ACCEPTED ARTICLE

Effect of powered disc coulters and residue holding wheel on cutting performance of rice residues under no-tillage system in soil bin

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ABSTRACT

The management of rice residue is still a challenging issue and factors such as poor feed quality of rice residue, limited and timely unavailability of suitable residue handling machines and narrow window period available prior to seeding of next crop act as driving forces for residue burning by the farmers. *In-situ* management of rice crop residue can prevent ill effects of residue burning on the natural resources. In this study, three types of power-driven disc coulter; serrated, plain, and toothed, with three different arrangements of residue holding device, viz. no holding wheel, single holding wheel, and twin holding wheels with speed ratio (ratio of rotational speed of coulter and forward speed) of 5.2, 6.94, and 8.67 were evaluated in the soil bin of Soil Dynamic Research Laboratory of ICAR-Central Institute of Agricultural Engineering, Bhopal, India. Horizontal forces, vertical forces, torque, and residue cutting performance were measured with residue density ranging from 3000 to 5000 kg ha^{-1}. The experiments (243 including replications) were conducted according to completely randomized (CRD) design. The mean horizontal forces, vertical forces, torques, and cutting percentage increased significantly at level of significance P< 0.05 with the increase in the number of residue holding wheel. Increasing the residue load had no effect on the cutting percentage of the residue. The results showed that the residue cutting performance of the plain coulter with twin holding wheels was nearly 100% at any combination of selected variables. Introduction of residue holding wheels to the coulters helped in sowing successive crop (like wheat, maize, etc.) in the combine harvested rice field with heavy residue.

Keywords: Conservation tillage, coulters, residue holding wheel assembly, residue cutting, residue clogged.

INTRODUCTION

Most of the South Asian countries produce rice, wheat and maize as main food crops (Gathala *et al.,* 2020). However, it has been observed that a significant quantity of crop residue is burned across the region, especially in rice-growing areas. (Devi *et al.*, 2017; Goswami *et al.*, 2020; Ravindra *et al.,* 2022; Lin *et al.,* 2022). This practice has created a long-term hazardous impact on the soil, human health and environmental. The Indo-Gangetic plain of South Asia, which covers 13.5 mha across India, Pakistan, Nepal, and Bangladesh, have been spotted with high levels of air pollution (The Energy and Resources Institute, 2019) due to burning of rice residue in combination with other injudicious practices. This practice of burning contributed up to 70% in PM2.5 and over 40% increase in level of atmospheric black carbon concentrations (Kumari et *al.,* 2021; Ravindra *et al.,* 2021).

India produces more than 650 million tons of crop residue every year, out of which approximately 70% of the residue is utilised as fodder, fuel and industrial purposes. The rest of the, 26% (178 Mt) of crop residue, is still available as a surplus, out of which 87 Mt is burned in the agricultural field directly (Kumar *et al.,* 2023). Rice-wheat alone contribute approximately 70% of the total crop residues in Indian agriculture. Rice-wheat rotation occupies about 10.5 mha and contributes to 40% of the country's total food grain basket (Bijarniya et al., 2020). As much as two-thirds to three-fourths of the residue is burnt in the case of rice due to a lack of economically viable options for managing the residue (Kumar *et al.,* 2015).

The anchored residues of height up to 300–400 mm do not affect the direct sowing performance with conventional no-till seeding equipment. However, the long loose retained residue, which is left on the soil surface after combine harvesting, frequently blocks the tyne and furrow openers, resulting in hindrance to the seeding operation, causing long delays, uneven seeding rate and depth and a patchy stand of plants (Singh *et al.,* 2014).

Several researchers have attempted to modify furrow openers, coulter size and shapes, coulter driving arrangements, and ground clearance of tynes to improve the performance of no-till sowing machines in terms of seed placement (Tola *et al.*, 2001; Magalhaes *et al.,* 2007; Bianchini and Magalhães, 2008; Ahmad *et al.,*2015; Aikins *et. al.*, 2019; Zeng *et al.*, 2021).

Bianchini and Magalhães (2008) in a soil bin experiment with smooth, notched, and toothed disc coulters found that the smooth coulter delivered the lowest performance in terms of horizontal forces, vertical forces, rolling resistance, and residue cutting percentage. The working depth for a toothed coulter to sufficiently cut the sugarcane residue was found to be 80 mm. Ahmad *et al.,* (2015) evaluated the draft requirements and residue cutting performances of different sized disc openers in no-till rice soil conditions. The disc opener with a 450 mm diameter provided higher residue cutting efficiency (88.6%) at 90 mm. Aikins et al., 2019 reported that the powered cutting unit increases the efficiency of residue cutting as compared to the rolling type. Zeng *et al.,* (2021) compared soil and corn residue cutting performance of different discs under soil bin conditions and found that the working depth had a stronger effect on the performances of discs as compared to the disc type.

Numerous studies have been conducted in the context of various aspects such as coulter types, power requirement, performance, etc., of residue management devices. Kushwaha *et al.*, (1986a) conducted a soil bin study with coulter sizes ranging from 360-460 mm in diameter. The vertical forces and horizontal forces were found to be in the range of 30-300 N and 45-130 N, respectively. The residue parameter had the most significant influence on residue cutting and forces on the coulters. Kushwaha *et al.,* (1986b) found that the power requirement of a plain coulter (35-121 W) was lower than that of a notched coulter (104-199 W) at a residue level of 5000 kg/ha. The study also revealed that when using powered and free disc coulters at a depth of 50-70 mm, the draft of the powered coulter was significantly lower (30.4–177.6 N) compared to the free-rolling coulter (106.1–428.6 N) for cutting wheat residue ranging from 0 to 5000 kg/ha. At all crop residue densities and at a depth of 70 mm, a plain coulter could achieve nearly 100% cutting efficiency. Bianchini and Magalhães (2008) in a soil bin experiment with smooth, notched, and toothed disc coulters found that the smooth coulter delivered the lowest performance in terms of horizontal and vertical forces, rolling resistance, and residue cutting percentage. Ahmad *et al.*, (2015) evaluated the draft requirements and residue cutting performances of different sized disc openers in no-till rice soil conditions. The disc opener with a 450 mm diameter provided higher residue cutting efficiency (88.6%).

The majority of recent studies focused on soil cutting forces (Malasli and Celik, 2019), soil disturbance (Zeng *et al.,* 2019), residue incorporation (Zeng and Chen 2018a, 2018b) and residue spatial distribution (Zhou *et al.,* 2020) but not on residue cutting effectiveness.

Several researchers carried out experiments on performance evaluation of various types of disc coulters and their finding based on selection of residue management device is presented in the Table 1.

Table 1: Selection of residue management device of selected studies.

Sl. no.	Residue management device	Crop residue	Sowing crop	Findings	References
1.	1. Turbo coulter blade (TCB), 2. Double dis opener with a seed press (DDP) and 3. notched disc row cleaner with a track wheel or floating star cleaner	Maize (*Zea mays* L.)	--	The treatment combining RC, TCB and DDP yielded the most favorable outcomes concerning crop stand and uniformity.	Soza *et al.*, 2003
2.	The residue management device (RME) consisted of nine parts; each part consisted of two powered wheels, one wheel for cutting the residue and the other wheel for removing them away from no-till drill furrow openers.	Rice residue	--	Incorporating RME into the no-till drill reduced residue clogging by 33% and raised the percentage of cut hills from 14.9% to 63.7%.	Hegazy and Dhaliwal 2011.
3.	Smooth and toothed coulters	Wheat residue and	maize	The Emergence Rate Index (ERI) demonstrated an increase of up to 18% with the toothed coulter compared to the smooth coulter.	Nejadi and Raoufat 2013.
4.	Active toothed coulter row cleaner attachment	wheat	maize	The findings indicate that utilizing a row crop planter equipped with an active toothed coulter is a viable option for direct corn planting with residues from the previous crop.	Nejadi and Raoufat 2013.
5.	Active coulters (different combination of number of notch and depth of notch; 6 combinations)	Wheat		Active disc coulter rotation at higher speeds, as experimentally observed, leads to more significant straw cutting compared to inactive disc coulter rotation in contact with the soil.	Sarauskis *et al.*, 2013.
6.	Plain disc with twin press wheels and serrated blade with twin press assembly.	Rice	--	The plain blade with a twin press wheels assembly achieved a 100% straw-cutting rate.	Badegaonkar, *et al.*, 2014.
7.	No-coulter, smooth and offset fluted.	Soybean	--	Coulters combined with furrow openers reduce soil swelling by around 8% for smooth and 20% for offset fluted configurations.	Francetto et al., 2016.
8.	Five coulters were four types of fluted coulters (8 W, 13 W, 18 W, and 25 W) and one notched-flat coulter (NF) (W: wave number)	Maize	--	The findings indicate that flat coulters and large-wavenumber fluted coulters (18 W and 25 W) exhibit lower cutting force and are more effective for cutting straw residue in fields with residue coverage.	Wang et al., 2018
9.	Crop residue cutting discs (plain flat disc, wavy disc, rippled disc, and helical wavy disc coulter)	--	--	The plain flat disc yielded the lowest values for traction force, hourly fuel consumption, and mobilized soil area.	Becker *et al.*, 2019

Residue handling and cutting largely depends on sharpness of the disc, quality and characteristics of residue (moisture, length, brittleness, softness etc.), moisture and softness of the soil, speed of operations, disc design etc. which are beyond control in actual field conditions. Therefore, relying exclusively on the cutting mechanism for residue handling and cutting is rarely effective (Baker, 2007). This necessitates integrating an additional assisting device that can enhance the performance of residue cutting and handling. No published work was found on crop residue holding devices, which may improve the residue cutting efficiency to facilitate smooth handling and right seed placement to make proper seed soil contact without any hair-pinning effect to overcome poor germination and establishment. The objective of the research was therefore set to study the residue cutting performance of different types of powered discs viz. plain, serrated, and toothed coulter in association with residue holding devices, under varying rice residue conditions in clay soil. The performance characteristics of powered disc coulters in cutting paddy residue, with and without any residue holding wheels, under controlled conditions in the soil bin, have been discussed.

MATERIALS AND METHODS

Experimental Details

The experimental work was carried out in the Soil Dynamic Research Laboratory, Agricultural Mechanization Division (23°18'33.3"N, 77°24'6.8"E), ICAR-Central Institute of Agricultural Engineering, Bhopal, India. The soil used in the bin was a mixture of sand (47.5%), silt (23.0%), and clay (29.5%) particles having good water retention and nutrient holding capacity and generally easy to work.

Soil Bin

The concrete structured soil bin, sized at 16 m in length, 2.5 m in width and 1 m deep as shown in Figure 1, was filled with a 900 mm soil column, enough soil volume to facilitate testing of full-sized equipment without side effects and variability. It was equipped with a tool bar and instrumentation carriage, soil processing gadgets, and a power transmission unit. The tool bar carriage contained two tool bars, a front and a rear**.** The front tool bar was used for mounting the experimental tool and the rear for attaching the soil processing gadgets. Each tool bar was equipped with a steering wheel and a chain sprocket drive to raise, lower, and lock the gadget in the desired position. The speed of the carriage was varied by varying the rpm of automatic variable speed (AVS) drive and measured by a linear speed sensor (Sick AG Ltd., Waldkirch, Germany). The tool carriage was driven at a travel speed of 2.5 km h^{-1} in all experiments (Tice and Hendrick, 1992; Rautaray, 2002; Bianchini and Magalhaes, 2008).

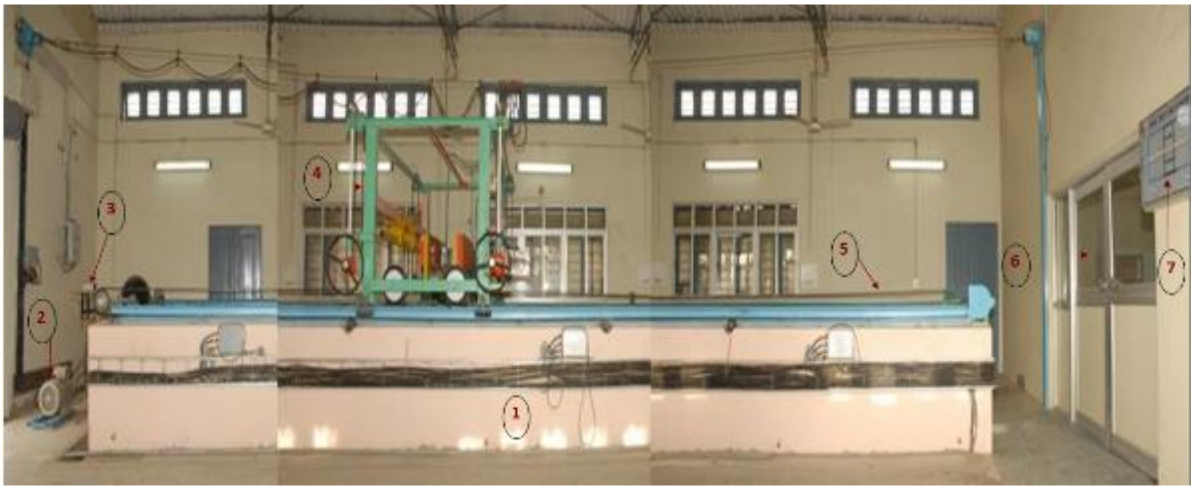


Figure 1. A view of soil bin system: 1. Rectangular soil bin; 2. Variable speed motor; 3. Linear speed sensor; 4. Tool and instrumentation carriage; 5. Chain drive and guide rail; 6. Control room, 7. Mimic panel.

Instrumentation for Measurement

The soil bin system was fitted with an electronic measuring, computing, and analysis system to evaluate the performance of the attached equipment. The instrumentation system was arranged to measure horizontal force (H), vertical force (V), and torque (T) acting on a tool in operation. Forces acting on a tool during operation were measured with the help of six S-type load cells (IPA, Pvt. Ltd., Bengaluru). Three vertically mounted load cells (Sensitivity: 1.5 ± 0.01 mV/V; Range 500 kg) for measuring vertical force, two horizontally mounted load cells for horizontal force or draft, and one load cell mounted on the side for measurement of lateral force. All load cells were calibrated (ISO 7500-1:2015) for both tensile and compressive loading. Each transducer consisted of a fixed end attached to the toolbar and a free end on which the tool was mounted. With such an arrangement, loads having any combination of translational and rotational soil reactions can be tested while parameters such as speed, rpm of the tool, depth of operation, etc. are varied. A separate provision was made for giving power to the residue cutting discs through the variable speed drive (VS-616 G5, Fukuoka, Japan) of capacity 20kW. A torque transducer (SA-10, Sushama Industries, Bangalore) of capacity 100 Nm was coupled between the motor and the rotational cutting discs with the help of a coupling and locking bolt at one end and a chain-sprocket arrangement at the other end of the rotational disc shaft. A computer-controlled SCADA based data acquisition and programmable logic control based system was utilized during the experiment. The acquisition rate was 0.5 Hz (Badegaonkar *et al.,* 2014). A close view of instruments used in this study is shown in Figure 2.

Figure 2. Close view of instruments used in this study.

Soil Bed Preparation

The soil in the bin was prepared to simulate the field conditions for sowing. The soil compaction level was measured in the field and in the soil bin with a cone penetrometer (M1.06.15.SA.E, Eijkelkamp, AgriSearch Netherlands) of maximum range of 5000 kPa which consisted of a force sensor, the logger, a probing rod, a cone, and an ultrasonic depth measurement system. Data for soil penetration resistance was collected at seeding time with stubble under no-till conditions on the experimental farm of the ICAR-Central Institute of Agricultural Engineering, India. Cone index (CI) values were evaluated at 0 to 300 mm depth by taking an average of five readings at five different locations.

The different operations in soil bed preparation included soil tilling, moistening of soil, levelling, and compaction followed by rotary tiller, sheep foot roller, soil leveller, plain roller, and water application system to maintain uniform moisture and penetration resistance throughout each experiment with repeatability measures. The soil moisture was managed across its entire width with the help of a spray boom attached to the carriage. A hollow drum roller of 1800 mm width and 500 mm diameter, filled with sand, was used to compact the surface soil to achieve soil conditions at par with the field conditions. The penetration resistance of a near value of 1.40 MPa was maintained in the top 150 mm of soil depth. The soil physical properties used in the soil bin for the experiment are given in Table 2.

Table 2: Physical properties of soil used in experiment.

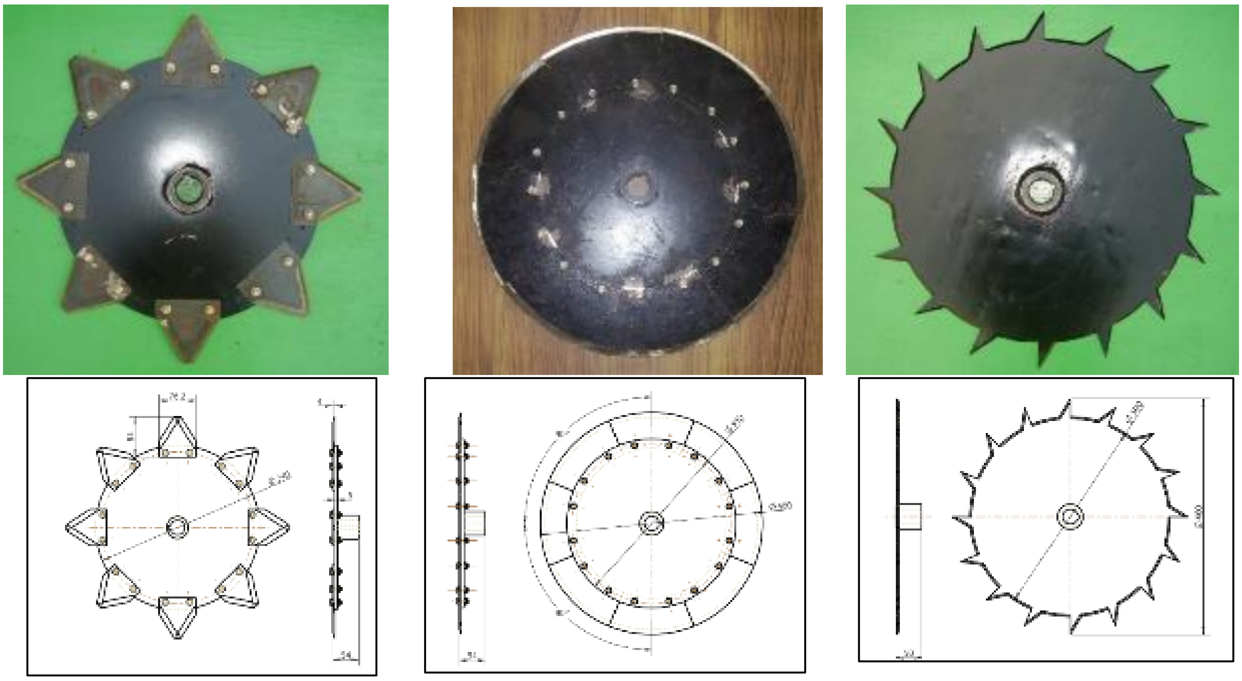
Soil type	**Values**
Soil texture	Clay soil
Particle size distribution	
Sand (20–2000 µm), %	47.5
Silt (2–20 µm), %	23.0
Clay (<2 µm), %	29.5
Mean weight diameter of wet aggregates, mm	0.713
Bulk density (0–150 mm depth), g cm^{-3}	1.45
Cone Index	1.40
Moisture content (wb) %	20–22

Rice Residue

The amount of residue leftover under actual field conditions, after combine harvesting of rice, was recorded. The height of stubbles ranged between 275 and 375 mm, the length of loose residue was 350–450 mm, and the density of loose residue varied between 3000 and 5000 kg ha^{-1}. Therefore, the residue length of 350–450 mm and density of 3000–5000 kg ha^{-1} at moisture content between 20–22% (wb) was used in the soil and was spread flat and perpendicular to the motion of the test tool, uniformly along the length of the soil bin during each experimental trial.

Residue Cutting Coulters

Three types of residue cutting coulters, viz., serrated coulter, plain coulter, and toothed coulter, were used in the investigation, which is shown in Figure 3 and Table 3. All cutting coulters were made of the same size (460 mm dia), based on the quality of performance reported by various researchers (Raoufat and Mahmoodieh 2005, Magalhães *et al.*, 2007, Fallahi and Raoufat 2008; Nejadi and Raoufat 2013). The dimensions of the major components of residue cutting systems are given in Table 3. The residue cutting system was attached to the carriage as shown in Figure 5.



Serrated coulter (B1) Plain coulter (B2) Toothed coulter (B3)

Figure 3. Different types of coulters used in the study.

Table 3. Specifications of selected coulters.

Particulars	Type of coulters		
	Serrated coulter (B1)	Plain coulter (B2)	Toothed coulter (B3)
Outer diameter of coulter, mm	460	460	460
Thickness of coulter, mm	4	4	4
No. of discs/or teeths	0/8	0/0	0/16

Residue Holding Wheel Assembly

A Residue holding wheel assembly with a single wheel and another twin wheel assembly having two wheels of the same size was developed, which is shown in Figure 4, aiming to holding and hold the loose residue in the original position while being cut. The holding wheels were made of mild steel material and had a diameter of 75 mm and a width of 35 mm. The wheel assembly consisted of a single or twin holding wheel, fork, and spring-loaded holding system. For experimentation, each type of holding wheel assembly was fixed on either side of each cutting disc on the frame and tested for effect on the residue cutting performance.

(a) (b)

Figure 4. Residue holding device (a) Single holding wheel assembly (b) Pair of twin holding wheels assembly.

Speed Ratio of Residue Cutting Coulters

The speed ratio of residue cutting discs is defined as the ratio of the rotational speed of the cutting disc to forward speed. Hegazy and Dhaliwal (2011) recommended a rotor shaft speed of 200 rpm for a power-driven residue manager for a no-till drill. Accordingly, three levels of rotational speeds of the residue cutting disc, one lower and one higher in equal proportion, i.e., 150, 200, and 250 rpm for the study. For a 460 mm diameter residue-cutting disc moving at 2.5 km h^{-1} forward speed of the carriage, three speed ratios of 5.20, 6.94, and 8.67 could be established.

Residue Cutting

Residue cutting is crucial to ensure adequate seed-soil contact, which leads to better germination and strong crop establishment. To measure the residue cutting, the initial weight of residue for a specific patch area of one square meter (0.4 m width and 2.5 m long) was measured, which was then placed on the soil surface across the plane of cutting. The uncut residue was carefully removed after the experimental coulters passed over it, and its weight was recorded. The percent residue cutting (Q) is measured by Eq. (1).

$$\text{Residue cutting (Q)}, \% = 1 - \frac{\text{weight of uncut residue (g)}}{\text{initial weight of the residue (g)}} \text{x}100 \quad (1)$$

Clogged Residue

Clogged residue is the amount of residue clogged or clumped with the no-till drill tool bar or residue management device during sowing operation. This clogged residue was found to be hindering smooth rotations of coulters subsequent cutting of residue and entangling in the furrow openers. Surface residue samples were collected from 2 m^2 area from the test run of soil bin. Clogged residue during cutting operation in the soil bin was collected from the furrow opener up to 5 m run. The collected residue was then weighed, and the quantity of clogged residue was reported in kg/ha.

Experimental Design

A factorial experiment with four factors, each at three levels, was set up with three replications to compare the effects of different speed ratios (S: 5.2, 6.94, and 8.67), number of holding wheels (P: without holding wheel, single holding wheel, and twin holding wheels) on both sides of the coulters, and different residue densities (R: 3000, 4000, and 5000 kg ha^{-1}). The performance of the coulters was evaluated by conducting tests in a comparative way using dependent parameters such as vertical force (V), horizontal force (H), torque (T) applied to different disc coulters and residue holding wheel, residue cutting percentage (Q) and residue clogged (C). An analysis of variance was performed to examine the effect of independent variables on response variables such as horizontal force, vertical force, torque requirements and percentage of rice residue cut, and F-test was conducted, and the results were evaluated at a 5% level of significance. Adjustment for multiple comparisons was performed using the Tukey-Kramer method. The statistical analysis of experimental data was carried out using SAS 9.3 software (SAS Institute, Inc., Cary, NC). Table 4 indicates the treatment combinations of variable levels used in the completely randomized design (CRD).

Table 4. Treatment combinations of variable levels.

Name of the variables	Range	Code (Xi)	Levels			Intervals
			Xi1	Xi2	Xi3	
			-1	0	+1	
Speed ratio (S)	5.2 - 8.67	X1	5.2	6.935	8.67	1.735
Pair of holding wheels (Nos.) (P)	0 - 2	X2	0	1	2	1
Residue load (kg/ha) (R)	3000-5000	X3	3000	4000	5000	1000
Type of disc coulters (B)	D_1- D_3	X4	D_1	D_2	D_3	-

Results

Evaluation of Horizontal Force (H)

Significant variation in the horizontal force was observed for different levels of speed ratios, residue holding wheels, residue loads and type of coulters. With an increase in speed ratio from 5.20 to 8.67, horizontal forces increased for all the three residue cutting coulters at all the residue load levels and the number of residue holding wheels increased from 0 to 2.

The effect of different factors and their interactions on horizontal force has been presented in Table 5. It was found from the ANOVA that all the considered factors significantly affected the requirement for horizontal forces. The LS-means of the effect of one factor are appropriately adjusted for the other factor effects in the model. The effect of different parameters on mean horizontal force is shown in Table 6. As speed increases, mean horizontal force also increases.

Table 5. ANOVA table for showing the effects of different factor on different response.

Source	df	F Value				
		H	V	T	Q	C
Model	32	80.76*	73.98*	69.45*	37.74*	805.09*
S	2	20.76*	5.81*	13.55*	6.81*	109.76*
P	2	945.83*	672.74*	450.10*	553.87*	7485.67*
S*P	4	0.84	0.44	1.23	0.21	9.16*
R	2	65.19*	134.75*	156.90*	0.28	2.08
S*R	4	0.68	0.39	0.44	0.34	1.20
P*R	4	1.06	0.40	1.20	0.43	2.63
B	2	212.06*	321.44*	379.85*	25.13*	3012.65*
S*B	4	0.63	0.52	0.27	3.99*	6.19*
P*B	4	2.32	3.65*	6.13*	3.50	1112.26*
R*B	4	7.02*	1.87	16.19*	2.11	4.22
Error	63					
Corrected total	95					

**Significant at 5%.*

Note: S-Speeds, P-Holding wheels, R-Residue loads, B-Type of coulters, C-Residue clogged.

Evaluation of Vertical Force (V)

Significant variation in the vertical force with changes in speed ratio, residue holding wheels, residue load, and type of disc coulter was observed (P < 0.001). With an increase in speed ratio from 5.20 to 8.67, vertical forces increased for all the three residue cutting coulters at all the residue load levels (3000 to 5000 kg ha^{-1}) and increased with the pair of residue holding wheels increased from 0 to 2.

The effect of different factors and their interactions on vertical force has been presented in Table 5. It was observed that there was significant variation in the vertical force with changes in speed ratio, residue holding wheels, residue loads, and type of disc coulters (P<0.001). The multiple comparisons between the effects of levels of factors are shown in Table 6. The LS-means of the effect of one factor are appropriately adjusted for the other factor effects in the model.

Table 6. Effect of different parameters on different responses

Parameters	Values	LS mean				
		H, N	V, N	T, Nm	Q, %	C, kg/ha
	5.20	105.17^{C}	282.07^{B}	13.09^{B}	46.49^{B}	42.46^{A}
Speeds (S)	6.94	111.55^{AB}	286.57^{AB}	13.45^{BC}	52.96^{A}	34.66^{C}
	8.67	115.10^{A}	294.05^{A}	14.27^{A}	45.62^{BC}	40.09^{B}
	0	77.47^{C}	219.02^{C}	10.38^{C}	12.91^{C}	20.11^{B}
Residue holding wheels (P)	1	108.93^{B}	295.00^{B}	13.14^{B}	44.19^{B}	77.24^{A}
	2	145.42^{A}	348.68^{A}	17.30^{A}	87.98^{A}	19.86^{B}
	B1	122.45^{B}	326.14^{A}	16.13^{A}	44.94^{B}	62.64^{A}
Coulters (B)	B2	93.14^{A}	240.89^{C}	10.18^{C}	57.18^{A}	22.49^{C}
	B3	116.22^{BC}	295.67^{B}	14.50^{B}	42.95^{BC}	32.08^{B}
	3000	101.42^{C}	258.64^{C}	11.46^{C}	48.70^{A}	39.67^{A}
Residue loads (R)	4000	111.16^{B}	287.07^{B}	13.79^{B}	47.44^{A}	38.59^{A}
	5000	119.24^{A}	316.98^{A}	15.57^{A}	48.95^{A}	39.67^{A}

Note: Number with different symbols (A, B and C) in each column are significantly different at $\alpha = 0.05$.

The vertical force requirements exhibit nearly equal effects for speed ratios of 5.20 and 6.94. Similarly, speed ratios of 6.94 and 8.67 also result in almost identical impacts on vertical force. The mean vertical forces differ significantly at 5% probability level as number of holding wheels increases.

Evaluation of Torque (T)

Significant variation in the torque with changes in speed ratio, a pair of holding wheels, residue loads, and type of coulters was observed ($P<0.001$). It is also observed that the torque requirement decreased linearly with increased speed ratio and increased linearly with a pair of holding wheels and residue loads, while it increased quadratically with speed ratio and number of residue holding wheels using all three coulters.

It has found from Table 6 and ANOVA that the mean torque was found to be statistically same at a lower level of speed ratio, but it was significantly different at 8.67 of speed ratio. The mean torque differed significantly at the 5% probability level as the number of holding wheels increases.

Evaluation of Residue Cutting percentage (Q)

The F-values indicated that the number of residue holding wheels was the most influential factor for residue cutting percentage. The effect of different factors and their interactions on cutting percentage has been presented in Table 5. The effect of speed ratio, holding wheels, and type of coulters had a significant effect on cutting percentage, whereas the levels of residue load had no significant effect.

Based on an LS means comparison (Table 6) of percentage residue cut, the machine setting at 6.94 speed ratio with the second pair of twin wheel holding wheels with coulter coulter (B2) was found to be superior. This implies that elevating the rotational speed of coulters up to a certain level did not impact the amount of crop residue cut. As a result, the machinery could potentially operate with greater efficiency and reduced energy consumption. The maximum mean cutting efficiency was 87.98% in the case with a system run with a twin holding wheel system, and the minimum was found when there was no holding wheel mounted on the residue cutting assembly.

Residue Clogged (C)

Table 5 illustrates the impact of various factors and their effect on residue clogging. The F-values suggest that the interaction of the number of residue holding wheels and coulters has the most significant effect on minimizing residue clogging. Through a comparison of LS means (Table 6) for residue clogging, it was determined that the optimal machine configuration for minimizing clogging involved a speed ratio of 6.94 paired with twin wheel holding wheels featuring coulter coulters (B2).

Overall effect of residue holding assembly

Combination of type of holding wheels and coulters revealed that pairing holding wheels and B2 coulter yielded 100% absolute cutting efficiency (Table 7). Overall, the machine set at speed ratio 6.93 using two holding wheels and a B2 type of coulter was found superior for cutting rice residue. Interaction showing effect of other parameters interaction (R × B, P × B, S × B and S × P) on studied parameters (H, V, T, Q and C) is shown in Table 8.

Table 7. Combination of type of holding wheels and coulters on cutting percentage.

Holding wheels	Type of disc coulters	LS mean of cutting efficiency %
0	B1	11.07[f]
0	B2	16.26[e]
0	B3	11.40[f]
1	B1	37.43[d]
1	B2	55.29[c]
1	B3	39.83[d]
2	B1	86.33[b]
2	**B2**	**100.00[a]**
2	B3	77.63[b]

Note: The numbers with different symbols of alphabets in the column are significantly different at α = 0.05.

Table 8: Interaction showing effect of other parameters interaction (R × B, P × B, S × B and S × P) on studied parameters.

Interactions			LS Means				
			H, N	V, N	T, Nm	Q, %	C, kg/ha
BxP	B1	P1	87.08ef	335.20abc	12.45e	11.07f	23.58e
	B1	P2	120.46d	341.80ab	16.04c	37.43d	128.82a
	B1	P3	158.76a	390.10a	19.80a	86.33b	35.53d
	B2	P1	63.49g	179.07d	7.70h	16.26e	18.44f
	B2	P2	89.23e	257.24bcd	9.61g	55.29c	43.84c
	B2	P3	126.91c	302.32abc	13.61d	100.00a	5.18g
	B3	P1	81.86f	228.67cd	11.01f	11.40f	18.32f
	B3	P2	117.21d	307.03abc	14.13d	39.83d	59.05b
	B3	P3	150.61b	373.90a	18.80b	77.63b	18.87f
BxS	B1	S1	115.70cd	397.99a	15.53b	41.68d	67.20a
	B1	S2	122.19b	331.02ab	16.02ab	48.17c	56.55c
	B1	S3	128.40a	338.09ab	16.73a	41.51d	64.18b
	B2	S1	88.70f	240.37b	9.76f	58.76b	24.12g
	B2	S2	95.03e	247.04b	10.03f	62.93a	19.56h
	B2	S3	95.90e	251.23b	11.13e	56.93b	23.79g
	B3	R1	111.12d	297.43a	14.01d	39.87d	36.07d
	B3	R2	117.55b	302.25a	14.65dc	50.59c	27.86f
	B3	R3	121.01b	309.93a	15.27bc	37.22e	32.31e
PXS	P1	S1	72.12f	289.03ab	9.64f	10.08f	22.54d
	P2	S2	77.44fe	222.17b	10.24f	18.29e	16.94e
	P3	S3	82.86e	231.77b	11.28e	8.94f	20.85d
	P1	S1	101.89d	295.56ab	12.79d	43.94d	82.52a
	P2	S2	110.48c	301.57ab	13.09d	52.69c	70.25c
	P3	S3	114.52c	308.96ab	13.90c	40.94d	78.95b
	P1	R1	141.50b	351.21a	16.89b	86.28b	22.33d
	P2	R2	146.83ab	356.58a	17.38ab	90.71a	16.78e
	P3	R3	147.93a	358.53a	17.95a	85.78b	20.48d
BxR	B1	R1	108.97d	373.24a	13.04d	43.39b	64.65a
	B1	R2	122.23bc	363.93a	16.22b	44.52b	60.55b
	B1	R3	135.09a	336.81a	19.02a	43.45b	62.73ab
	B2	R1	89.18f	329.93ac	9.34h	59.86a	22.38d
	B2	R2	94.56ef	304.26ac	10.39g	59.62a	23.16d
	B2	R3	95.89e	268.63ac	11.19f	59.14a	21.93d
	B3	R1	106.11d	268.54ac	12.02e	42.90b	31.98c
	B3	R2	116.79c	247.64c	15.10c	42.17b	32.06c
	B3	R3	126.77b	222.37c	16.81b	42.60b	32.20c

The plot of attributes such as horizontal force, vertical force, torque and cutting efficiency, reflecting the effect of residue holding assembly, has been shown in Figure 5. The value measurement data of all attributes increased significantly at a 5% level of significance as the number of holding wheels increased (Figure 4) for all levels of residue load.

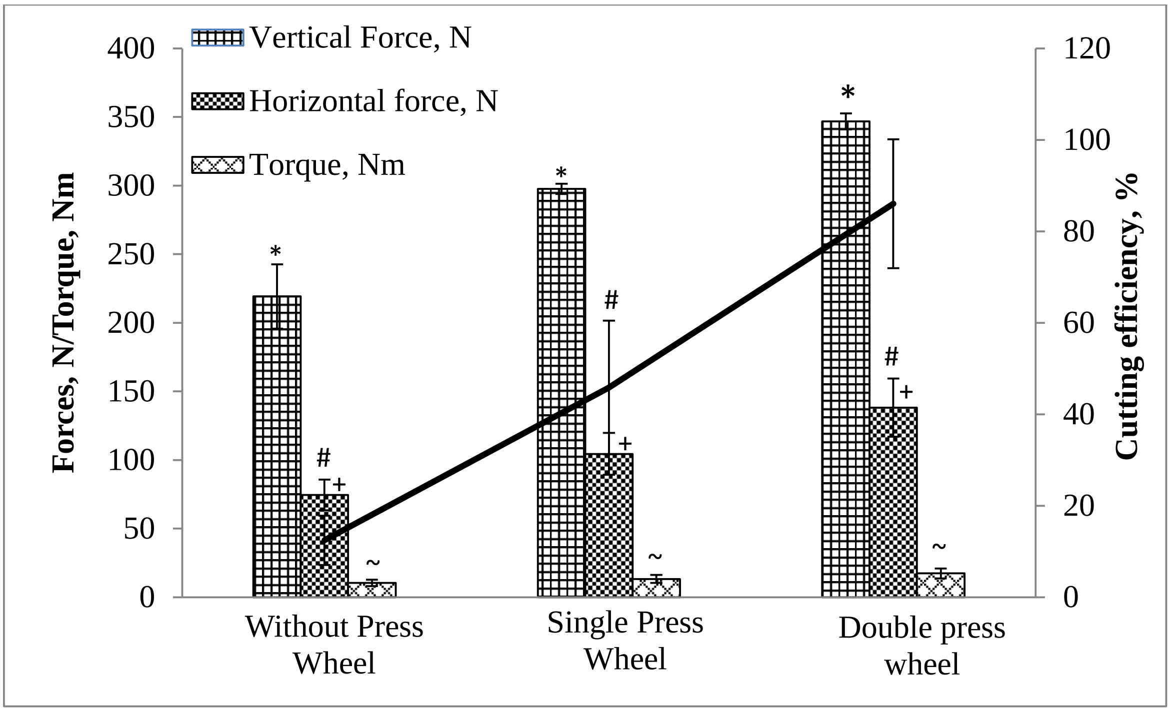


Figure 5. Effect of holding wheel assembly on different attributes. * Vertical force significantly differ with types of holding wheel; + Horizontal force significantly differ with types of holding wheels; # Torque significantly differ with types of holding wheel, ~ cutting efficiency significantly differ with types of holding wheel.

The seeding attachment as shown in Figure 7a was mounted just behind the residue cutting mechanism of the plain coulter with a pair of twin holding wheels for the sowing of wheat seeds with 5000 kg ha^{-1} of residue load of rice in the soil bin to check their emergence and accumulation of rice residue found with the incorporation of the furrow opener. The residue cutting mechanism with seeding attachment carriage, which is shown in Figure 6, was operated at 2.5 km h^{-1} speed, maintaining the minimum speed ratio of 6.94 and maintaining the depth of residue cutting of 15 mm. Figure 7b depicts a view of wheat seedlings after 7 days of sowing.

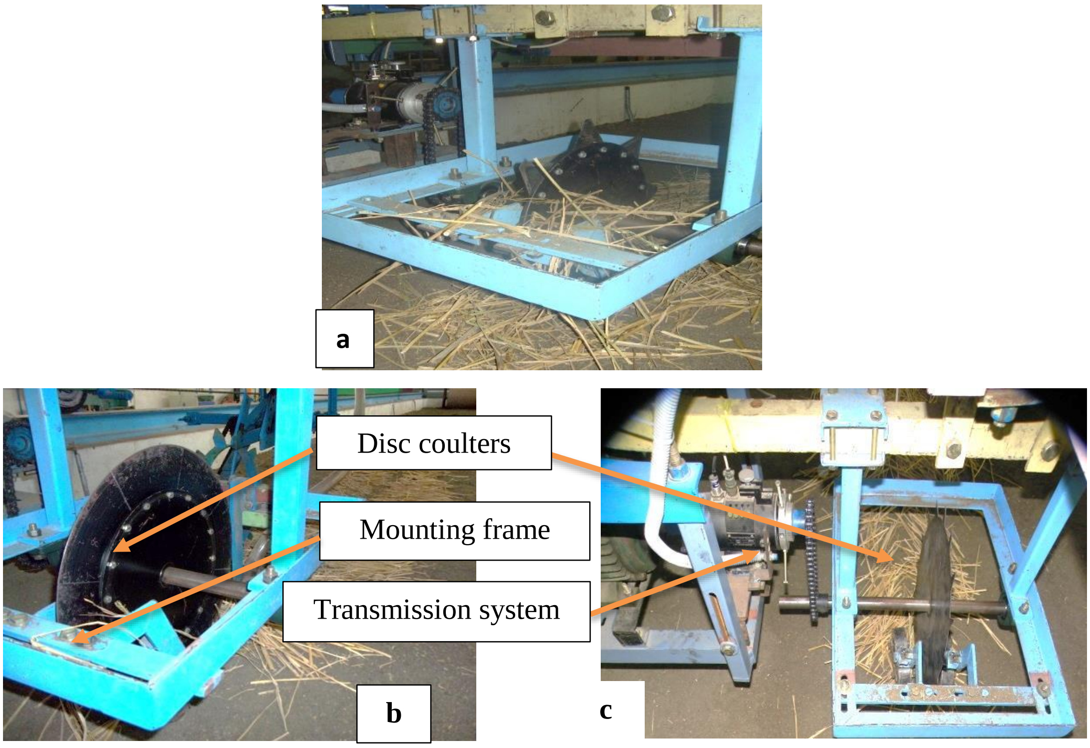
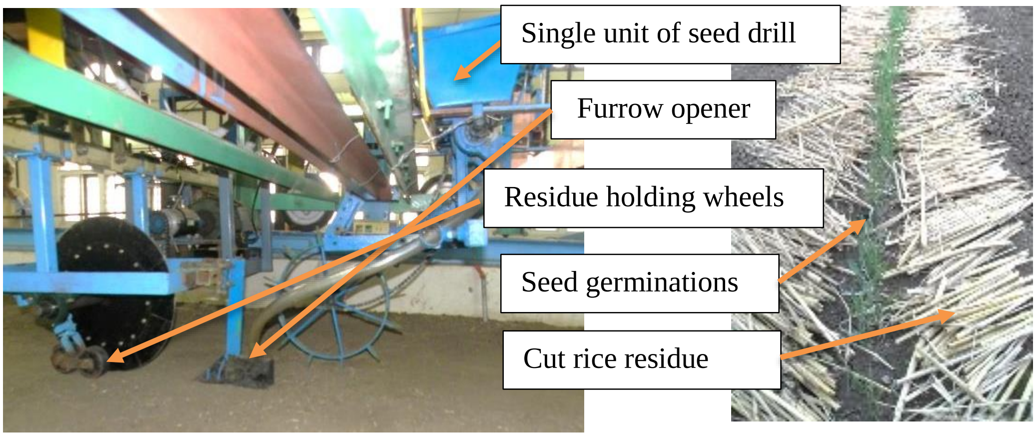


Figure 6. Cutting of residue by (a) serrated coulter, (b) plain coulter and (c) toothed coulter with two residue holding wheel assembly.



(a) **(b)**

Figure 7. (a) Residue cutting-holding wheels with seed drill attachment and (b) wheat seedling emergence after 7 days after sowing in soil bin

DISCUSSION

Horizontal Force (H)

The LS means (Table 6) showed that the horizontal force was significantly higher for twin holding wheels, followed by the single holding wheel and no holding wheel. As the number of holding wheel increases, normal force and rolling resistance increases. This causes an increase in horizontal force on coulter. The mean horizontal force (101.42–119.24 N) was proportional to the residue level (0-500 kg) at each level of increased residue load. The increased number of holding wheels affects normal force and rolling resistance by enhancing soil compression, increasing frictional forces, improving traction, contributing to soil and residue compaction and stabilizing coulters. Plain disc provided smooth operation and exerted less horizontal force compared to the other disc coulters i.e. serrated disc and disc toothed. Becker *et al.*, (2019) observed that the horizontal force exerted by a plain disc coulter was the lowest at 115 N, compared to the wavy (135 N), rippled (128 N), and helical wavy (125 N) disc coulters. Kushwaha *et al.*, (1984) reported that the lowest horizontal force was in the range of 59.8–92.1 N for a plain coulter on straw density of 5000 kg/ha, as compared to notched and serrated coulters. Increased speed ratio also increased draft force for all residue levels from 0 to 5000 kg/ha. However, Bianchini and Magalhaes' (2008) study revealed a contrasting result, indicating a descending order of horizontal force for smooth (0.94 kN), followed by notch (0.60 kN), and toothed surfaces (0.32 kN) at 80 mm depth. Ahmad *et al.*, (2019) concluded that the draft of the toothed type disc was found to be the lowest (421 N) in comparison to notched (444.3 N) and smooth (781.3 N) type discs. Zeng *et al.*, (2021) found that the draft force required to cut corn residue (load 7500 kg/ha) was lowest in the case of the notched (579 N) disc, followed by plain and ripple (675 N) discs.

Vertical Force (V)

The minimum vertical force was found with B2 coulters, which significantly differ from the other two types of coulters (Table 6). The serrated disc coulters B1 and B3 touched to the ground surface, experienced sudden load resulted in higher vertical force compared to plain disc coulter (B2). The higher vertical force associated with the coulters may lead to increased wear and tear on the coulters and increases the power requirements. The lowest mean vertical force was found at 3000 kg ha^{-1} of residue load and increased significantly with an increased level of residue load. As residue load increases, the depth required to cut increases which increase vertical force on the disc coulter. The relationship between residue load, cutting depth, and vertical force extend to optimizing machinery performance. This will help to mitigate excessive forces, leading to prolonged equipment lifespan and reduced maintenance costs. Kushwaha *et al.*, (1984) observed that the lowest vertical force for a plain coulter at 5000 kg/ha straw density was in the range of 262.9–309.6 N, which was lower than for notched and serrated coulters. It was also found that increasing the speed ratio decreased the vertical force for all residue levels, ranging from 0 to 5000 kg/ha. However, Bianchini and Magalhaes' (2014) study revealed a contrasting result, indicating a descending order of vertical force for smooth (3.54 kN), followed by notch (2.12 kN), and toothed surfaces (1.24 kN) at 80 mm depth. Ahmad *et* *al.,* 2019 determined that the vertical force of the toothed disc type was the lowest at 903.7 N, as opposed to the notched (1105.3 N) and smooth (923 N) disc types. Zeng *et al.,* (2021) also found that the notched disc exhibited a minimal vertical force of 164 N, which was lower than that of the rippled disc (289 N), as well as the plain disc.

Torque (T)

The torque produced was significantly lower for the plain coulter (10.18 Nm) followed by the B3 and B1 coulters. The lowest mean torque was found at 3000 kg ha^{-1} of residue load and increased significantly with an increased level of residue load. The highest mean torque (15.57 Nm) was observed at 5000 kg ha^{-1} of residue load. The plain coulter showed the lowest minimum mean torque (10.18 Nm) due to lower rolling resistance as compared to the other selected coulters. The absence of serrations on the plain coulter might result in a smoother cutting action, reducing the resistance encountered during soil penetration. Magalhaes and Bianchini's 2014 study revealed a contrasting result, indicating a descending order of torque required for smooth, followed by notch and toothed surfaces. Lower torque requirements for cutting residue can potentially operate machinery more efficiently and consume less energy.

Residue Clogged (C)

The residue cutting coulter, equipped with twin holding wheels, effectively cuts rice residue to a shorter length, facilitating its smooth passage between two furrow openers. The cutting coulter efficiently slices through the remaining rice stalks, while the twin holding wheels play a crucial role in compacting and preparing the cut residue for easy traversal. The shortened residue can then move smoothly between the furrow openers, resulting in minimal residue clogging.

Cutting Performance and Residue Holding Assembly

The toothed and serrated coulter caused greater residue disturbance, either by throwing it backward at high rotation or by carrying the residue along the periphery at lower rotation, and thereby, in the process, caused greater soil disturbance too. The plain disc coulter, in combination with the holding device, greatly facilitated the residue cutting without displacing the residue from its original position and created a clean and clear space for dropping the seed into the furrow with good soil contact. Variations in cutting percentage influence residue management, leading to improved sowing operations without any mechanical blockages. This results in better short-term crop growth and long-term soil health.

The effectiveness of disc coulter coulters to cut rice residue increased significantly with the use of holding wheel assembly because more continuous holding of residue with soil surface took place when the cutting coulter rolled over on the residue surface with double holding wheel assembly than with single holding wheel assembly. There was no such holding of residue observed without holding wheel assembly. The serrated and toothed coulters didn't make smooth contact with loose residue, resulting in more throwing of residue than cutting, even with the use of holding wheel assembly, resulting in poor residue cutting performance, which could be seen in Figures 5a&c.

Kushwaha *et al.,* 1986 observed and analysed that the straw cutting performance of the plain coulter reached nearly 100%. The quantity of straw cut increased with higher rotational speeds and decreased with elevated straw density with notch and serrated coulters. Kumar *et al.,* 2021 found that the star wheel disc coulter exhibited the highest mean residue cutting at 98.15%, surpassing notched (84.12%), curved teeth (75.82%), plain (61.82%), and cutter bar blade disc coulter (52.12%) when no residue holding devices was used. Conversely, other researchers such as Bianchini and Magalhães (2008), Ahmad *et al.*, 2017, and Zeng *et al.*, 2021 reported contrasting results regarding the cutting performance of plain coulter. The residue cutting effectiveness of the discs showed variations, ranging from the highest to the lowest, with no significant differences observed among the rippled, notched, and plain discs as results reported by Zeng *et al.*, 2021. Ahmad *et al.*, 2017 found that the average straw-cutting efficiency for notched, toothed, and smooth-edge single disc, and double disc furrow openers were 12.4%, 46.2%, 11.4%, and 78.5%, respectively. Despite this, from a practical standpoint, the fabrication of plain coulters is economically viable and can be carried out by local fabricators. The incorporation of a residue holding wheel enhances cutting efficiency.

As shown in Fig 7, after passing the residue cutting mechanism over the rice residue, a clear furrow was observed and seed was placed in the soil at an average depth of 35 mm as the furrow opener was fitted at a 20 mm higher depth than that of the residue cutting mechanism. The study conducted by other author, the depth of operation of residue cutting coulters has been in the range of 50–90 mm in order to achieve complete cutting of residue and overcome the problem of 'hair pinning' in softer soil (RL Kushwaha 1986a; RL Kushwaha 1986b; Magalhães *et al.*, 2007; Bianchini and Magalhaes 2008).

CONCLUSIONS

Our research investigated the performance of various disc coulters with a combination of residue-holding wheels for cutting rice residue in direct seeding applications. Based on that, the following conclusions have been drawn from this study:

1. The performance of the disc coulter with twin wheel residue holding assembly in cutting rice residue was superior to that of the serrated and toothed coulters for all levels of residue loads.
2. Horizontal forces, vertical forces, and torques increased with an increase in speed ratio, residue load and the number of residue holding wheels for all tested coulters. The horizontal forces, vertical forces and torques were found to be lower in case of plain disc coulter as compared to other disc coulters.
3. The residue holding device had a greater influence on the rice residue cutting performance to facilitate direct seeding in residue condition. The combinations of plain disc coulter and double holding wheel assembly performed nearly 100% cutting at all residue levels and coulter speed ratios.
4. The seeding machine could be fabricated with this coulter accompanied by twin residue holding wheels to evaluate its performance under real field conditions.

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Nomenclature

B	Different types of disc coulters (dimensionless)
H	Horizontal force (N)
P	Holding wheel (dimensionless)
Q	Residue cutting percentage (%)
R	Residue density (kg ha^{-1})
S	Speed ratio (m s^{-1})
T	Torque (Nm)
V	Vertical force (N)
wb	Wet basis (%)