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PERFORMANCE EVALUATION OF DEVELOPED STRAW COMBINE IN PADDY STRAW RETRIEVAL USING RESPONSE SURFACE METHODOLOGY

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SUMMARY

A newly developed straw combine suitable for paddy and wheat crop was evaluated in PUSA – 1121 paddy variety for its performance and retrieval of paddy straw. The straw combine was evaluated at three levels of moisture content (20, 35 and 50 %) and three levels of cylinder speed (29.6, 31.4 and 33.2 m/s) and forward speed (1.7, 1.9 and 2.1 km/h) 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 paddy variety PUSA–1121 was found to be moisture content of 20 %, forward speed of 1.91 km h^{-1} and cylinder speed of 33.20 m/s.

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

Rice-wheat is the major cropping system in North-Western Indian plains covering more than 4 million ha area and is very important for country food security (Singh *et al.*, 2018). 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 easily collected by using straw reapers/combines (Kumar, *et al.*, 2010) 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). Moreover, the paddy straw is considered as inferior quality feed due to lower lignin content (6-7%) and higher silica content (12-16%) and is hardly used as fodder (Castrillo *et al.*, 1990, Singh and Sidhu, 2014). Thus, the farmers burnt most of paddy straw in the field (Singh et *al.*, 2010b). On the other hand we are not fulfilling the demand of fodders for our animals and it was reported that the country is facing 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). Today, there is a need to develop cost effective machine for removing paddy straw from the field after combine harvesting (Kumar *et al.*, 2020). At present, the locally developed tractor operated machine commonly known as 'straw reaper' or 'straw combine' is used for removing wheat straw (Bhardwaj and Mahal, 2014), but these machines are not effective in paddy fields and need modifications. The balers are also 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 paddy straw for use as fodder. 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 paddy variety PUSA-1121 for its performance in terms of field capacity, efficiency, fuel consumption, straw split and straw size.

MATERIAL 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 paddy variety PUSA - 1121. 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 were analyzed using RSM approach for multi-objective optimization.

RESULTS AND DISCUSSION

Performance evaluation of straw combine in paddy 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), field efficiency (%), fuel consumption (l/h), chopping efficiency (%), straw split (%) and straw size (mm). The regression equation is based on experimental data. The prediction equation was:

FC	=	$0.137-0.00192\times MC+0.075\times FS+0.00208\times CS$	(R^2 = 92.90)……….(i)
FE	=	$94.4328-0.0470\times MC-15.937\times FS+0.569448\times CS$	(R^2 = 98.06)......…...(ii)
Fuel C	=	$-0.1087+0.051667\times MC+1.4375\times FS+0.0763\times CS$	(R^2 = 99.33)……..…(iii)
SS	=	$72.3811-0.54667\times MC-3.625\times FS+0.875\times CS$	(R^2 = 90.12)……....(iv)
S Size	=	$35.8341+1.59166MC+11.25FS-1.59722CS$	(R^2 = 93.35)……….(v)

TABLE 2

Crop and field parameters of paddy

Particulars	Range
Crop	Paddy
Variety	Pusa-1121
Straw moisture content (%)	20-50
Weight of loose straw (g/m^2)	125-150
Length of loose straw (cm)	22-40
Height of stubble before harvesting (cm)	25-42
Height of stubble after harvesting (cm)	6-9
Weight of standing stubble (g/m^2)	390-445
Stem diameter of straw (mm)	1.26-5.10
Stem thickness of straw (mm)	0.15-0.59
Length of straw (cm)	86.50-91.90
Straw availability (q/ha)	54.0-57.0

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

The regression coefficient of moisture content is negative in equation (i), which indicated that field capacity decreased with increase in moisture content. The positive values of regression coefficients of forward speed and cylinder speed indicated that field capacity increased with the increase in forward speed and cylinder speed. The coefficient of determination indicated that these variables contributed 92.90% to total variation in field capacity. The effect of moisture content, forward speed and cylinder speed on field capacity was significant. The interaction effect of moisture content and forward speed was significant, however, the interaction effect of moisture content and cylinder speed, forward speed and cylinder speed and combined effect of interaction of all variables was non-significant. The F - value for the moisture content was highest (946.463) indicating that it had maximum effect on field capacity (Table 3). The effect of moisture content, forward speed and cylinder speed on field capacity of straw combine is presented in Fig. 1-3. The field capacity was minimum (0.23 ha/h) at moisture content of 50%, forward speed of 1.7 km/h and cylinder speed of 29.6 m/s and maximum (0.33 ha/h) at moisture content of 20%, the forward speed of 2.1 km/h and cylinder speed of 33.2 m/s. The average field capacity increased significantly from 0.25 to 0.31 ha/h as the moisture content decreased from 50 to 20%. The average field capacity increased

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	20, 35, 50
2.	Forward speed	FS	km/h	3	1.7, 1.9, 2.1
3.	Cylinder speed	CS	m/s	3	29.6, 31.4, 33.2

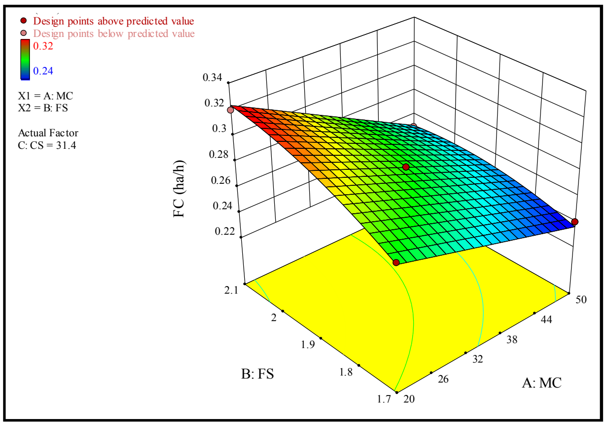

Fig. 1. Effect of moisture content and forward speed on field capacity (ha/h) of straw combine.

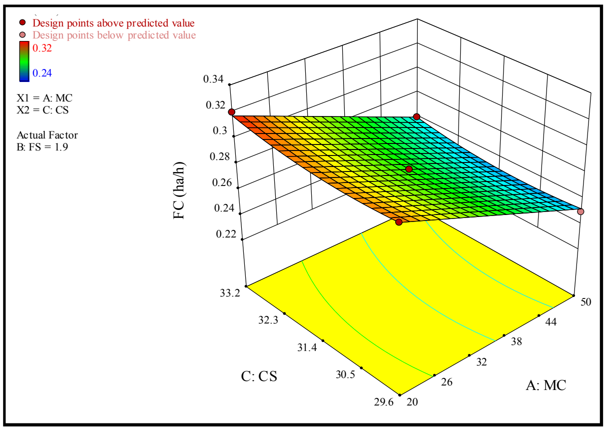

Fig. 2. Effect of moisture content and cylinder speed on field capacity (ha/h) of straw combine.

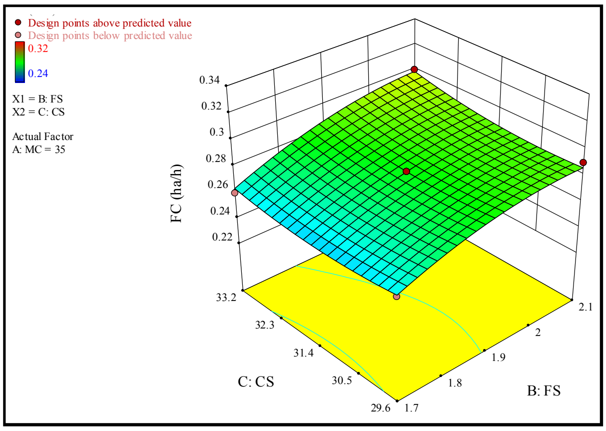

Fig. 3. Effect of cylinder speed and forward speed on field capacity (ha/h) of straw combine.

significantly from 0.26 to 0.29 ha/h as forward speed increased from 1.7 to 2.1 km/h. The average field capacity increased significantly from 0.27 to 0.28 ha/h as the cylinder speed increased from 29.6 to 33.2 m/s. The maximum field capacity at higher forward speed was due to more coverage area. The minimum field capacity at higher moisture content may be due to the fact that at higher moisture content the straw chocking problem was more which increased productive time loses. The field capacity was more at higher cylinder speed might be due to 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. Ujala *et al*., 2020 also reported that field capacity of paddy straw reaper increased with increase in forward speed and cylinder speed and decreased with increase in moisture content. Similar results were observed by Mahmood *et al*., 2016 and Upadhyay *et al*., 2018 in wheat crop.

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	2,647.97	1,323.99	946.463	0.00001
FS	2	584.181	292.091	208.804	0.00001
MC x FS	4	38.415	9.604	6.865	0.00015
CS	2	56.255	28.127	20.107	0.00001
MC x CS	4	0.536	0.134	0.096	0.98336
FS x CS	4	0.349	0.087	0.062	0.99262
MC x FS x CS	8	0.874	0.109	0.078	0.99963
Error	54	75.539	1.399		
Total	80	3,404.12			

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

The regression coefficient of moisture content and forward speed is negative in equation (ii), which indicates that increase of these variables resulted in a decrease in field efficiency; however, the positive value of cylinder speed indicated that field efficiency increased with increase in cylinder speed. The coefficient of determination indicated that these variables contributed 98.06 % to total variation in field efficiency. The effect of moisture content, forward speed and cylinder speed on field efficiency was significant; however, the combined effect of interaction of variables was non-significant. The F - value for the moisture content was highest (756.019), indicating that moisture content had a maximum effect on field efficiency (Table 4). The effect of moisture content, forward speed and cylinder speed on field efficiency of straw combine is presented in Fig. 4 - 6. The field efficiency was minimum (52.40%) at moisture content of 50%, forward speed of 2.1 km/ h and cylinder speed of 29.6 m/s and maximum (75.13%)

at moisture content of 20%, forward speed of 1.7 km/h and cylinder speed of 33.2 m/s. The average field efficiency increased significantly from 57.92 to 71.89% as the moisture content decreased from 50 to 20%. The average field efficiency increased significantly from 61.64 to 68.13% as the forward speed decreased from 2.1 to 1.7 km/h. The average

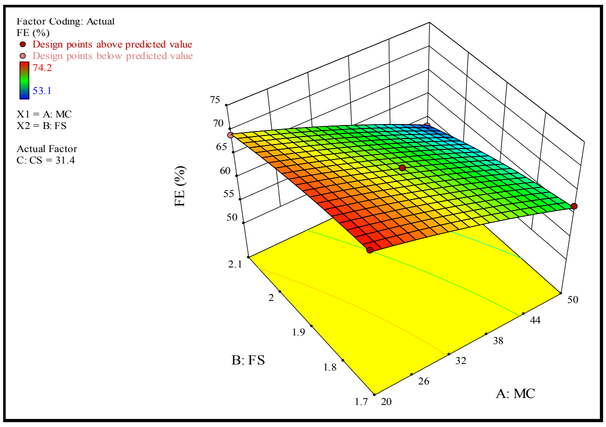

Fig. 4. Effect of moisture content and forward speed on field efficiency (%).

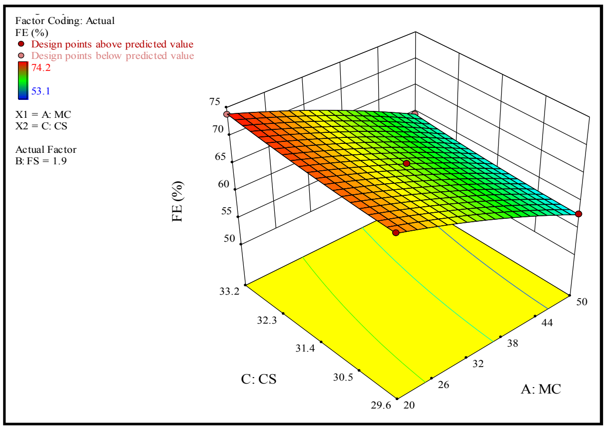

Fig. 5. Effect of moisture content and cylinder speed on field efficiency (%).

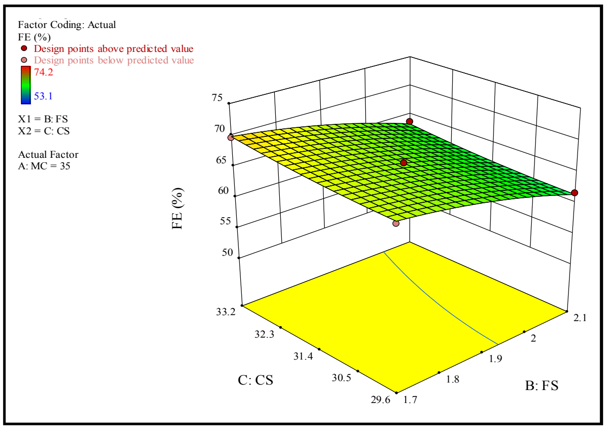

Fig. 6. Effect of cylinder speed and forward speed on field efficiency (%).

field efficiency increased significantly from 64.13 to 66.16 % as the cylinder speed increased from 29.6 to 33.2 m/s. The interaction effects of different variables on field efficiency of straw combine in wheat straw were non-significant. 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 lower field efficiency at higher moisture content may be due to the fact that at higher moisture content the straw chocking problems was more which increased productive time loses. The field efficiency was maximum 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 of straw and less incidences of cylinder chocking. Ujala *et al.*, 2020 also observed that field efficiency of paddy straw reaper decreased from 66 to 42 % with increase in moisture content from 20.4 to 49.5 %, forward speed from 1 to 2 km h^{-1} and decrease in cylinder speed from 950 to 550 rpm. Singh *et al.* (2011) also observed similar results.

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	32.667	16.334	756.019	0.00001
FS	2	4.959	2.479	114.755	0.00001
MC x FS	4	0.03	0.007	0.343	0.84798
CS	2	1.215	0.607	28.115	0.00001
MC x CS	4	0.182	0.046	2.108	0.09239
FS x CS	4	0.169	0.042	1.954	0.11469
MC x FS x CS	8	0.085	0.011	0.493	0.85585
Error	54	1.167	0.022		
Total	80	40.473			

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

The regression coefficient of moisture content, forward speed and cylinder speed is positive in equation (iii), which indicates that increase of these variables resulted in an increase in fuel consumption. The coefficient of determination indicated that these variables contributed 99.33 % to total variation in fuel consumption. The effect of moisture content, forward speed and cylinder speed on fuel consumption was significant, however interaction effect among variables as well as combined effect was non significant. The

F - value for the moisture content was highest (75.195), indicating that moisture content had maximum effect on fuel consumption (Table 5). The effect of moisture content, forward speed and cylinder speed on fuel consumption of straw combine are presented in Fig. 7-9. The fuel consumption was minimum (5.80 l/h) at moisture content of 20%, forward speed of 1.7 km/h and cylinder speed of 29.6 m/s and maximum (8.40 l/h) at moisture content of 50 %, forward speed of 2.1 km h^{-1} and cylinder speed of 33.2 m/s. The average fuel consumption significantly increased from 6.09 to 7.64 l/h as the moisture content increased from 20 to 50%. The average fuel consumption significantly increased from 6.59 to 7.19 l/h as forward speed increased from 1.7 to 2.1 km/h. The average fuel consumption significantly increased from 6.73 to 7.02 l/h as the cylinder speed increased from 29.6 to 33.2 m/s. The interaction effects of different variables on fuel consumption of straw combine in wheat straw were non-significant. The fuel consumption was minimum at lower moisture content and lower forward speed and it may be due to fact that at lower moisture content and lower forward speed straw load on the machine is minimum and less power is required to handle it. The fuel consumption was maximum 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 increased power requirement. Similar results were reported by Singh *et al.*, 2011. Kanafojski and Karwawski (1976) also reported that increase in cylinder speed needs more energy to overcome increase in ventilation resistance along with force impulse resistance of cut plants and with the increase in forward speed cutting resistance increased and to counter this resistance more power/energy is needed. Ujala *et al.*, 2020 also confirmed the validity of these results.

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	869.443	434.721	75.195	0.00001
FS	2	133.721	66.861	11.565	0.00007
MC x FS	4	5.699	1.425	0.246	0.91059
CS	2	33.976	16.988	2.939	0.06146
MC x CS	4	0.018	0.005	0.001	1.00000
FS x CS	4	0.037	0.009	0.002	0.99999
MC x FS x CS	8	0.291	0.036	0.006	1.00000
Error	54	312.187	5.781		
Total	80	1,355.37			

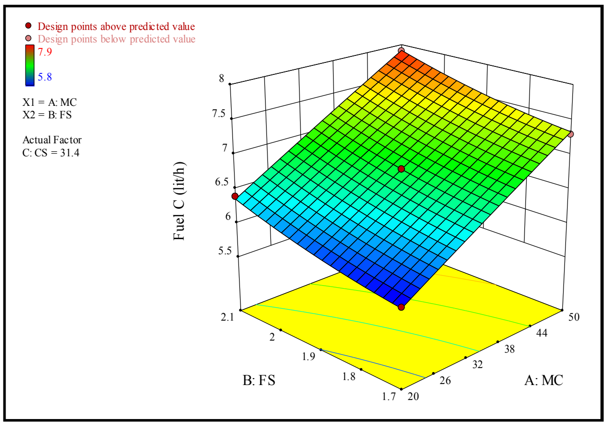

Fig. 7. Effect of moisture content and forward speed on fuel consumption (l/h).

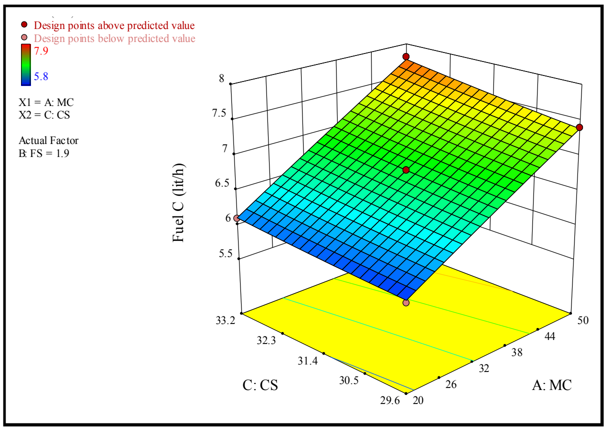

Fig. 8. Effect of moisture content and cylinder speed on fuel consumption (l/h).

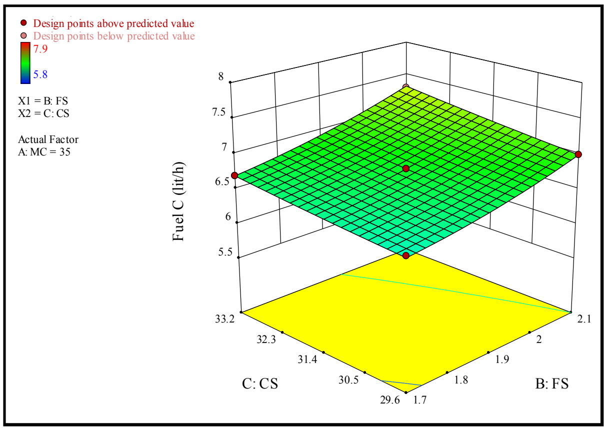

Fig. 9. Effect of cylinder speed and forward speed on fuel consumption (l/h).

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

The regression coefficient of moisture content and forward speed is negative in equation (iv), which indicates that increase in these factors resulted in decrease in the straw split, however, the positive value of cylinder speed indicated that straw split increased with the increase in cylinder speed. The coefficient of determination indicated that these variables contributed 90.12% to total variation in straw split. The effect of moisture content, forward speed and cylinder speed was significant. The interaction effect of moisture content and cylinder speed and combined effect of all the three variables on straw split was significant; however, the interaction effect of moisture content and forward speed and forward speed and cylinder speed was non-significant. The F - value for the moisture content was highest (944.775) indicating that moisture content had a maximum effect on straw split (Table 6). The effect of moisture content, forward speed and cylinder speed on the straw split are presented in Fig. 10-12. The straw split was minimum (62.70%) at moisture content of 50%, forward speed of 2.1 km/h and cylinder speed of 29.6 m/s and maximum (83.77%) at moisture content of 20%, forward speed of 1.7 km/h and cylinder speed of 33.2 m/s. The average straw split increased significantly from 63.72 to 80.03% as the moisture content decreased from 50 to 20%. The average straw split increased significantly from 72.31 to 73.78% as forward speed decreased from 2.1 to 1.7 km/h. The average straw split increased significantly from 71.48 to 74.65% as the cylinder speed increased from 29.6 to 33.2 m/s. The minimum straw split at higher moisture content may be due to the fact that at higher moisture content the straw split was difficult due to more ductility of straws. The straw split increased with increase in cylinder speed. It 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. Similar results were reported by Ujala *et al.*, 2020.

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	3,827.78	1,913.89	944.775	0.00001
FS	2	29.355	14.678	7.246	0.00163
MC x FS	4	6.01	1.503	0.742	0.56776
CS	2	135.969	67.984	33.56	0.00001
MC x CS	4	36.648	9.162	4.523	0.00318
FS x CS	4	0.681	0.17	0.084	0.98701
MC x FS x CS	8	0.133	0.017	0.008	0.00001
Error	54	109.391	2.026		
Total	80	4,145.97			

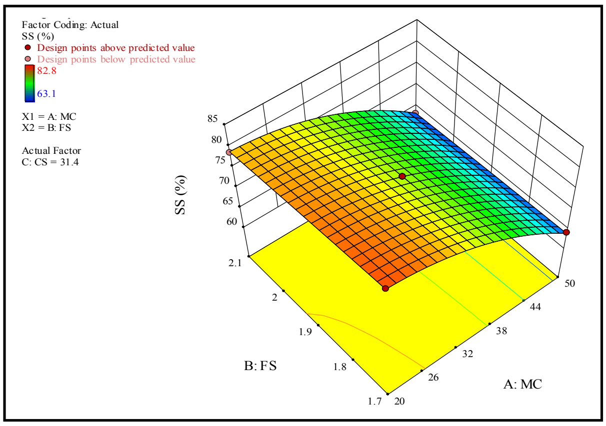

Fig. 10. Effect of moisture content and forward speed on straw split (%).

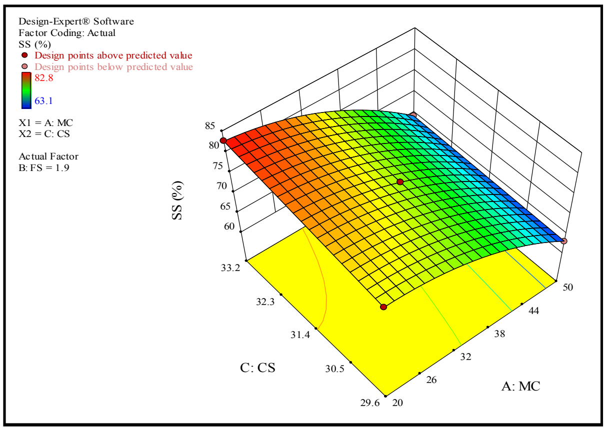

Fig. 11. Effect of moisture content and cylinder speed on straw split (%).

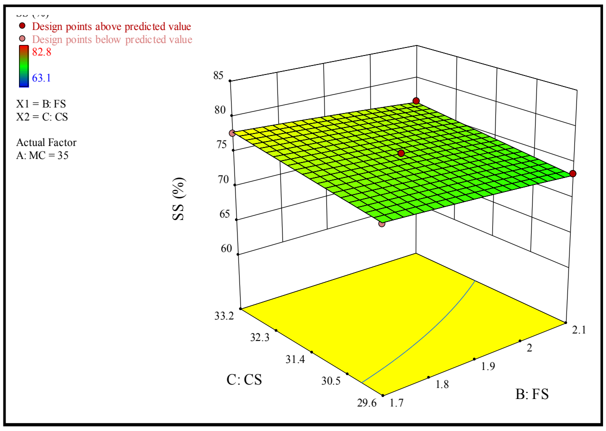

Fig. 12. Effect of cylinder speed and forward speed on straw split (%).

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

The regression coefficient of moisture content and forward speed is positive in equation (v), which indicates that straw size increased with increase in these variables, however, the negative value of cylinder speed indicated that straw size decreased with increase in cylinder speed. The coefficient of determination indicated that these variables contributed 93.35% to total variation in straw size. The effect of moisture content, forward speed and cylinder speed on straw size was significant; however, the interaction among variables and combined effect of all variables on straw size was non-significant. The F - value for the moisture content was highest (2260.92) indicating that moisture content had a maximum effect on straw size (Table 7). The effect of moisture content, forward speed and cylinder speed on straw size are presented in Fig. 13-15. The straw size was minimum (40 mm) at moisture content of 20 %, forward speed of 1.7 km h^{-1} and cylinder speed of 33.2 m s^{-1} and maximum (98 mm) at moisture content of 50 %, forward speed of 2.1 km h^{-1} and cylinder speed of 29.6 m/s. The average straw size significantly decreased from 91.26 to 43.56 mm as the moisture content decreased from 50 to 20%. The average straw size significantly decreased from 67 to 61.85 mm as the forward speed decreased from 2.1 to 1.7 km/h. The average straw size significantly decreased from 67.11 to 61.52 mm as the cylinder speed increased from 29.6 to 33.2 m/s. The interaction effect of different variables on straw

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	32,155.28	16,077.64	2,260.92	0.00001
FS	2	357.802	178.901	25.158	0.00001
MC x FS	4	47.679	11.92	1.676	0.16893
CS	2	424.469	212.235	29.845	0.00001
MC x CS	4	24.79	6.198	0.872	0.48708
FS x CS	4	2.716	0.679	0.095	0.98348
MC x FS x CS	8	3.136	0.392	0.055	0.9999
Error	54	384	7.111		
Total	80	33,399.88			

TABLE 8

Variable and their levels for desirability in paddy straw

Variable	Goal	Lower limit	Upper limit	Importance
A:MC	in range	20	50	3
B:FS	in range	1.7	2.1	3
C:CS	in range	29.6	33.2	3
FC	maximize	0.24	0.32	3
FE	maximize	53.1	74.2	3
Fuel C	minimize	5.8	7.9	3
SS	maximize	63.1	82.8	3
S Size	minimize	42	95	3

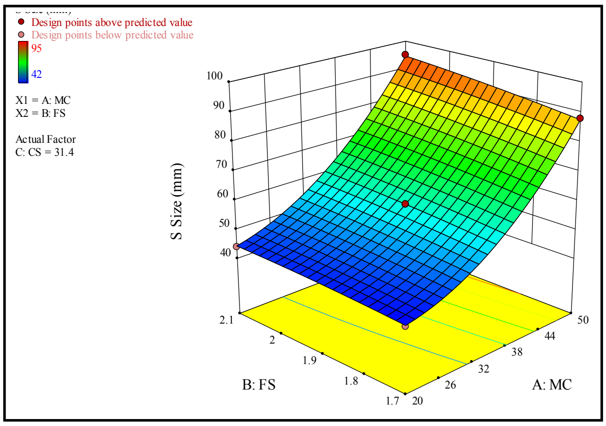

Fig. 13. Effect of moisture content and forward speed on straw size (mm).

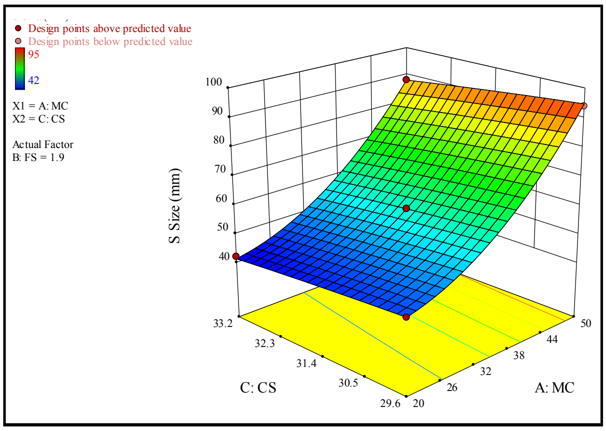

Fig. 14. Effect of moisture content and cylinder speed on straw size (mm).

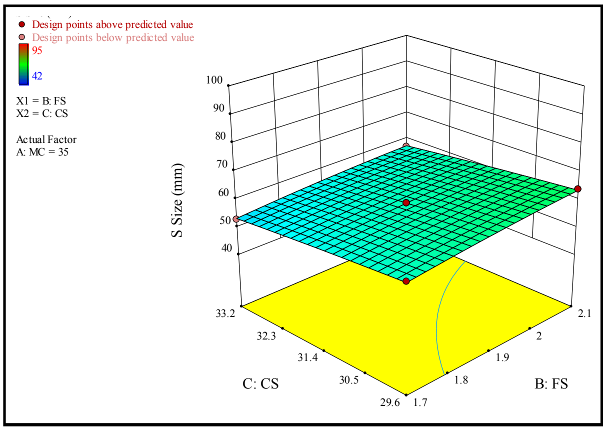

Fig. 15. Effect of cylinder speed and forward speed on straw size (mm).

size in wheat straw was non-significant. The straw size decreases as the moisture content and forward speed decreased and cylinder speed increased, it may be 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

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

No	MC	FS	CS	FC	FE	Fuel C	SS	S Size	Desirability	Decision
1	20.00	1.91	33.20	0.32	73.76	6.13	82.66	41.29	0.963	Selected
2	20.00	1.91	33.20	0.32	73.78	6.13	82.67	41.28	0.963	
3	20.00	1.91	33.20	0.32	73.73	6.13	82.64	41.30	0.963	
4	20.00	1.91	33.20	0.32	73.79	6.13	82.68	41.28	0.963	
5	20.00	1.91	33.20	0.32	73.83	6.12	82.69	41.27	0.963	
6	20.00	1.92	33.20	0.32	73.67	6.14	82.61	41.32	0.963	
7	20.00	1.92	33.20	0.32	73.65	6.14	82.60	41.32	0.962	
8	20.00	1.90	33.20	0.32	73.87	6.11	82.72	41.26	0.962	
9	20.01	1.92	33.20	0.32	73.69	6.14	82.63	41.31	0.962	
10	20.00	1.90	33.20	0.32	73.91	6.11	82.74	41.24	0.962	
11	20.00	1.90	33.20	0.32	73.93	6.11	82.75	41.24	0.962	
12	20.00	1.89	33.20	0.32	73.96	6.10	82.77	41.23	0.962	
13	20.00	1.89	33.20	0.32	74.01	6.10	82.79	41.21	0.962	
14	20.00	1.89	33.20	0.32	74.04	6.09	82.81	41.20	0.962	
15	20.00	1.88	33.20	0.32	74.10	6.08	82.84	41.18	0.961	

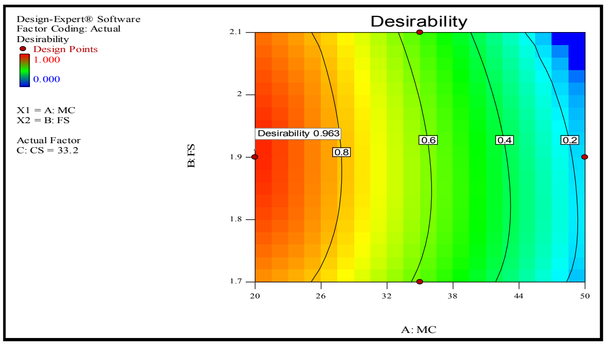

Fig. 16. Contour plot for overall desirability at 33.2 m/s cylinder speed.

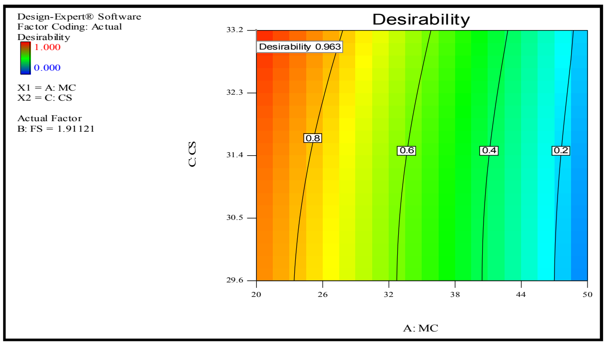

Fig. 17. Contour plot for overall desirability at 1.91 km/h forward speed.

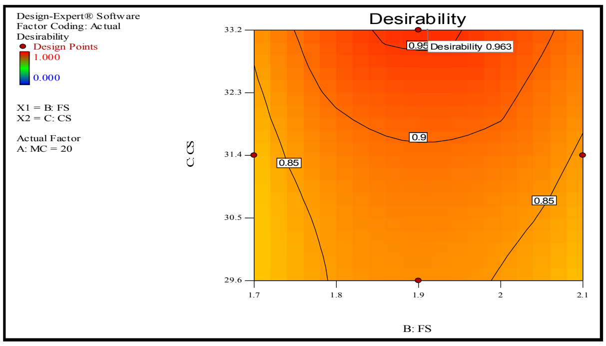

Fig. 18. Contour plot for overall desirability at 20% moisture content.

content elasticity of straw increased and it becomes difficult to chop. Ujala *et al.*, 2020 concluded that paddy straw size decreased from 6.08 to 3.36 cm with decrease in moisture content from 49.5 to 20.4 %, forward speed from 2 to 1 km/h and increase in cylinder speed from 550 to 950 rpm. Similar results were also observed by Singh *et al.*, 2011.

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

The parametric combination having the highest value of desirability will be selected as an optimal solution (Antil *et al.* 2020, Antil *et al.* 2022). The value of desirability lies between 0 to 1. If the value approaches 1, then response meets the ideal values, and if the value of desirability comes out to be 0, then the response will not fall in the satisfactory region of the anticipated quality zone (Kharb *et al.* 2020, Jakhar *et al.* 2022). The ranges and targets of process parameters and output quality characteristics (OCQs) are shown in Table 8. The optimal parametric combination which can give a high value of desirability concerning output quality characteristics (OCQs) is tabulated in Table 9. For multi-objective optimization, contour plots are generated, which provided overall desirability for moisture content, forward speed and cylinder speed as shown in Fig. 16-18. As per the obtained optimal parametric combination, the moisture content of 20%, forward speed of 1.91 km/h and cylinder speed of 33.20 m/s was found optimum for using straw combine in paddy straw.

CONCLUSIONS

Based on the experimental results it is concluded that moisture content is the most influential parameter for response parameters. The field capacity decreased with increase in moisture content and increases with increase in forward speed and cylinder speed. The field efficiency and straw split decreased with increase in moisture content and forward speed, whereas, increases with increase in cylinder speed. The fuel consumption increased with increase in moisture content, forward speed and cylinder speed. The straw size decreased with decrease in moisture content and forward speed, whereas, decreases with increase in cylinder speed. The optimum combination for harvesting of paddy variety PUSA–1121 was found to be moisture content of 20 %, forward speed of 1.91 km/h and cylinder speed of 33.20 m/s.

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