	12.5	250	50	88.68
15	15.0	225	20	89.60
16	10.0	225	40	88.75
17	15.0	225	40	88.26
18	12.5	250	30	90.00
19	12.5	250	30	90.00
20	12.5	250	30	90.00

Table 4. Analysis of variance (ANOVA) table for the on effect of reel speed, cutter bar speed and height of cut on harvesting efficiency

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	26.82	9	2.98	56.99	< 0.0001	Significant
R_S -reel speed	0.0124	1	0.0124	0.2367	0.6371	
C_S -cutter bar speed	17.02	1	17.02	325.38	< 0.0001	
H_C -height of cut	7.95	1	7.95	152.07	< 0.0001	
$R_S \times C_S$	0.3281	1	0.3281	6.27	0.0312	
$R_S \times H_C$	0.0242	1	0.0242	0.4628	0.5118	
$C_S \times H_C$	0.1985	1	0.1985	3.79	0.08	
R_S^2	0.1823	1	0.1823	3.49	0.0915	
C_S^2	0.9745	1	0.9745	18.63	0.0015	
H_C^2	0.0347	1	0.0347	0.6629	0.4345	
Residual	0.5229	10	0.0523			
Lack of Fit	0.5229	5	0.1046			Non-Significant
Pure Error	0	5	0			
Cor Total	27.35	19				

It was also observed based on the F-value for the linear term cutter bar speed, height of cut, and quadratic term of cutter bar speed had significant effect at 1 percent significance level on the harvesting efficiency ($p<0.0001$).The interaction term of reel speed and cutterbar speed, cutter bar speed and height of cut, and quadratic term of reel speed had significant effect on harvesting efficiency at 5 per cent level of significance. The other remaining terms i.e reel speed, interactive term of reel speed and height of cut, and quadratic term of height of cut had no significant effect on harvesting efficiency.

The predicted R^2 (0.8092) for thesemodel was also found to be in agreement with the value of adjusted R^2 (0.9637) i.e. the difference is less than 0.2, meaning that the predicted value of this model is very similar to the actual value and that the models have high statistical significance.

The variation of the harvesting efficiency (%) was represented by the regression equation 7with different independent variables i.e. reel speed, cutter bar speed and height of cut on harvesting efficiency. The accompanying information describe a mathematical model that predicts harvesting efficiency *(ΨE)* based on three key factors viz. reel speed, cutter bar speed and height of cut. The regression equation fitted in polynomial form is given below:

$$\Psi_E = +90.03 + 0.0343R_s + 1.03C_s - 0.050H_s + 0.2025R_s \times C_s - 0.0550R_s \times H_s - 0.1575CS \times H_s - 0.1181RS2Rs^2 + 0.1941Cs^2 + 0.0366Cs^2 \quad (7)$$

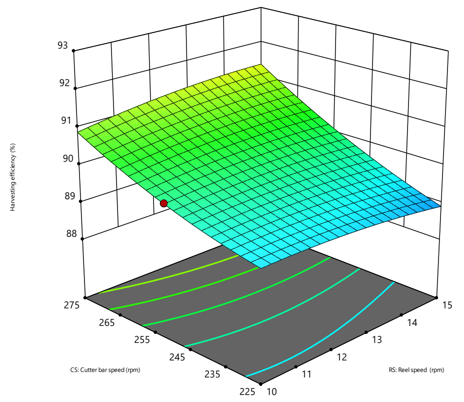

Fig. 2. Effect of reel speed and cutter bar speed on harvesting efficiency

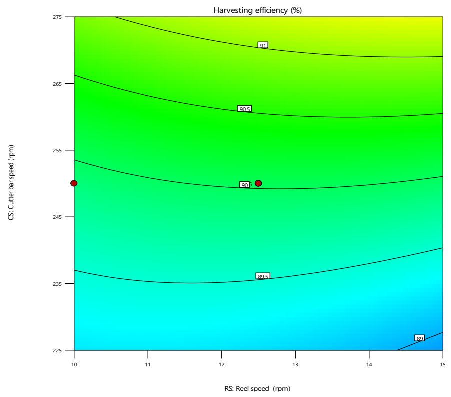

Fig. 3. Contour image on effect of reel speed and cutter bar speed on harvesting efficiency

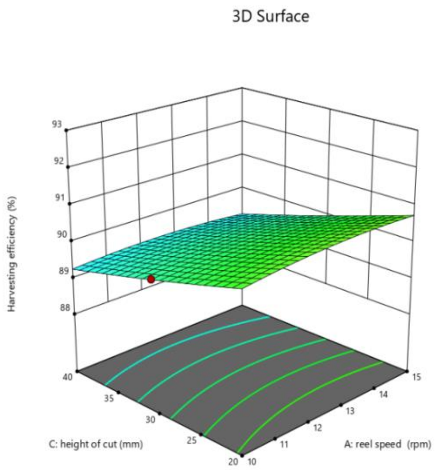

Fig. 4. Effect of reel speed and height of cut on harvesting efficiency

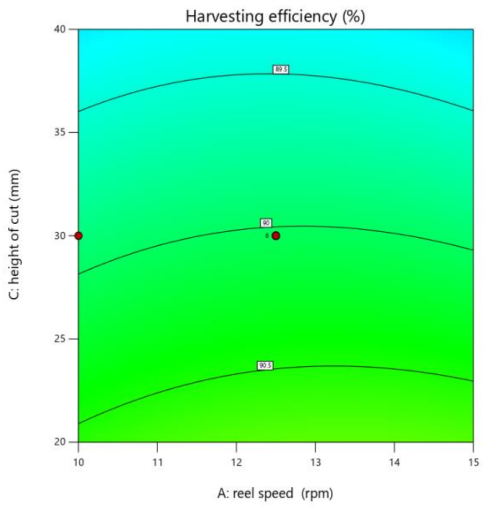

Fig. 5. Contour image on effect of reel speed and height of cut on harvesting efficiency

Where,

Ψ_E = Harvesting efficiency, %;
R_S = Reel speed, rpm;
CS = Cutter bar speed, rpm; and
HC =Height of cut, mm.

Other researchers also work on the same line like Liang *et al.*2017 developed a threshing model and found that combine performance could be improved by analyzing and optimizing the structure and variables of the threshing unit. Siska and Hurburgh (1994) developed the corn breakage prediction model using multiple linear regression techniques, with R^2 of 0.65. Additionally, Maertens et al. [6] Maertens and Baerdemaeker [7] and Miu and Kutzbach (2007) forecasted the characteristics of the material moving inside combine harvesters.

3.2 Effect of Reel Speed and Cutter Bar Speed on Harvesting Efficiency

The three dimensional graph depicting the effect of reel speed and cutter bar speed on harvesting efficiency is shown in Fig.2. It was concluded that the harvesting efficiency slightly decreased with increase in reel speed. The reason might be at higher level of reel index(and therefore higher reel rotational speed) reel fingers strongly hit to crop and lead to an increase in header loss. This result is consistent with the findings of Junsiri and Chinsuwan [8],Sangwijit and Chinsuwan [9]. It was also observed that by increasing cutter bar speed the harvesting efficiency was increased. Similar results were also concluded by Zareei et al., [10] for wheat harvester. The highest harvesting efficiency (92.54 %) was observed at 15 rpm reel speed and 275 rpm cutter bar speed. The contour of the effect of reel speed and cutter bar speed on harvesting efficiency is presented in Fig. 3. A decrceasing trend was also observed for the harvesting efficiency with the decrease in cutter bar speed. It might be due to availability of less opportunity time for cutter bar for cutting plants at lower cutter bar speed. A similar decreasing trend for was reported by Bhedaet al. [11] and Similar findings were also confirmed by Tanti et al. [12] Ogunlowo and Olaoye [13].

3.3 Effect of Reel Speed and Height of Cut on Harvesting Efficiency

The effect of reel speed and height of cut on harvesting efficiency was shown in Fig. 4. The data observed from the graph showed that the harvesting efficiency decreased with increase in reel speed as well as height of cut. The reason might be a higher reel speed can lead to more aggressive crop handling, resulting in increased shattering and loss of grains or pods. The crop might be subjected to excessive force, causing it to break and disperse. More over a higher cutting height can result in more crop being left unharvested in the field. This is particularly true for lodged or tangled crops, where a lower cutting height is necessary to capture the entire plant. These finding were also confirmed by Sun et al. (2020) and Lammari *et al.,* 2021 and Zami *et al.,* 2014 for other types of crops.

The highest harvesting efficiency (92.54 %) was observed 15 rpm reel speed and 20mm height of cut. The contour of the reel speed and height of cut on harvesting efficiency is presented in Fig. 5. Similar findings were obtained by Junsiri and Chinsuwan [8] showed that head grain loss increased with increase in reel rotational speed and reel height.

3.4 Effect of Cutter Bar Speed and Height of Cut on Harvesting Efficiency

The effect of cutter bar speed and height of cut on harvesting efficiency is shown in Fig. 6. It was found that both the factors affect the harvesting efficiency. The highest harvesting efficiency (92.54%) was observed at 275 rpm cutter bar speed and 20mm height of cut while the lowest harvesting efficiency (88.26%) was found at 225rpm cutter bar speed and 40mm height of cut. The probable reason for this may be the bending and skipping of short height plants at higher cutting height because the top portion of the plant (seed portion) has less bending strength. Similar observations were also reported by Pishgar-Komle et al. (2012) Bawatharani et al. [14] also reported that at increased cutter bar heights, crops with lower height cannot be cut by the cutter bar. The contour of the effect of effect of cutter bar speed and height of cut on harvesting efficiency was presented in Fig. 7.

"In order to optimize the harvester performance based on data and statistical analysis, this study used the desirability function method to numerically optimize the one responses, so as to obtain the best level of cutter bar speed, cutting height and reel speed, and minimize the harvesting efficiency Yolmeh *et al.,* [15] "The optimization method was proposed by Derringer and Suich, [16-18] and is widely used in the optimization of multi-response processes in industry. The optimization results show that the optimal parameter combination consists of the reel speed of 12.5 rpm, the cutting height of 30 mm, and cutter bar speed of 250 rpm. To verify the accuracy of the optimization results, a validation test was carried out under the optimal conditions. The actual values of harvesting efficiency were 90.17%, and the predicted values were 90%, which were in good agreement with the observed values. The above results verified that the developed RSM model could be effectively used to study or optimize the header performance of developed harvester" [19,20].

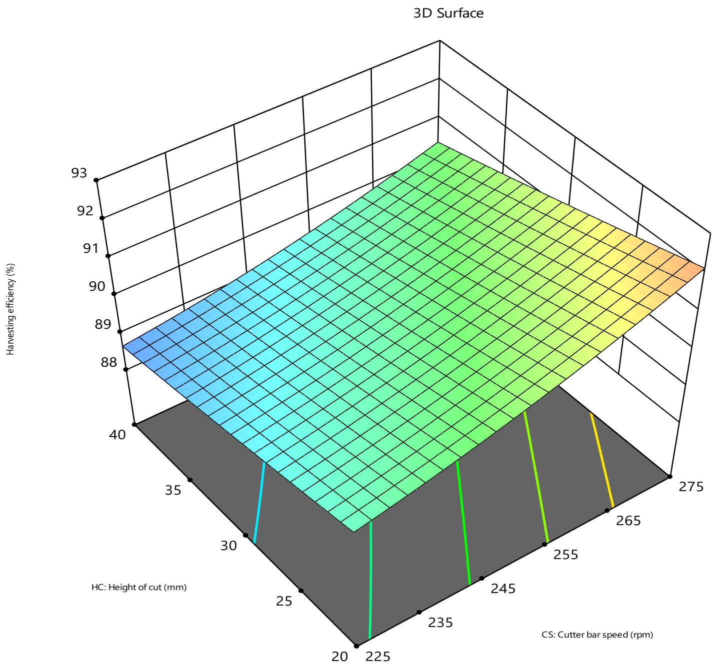

Fig. 6. Effect of cutter bar speed and height of cut on harvesting efficiency

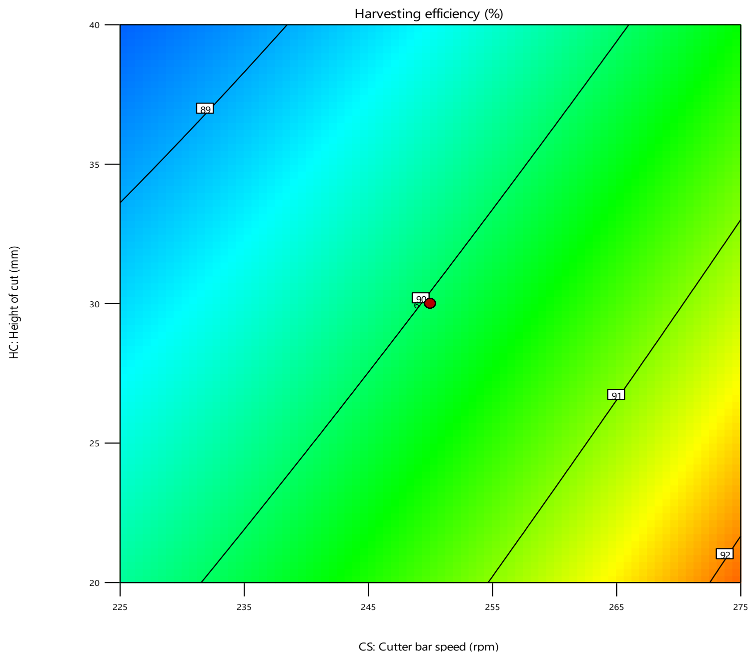

Fig. 7. Contour image on effect of cutter bar speed and height of cut on harvesting efficiency

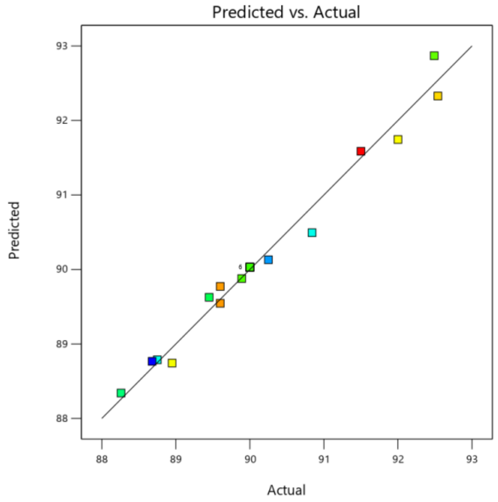

Fig. 8. Graphical presentation of actual and predicated value of harvesting efficiency

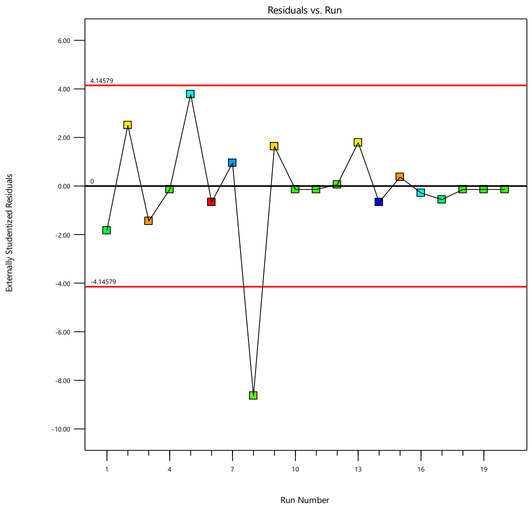

Fig. 9. Graphical presentation of residual and time of harvesting efficiency

4. CONCLUSIONS

The results showed that response surface method is well capable to predict data with negligible error and present the proper relationship between the independent variables (reel index, the cutting height of crop, horizontal distance of reel from cutter bar and vertical distance of reel from cutter bar) and header loss. The numerical optimization method was used to optimize the values of independent variables using Design Expert 13.0 software. The software predicted the optimum values of height of cut, cutter bar speed and reel speed as 30mm, 250 rpm and 12.5 rpm respectively. The predicted value for the dependent variable according the criteria selected during the numerical optimization for harvesting efficiency was 90% while the actual harvesting efficiency was reported as 90.17% which were in good agreement with the predicted valuessuggested by the mentioned software. In short, the RSM method can better predict and optimize header performance of developed lathyrus harvester. This study can provide data and method references for the design and optimization of agricultural machinery, prediction and intelligent fault diagnosis of the operation parameters of harvesters.

5. SUGGESTIONS FOR FUTURE WORK

1. More study will be required for making it suitable for multi crop harvester.
2. Studies can be done for other operational parameters on harvester.
3. Consecutive study may be done for harvesting of other pulses crop like moong, soybean, pea, chickpea etc.

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DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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