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Performance evaluation and statistical optimization of a tractor-operated grain recovery machine under laboratory conditions

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Abstract

Wheat is one of the most important cereal crops and contributes directly to food security, farm income and rural livelihood. In manually harvested wheat fields, a considerable quantity of spikes and loose grains may remain scattered on the soil surface during cutting, bundling, handling and transportation. Conventionally, these leftover spikes are collected manually, which requires repeated bending, squatting and slow movement across the field. This operation is labour-intensive, time-consuming and physically stressful for farm workers. Therefore, the development of a suitable grain recovery machine is important for reducing field losses and improving the working conditions of labourers involved in post-harvest field operations.

The present study was conducted to evaluate the laboratory performance of a tractor-operated grain recovery machine designed for collecting wheat spikes and loose grains left in manually harvested fields. The machine works on the principle of pneumatic suction. It consists of a suction unit, blower assembly, suction duct, collection chamber, frame, power transmission system and ground-supporting components. The performance evaluation was carried out in two stages. In the first stage, the relationship between engine speed, PTO speed, blower speed and suction pressure was evaluated. Five engine speeds, namely 900, 1200, 1500, 1800 and 2100 rpm, were used. In the second stage, grain recovery performance was studied under different suction pressures, forward speeds and wheat spike weights. Suction pressure was tested at five levels: 12, 27, 62, 70 and 96 Pa. Forward speed was tested at three levels: First Low (FL), First High (FH) and Second Low (SL). Wheat spike weight was tested at three levels: 50, 75 and 100 g.

The results showed that PTO speed and blower speed increased almost linearly with engine speed. The relationship between blower rpm and suction pressure was also strong, with $R^2 = 0.9724$. The ANOVA table showed that forward speed, suction pressure and weight significantly affected grain recovery efficiency. Suction pressure was the most influential factor, with the highest F value of 1687.45 and probability value less than 0.0001. Forward speed and weight were also highly significant. All two-factor and three-factor interactions were significant, indicating that grain recovery was governed by combined operational effects rather than by a single parameter. The regression model showed good prediction ability, with $R^2 = 0.948$, adjusted $R^2 = 0.943$, RMSE = 5.86, MAE = 4.11 and MAPE = 11.72%. The best operational combination under laboratory conditions was FL forward speed, 96 Pa suction pressure and 100 g spike loading, which produced the maximum grain recovery of 66.0%. The study confirms that suction pressure and forward speed are the key operational variables for improving the performance of the developed grain recovery machine.

Keywords: Grain recovery machine, wheat spike recovery, pneumatic suction, suction pressure, forward speed, ANOVA, regression model, RSM, laboratory evaluation

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops and is widely cultivated as a staple food crop. It contributes significantly to food security, human nutrition and farm income. In India, wheat is one of the major rabi-season crops and supports the livelihood of millions of farmers. The harvesting and post-harvest handling of wheat directly influence final grain availability. Even after harvesting, threshing and field handling, some wheat spikes and loose grains may remain scattered on the soil surface. These unrecovered

materials represent a direct economic loss and reduce the overall efficiency of the production system.

Manual harvesting is still common in many small and fragmented farms. Although combine harvesters are increasingly used in larger fields, small and marginal farmers often continue to harvest wheat manually with sickles because of field size, cost limitations, crop condition and local availability of machinery. During manual harvesting, bundling, transport and handling, some spikes fall on the ground. These spikes are generally collected manually by labourers. This operation requires workers to bend repeatedly and move slowly over the field surface. As a result, manual spike collection becomes labour-intensive, time-consuming and physically stressful.

The physical stress associated with manual collection is an important concern. Continuous bending, squatting and repetitive hand movements may cause fatigue and discomfort in the lower back, neck, shoulders and knees. During peak harvesting season, labour availability is also limited, and wage rates often increase. Therefore, dependence on manual spike collection increases both labour burden and operational cost. Mechanized recovery of leftover spikes can reduce grain loss, improve labour productivity and reduce drudgery.

A tractor-operated grain recovery machine was developed to address this problem. The machine operates on the principle of pneumatic suction. In this system, a blower generates air suction, and the suction duct lifts wheat spikes and loose grains from the ground surface. The lifted material is then conveyed into a collection chamber. The effectiveness of such a machine depends on the ability of the suction system to lift the material and the ability of the operator to maintain suitable travel speed. If suction pressure is too low, spikes may not be lifted properly. If forward speed is too high, the suction inlet may not remain over the material long enough for effective pickup.

The present study was conducted to evaluate the performance of the developed grain recovery machine under laboratory conditions. The study focused on the effects of suction pressure, forward speed and spike loading on grain recovery percentage. The experiment also examined the relationship between engine rpm, PTO rpm, blower rpm and suction pressure. Statistical analysis was carried out using ANOVA, mean comparison and regression modelling. The

main objective was to identify the best operational combination for maximum grain recovery under controlled laboratory conditions.

2. Materials and Methods

2.1 Description of the Grain Recovery Machine

The developed machine was designed for collecting wheat spikes and loose grains left after manual harvesting. The machine was tractor-operated and powered through the tractor PTO. The main components included a frame, blower assembly, suction unit, suction duct, collection chamber, power transmission system and supporting wheels. The machine worked on pneumatic suction. During operation, the blower generated suction pressure at the inlet. Wheat spikes lying on the soil surface were lifted by airflow and conveyed through the suction duct into the collection chamber.

The working principle of the machine depends on air movement and suction pressure. When the blower rotates, it creates a pressure difference between the suction inlet and atmosphere. This pressure difference produces airflow at the suction mouth. If the generated suction is sufficient to overcome the weight and surface resistance of the wheat spikes, the material is lifted and transported into the collection chamber. Therefore, suction pressure and blower rpm are critical parameters for machine performance.

2.2 Experimental Design for Suction Pressure Measurement

The first part of the experiment was conducted to study the relationship between engine rpm, PTO rpm, blower rpm and suction pressure. The experimental design for suction pressure measurement is presented in Table 1. RPM was taken as the independent variable at five levels, and suction pressure was measured as the dependent variable. The experiment was replicated three times.

The engine speed was adjusted at 900, 1200, 1500, 1800 and 2100 rpm. At each engine-speed level, PTO rpm and blower rpm were measured. Suction pressure was recorded using a digital manometer. This experiment was necessary to determine whether the power transmission system could generate the required suction pressure in a stable and predictable manner.

Table 1: Experimental design for suction pressure measurement

Parameter type	Parameter	Levels	Replication	Dependent variable
Independent	RPM	5 levels	3	Suction pressure (Pa)

As shown in Table 1, the suction pressure experiment was structured to relate the machine's rotational input to the suction output. This step was important because suction pressure later became one of the main independent variables in the grain recovery experiment.

2.3 Experimental Design for Grain Recovery

The grain recovery experiment was conducted under

laboratory conditions using three independent variables: suction pressure, forward speed and spike weight. The experimental design is shown in Table 2. Suction pressure was tested at five levels: 12, 27, 62, 70 and 96 Pa. Forward speed was tested at three levels: FL, FH and SL. Weight was tested at three levels: 50, 75 and 100 g. The dependent variable was grain recovery percentage. Each treatment combination was replicated five times.

Table 2: Experimental design for grain recovery evaluation

Parameter type	Parameter	Levels	Replication	Dependent variable
Independent	Suction pressure	12, 27, 62, 70 and 96 Pa	5	Grain recovery (%)
Independent	Forward speed	FL, FH and SL		
Independent	Spike weight	50, 75 and 100 g		

Laboratory plots of 1 m × 1 m were prepared on level ground. A spacing of 1 m was maintained between adjacent plots to avoid interference during machine movement and suction action. Wheat spikes of known weight were uniformly spread in each plot. After this, the machine was operated over the plot. The material collected in the collection chamber was removed and weighed using a digital balance. Grain recovery percentage was calculated by comparing recovered material with the total material placed in the plot.

2.4 Measurement Procedure

The RPM measurement procedure is represented in Figure 1. Engine rpm levels of 900, 1200, 1500, 1800 and 2100 were selected. S1 represented the driver pulley shaft and S2 represented the impeller shaft. The experiment was replicated three times. This flow chart provided the basis for understanding the rotational relationship between input shaft and blower shaft.

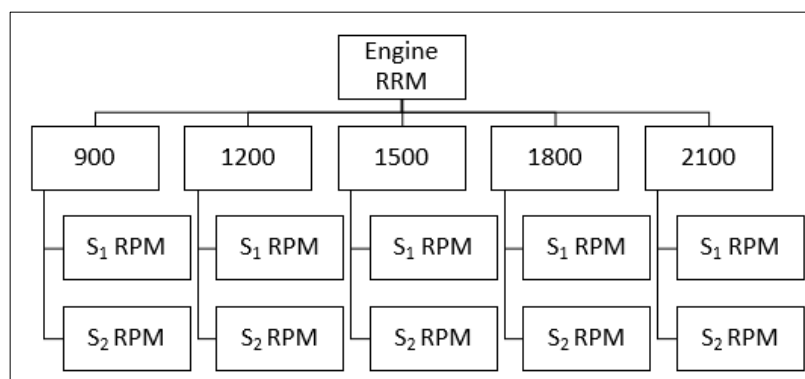


Fig 1: Flow chart of RPM measurement

The suction measurement procedure is shown in Figure 2. Suction pressure was measured at different forward-speed conditions and engine rpm levels. The repeated observations

were represented as S1, S2 and S3, while SF represented the final value. This procedure helped in obtaining stable suction pressure values for performance evaluation.

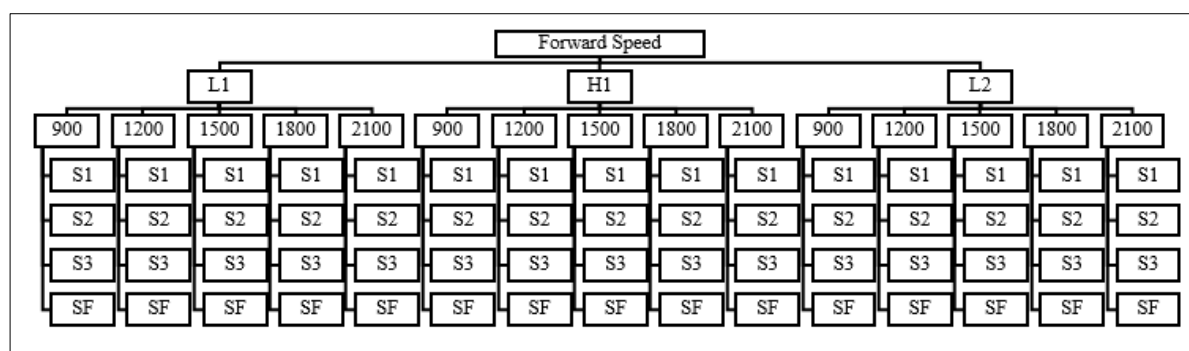


Fig 2: Flow chart of suction pressure measurement

2.5 Calculation of Grain Recovery

Grain recovery efficiency was calculated as the percentage of recovered wheat spikes relative to the total wheat spikes placed in the plot. The general equation may be written as:

$$\text{Grain Recovery (\%)} = \frac{\text{Recovered wheat spike weight}}{\text{Total wheat spike weight}} \times 100$$

This response variable was used to compare the effect of suction pressure, forward speed and spike weight on machine performance.

2.6 Statistical Analysis

The data were analysed using analysis of variance to determine the significance of main factors and interaction effects. The factors included forward speed, suction pressure

and spike weight. Mean comparison statistics, including standard deviation, critical difference, coefficient of variation and R^2 , were used to interpret treatment response. Regression modelling was used to develop a prediction equation for grain recovery. Model adequacy was evaluated using R^2 , adjusted R^2 , RMSE, MAE and MAPE.

3. Results and Discussion

3.1 Relationship between Engine RPM and PTO RPM

The relationship between engine rpm and PTO rpm is presented in Figure 3. Engine rpm increased from 900 to 2100 rpm. The corresponding PTO rpm increased from approximately 270 to 630.4 rpm. The graph showed a very high R^2 value, indicating that PTO rpm increased almost proportionally with engine rpm.

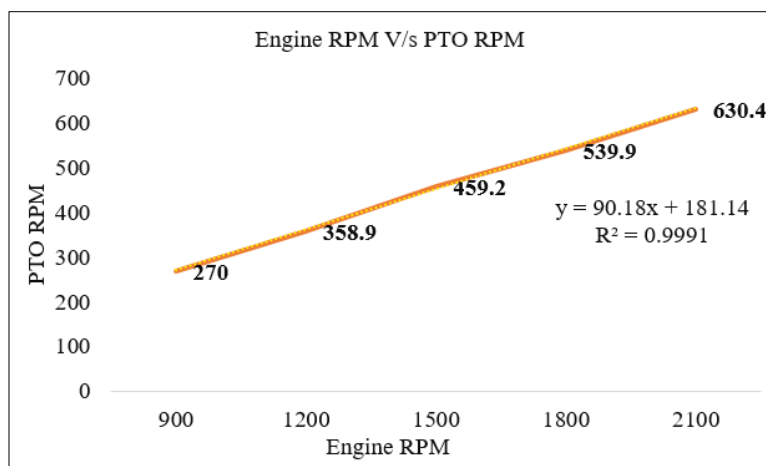


Fig 3: Engine rpm versus PTO rpm

The strong relationship shown in Figure 3 indicates stable power transmission from the tractor engine to the PTO shaft. This is important because the developed machine depends on tractor power for blower operation. If PTO rpm fluctuates strongly, blower rpm and suction pressure may also fluctuate. The near-linear relationship suggests that engine rpm can be used as a reliable control variable for regulating PTO speed under laboratory conditions.

3.2 Relationship between PTO RPM and Blower RPM

The relationship between PTO rpm and blower rpm is shown in Figure 4. PTO rpm increased from 270 to 630.4 rpm, while blower rpm increased from 564.66 to 1305.6 rpm. The regression equation shown in the graph was $y = 186.86x + 378.82$, with $R^2 = 0.9994$.

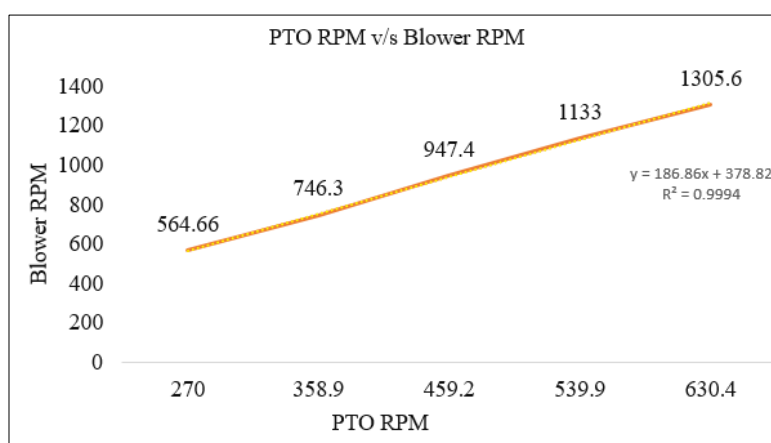


Fig 4: PTO rpm versus blower rpm

The high R^2 value indicates a very strong relationship between PTO rpm and blower rpm. This means that the transmission system was effective in transferring rotational power to the blower shaft. The increase in blower rpm with PTO rpm confirms that the machine was mechanically responsive to changes in engine speed. Since blower rpm controls suction generation, this result is important for further interpretation of suction pressure and grain recovery.

3.3 Effect of Blower RPM on Suction Pressure

The effect of blower rpm on suction pressure is shown in Figure 5. Suction pressure increased from 12 Pa at 564.66 blower rpm to 96 Pa at 1305.6 blower rpm. The regression equation shown in the graph was $y = 21.142x - 9.8569$, with $R^2 = 0.9724$.

The result shows that suction pressure increased with blower speed. This is expected because higher blower speed

increases airflow and pressure difference at the suction inlet. The R^2 value of 0.9724 indicates that blower rpm explained most of the variation in suction pressure. This relationship confirms that suction pressure can be controlled by regulating blower speed through engine and PTO rpm. Therefore, the suction system was suitable for recovery testing.

3.4 ANOVA for Grain Recovery Efficiency

The ANOVA table for grain recovery efficiency is presented in Table 3. The table shows that all main effects and interactions were statistically significant. Forward speed had a highly significant effect on grain recovery, with F value = 511.01 and $Pr > F < 0.0001$. Suction pressure had the strongest effect, with F value = 1687.45 and $Pr > F < 0.0001$. Weight also significantly affected grain recovery, with F value = 458.28 and $Pr > F < 0.0001$.

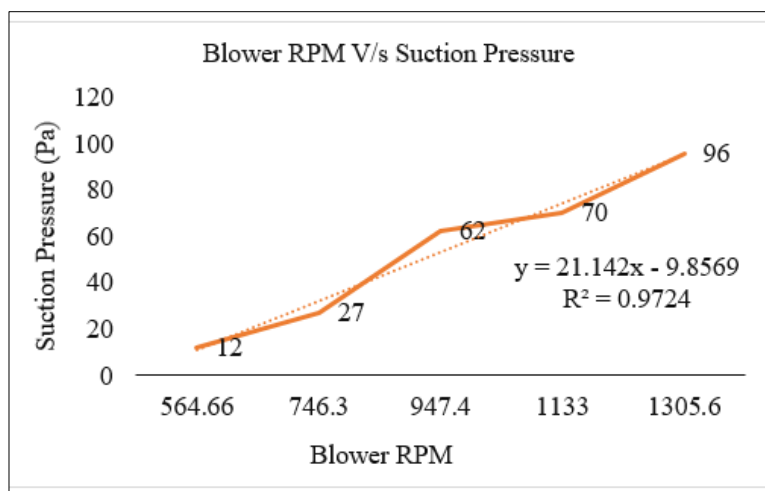


Fig 5: Effect of blower rpm on suction pressure

Table 3: ANOVA table for grain recovery efficiency

Source	DF	Sum of square	Mean square	F value	Pr > F
Forward speed	2	7019.97	3509.98	511.01	<0.0001
Suction pressure	4	46362.39	11590.59	1687.45	<0.0001
Weight	2	6295.61	3147.80	458.28	<0.0001
Forward speed × Suction pressure	8	1837.32	229.66	33.44	<0.0001
Forward speed × Weight	4	118.08	29.52	4.30	0.0024
Suction pressure × Weight	8	1290.33	161.29	23.48	<0.0001
Forward speed × Suction pressure × Weight	16	308.32	19.27	2.81	0.0005

The ANOVA results in Table 3 confirm that suction pressure was the most influential factor affecting grain recovery. This is evident from the highest sum of squares and highest F value. The result is technically reasonable because the developed machine works on pneumatic suction. When suction pressure increases, the suction force available at the inlet also increases, allowing more wheat spikes to be lifted from the plot surface and transported into the collection chamber.

Forward speed was also highly significant. The significance of forward speed indicates that the time available for suction pickup strongly influenced the amount of recovered material. At lower forward speed, the suction inlet remains over the material for a longer duration, which increases pickup probability. At higher forward speed, the machine moves quickly over the plot, reducing the time available for lifting and conveying the spikes.

Weight was also significant. This shows that the amount of spike material placed in the plot affected the recovery percentage. Higher spike loading increased the availability of recoverable material within the suction path. Therefore,

the machine showed better recovery when material availability was higher.

The interaction terms in Table 3 are important. The significant forward speed × suction pressure interaction means that the effect of suction pressure was not the same at all forward speeds. High suction pressure improved recovery, but its benefit was stronger at suitable lower speed. The significant suction pressure × weight interaction means that the pressure response depended on spike loading. The significant three-way interaction indicates that grain recovery was controlled by the combined effect of all three variables. Therefore, the optimum performance of the machine must be determined using factor combinations rather than individual factor effects alone.

3.5 Interpretation of Mean Table

The mean table of wheat spike recovery percentage is presented in Table 4. The table includes mean values for speed, suction pressure and weight, along with standard deviation, critical difference, R² and coefficient of variation.

Table 4: Mean table of wheat spike recovery percentage

Level	Treatment		
	Speed	Suction pressure	Weight
1	30.9467	45.0444	30.0533
2	21.9545	33.4000	23.2665
3	71.5200*	22.3331	17.1013
4	—	9.7778	—
5	—	6.8133	—
SD	4.460	2.6208	2.6208
CD	0.8445	—	—
R ²	0.980822	—	—
CV	11.16490	—	—

*The speed value 71.5200 appears inconsistent with graph data and may be a typographical error for 17.5200.

The speed means in Table 4 indicate that the best forward-speed condition was FL, followed by FH and SL. Based on the plotted data, FL produced the highest average recovery. The value shown as 71.5200 for the third speed level appears inconsistent and should be verified from the original data. The graph data suggest that this value should likely be 17.5200. If corrected, the ranking becomes logical: FL gives the highest mean recovery, FH gives intermediate recovery and SL gives the lowest recovery.

The suction-pressure means in Table 4 show that grain recovery increased with suction pressure. The highest mean value was associated with the highest suction pressure, while the lowest mean value was associated with the lowest suction pressure. This confirms the central role of suction pressure in pneumatic recovery. The result agrees with the mechanical principle that higher suction pressure provides greater lifting ability at the inlet.

The weight means in Table 4 show that recovery increased with spike loading. The highest mean recovery was recorded at 100 g, followed by 75 g and 50 g. In laboratory testing, higher spike load likely increased the contact probability between the suction mouth and recoverable material. However, in actual field operation, spike load is not an adjustable machine parameter. It represents the amount of field loss present after harvesting.

The R^2 value of 0.980822 reported in Table 4 indicates that the factorial treatment structure explained a very high proportion of the variation in grain recovery. The CV value of 11.16490% indicates acceptable experimental variability for a laboratory evaluation involving biological material and machine operation. The critical difference value of 0.8445 suggests that differences among treatment means were statistically meaningful when the difference exceeded this value.

3.6 Regression Model and Mathematical Equation

The regression model for grain recovery is given as:

$$GR = -8.214 + 0.482P + 0.318M - 7.126FS + 0.0021P^2 - 0.0018M^2 - 0.0057(P \times FS)$$

Where;

- GR is grain recovery percentage,
- P is suction pressure in Pa,
- M is grain or spike mass in g and
- FS is the coded forward-speed variable.

The positive coefficient of suction pressure indicates that grain recovery increased as suction pressure increased. This is expected because higher pressure increases the suction force available for lifting wheat spikes. The positive coefficient of mass indicates that recovery increased with spike loading in the tested range. The negative coefficient of forward speed indicates that recovery decreased as forward speed increased. This confirms that excessive travel speed reduces suction exposure time.

The positive quadratic term for suction pressure suggests that the response continued to increase at higher pressure levels within the tested range. The negative quadratic term for mass suggests that the effect of spike loading may not continue indefinitely and may reach a saturation point. The negative interaction term between pressure and forward

speed indicates that the positive effect of suction pressure was reduced at higher forward speed. In practical terms, high suction pressure alone cannot produce maximum recovery if the machine is operated at unsuitable travel speed.

The regression equation is useful because it provides a mathematical relationship among the main operating variables. It can be used for prediction within the tested range. However, the model should not be extrapolated beyond the tested pressure, speed and loading conditions without validation.

3.7 Model Adequacy Statistics and Regression Prediction

Table: The regression statistics are presented in Table 5.

Table 5: Regression statistics for grain recovery prediction model

Parameter	Value
R^2	0.948
Adjusted R^2	0.943
RMSE	5.86
MAE	4.11
MAPE	11.72%

The R^2 value of 0.948 indicates that the regression model explained 94.8% of the variation in grain recovery. This shows strong model fit. The adjusted R^2 value of 0.943 is close to the R^2 value, indicating that the model was not inflated by unnecessary terms. The small difference between R^2 and adjusted R^2 supports the stability of the model.

The RMSE value of 5.86 indicates the average magnitude of prediction error in the same unit as the response variable. The MAE value of 4.11 indicates that the average absolute prediction error was relatively low. The MAPE value of 11.72% indicates that the prediction error was acceptable for laboratory machine-performance evaluation. Overall, Table 5 shows that the model had good prediction ability and could be used for estimating grain recovery within the studied range.

3.8 Effect of Suction Pressure and Weight at FL Forward Speed

The effect of suction pressure and weight on grain recovery at FL forward speed is presented in Figure 6. At 50 g weight, grain recovery increased from 8.4% at 12 Pa to 37.2% at 96 Pa. At 75 g weight, recovery increased from 11.4% to 54.0%. At 100 g weight, recovery increased from 13.6% to 66.0%.

Fig. 6 clearly shows that grain recovery increased with suction pressure at all weight levels. The highest recovery of 66.0% was obtained at 96 Pa suction pressure and 100 g spike loading. This indicates that FL was the most favorable forward-speed condition for recovery. The lower speed likely allowed the suction inlet to remain over the material for a longer period, improving pickup efficiency.

3.9 Effect of Suction Pressure and Weight at FH Forward Speed:

The effect of suction pressure and weight on grain recovery at FH forward speed is shown in Fig. 7. At 50 g weight, recovery increased from 2.12% at 12 Pa to 41.2% at 96 Pa. At 75 g weight, recovery increased from 5.0% to 47.0%. At 100 g weight, recovery increased from 6.2% to 56.0%.

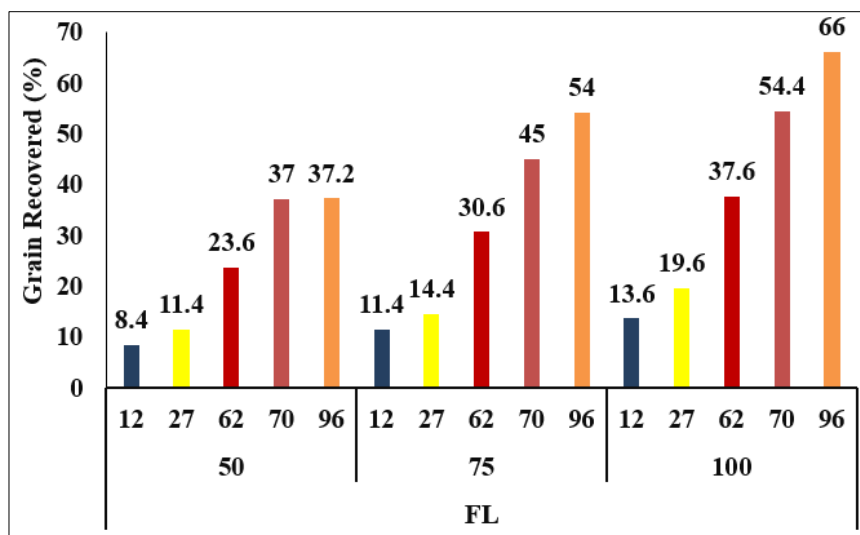


Fig 6: Effect of suction pressure and weight on grain recovery at FL forward speed

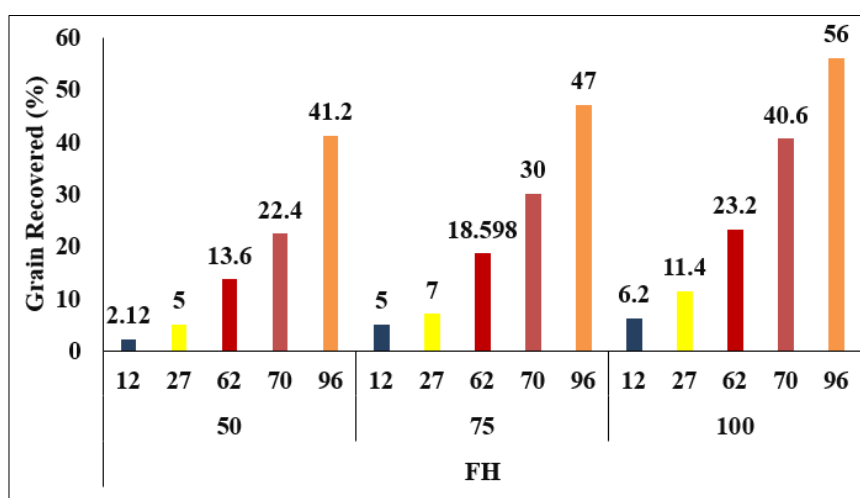


Fig 7: Effect of suction pressure and weight on grain recovery at FH forward speed

Fig. 7 shows that recovery increased with suction pressure, but the values were lower than those recorded under FL. This confirms that higher forward speed reduced recovery performance. However, the increasing trend with suction pressure remained consistent, which indicates that suction pressure was still an effective factor under FH operation.

3.10 Effect of Suction Pressure and Weight at SL Forward Speed: The effect of suction pressure and weight on grain recovery at SL forward speed is presented in Fig. 8. At 50 g weight, recovery increased from 1.6% at 12 Pa to 25.8% at 96 Pa. At 75 g weight, recovery increased from 3.8% to 35.8%. At 100 g weight, recovery increased from 9.2% to 42.4%.

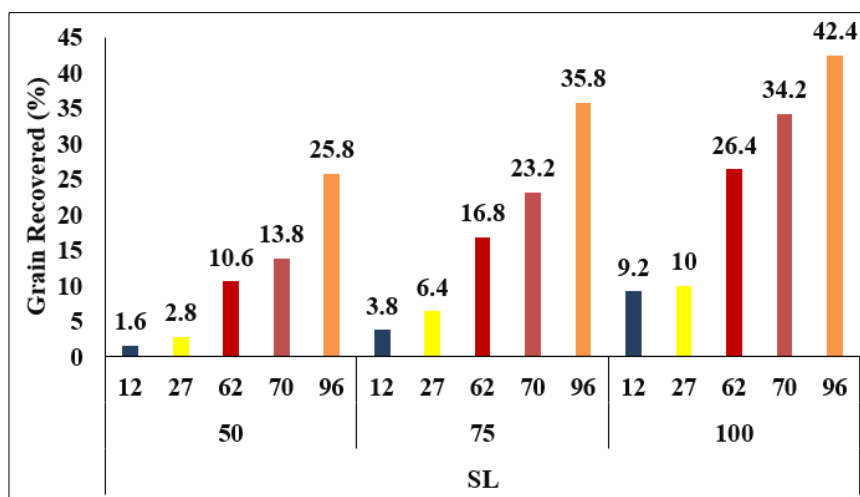


Fig 8: Effect of suction pressure and weight on grain recovery at SL forward speed

Fig. 8 shows that recovery improved with suction pressure and spike weight, but the response values were lower than FL and FH. This suggests that SL was not the most suitable speed condition under the tested laboratory setup. The lower response may be due to machine travel characteristics, suction alignment or reduced effectiveness of the suction inlet under this gear condition. Further field testing is required to explain this behaviour more clearly.

3.11 Radar Plot Analysis of Normalized Factor-Response Profile

Fig.4.13. presents the radar plot showing the normalized relationship among suction pressure (12-96 Pa), grain mass (50-100 g), and grain recovery efficiency (%) under three forward speed conditions, namely First Low (FL), First

High (FH), and Second Low (SL). The radar plot was developed to compare the overall performance of the grain recovery machine by integrating the major operating variables and response parameters into a single graphical representation.

The plot indicates that the First Low (FL) forward speed exhibited the highest normalized grain recovery response, achieving a maximum recovery of approximately 66.0% at 96 Pa suction pressure and 100 g grain mass. Under First High (FH) conditions, the maximum grain recovery was approximately 56.0%, whereas Second Low (SL) recorded the lowest maximum recovery of about 42.4%. The larger enclosed response area associated with FL demonstrates its superior performance compared with FH and SL operating conditions.

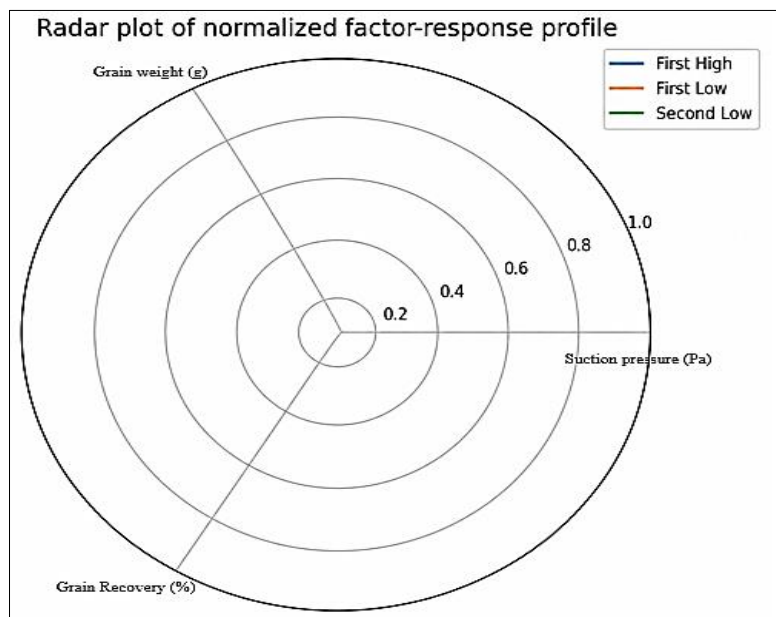


Fig 9: Radar plot showing the normalized factor-response profile of all response

The radar profile further shows that grain recovery increased consistently with increasing suction pressure and grain mass across all speed levels. The superior performance of FL may be attributed to the longer interaction time between the suction nozzle and field surface, which enhanced grain entrainment and collection efficiency. In contrast, higher travel speeds reduced the residence time available for grain pickup, resulting in comparatively lower recovery percentages.

The observed trend agrees with the findings of Srivastava *et al.* (2006) ^[14], who reported that pneumatic conveying efficiency is strongly dependent on airflow characteristics and exposure time between the conveying system and the material being handled. The present results also support the observations of Kepner *et al.* (2018) ^[5], who stated that machine operating speed is one of the most critical factors affecting the collection efficiency of agricultural harvesting and conveying systems.

The radar plot confirms that the combination of higher suction pressure, greater grain mass, and lower forward speed provided the most favorable operating conditions for grain recovery. The graphical representation effectively summarizes the interaction among the major factors and validates the results obtained from the heat map, contour, and interaction plot analyses.

3.12 Best Operational Combination

The best operational combination was identified from the treatment response graphs. The highest grain recovery was recorded at FL forward speed, 96 Pa suction pressure and 100 g spike loading. This combination produced 66.0% grain recovery. Therefore, this combination may be considered the optimum laboratory condition for the developed machine.

The result indicates that high suction pressure alone is not sufficient. Maximum recovery requires high suction pressure along with a suitable low forward speed. The 100 g spike loading condition represents higher material availability in the test plot. In practical field conditions, this means the machine will perform more effectively in fields where recoverable wheat spikes are sufficiently present and distributed within the suction path.

3.13 General Discussion

The performance of the developed grain recovery machine was strongly affected by the pneumatic suction system. The increase in suction pressure with blower rpm confirmed that the machine was capable of generating different suction levels through engine and PTO speed control. The high R^2 values in the rpm and suction-pressure graphs indicate that the mechanical transmission system was stable under laboratory conditions.

The ANOVA results showed that suction pressure was the most important factor. This is consistent with the working principle of the machine. A pneumatic recovery machine depends on airflow to lift and convey material. If the pressure is low, the suction stream may not overcome the resistance between the wheat spike and ground surface. At high pressure, the lifting force increases and more material enters the suction duct.

Forward speed was also important because it controlled exposure time. In suction-based recovery, the suction inlet needs time to act on the material. At lower speed, the machine provides longer suction contact over the plot. At higher speed, the suction inlet passes quickly, leaving less time for pickup. This explains why FL produced better recovery than FH and SL.

The effect of spike weight shows that material availability influenced recovery. At 100 g, more wheat spikes were present in the plot, increasing the probability of pickup. At 50 g, the material was more sparsely distributed, and some spikes may not have aligned with the suction path. However, this result should be interpreted carefully because spike loading is a field condition rather than a machine control variable.

The significant interaction effects indicate that the machine should be optimized as a system. A single-factor recommendation may be misleading. For example, high suction pressure improves recovery, but its effect depends on forward speed. Similarly, low speed improves recovery, but low speed with insufficient pressure may not be effective. Therefore, the recommended operating condition should combine suitable forward speed and suction pressure. The regression model provides a useful prediction tool. The model statistics show good agreement between observed and predicted recovery values. However, the absence of a complete RSM coefficient table and residual diagnostic plots limits the strength of the model adequacy interpretation. The final paper should include these additional details.

The developed grain recovery machine has practical potential for reducing wheat spike losses from manually harvested fields. It may also reduce the need for manual spike picking and thereby reduce drudgery. However, laboratory performance does not fully represent field performance. Actual field conditions may include uneven ground, stubble, straw, soil clods, wind and variable moisture. Therefore, field validation is essential before recommending the machine for large-scale adoption.

4. Conclusion

1. The developed tractor-operated grain recovery machine successfully recovered wheat grains and spikes under laboratory conditions using a pneumatic suction mechanism.
2. Blower speed increased with PTO speed, resulting in higher suction pressure and improved grain recovery performance.
3. ANOVA revealed that forward speed, suction pressure, grain mass, and their interactions significantly ($p < 0.05$) affected grain recovery efficiency.
4. Suction pressure was identified as the most influential factor, followed by forward speed and grain mass.
5. Grain recovery efficiency increased with increasing suction pressure and grain mass, while lower forward speed (FL) provided superior recovery.

6. The regression model showed good predictive performance with $R^2 = 0.948$, Adjusted $R^2 = 0.943$, RMSE = 5.86, MAE = 4.11, and MAPE = 11.72%.
7. The experimental data exhibited high reliability with an ANOVA R^2 of 0.9808 and a coefficient of variation (CV) of 11.16%.
8. Graphical analyses, including interaction plots, contour plots, heatmaps, and PCA, confirmed that higher suction pressure significantly enhanced grain recovery.
9. The optimum operating condition was obtained at First Low (FL) forward speed, 96 Pa suction pressure, and 100 g grain mass, resulting in a maximum grain recovery efficiency of 66.0%.
10. The developed machine demonstrated satisfactory technical performance and has potential for reducing post-harvest grain losses in manually harvested wheat fields.

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