PERFORMANCE EVALUATION OF STRAW COMBINE IN WHEAT USING RESPONSE SURFACE METHODOLOGY

ANIL KUMAR*[1], VIJAYA RANI[1], SUNDEEP KUMAR ANTIL[2] AND PARVESH ANTIL[1]

[1]COAE&T, CCS Haryana Agricultural University, Hisar-125 004 (Haryana), India
[2]KVK, Sonipat, CCS HAU, Hisar
(e-mail: anilsaroha@hau.ac.in)

(Received: 3 May 2025; Accepted: 23 June 2025)

SUMMARY

A newly developed straw combine suitable for paddy and wheat crop was evaluated in HD - 2967 wheat variety for its performance and retrieval of wheat straw. The straw combine was evaluated at three levels of moisture content (5, 10 and 15 %) and three levels of cylinder speed (29.6, 31.4 and 33.2 m s^{-1}) and forward speed (1.7, 1.9 and 2.1 km $h^{-1)}$ in terms of field capacity, field efficiency, fuel consumption, straw split and straw size. The response surface methodology (RSM) was adopted for multi response optimization of straw combine parameters. Based on results obtained through RSM, it was found that the optimum combination for harvesting of wheat variety HD - 2967 was found to be moisture content of 5%, forward speed of 1.91 km h^{-1} and cylinder speed of 33.20 m s^{-1}.

Key words: Cylinder speed, field capacity, forward speed, fuel consumption, moisture content

Rice-wheat is the major cropping system in Haryana and is very important for country food security. In this system use of combine harvesters is increasing mainly because of shortage of farm labour. Combine harvesting leaves large amount of crop residues in the field (Ingole *et al.*, 2019, 2019a). The left over wheat straw is collected by using straw reapers/combines (Kumar, *et al.*, 2010, Ujala *et al.*, 2020) and balers (Thakur, *et al.*, 2000, Kumar *et al.*, 2020) and is normally used as animal feed (Shrivastava *et al.*, 2012), but these machines are not effective in paddy fields, mainly because of higher moisture content of paddy straw at the time of harvesting and cutting behavior of straw (Kumar *et al.*, 2022, 2022a) and need modifications in cutting and conveying system of straw combine (Kumar *et al.*, 2020, 2024). The balers are available for removing the paddy straw from the field (Kumar *et al.*, 2020a), but the cost of balers is too high (Kathpalia *et al.*, 2024) and are not economical for removing straw from the field. Today, there is a need to develop cost effective machine for removing paddy straw from the field after combine harvesting (Kumar *et al.*, 2020).In India, presently there is net deficit of 10.95 % dry fodder, 35.60 % green fodder and 44.00 % concentrate feed ingredients (IGFRI, Vision, 2050). These situations call for use of alternative sources of feed and fodder to fill up the demand and supply gap. The rice straw is a good alternative and it can be used as fodder for animals by improving its nutritional values (Kumar *et al.*, 2014), but needs economically viable option for removing paddy straw from the field. Therefore, the machines, straw reaper/combine and straw balers are used only in one season and resulted in high economical losses to the farmers. Keeping in view of the above, a straw combine suitable for both paddy and wheat crop was developed in the department of Farm Machinery and Power Engineering, COAE&T, CCSHAU, Hisar by modifying the chopping and blowing unit of the straw reapers which is farmer-friendly, economical and having options of removing or leaving full/ partial residue from the field. The developed version of straw combine was evaluated in wheat variety HD - 2967 for its performance in terms of field capacity, efficiency, fuel consumption, straw split and straw size.

MATERIALS AND METHODS

The straw combine was evaluated for optimization of parameters *viz.*, cylinder speed, forward speed and crop parameter *viz.*, moisture content in relation to field capacity, fuel consumption, straw size and straw recovery in wheat variety HD - 2967. The experimental variables are presented in Table 1. This study was conducted at farmer's field in Ludas village of Hisar district. The crop and field parameters of the study are presented in Table 2. The quantitative data was quantified according to standards laid down and tabulated to draw meaningful inferences. The data

TABLE 1
Independent variables and their levels for paddy crop

S. No.	Independent variable	Abbreviation	Units	Levels	Values
1.	Moisture content (*w.b.*)	MC	%	3	5, 10, 15
2.	Forward speed	FS	km h^{-1}	3	1.7, 1.9, 2.1
3.	Cylinder speed	CS	m s^{-1}	3	29.6, 31.4, 33.2

TABLE 2
Crop and field parameters of wheat

Particulars	Range
Crop	Wheat
Variety	HD - 2967
Straw moisture content (%)	5 - 15
Weight of loose straw (g m^{-2})	140 - 150
Height of stubble before operation (cm)	25 - 40
Height of stubble after operation (cm)	5 - 7
Weight of standing stubble (g m^{-2})	470 - 520
Stem diameter of straw (mm)	2.14 – 4.86
Stem thickness of straw (mm)	0.33 - 0.58
Length of straw (cm)	83.25 - 97.20
Straw availability (q ha^{-1})	62.0 - 70.0

were analyzed using RSM approach for multi-objective optimization.

RESULTS AND DISCUSSION

Performance evaluation of straw combine in wheat straw

Multiple regression techniques was used to study the relationship between cylinder speed, forward speed and moisture content in relation to field capacity (ha h^{-1}), field efficiency (%), fuel consumption (l h^{-1}), chopping efficiency (%), straw split (%) and straw size (mm). The regression equation is based on experimental data. The prediction equation was:

Effect of moisture content, forward speed and cylinder speed on field capacity

The analysis of variance of the field capacity revealed that the effect of moisture content, forward speed and cylinder speed on field capacity was significant, however, the effects of interaction of variables were non-significant (Table 3). The F - value for the forward speed was highest (295.92) indicating that forward speed had maximum effect on field capacity. The regression coefficient of moisture content was negative in equation (i), which indicated that increase of moisture content resulted in decrease in field capacity, however, positive value of forward speed and cylinder speed indicated that field capacity increased with increase in forward speed and cylinder speed. The coefficient of determination indicated that these variables contributed 98.21 % in total variation to field capacity. The field capacity was minimum (0.26 ha

$$FC = -0.01233-0.00225\times MC+0.13125\times FS+0.0027\times CS \quad (R^2 = 98.21)\ldots\ldots\ldots\text{(i)}$$
$$FE = 69.3742-0.5625\times MC-5.6875\times FS+0.56944\times CS \quad (R^2 = 92.51)\ldots\ldots\ldots\text{(ii)}$$
$$\text{Fuel C} = -0.84845+0.11\times MC+1.375\times FS+0.11111\times CS \quad (R^2 = 98.31)\ldots\ldots\ldots\text{(iii)}$$
$$SS = 92.847-0.1375\times MC+1\times FS+0.1597\times CS \quad (R^2 = 96.84)\ldots\ldots\ldots\text{(iv)}$$
$$\text{S Size} = 43.8831+0.725\times MC-5\times FS-0.7638\times CS \quad (R^2 = 95.79)\ldots\ldots\ldots\text{(v)}$$

TABLE 3
ANOVA for the effect of moisture content, forward speed and cylinder speed on field capacity

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated	Significance
MC	2	0.008	0.004	63.221	0.00001
FS	2	0.037	0.019	295.92	0.00001
MC x FS	4	0	0	0.683	0.60691
CS	2	0.001	0.001	11.692	0.00006
MC x CS	4	0	0	0.829	0.5125
FS x CS	4	0	0	0.243	0.91274
MC x FS x CS	8	0	0	0.115	0.99848
Error	54	0.003	0		
Total	80	0.051			

h^{-1}) at moisture content of 15 %, forward speed of 1.7 km h^{-1} and cylinder speed of 29.6 m s^{-1}. It increased as the moisture content decreased from 15 to 5 %, forward speed increased from 1.7 to 2.1 km h^{-1} and cylinder speed increased from 29.6 to 33.2 m s^{-1} (Fig. 1-3). The maximum field capacity at higher forward speed was due to more coverage area. The minimum field capacity at higher moisture content might be due to the fact that at higher moisture content the straw chocking problem was more which increased the operating time in the field. The higher field capacity at higher cylinder speed might be due to the fact that at higher cylinder speed there are more number of cuts per unit time resulted in effective cutting of straw and less incidences of cylinder chocking. The results are in line with the results observed by Mahmood *et al.* (2016), Virk (2016) and Upadhyay *et al.* (2018).

Effect of moisture content, forward speed and cylinder speed on field efficiency

The analysis of variance data of the field efficiency showed that the effect of moisture content, forward speed and cylinder speed on field efficiency was significant; however, the effects of interaction of variables were non-significant (Table 4). The F - value for moisture content was highest (66.094) indicating that moisture content had maximum effect on the field efficiency. The regression coefficient of moisture content and forward speed was negative in equation (ii), which indicated that increase in these variables resulted in decrease in field efficiency, however, positive value of cylinder speed indicated that field efficiency increased with increase in cylinder speed. The coefficient of determination indicated that these independent variables contributed 92.51 % to total variation in field efficiency. The field efficiency was minimum (66.40 %) at moisture content of 15 %, forward speed of 2.1 km h^{-1} and cylinder speed of 29.6 m s^{-1}. It increased as the moisture content decreased from 15 to 5 %, forward speed decreased from 2.1 to 1.7 km h^{-1} and cylinder speed increased from 29.6 to 33.2 m s^{-1} (Fig. 4-6). The field efficiency decreased with increase in forward speed as at higher speed, it becomes difficult to control the machine in the field. The results are in conformity with the results reported by Anjum *et al.* (2015). The minimum field efficiency at higher moisture content may be due to the fact that at higher moisture content the straw chocking problem was more which

TABLE 4

ANOVA for the effect of moisture content, forward speed and cylinder speed on field efficiency

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated	Significance
MC	2	404.358	202.179	66.094	0.00001
FS	2	95.535	47.768	15.616	0.00001
MC x FS	4	12.077	3.019	0.987	0.42251
CS	2	65.416	32.708	10.693	0.00012
MC x CS	4	3.523	0.881	0.288	0.88455
FS x CS	4	0.547	0.137	0.045	0.99611
MC x FS x CS	8	1.9	0.238	0.078	0.99964
Error	54	165.184	3.059		
Total	80	748.54			

TABLE 5

ANOVA for the effect of moisture content, forward speed and cylinder speed on fuel consumption

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated	Significance
MC	2	16.66	8.33	168.684	0.00001
FS	2	3.93	1.965	39.789	0.00001
MC x FS	4	0.047	0.012	0.236	0.91664
CS	2	2.848	1.424	28.839	0.00001
MC x CS	4	0.135	0.034	0.683	0.60705
FS x CS	4	0.252	0.063	1.275	0.29117
MC x FS x CS	8	0.083	0.01	0.21	0.98793
Error	54	2.667	0.049		
Total	80	26.621			

increased operation time in field. The field efficiency was maximum at higher cylinder speed which may be due to the reason that there is more number of cuts per unit time at higher cylinder speed resulting in effective cutting of straw and less incidences of cylinder chocking. The results are in conformity with the results reported by Singh *et al.* (2011), Mahmood *et al.* (2016), Virk (2016) and Upadhyay *et al.* (2018).

Effect of moisture content, forward speed and cylinder speed on fuel consumption

The effect of moisture content, forward speed and cylinder speed on fuel consumption was significant. The effects of individual interaction of variables were non-significant, however, the combined effect of straw moisture, forward speed and cylinder speed was found significant (Table 5). The F - value for the moisture content was highest (168.684) indicating that moisture content had maximum effect on fuel consumption. The regression coefficient of moisture content, forward speed and cylinder speed was positive in equation (iii), which indicated that increase of these variables resulted in increase in fuel consumption. The coefficient of determination indicated that these variables contributed 98.31% in total variation in fuel consumption. The fuel consumption was minimum (5.57 l h^{-1}) at moisture content of 5%, forward speed of 1.7 km h^{-1} and cylinder speed of 29.6 m s^{-1}. It increased as the moisture content increased from 5 to 15%, forward speed increased from 1.7 to 2.1 km h–1and cylinder speed increased from 29.6 to 33.2 m s^{-1} (Fig. 7-9). It might be due to the fact that at lower moisture content and forward speed straw load on the machine is less and it increased with increase in moisture content and forward speed as more power is required to handle it. The fuel consumption was more at higher cylinder speed might be due to the fact that there are more number of cuts per unit time at higher cylinder speed resulting in effective cutting but more power requirement. The results are in line with the results observed by Anjum *et al.* (2015), Mahmood *et al.* (2016) and Virk (2016).

Effect of moisture content, forward speed and cylinder speed on straw split

The analysis of variance of straw split indicated that the effect of moisture content, forward speed, cylinder speed and effect of their interactions on straw split were non-significant (Table 6). The F - value for the moisture content was highest (1.821) indicating that moisture content had maximum effect on straw split. The regression coefficient of moisture content was negative in equation (iv), which indicated that increase of moisture content resulted in decrease in straw split, however, positive value of forward speed and cylinder speed indicated that straw split increased with the increase in forward speed and cylinder speed. The coefficient of determination indicated that these variables contributed 96.84 % to total variation to straw split. The straw split was minimum (97.07 %) at moisture content of 15 %, forward speed of 1.7 km h^{-1} and cylinder speed of 29.6 m s^{-1}. It increased as the moisture content decreased from 15 to 5 %, forward speed increased from 1.7 to 2.1 km h^{-1} and cylinder speed increased from 29.6 to 33.2 m s^{-1} (Fig. 10-12). The lower straw split at higher moisture content may be due to the fact that at higher moisture content the ductile nature of straw made difficulty in straw split. The straw split increased with increase in forward speed. It might be due to fact that at higher forward speed more material present in cylinder causes compression, vigorous rubbing and agitation

TABLE 6

ANOVA for the effect of moisture content, forward speed and cylinder speed on straw split

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated	Significance
MC	2	25.381	12.69	1.821	0.17172
FS	2	2.72	1.36	0.195	0.82332
MC x FS	4	0.122	0.03	0.004	0.99996
CS	2	5.625	2.813	0.404	0.66996
MC x CS	4	0.305	0.076	0.011	0.99976
FS x CS	4	-0.002	-0.001	0	1.00000
MC x FS x CS	8	0.056	0.007	0.001	1.00000
Error	54	376.389	6.97		
Total	80	410.595			

TABLE 7
ANOVA for the effect of moisture content, forward speed and cylinder speed on straw size

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated	Significance
MC	2	642.247	321.123	101.21	0.00001
FS	2	35.951	17.975	5.665	0.00584
MC x FS	4	4.198	1.049	0.331	0.8561
CS	2	91.358	45.679	14.397	0.00001
MC x CS	4	0.79	0.198	0.062	0.99264
FS x CS	4	2.42	0.605	0.191	0.94227
MC x FS x CS	8	5.21	0.651	0.205	0.98874
Error	54	171.333	3.173		
Total	80	953.506			

amongst different layers of crop material. The straw split also increased with increase in cylinder speed may be due to the fact that at higher cylinder speed, the motion of blades of cylinder relative to the material was higher, which causes maximum bruising of straw. The results are in conformity with the results of Singh (1995) and Dhimate (2014).

Effect of moisture content, forward speed and cylinder speed on straw size

The analysis of variance of straw size showed that the effect of moisture content, forward speed and cylinder speed on straw size was significant (Table 7), however, the effects of interaction of variables were non-significant. The F - value for the moisture content was highest (101.21) indicating that moisture content had maximum effect on straw size. The regression coefficient of moisture content was positive in equation (v), which indicated that increase of moisture content resulted in increase in straw size, however, negative value of regression coefficient of forward speed and cylinder speed indicated that straw size decreased with increase in forward speed and cylinder speed. The coefficient of determination indicated that these variables contributed 95.79 % in total variation in straw size. The straw size was maximum (23.67 mm) at moisture content of 15%, forward speed of 1.7 km h^{-1} and cylinder speed of 29.6 m s^{-1}. It decreased as the moisture content decreased from 15 to 5 %, forward speed increased from 1.7 to 2.1 km h^{-1} and cylinder speed increased from 29.6 to 33.2 m s^{-1} (Fig. 13-15). It may due to the fact that at higher forward speed and lower cylinder speed more straw comes into chopping unit and due to less number of cuts per unit time, the straw size increased. Secondly, at higher moisture content elasticity of straw increased and it becomes difficult to chop. Similar results were reported by Dhimate (2014) who reported that straw size decreased from 20.23 to 12.22 mm with increase in cylinder speed from 28.35 to 36.4 m s^{-1} and feed rate from 14 to 19 q h^{-1} in wheat by using straw combine. Anjum *et al.* (2015) also observed similar results in wheat crop.

Multi Response Optimization (MRO) using Desirability Factor (DF) in wheat straw

The response surface methodology based desirability approach was used to optimize the process parameters for multi response characteristics (Antil *et al.,* 2020, Antil *et al.,* 2022). The obtained models for each response characteristic was proved to be significant and generated regression equation closed to 1 in each case (Kharb *et al.,* 2020, Antil *et al.,* 2021, Jakhar *et al.* 2022). The RSM model showed that field capacity was minimum at higher moisture content, lower forward speed and lower cylinder speed. The field efficiency and chopping efficiency were obtained as minimum at higher level

TABLE 8
Variable and their levels for desirability in wheat straw

Variable	Goal	Lower Limit	Upper Limit	Importance
A:MC	in range	5	15	3
B:FS	in range	1.7	2.1	3
C:CS	in range	29.6	33.2	3
FC	maximize	0.26	0.34	3
FE	maximize	67.2	76.4	3
Fuel C	minimize	5.6	7.2	3
SS	maximize	97.3	99.3	3
S Size	minimize	13	23	3

TABLE 9
Possible combinations for optimum use of straw combine in wheat straw

No	MC	FS	CS	FC	FE	Fuel C	SS	S Size	Desirability	Decision
1	5.0	1.9	33.2	0.32	75.04	5.95	99.28	13.00	0.880	Selected
2	5.0	1.9	33.2	0.32	75.05	5.95	99.27	13.01	0.880	
3	5.0	1.9	33.2	0.32	75.07	5.94	99.27	13.03	0.880	
4	5.0	1.9	33.2	0.32	75.01	5.95	99.28	12.98	0.880	
5	5.0	1.9	33.2	0.32	75.12	5.94	99.27	13.08	0.880	
6	5.0	1.9	33.2	0.32	75.02	5.95	99.28	13.00	0.880	
7	5.0	1.9	33.2	0.32	75.16	5.93	99.26	13.11	0.879	
8	5.0	1.9	33.2	0.32	74.97	5.96	99.28	12.94	0.879	
9	5.0	1.9	33.2	0.32	75.00	5.95	99.28	13.00	0.879	
10	5.0	1.9	33.2	0.32	75.18	5.93	99.26	13.13	0.879	
11	5.0	1.9	33.2	0.32	74.96	5.96	99.29	12.93	0.879	
12	5.0	1.9	33.2	0.32	74.92	5.97	99.29	12.89	0.879	
13	5.0	1.9	33.2	0.32	74.90	5.97	99.29	12.87	0.879	
14	5.0	1.9	33.2	0.32	75.29	5.91	99.25	13.23	0.879	
15	5.0	1.9	33.2	0.32	75.00	5.96	99.27	13.00	0.879	

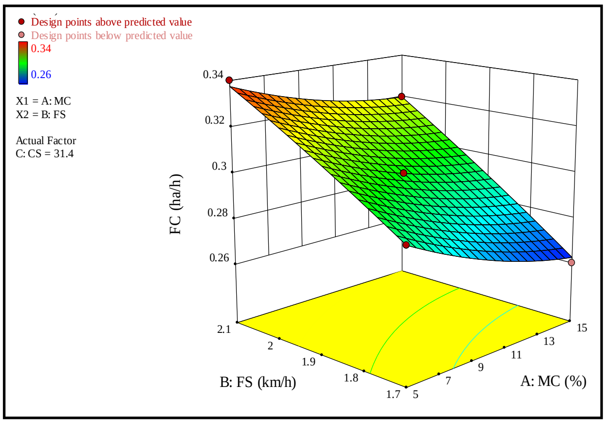

Fig. 1. Effect of moisture content and forward speed on field capacity (ha h^{-1}).

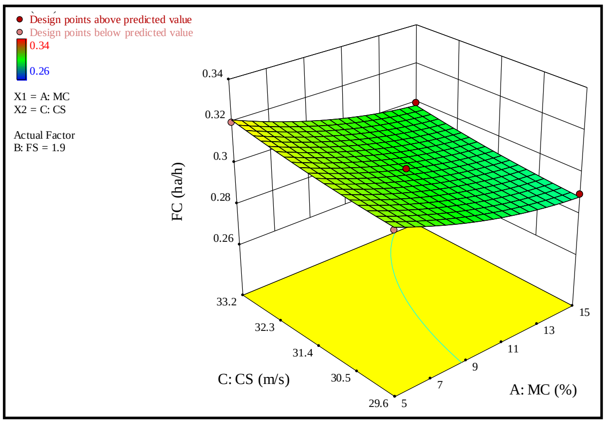

Fig. 2. Effect of moisture content and cylinder speed on field capacity (ha h^{-1}).2

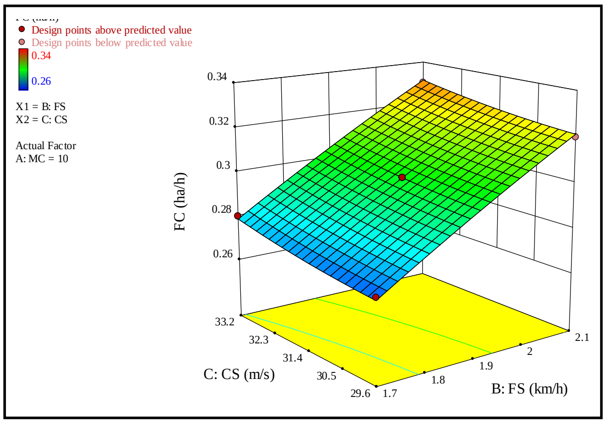

Fig. 3. Effect of cylinder speed and forward speed on field capacity (ha h^{-1}).

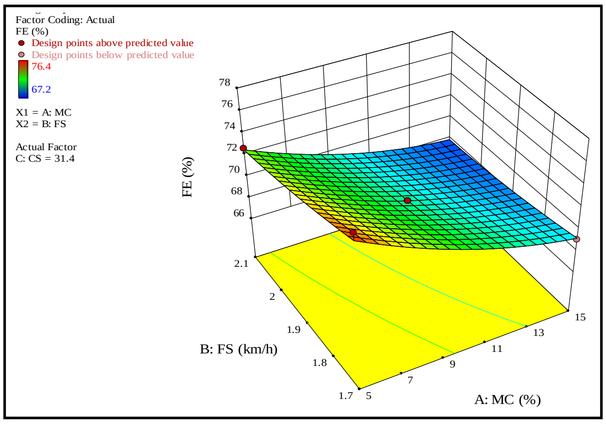

Fig. 4. Effect of moisture content and forward speed on field efficiency (%).

of moisture content as well as forward speed and lower level of cylinder speed. The fuel consumption decreased at lower level of each input parameter. The straw split was minimum at higher level of moisture content and lower level of forward speed and cylinder speed. The minimum straw size was obtained at lower level of moisture content and higher level of forward speed and cylinder speed. The single

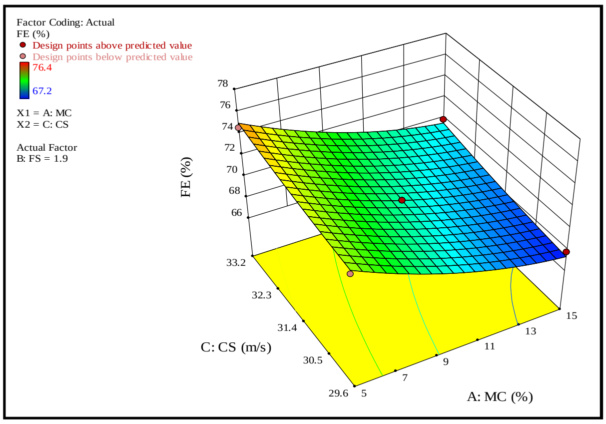

Fig. 5. Effect of moisture content and cylinder speed on field efficiency (%).

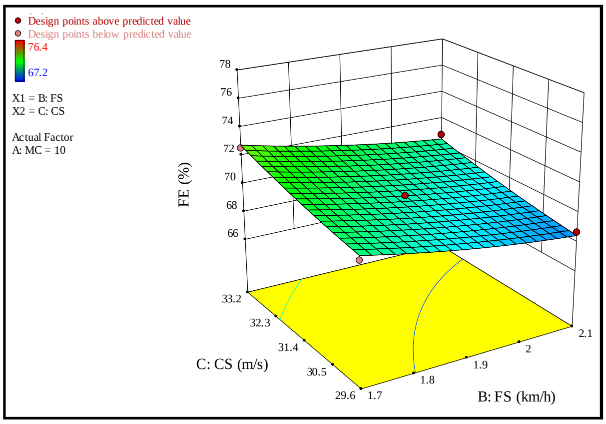

Fig. 6. Effect of cylinder speed and forward speed on field efficiency (%).

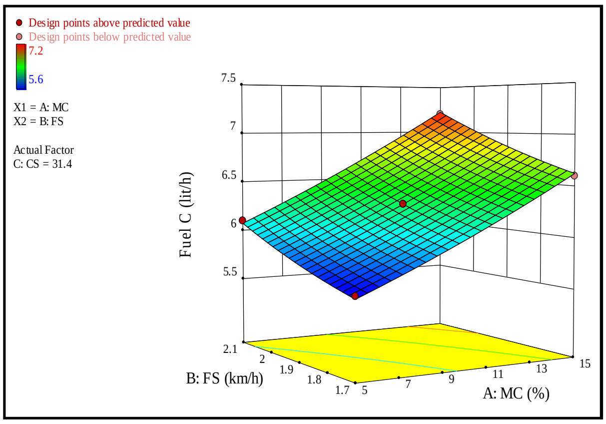

Fig. 7. Effect of moisture content and forward speed on fuel consumption (l h^{-1}).

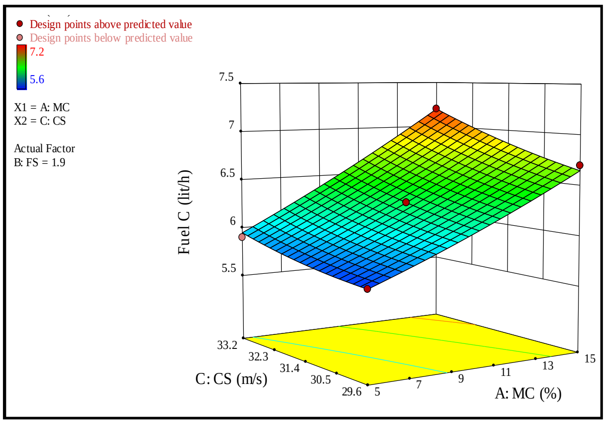

Fig. 8. Effect of moisture content and cylinder speed on fuel consumption (l h^{-1}).

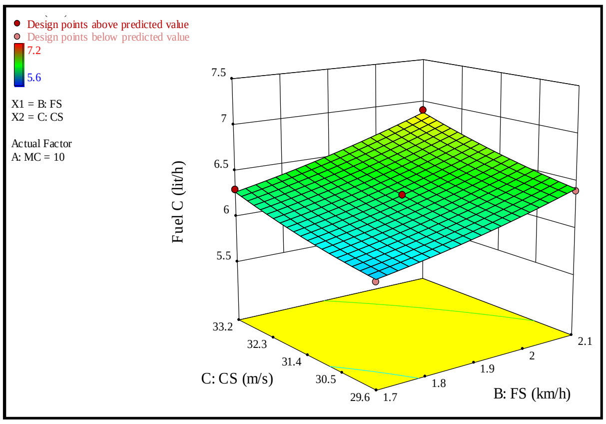

Fig. 9. Effect of cylinder speed and forward speed on fuel consumption (l h^{-1}).

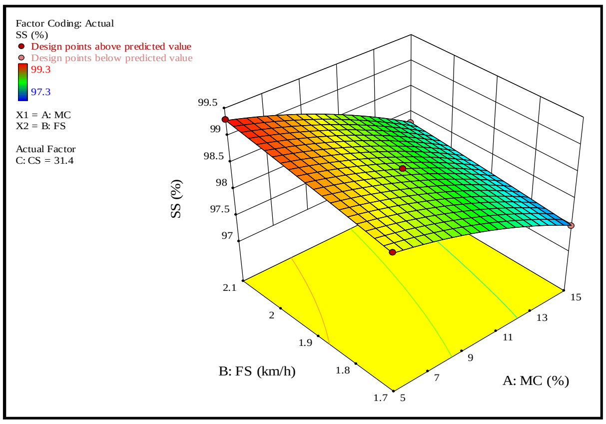

Fig. 10. Effect of moisture content and forward speed on straw split.

response optimization through RSM produced results which give the optimum results which suits the individual output at a time (Antil *et al.* 2019). In harvesting process it becomes necessary to optimize all the process parameters to produce optimized results for all response parameters. The desirability function was employed in order to obtain the only one set of parameters which can give cumulative result for output responses. The variable and their levels for desirability are shown in Table 8. The desirability function indicated that best field capacity (0.32 ha h-^{3}), field efficiency (75.04%), chopping efficiency (99.50%), straw split (99.28), minimum straw size (13 mm), and fuel consumption (5.95 l h$^-$

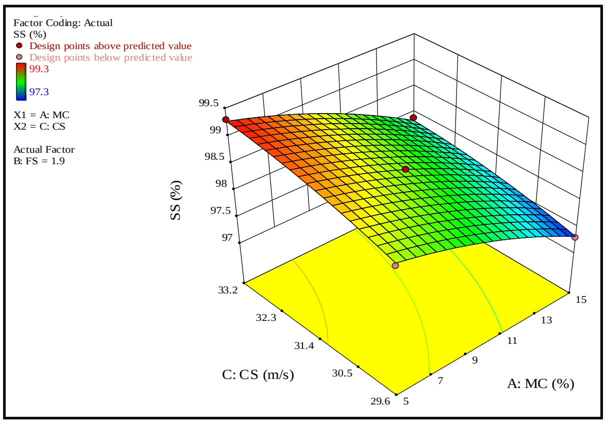

Fig. 11. Effect of moisture content and cylinder speed on straw split (%).

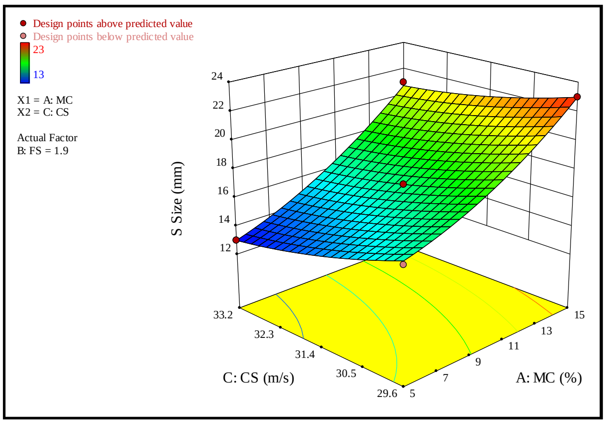

Fig. 14. Effect of moisture content and cylinder speed on straw size (mm).

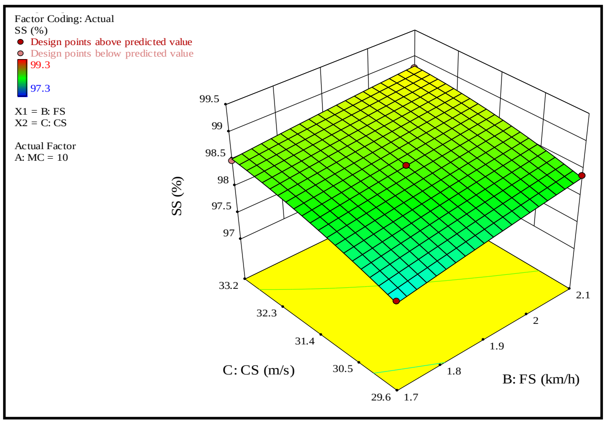

Fig. 12. Effect of cylinder speed and forward speed on straw split (%).

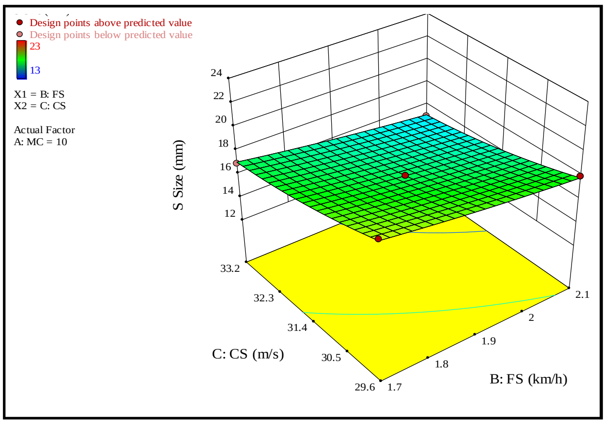

Fig. 15. Effect of cylinder speed and forward speed on straw size (mm).

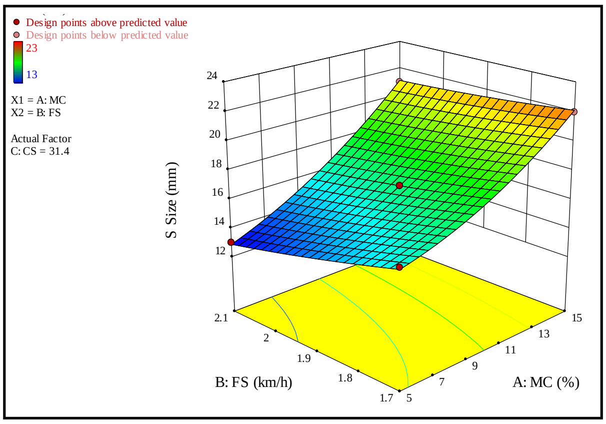

Fig. 13. Effect of moisture content and forward speed on straw size (mm).

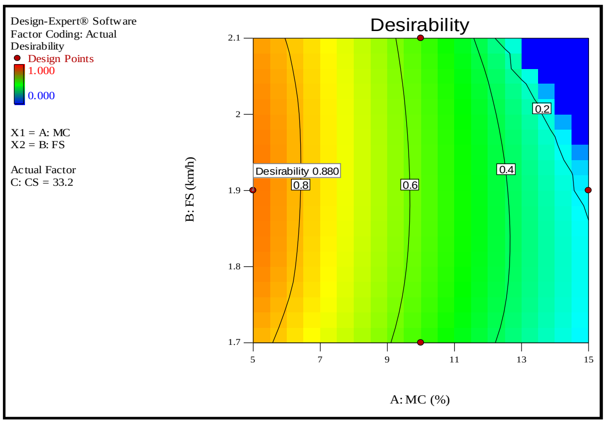

Fig. 16. Contour plot for overall desirability at 33.2 m s^{-1} cylinder speed.

³) could be reached as long as the moisture content stayed low (5%), the forward speed stayed medium (1.9), and the cylinder speed stayed high (33.2) (Table 9). The contour plots for cylinder speed, forward speed and moisture content having respective desirability are shown in Fig. 16-18.

CONCLUSIONS

Based on the experimental results it is concluded that the optimal condition of machine-crop parameters in wheat variety HD - 2967 was moisture content at 5%, forward speed at 1.9 km h^{-1} and cylinder

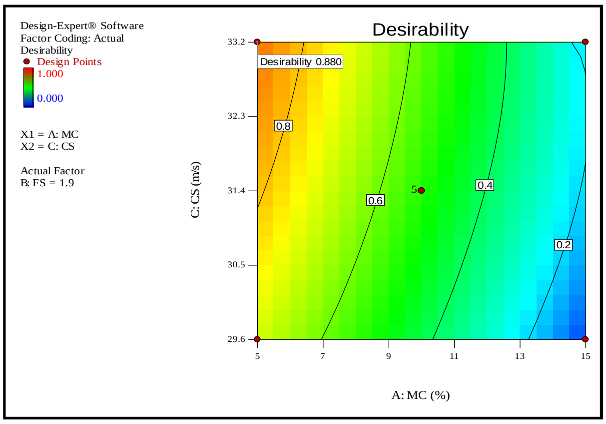

Fig. 17. Contour plot for overall desirability at 1.9 km h^{-1} forward speed .

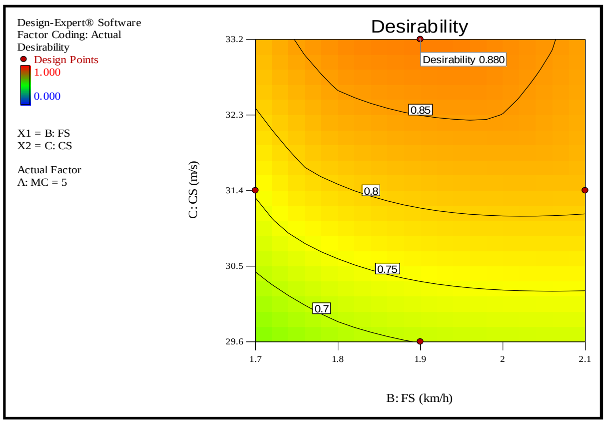

Fig. 18. Contour plot for overall desirability at 5 % moisture content.

speed at 33.2 m s^{-1} which gives maximum field capacity (0.32 ha h^{-1}), field efficiency (75.04 %), straw split (99.28 %), minimum straw size (13 mm) and fuel consumption (5.95 l h^{-1}).

REFERENCES

Anjum, A., A. Ghafoor, A. Munir, M. Iqbal and M. Ahmad, 2015: Design modification of conventional wheat straw chopper. *Agricultural Engineering International: CIGR Journal*, **17**(1): 50-57.

Antil, P., A. Saroha, C. Jakhar, M. Singh, and R. Singh, 2022: Optimization of wear behavior of straw combine blade through RSM and ANN models. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, **17**: 2237-2246.

Antil, S.K., P. Antil, S. Singh, A. Kumar and C.I. Pruncu, 2020: Artificial neural network and response surface methodology based analysis on solid particle erosion behavior of polymer matrix composites. *Materials*, **13**(6): 1381

Antil, P., S. Singh, A. Manna, N. Katal, and C. Pruncu, 2021: An improvement in drilling of SiCp/glass fiber-reinforced polymer matrix composites using response surface methodology and multi-objective particle swarm optimization. *Polymer Composites*, **42**: 5051-5064.

Antil, P., S. Singh and A. Manna, 2019: Experimental investigation during electrochemical discharge machining (ECDM) of hybrid polymer matrix composites. *Iran J Sci Technol Trans Mech Eng*, **44**: 813-824.

Dhimate, A.S. (2014) Refinement and evaluation of straw bruising and sieving system for wheat straw. *Unpublished M. Tech. thesis*. Department of Farm Machinery and Power Engineering, PAU, Ludhiana, Punjab, India.

IGFRI Vision 2050: Indian Grassland and Fodder Research Institute, Jhansi (UP).

Ingole, O.A., A. Kumar, S. Mukesh, V. Rani, N. Kadwasra and K. Verma, 2019: Optimization of combine and crop parameters for harvesting of scented and non scented paddy by head feed combine. *Indian Journal of Agricultural Sciences*, **89**(3): 522-530.

Ingole, O.A., A. Kumar, M. Jain, V. Rani and Naresh, 2019a: Optimization of parameters for harvesting of paddy by head feed combine. *Agri. Engineering Today*, **43**(4), 18-26.

Jakhar, C., A. Saroha, P. Antil, V. Ahlawat, A. Rani, D. Buddhi and V. Kumar, 2022: Deep cryogenic treated high carbon steel blades: Tribological, morphological and economic analysis, *Surface Review and Letters*, https://doi.org/10.1142/S0218625X22410025.

Kathpalia, J., R. Tyagi, A.K. Saroha, R. Sihag, 2024: Knowledge and advantages of adoption of Straw baler among farmers in Haryana, *International Journal of Education & Management Studies*, **14**(2): 189-193

Kharb, S.S., P. Antil, S. Singh, K. Singh, P. Sihag and A. Kumar, 2020: Machine learning based erosion behavior of silicon carbide reinforced polymer composites. *Silicon*, 1**3**: 1113-1119.

Kumar, A., Kapil, N.K. Bansal and S. Arya, 2010: Wheat straw retrieval from combine harvested field for use as cattle feed. *Journal of Forage Research*, **36**(3): 146-149.

Kumar, A., S.K. Antil and V. Rani, 2022: Effect of moisture content and internode position on cutting behavior of paddy straw. *Forage Research*, **48**(2): 264-271.

Kumar, A., V. Rani, S.K. Antil and A. Chillar, 2022a: Cutting force requirement of wheat straw for use as animal fodder. *Forage Research*, **48**(1): 118-124.

Kumar, A., S.K. Antil, V. Rani, P. Antil, D. Jangra, R. Kumar and C.I. Pruncu, 2020: Characterization on physical, mechanical and morphological properties of Indian wheat crop. *Sustainability*, **12**: 2067.

Kumar, A., S.K. Antil, V. Rani, P. Antil and R. Kumar, 2024: Performance evaluation of developed straw combine in paddy straw retrieval using response surface methodology. *Forage Res.*, **50**(3), 320-329.

Kumar, A., V.K. Singh, Narender and R. Kumar, 2014: Utilization of paddy straw as animal feed. *Forage Res.*, **40**(3): 154-158.

Kumar, A., V. Rani, M. Jain, R. Kumar and N. Karwasra, 2020a: Paddy straw retrieval by using straw baler for use as animal feed. *Forage Res*., **46**(1): 84-87.

Mahmood, H.S., T. Ahmad, Z. Ali, M. Ahmad and N. Amjad, 2016: Field evaluation of a wheat straw chopper. *Pakistan Journal of Agricultural Research*, **29**(3): 301–314.

Shrivastava, B., P. Nandal, A. Sharma, K.K. Jain and Y.P. Khasa, 2012: Solid state bioconversion of wheat straw into digestible and nutritive ruminant feed by Ganoderma. *Bioresource Technology*, **107**: 347-351.

Singh, M. 1995: Investigation into some design and operational parameter of a straw combine. *Unpublished M. Tech. thesis*, Department of Farm Machinery and Power Engineering, Punjab Agricultural University, Ludhiana, Punjab, India.

Thakur, T.C., O.A. Bamaga and M.L. Verma, 2000: Collection, densification and utilization of paddy and wheat straw - present status and future prospective. *Agricultural Engineering Today*, **24**(4): 1-16.

Ujala, A. Kumar, S. Kumar, R. Kumar and S. Kumar, 2020: Performance evaluation of paddy straw reaper in paddy variety Pusa - 44. *Forage Res*., **45**(4): 328-334.

Upadhyay, A.K., V. Singh and S.C. Moses, 2018: To study the effective speed of harvesting of wheat straw by straw combine. *International Journal of Agricultural Engineering*, **11**(1): 54–59.

Virk, G. 2016: Performance evaluation of paddy straw chopper with combine cutting head mechanism. *Unpublished M. Tech. thesis*, Department of Farm machinery and Power Engineering, PAU, Ludhiana, Punjab, India.