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Field Test Analysis of Straw Reaper Combine for Optimized Operating Condition to Improve the Performance

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Authors' contributions

This work was carried out in collaboration among all authors. Author Shukla Prabhakar designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors NS and Shau Parmanand managed the analyses of the study. Authors PA and TH managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The profitability of *ex-situ* straw management largely depends on the quantity and quality of straw recovered from the field. The straw reaper-combine is one of the widely used *ex-situ* straw management technologies being used to retrieve the leftover residue in the field after grain combine operation. Besides considering the positive implication of this technology in recent times, the quality of operation, which accounts for maximizing the performance parameters of straw reaper-combine in a wheat crop. The relationship among these parameters was established using multiple linear regression techniques through the regression equation. The ANOVA test of this experiment also established the significant (P<0.01) effect of forwarding speed and cutting height on all performance parameters. It was observed from the experiment that when the forward speed was increased while keeping the cutting height at a constant level the recovery percentage and specific energy consumption were decreased whereas, straw split percentage and actual field capacity were

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increased. Likewise, when cutting height was increased keeping the forward speed at a constant level the recovery and split percentage were reduced but, the actual field capacity and specific energy consumption were increased. In order to achieve maximum performance at optimum energy consumption, the straw reaper should be operated at a speed between 3-4 km/h with cutting height between 30-60 mm.

Keywords: Cutting height; specific energy consumption; straw reaper; straw recovery; straw split.

1. INTRODUCTION

The RWS (Rice-Wheat system) is one of the widely practiced cropping systems in India and covers about 12.3 Mha Ladha et al. [1]. In the IGP (Indo-Gangetic plane) regions of India, the RWS constitutes about 85% of the total area under cultivation Timsina and Connor [2]. With the widespread use of green revolution technologies, the expansion of area under the RWS was increased considerably and subsequently increased in the yield of grain and residues were also observed. According to Sarkar et al. [3], the RWS accounts for one-fourth of crop residue produced in India.

Traditionally these crops are harvested manually or by the help of a reaper. After harvesting, grains are separated from straw and straw become chaff using a threshing unit. But, with the increasing cropping intensity, where little time left for the sowing of subsequent crop and increasing labour shortage resulted in the popularization of the combine harvester in India. Mostly in RWS cropping system, there is less time available between the harvesting of paddy and sowing of wheat. Moreover, the performance of wheat crop is highly susceptible to the delay in sowing. So, the use of combine harvester has become relevant.

However, due to the use of combine harvester, there has been increase in the share of residue that is left in the field. Farming system residues are biomass of crop remains at the field after reaping of profitable constituents like the kernel and these include anchored stubbles and loose straw deposited after combine operation. As per a study conducted by Gupta and Dadlani, [4,5] estimated that maximum residues generated by cereal crops is 352 Mt and out of which 34% and 22% are contributed by paddy and wheat crops, respectively. Likewise, approximately 371 Mt of crop residues are generated annually in India, out of which paddy and wheat account for 51-57% and 27-36% share, respectively Gupta, [4,5] Hayashi et al. [6]. With the increasing piles of residue and lack of an economically feasible solution to manage them create a huge burden on farmers and that leads to farmers resort to burning these residues as a cheap option to clear their field for succeeding crop Jain et al. [7]. About 75% of combine harvested stubbles and loose straws go to waste besides causing environmental problem due to residue burning, as revealed by Mangaraj and Kulkarni [8].

Extensive research in the development of technology to the management of crop residues both *in-situ* and *ex-situ* has made it realised the economic viability option for farmers. *In-situ* straw management is highly popular in case of paddy straw owing to the limited time for sowing of succeeding crops. Whereas in *ex-situ* straw management residues are reaped and collected from the field using different technology for its external use and this method is widely used for the wheat crop. The Straw reaper combine has been a highly adoptive machine owing to its use in *ex-situ* straw management and collects the leftover straw and ear-head bearing plants and does the threshing. The popularity of using this machine after combine operation has been gained over the decade with the increase in area covered under combine harvester.

Various studies have been done on this machine to evaluate its performance and modify the design to suit different operating conditions. A study by Mahmood et al. [9], revealed that a 75 hp tractor was suitable for operating a straw combine at an average speed of 2.7 km/h. They also observed the field capacity of 0.4 ha/h with an efficiency of 67.9%. Similarly, Dhimate et al. [10] had modified the existing straw reaper combine to get better quality straw by removing dirt. They observed that feed rate, drum speed, and concave opening have a significant effect on the straw split or maximum size reduction. Singh et al. [11], worked on the performance evaluation of tractor mounted straw chopper cum spreader and found that by increasing threshing speed size reduction of straw increased. Whereas, the size reduction decreased when forward speed was increased. Diaz et al. [12], found that rice straw residue should be cut to a size within the range of 1.27-7.62 cm for better composting.

It can be inferred from the above reviews that the quality and quantity of straw recovered for the different purpose were significantly influenced by the varying operating conditions. Looking at the combine harvested field, where straw density drastically varies due to leftover straw height and non-uniform spread of loose straws over the field, it is imperative to reckon with the cutting height of straw reaper for maximum recovery of bhusa as well as to accommodate with the speed of travel for uninterrupted operation. Furthermore, to augment the studies done on straw reaper combine, we have intended to see the influence of forward speed and cutting height of anchored stubble on the machine parameters as well as on the quality of operation and to establish an empirical relationship among different variables to predict the required outcome.

2. MATERIALS AND METHODS

2.1 Brief Summary of the Test Machine

The test machine namely straw-reaper-combine of Metal weld Engineering Pvt. Ltd. make was used in this experiment as the schematic diagram of this machine is shown in Fig. 1. The straw reaper is normally used after the grain-combine harvester operation to serrate the leftover stubble and making it into bhusa either for animal feed or spread over the field for mulching purpose. It is a trailed type pulled by a tractor and the power supplied to the machine unit through the tractor PTO using a universal shaft during field operation. Then this power is supplied to the pick-up reel, cutter-bar, threshing drum, blowing fans, oscillating sieves and feeding auger for their respective operations. It normally performs four major operations such as loose straw pick up, serrating the anchored stubbles, straw brushing and chaff blowing. There are two different types of straw bruising/threshing mechanisms are commonly used in the straw combines. These include a spike tooth cylinder and serrated saw type mechanisms. But in this test machine, Serrated saw type cylinder was used for bruising. The cut straw after passing through the different process get brushed and converted to bhusa, which thrown back to the mesh covered trolley through a duct using blowers. Few important specifications of the test machine are given in Table 1.

2.2 Evaluation Procedure

The test machine, straw reaper combine, fitted with a 45 hp tractor was operated in a wheat harvested field for collection of leftover wheat straw. A trolley having a wire-mesh canopy was hitched behind the straw reaper for bhusa collection. For this experiment, the test machine was operated at four different forward speeds such as 2.5 km/h, 3.5 km/h, 4 km/h and 4.5 km/h while keeping the stubble cutting height at three different settings such as 30 mm, 60 mm and 100 mm from the ground. The test field was divided into a number of plots as per test run length and 60 m test run length was marked with the use of measuring tape and two wooden coloured poles. The required crop conditions as per IS: 1580:2008 were recorded before the test run and mentioned in Table 2. Moisture content is the most important parameter for harvesting wheat straw. The straw was harvested when the moisture of straw was about 18% or less so that proper threshing could be ensured.

Table 1. Concise specifications of the test machine

Model	Straw reaper
Power source	45hp tractor operated PTO driven
Overall size (mm) (L×W×H)	3370×2450×2150
Size of brushing drum diameter (mm) (L×D)	1370×700
Length of cutter bar (mm)	2020
Speed of brushing drum, rpm	550
Concave opening, mm	12
Type of brushing drum	Serrated tooth type blade
Type of cutter bar	Reciprocating type
Straw cleaning sieve	Reciprocating wear mesh type
Size of blower dia., mm	280

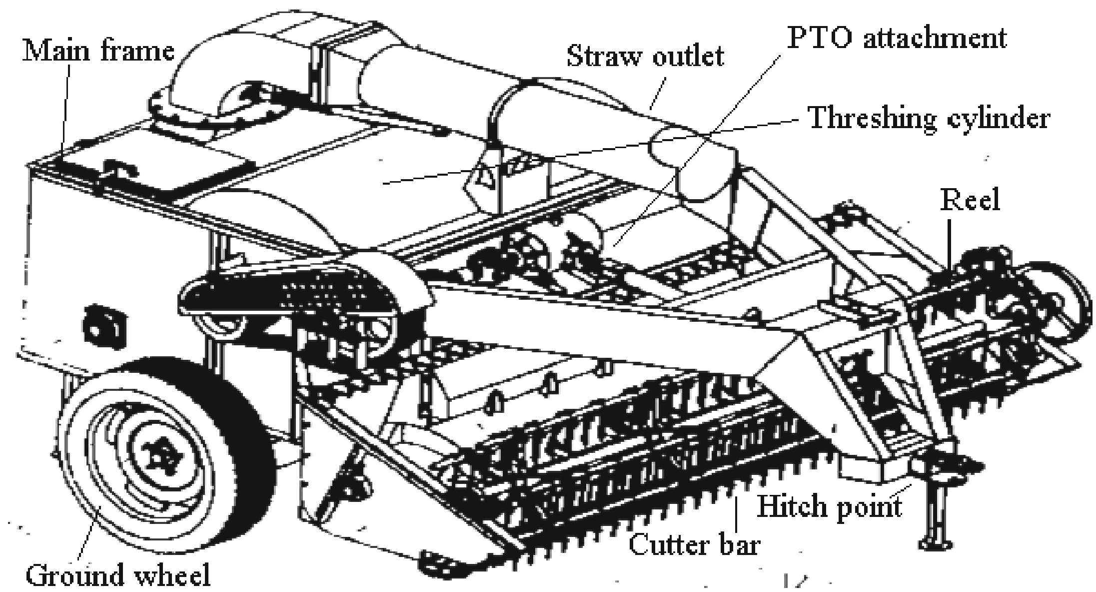

Fig. 1. Schematic view of a straw reaper combine

Table 2. Summary of field crop conditions

Parameters	Ranges
Verity	PBW-502
Plant population, No./m^2	270-425
Available straw. g/m^2	390-1200
Moisture content of straw, %	8-10
Loose straw per square meter. g	167-304
Height of stubbles before harvesting. mm	250-350
Height of stubbles after harvesting. mm	30, 60 &100
Average straw mass density recovered manually at 10% moisture and at a height of 30 mm, 60 mm and 100 mm (kg/m^2)	0.034, 0.025 & 0.020

2.3 Measurement of Machine Parameters

To assess the performance of test machine in terms of quality and rate of work and different parameters were observed during the field test at each set of treatment i.e., the combination of operating speed and cutting height of stubble. These machine parameters are also called as dependent parameters. The specific energy consumption of the straw reaper-combine was estimated by dividing the straw feeding rate to the power required to conduct each operation. Singh et al. [13] given the equation 1 and 2 for calculating the specific energy consumption in kW-h/kg and feed rate in kg/h respectively and considering the straw density at different cutting heights, mentioned in Table 2, and speeds.

Specific energy consumption (kW-h/kg) = $\frac{P}{FR}$ (1)

where,

P: Power requirement (kW);
FR: Feed rate (kg/h).

Feed rate (kg/h) = $2 \times \rho \times v$ (2)

where,

ρ: straw density, kg/m^2; (2 m width of cut of straw combine is effective for calculation)
v: forward speed of straw combine, m/h.

Estimation of the fuel consumption to operate the machine was carried out by accurately measuring the decrease in fuel level in the fuel tank immediately after executing each operation. The actual field capacity is the indicator of the rate of work of the test machine. This value was estimated using the following equation.

Table 3. Parameters used for experimental design

Variables	Levels
Predictors	
Forward speed (S_1-2.5, S_2-3.5, S_3-4 & S_4-4.5 km/h)	4
Cutting height (mm) CH_1-30, CH_2-60 & CH_3-100	3
Responses	
Straw recovery	%
Straw split	%
Actual field capacity	ha/h
Specific energy consumption	kW-h/kg

Actual field capacity (ha/h) = $\frac{A}{T_p+T_n}$ (3)

where,

A: area covered (ha);
T_p&T_n: productive and unproductive time required (h).

The quality of work parameters measured were: straw recovery percentage and splitting of straw percentage. To calculate the straw recovery percentage, the following formula was used.

Straw recovery (%) = $\frac{B-A}{B} \times 100$ (4)

where,

B: Available straw per meter square area before searing (kg);
A: Straw collected as bhusa from the outlet from a meter square area (kg).

Likewise, the measurement of split straw percentage was done by taking about 100 g of straw sample from the outlet for each replication. These samples were sorted manually for un-split straw. As suggested Singh et al. [13] the average acceptable range of straw split percentage should be (92- 95)%.

2.4 Statistical Analysis

The performance of the Straw reaper-combine was analysed against different forward speeds and cutting heights of stubble by using a randomized complete block design with three replications in each treatment. Table 3 shows the different factors or predictors and their levels considered for the ANOVA test at 5% level of confidence to find out the significant influence on the responses as dependent variables. All measured variables were also considered in the statistical development of the multiple linear regression models. The linear model of maximum correlation was determined.

3. RESULTS AND DISCUSSION

3.1 Effect on Straw Recovery Percentage (%)

The quantity of straw (qt/ha) recovered indicates the quality of operation of a straw reaper combine. Fig. 2 depicts the relationship of response as straw recovery with respect to the predictors like forward speed and cutting height. The statistical analysis reveals that both the predictors have a negative correlation with the percentage of straw recovery and variance inflation factor (VIF) quantifies the severity of multicollinerity in an ordinary least square regression analysis shows in Table 4. The negative coefficient indicates the reduction of the quantity of straw recovered with an increase in the forward speed and cutting height from the ground. The overall percentage change in straw recovery at cutting height 30 mm, 60 mm and 100 mm was observed to be 81.6-68.0%, 72-57.7% and 65-52% respectively, over different levels of speed. Increasing the cutting height reduced the quantity of straw to be cut and leaving maximum straw, both uncut stubble and lose straws, in the field. However, decreasing the cutting height prevented from the abrupt chocking due to straw overload and undesirable stones and debris and smoothen the field operation uninterrupted. But the drastic fall in the recovery was seen when the cutting height was moved above 60 mm and the speed was increased to 4 km/h and above. The ANOVA analysis presented as F statistics value in Table 6 tells the significance of the main and interaction effects of predictors on the response. If we write the relationship among these variables in a mathematic term the empirical equation will look like as follow:

$$Y= c -aX_1 -bX_2 \quad (5)$$

where,

Y: Predicted straw recovery (%)

3.2 Effect on Straw Split Percentage (%)

The straw split is also a measure of one of the quality parameters of a straw combine that is seen as how finely the straws get chopped to form bhusa. Fig. 3 represents the trend of straw split percentage with the variation of cutting height and forward speed. The statistical analysis indicating in Table 5, cutting height was predictor and found the negative correlation and the second predictor forward speed holds the positive correlation with the response as a straw split percentage. It was indicate the decreases the bhusa quality because of increase the height of cutting. The change in percentage split was found to be from 90-97%, at 30 mm cutting height, for the speed variation of 2.5 km/h to 4.5 km/h. Likewise, at 60 mm cutting height, the increase was from 86-95% and at 100 mm cutting height the severe drop was observed as 84-92%, which is below the allowable bhusa quality standard as per the IS: 15805-2008 for straw reaper combine. The reason for decreasing split percentage can be inferred from the fact that with the increasing cutting height the quantities of cut straw fed into the threshing cylinder get reduced. However, the variation of speed, up to 4 km/h, had increased the percentage of split and above that speed, the split percentage started to drop. The increasing split of straw due to increasing speed could be due to the increased feed rate (kg/h) to the threshing unit. In a similar study conducted on straw combine observed that by increasing the feed rate split percentage of straw got increased [10]. The analysis of variance of different variables indicating the main effect and interaction effect is represented in Table 6. The empirical equation representing the relationships among these variables is as follow.

$$Y = c - aX_1 + bX_2 \quad (6)$$

where,

Y: Predicted straw split percent

Table 4. Statistical interpretation of models for straw recovery

Model	Coefficient	F statistics	P-Value	Collinearity VIF	R^2
Constant	106.19 (c)	268.57			0.942
Cutting height (X_1)	-0.226 (a)		0.000	1.00	
Speed (X_2)	-7.141 (b)			1.00	

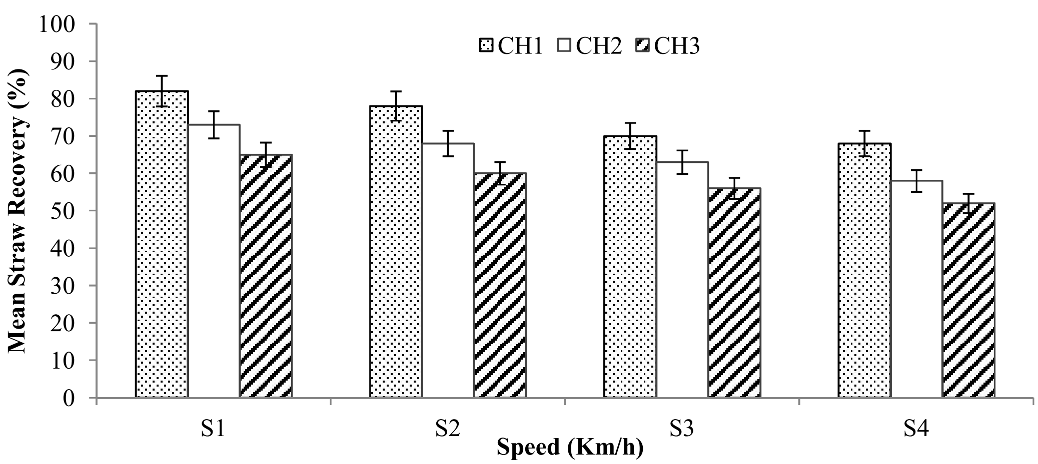

Fig. 2. Effect of cutting height and forward speed on straw recovery percentage

Table 5. Statistical interpretation of models for straw spliting

Model	Coefficient	F statistics	P-Value	Collinearity VIF	R^2
Constant	80.60 (c)	63.90	0.00		0.79
Cutting height (X_1)	-0.06 (a)			1.00	
Speed (X_2)	4.29 (b)			1.00	

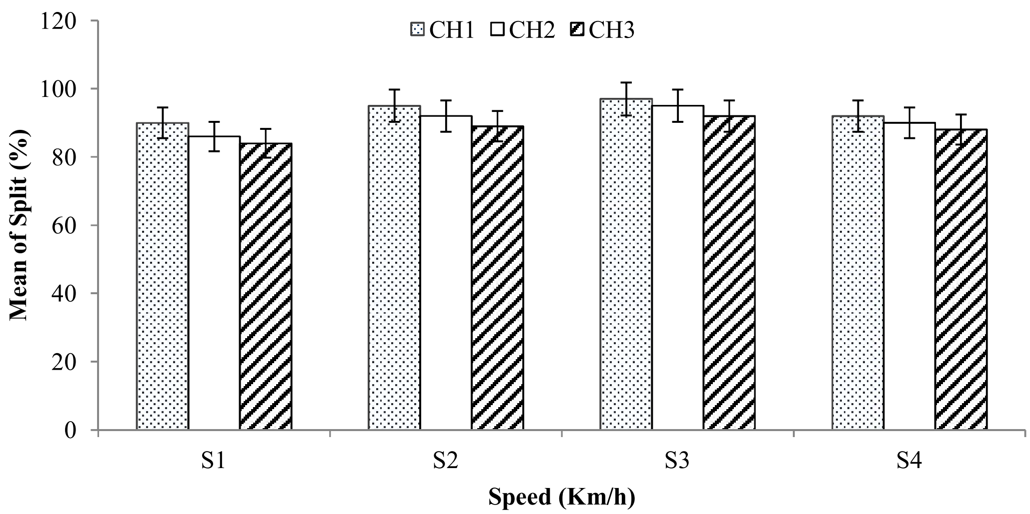

Fig. 3. Effect of cutting height and forward speed on the percentage split

Table 6. Test results of ANOVA showing the effect of predictors on responses

Source	DF	F statistics			
		Straw recovery (%)	Straw split (%)	AFC (ha/h)	Specific energy consumption (kWh/q)
Forward Speed (km/h)	3	124.88*	38.98*	694.56*	1866.02*
Cutting height (mm)	2	280.71*	19.57*	48.70*	380.08*
Speed × cutting height	6	1.30^{NS}	1.00^{NS}	3.05*	22.00*

*Note: * Significant at 5% level of confidence; ^{NS}Non-significant; DF- Degree of Freedom*

3.3 Effect of Actual Field Capacity (ha/h)

Actual field capacity (AFC) is always less than the theoretical field capacity and is highly affected by the travel speed, unproductive time and swath overlap. In our experiment, the positive correlation of both the predictors with the response represented (Table 7) the direct relation existed between the AFC and its operational parameters such as cutting height and forward speed. The minimum AFC was obtained 0.28 ha/h at 30 mm cutting height when forward speed of 2.5 km/h and maximum AFC was 0.54 ha/h at 100 mm cutting height and forward speed of 4.5 km/h. Fig. 4 reveals the uniform rate of increments in AFC with respect to the forward speed and cutting height and it can be inferred from the observation that the increasing straw load at lower cutting height tended increased the unproductive operational time for a fixed set of the test area. However, the overlapping, which was kept within 5%, could have a very minor impact on the AFC. As per the ANOVA analysis presented in Table 6 verified that the forward speed and cutting height, as well as their interaction, have a significant effect on the AFC. The basic regression equation to helps in predicting the AFC with respect to the independent parameters can be written as followed:

$$Y = aX_1 + bX_2 - c \quad (7)$$

where,

Y: Predicted actual field capacity

3.4 Effect on Specific Energy Consumption (kWh/kg)

The statistical analysis in Table 8 reveals that specific energy consumption has a positive and a negative correlation with the cutting height of stubble and forward speed of travel, respectively. The amount of energy consumption per unit of cut straw yield got increased as the cutting height increased but the reverse phenomenon was observed when speed increased. It can also be seen from Fig. 5, how the specific energy consumption value responded to the variation of different parameters. The overall change in the specific energy consumption was found to be 0.10-0.15 kWh/kg for the changing cutting height (30-100 mm) at the forward speed of 2.5 km/h. Likewise, at 3.5 km/h, 4km/h and 4.5 km/h forward speed the specific energy consumption were obtained to be 0.05-0.08 kWh/kg, 0.04-0.06 kWh/kg and 0.03-0.05 kWh/kg, respectively. It can be inferred from these results that the increasing cutting height at a certain speed the amount of cut straw yield got reduced which led to increase in the specific energy consumption. However, as the speed increased both the power requirements and the cut straw yield got reduced thus the specific energy consumption also reduced at a uniform rate. The ANOVA test values presented in Table 6 also shows that the cutting heights of stubbles and forward speeds have significantly affected the specific energy consumption (SEC). To represent the behaviour of different variables to predicting the specific energy consumption it can also be written in an empirical form mentioned below:

$$Y = c + aX_1 - bX_2 \quad (8)$$

where,

Y: Predicted specific energy consumption (kWh/kg)

Table 7. Statistical interpretation of models for field capacity

Model	Coefficient	F statistics	P-value	Collinearity VIF	R^2
Constant	-0.047 (c)	410.24	0.000		0.961
Cutting height (X_1)	0.001(a)			1.00	
Speed (X_2)	0.117(b)			1.00	

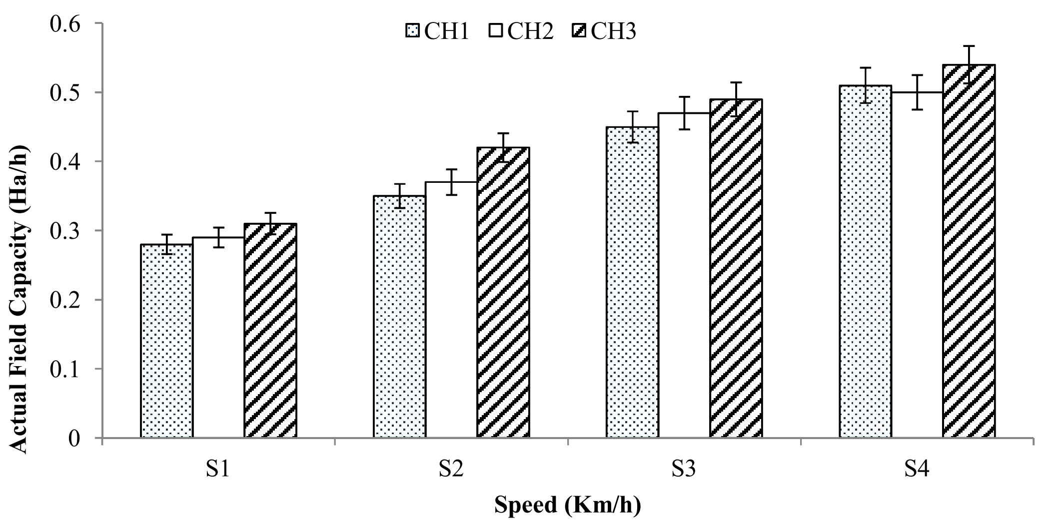

Fig. 4. Effect of cutting height and forward speed on actual field capacity

Table 8. Statistical interpretation of models for energy consumption

Model	Coefficient	F statistics	P-value	Collinearity VIF	R^2
Constant	0.204 (c)	227.84	0.000		0.932
Cutting height (X_1)	0.001(a)			1.00	
Speed (X_2)	-0.04(b)			1.00	

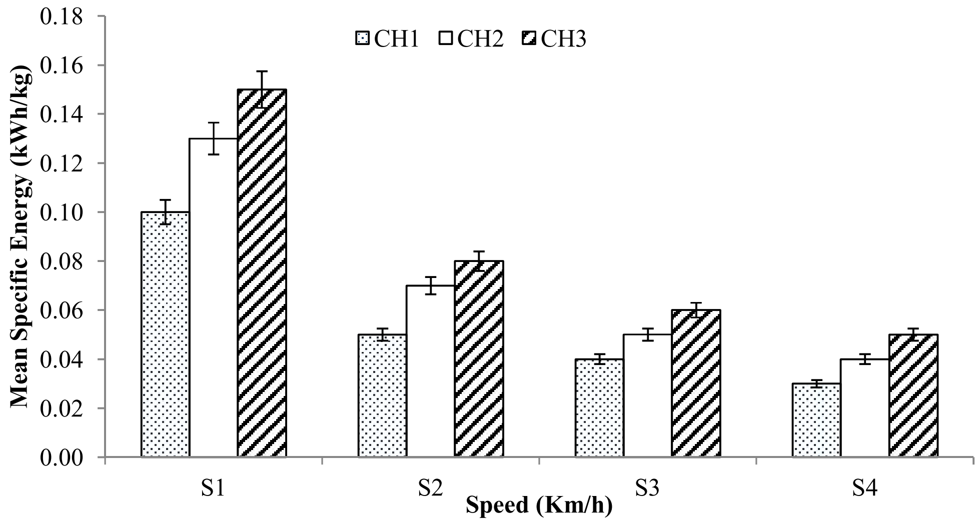

Fig. 5. Effect of cutting height and forward speed on specific energy consumption

4. CONCLUSION

Based on the observations made in the study, it can be construed that the forward speed of travel and the cutting height of stubbles from the ground have a significant influence on the performance quality of a straw reaper-combine.

- The straw recovery percentage of the straw reaper-combine decreased with the increase in speed and cutting height. The maximum recovery was found when the cutting height was maintained within the range of 30 mm to 60 mm from the ground at a forward speed of travel between 2.5 km/h and 4 km/h.
- The straw split percentage of the straw reaper-combine was increased when the cutting height of stubbles reduced and the forward speed was increased. But, to get optimum splitting the cutting height and forward speed should be in the range of 30 mm to 60 mm and 3 km/h to 4 km/h, respectively and range of straw recovery was 86-97%.
- The actual field capacity was found to have a direct relationship with the cutting height and forward speed.
- The specific energy consumption during the operation was increased with the increasing cutting height but it decreased when the forward speed was increased. So to keep the consumption low the straw reaper-combine should be operated at speed of 3 km/h to 4 km/h with cutting height between 30 mm and 60 mm and overall change in the specific energy consumption was 0.10-0.15 kWh/kg for cutting height 30 mm to 100 mm.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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