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Combined Effect of Disc Coulters and Operational Speeds on Soil Disturbance and Crop Residue Cutting under No-Tillage System in Soil Bin

Neeraj Kumar[1]*, C P Sawant[2], R K Sharma[1], R S Chhokar[1], P S Tiwari[2], Dushyant Singh[2], A K Roul[2], S C Tripathi[1], S C Gill[1] and G P Singh[1]

[1]ICAR– Indian Institute of Wheat and Barley Research Karnal, 132001, Haryana, India

[2]ICAR– Central Institute of Agricultural Engineering, 462038, Madhya Pradesh, India

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In the present study, a residue cutting system comprising of different disc coulters (plain, notch, curved teeth, cutter bar and star wheel) was developed and its performance was evaluated under no-tillage system in soil bin. The performance of residue cutting system was evaluated by performing a total of 135 experiments (including replications) in soil bin (black cotton soil, moisture content: 16.8–18.4% db and cone index: 1600±100 kPa) using forward speeds of 0.56, 0.83 and 1.11 $m{\cdot}s^{-1}$ under the crop residues of rice (8 $t{\cdot}ha^{-1}$), wheat (8 $t{\cdot}ha^{-1}$) and maize (16 $t{\cdot}ha^{-1}$). The effects of disc coulters and operational speeds on performance parameters *viz.* penetration depth, top width, soil disturbance and residue cutting were investigated. For all type of disc coulters, penetration depth and top width were found in the range of 5–10 and 0.6–5.7 cm, respectively. The least soil disturbance was observed for star wheel disc coulter under maize residue. The operational speeds of 0.56 and 1.11 $m{\cdot}s^{-1}$ favored lesser soil disturbance. The highest mean residue cutting was observed for star wheel disc coulter (98.15%) followed by notched (84.12%), curved teeth (75.82%), plain (61.82%) and cutter bar blade disc coulter (52.12%). The change in forward speed did not produce significant effect on residue cutting. Star wheel disc coulter was effective in cutting of medium to heavy residue loads of rice, wheat and maize crops along with minimal soil disturbance.

Keywords: Conservation agriculture, Crop residue management, Residue cutting system, Rice residue, Star wheel disc

Introduction

The burgeoning population and over exploitation of natural resources have put more challenges before researchers and policy makers to meet the food grains demand in a sustainable way. Researchers expressed concerns on soil health deterioration, poor crop response, falling water table, rising environmental pollution and declining factor productivity of agriculture sector.[1–3] Climate change along with some on-going practices like intensive tillage, adoption of same cropping pattern over the years e.g. rice-wheat in Indo-Gangetic Plains (IGP), and unbalanced fertilizer application are believed to be major factors responsible for decline in soil health, crop response and factor productivity.[3] In long-term, intensive tillage coupled with residue burning is associated with soil structure destruction, soil quality deterioration and subsurface compaction.[4–6] Therefore, to overcome such problems, some alternative practices need to be implemented for sustainable farming. Conservation agriculture (CA) is one such practice which emphasizes on minimum soil disturbance, soil cover (≥30%) with residue and crop rotation. It has the potential to reverse the degradation of natural resources, while providing other benefits of soil, water and energy conservation in long run.[7] However, amidst multiple advantages, adoption rate of CA has been slow on farmers' fields due to lack of commercial availability of suitable and efficient seeding machines for multi-cropping systems.

In some regions, farmers partially adopted the CA mainly in the form of zero-till drilling, where crops are directly seeded into soil without any tillage operation. The ability of zero-till drilling to overcome the late sowing problem in wheat after rice harvesting greatly motivated the farmers of IGP to adopt this technology as any delay in sowing beyond 30th November can reduce the wheat grain yield by 26.8 $kg{\cdot}day^{-1}{\cdot}ha^{-1}$.[8] Over the years, the application of zero-till drill extended for direct seeding of other crops such as green gram, black gram, soybean, maize, rice, etc., under residue free or anchored residue covered fields. However, the presence of loose residue in the field causes frequent clogging of inverted T-type furrow openers of zero-till drill

*Author for Correspondence
E-mail: neerajkumarsaini.126@gmail.com

machine, which could be as high as 90−100%.[(9)] It restricts the application of zero-till drill machine to residue free or anchored residue covered fields. Moreover, it has limited applicability for direct seeding of wheat in north-western India, where rice is harvested by the combine, which leaves anchored and loose residue on the field, thereby creating in-situ residue management challenges.[10] The inability of zero-till dill to work under loose residue and lack of other suitable and efficient CA machines have been identified as key reasons for slow adoption of CA in this region. These problems encourage the farmers to adopt injudicious practice of residue burning for managing the crop residue in rapid and economical way to avoid any delay in wheat sowing. Alternatively, some farmers are using Turbo Happy Seeder (THS) developed by Sidhu *et al.* (2007, 2015) for direct seeding of wheat and other crops under loose and anchored residue covered fields.[11,12] In wheat sown with THS, the operational cost was 50−60% lesser along with lower canopy temperature, reduced evaporation losses and lesser irrigation requirement over conventional practice. Despite these advantages, incapability of machine to work in moist residue, high power requirement (≥45 hp) and small operational window are the major constraints in large scale adoption of THS as CA machine.[13] Based on the problem of clogging in furrow openers of THS, Sidhu *et al.* (2015) recommended to use disc furrow openers for effective seeding operation under moist straw.[12]

The problem of frequent clogging in dragging type furrow openers used for direct seeding of crops under loose residue can be addressed by rolling type attachment like double disc furrow openers. However, it is necessary to cut the loose residue with special attachment like coulter fitted just ahead of double disc furrow openers to avoid the hairpining problem for proper opening of furrow and seed-soil contact to have better germination of crops. The performance and energy requirement of disc coulters are affected by design parameters (disc type, size, thickness and material), operational conditions (forward and rotational speeds), soil characteristics (soil texture, structure, bulk density and moisture content) and residue conditions (residue type, its moisture content and load). Tourn *et al.* (2003) studied the effect of turbo coulter blade and row cleaners (notched and floating star) on residue clearance and plant emergence of corn, when used in combination with double disc furrow opener followed by packing wheels.[14] It was reported that residue clearance and crop emergence was maximum with seeding assembly having notched row cleaner and turbo coulter blade with double disc furrow opener and packing wheels over other combinations. Bianchini & Magalhaes (2008) evaluated the performance of power driven toothed, notched and smooth coulters (dia 610 mm) in cutting of sugarcane residue (load 10 $t{\cdot}ha^{-1}$, mc 40−60%) at a forward speed of 0.7 $m{\cdot}s^{-1}$ in soil bin filled with sandy clay loam soil (mc 13.4% db).[15] In the experiments, depth of operation was kept as 8 and 10 cm, while maintaining the mean cone index as 1500 kPa. The performance of toothed type disc coulter was found better, which pushed 2 gm^{-1} of residue into the soil. Hegazy & Dhaliwal (2011) studied the performance of active toothed cutting wheel in combination with curved plugs type residue removing wheel for cutting of rice residue (2.54 $t{\cdot}ha^{-1}$ loose and 2.14 $t{\cdot}ha^{-1}$ anchored residue) in sandy loam soil (mc 13.5%, cone index 3800 kPa).[16] The maximum residue cutting was found to be 70% when toothed cutting wheel was used in combination of residue removing wheel. Nejadi & Raoufat (2013a) investigated the effect of active toothed coulter on pneumatic corn planter's penetration in semi-dried soils covered with wheat residue (3.52 and 5.65 $t{\cdot}ha^{-1}$).[17] It was found that active toothed coulter in combination with row cleaner managed the previous crop residue efficiently along with deeper seed placement, better emergence rate index and seed indices to facilitate direct drilling of maize. In another study, Nejadi & Raoufat (2013b) assessed the performance of smooth and toothed coulters at two forward speeds of 1.39 and 1.94 $m{\cdot}s^{-1}$ under wheat residue load of 3.75 and 5.83 $t{\cdot}ha^{-1}$.[(18)] It was revealed that emergence rate index and seed placement depths were higher with toothed coulter than smooth coulter. The forward speed of 1.39 $m{\cdot}s^{-1}$ favoured the higher seeding depth. However, miss and precision indices were lower at the forward speed of 1.94 $m{\cdot}s^{-1}$.

Sarauskis *et al.* (2013) evaluated the performance of smooth and notched disc coulters in cutting of wheat residue when operated at different speed ratios (rotational to forward speed ratio) under no-tillage system.[19] The maximum cutting of wheat residue with 10.1 and 22.3% moisture content was found to be 69.3 and 48%, respectively, for notched disc coulter with speed ratio of 1.5. Badegaonkar *et al.* (2014) conducted the soil bin experiments to evaluate the performance of plain and serrated disc coulters in cutting of rice residue (5 t·ha^{-1}) when operated at 15 mm depth and 0.69 m·s^{-1} forward speed with different speed ratio (5.2–8.67).[(20)] The maximum residue cutting of plain disc coulter with a pair of twin press wheels was found to be 100% under all speed ratios. Francetto *et al.* (2016) investigated the effect of smooth and offset fluted coulters in combination with hoe and double disc furrow openers on soil elevation, soil disturbance area and soil swelling when operated at forward speeds of 1.11, 1.67, 2.22 and 2.78 m·s^{-1}.[(21)] The depth of furrow reduced with forward speed. The use of different coulters increased the furrow width by 10%, irrespective of the edge of the coulter. The soil disturbance area was reduced by 12.26% when plain coulter was used with furrow openers replacing the offset coulter. Soil elevation, disturbance area and swelling were lesser with double disc furrow opener over hoe furrow opener. In a different study, Sawant *et al.* (2016) observed that double disc furrow opener with plain rolling coulter was effective in cutting of maize stalk at all test speeds (0.42–0.69 m·s^{-1}).[(22)] The maximum soil moisture retention of 11.2%, soil bulk density of 1.52 g·cc^{-1}, soil penetration resistance of 1370 kPa and minimum soil disturbance were observed for double disc furrow opener with plain rolling coulter, indicating its suitability for conservation agriculture. In a different study on performance of wheat seed-cum-fertilizer plot drill attached with plain coulter followed by double disc furrow opener under pearl millet crop residue, higher plant stands of wheat were observed as compared to precision plot drill attached with inverted T-type furrow openers.[23] Wang *et al.* (2018) evaluated the performance of notched-flat and fluted (8W, 13W, 18W and 25W) coulters at different forward speeds of 2.22, 2.78 and 3.33 m·s^{-1} under no and full residue conditions, while maintaining the working depth as 80 mm.[24] It was observed that notched-flat coulter and fluted coulters with large wave number (18W and 25W) required lesser cutting force and were suitable for residue covered field. Contrary, fluted coulters with small wave number were suitable for preparing the seedbed. Becker *et al.* (2019) conducted the field experiments to evaluate the performance of plain, wavy, rippled, and helical wavy disc coulters in cutting of wheat residue (0.6 t·ha^{-1}) at different forward speeds (1.11–2.78 m·s^{-1}).[25] It was found that tractive force requirement increased with speed. The minimum mean mobilized area was observed for plain disc followed by rippled, helical wavy and wavy disc coulters.

Based on the outcomes of above mentioned studies, it is clear that use of suitable coulter in combination with furrow openers is necessary for direct seeding with proper seed-soil contact under loose crop residue. However, coulter design, soil condition, speed of operation, residue type, its moisture content and load affect the performance of coulter in terms of residue cutting and soil disturbance. Considering these aspects, the present study was undertaken to develop a residue cutting system comprising with different disc coulters and to evaluate its performance in terms of soil disturbance and crop residue cutting of rice, wheat and maize under no-till condition in soil bin at different forward speeds.

Materials and Methods

Experimental Set-up

The residue cutting system was developed at Prototype Production Centre (23°18'33.0"N, 77°24'7.0"E) of ICAR–Central Institute of Agricultural Engineering (CIAE), Bhopal. It comprised five different types of disc coulter namely plain, notched, curved teeth, cutter bar blade and star wheel disc coulter (dia 450 mm, thickness 4 mm). In present study, different types of disc coulters were considered based on the null hypothesis, which states that type of disc coulter affects the crop residue cutting. The dimensions of major components of residue cutting systems are given in Table 1. The disc coulters used in the study are shown in Fig. 1. Disc coulters were mounted vertically on the shaft without any disc angle. Initially, the developed residue cutting system equipped with multiple disc coulters (two at front shaft and one at rear shaft with side press wheels

Table 1 — Dimension of major components of residue cutting system

Sl. No.	Component	Dimensions/Specifications
1	Shaft	⌀ 50 mm, length = 1820 mm
2	Spacing between shafts	280 mm (centre to centre)
3	Disc coulter	⌀ 450 mm, thickness = 4 mm
4	Press wheel	⌀ 250 mm, width = 50 mm
5	Flange	Internal ⌀ 50.5 mm, external ⌀ 65 mm, overall length = 70 mm with a collar of external ⌀ 110 mm and 6 mm width
6	Side plate	620 × 400 × 8 mm
7	Bearing	Radial ball bearing (6008), internal ⌀ 40 mm, external ⌀ 68 mm, width = 15 mm
8	Frame	40 × 40 × 5 mm

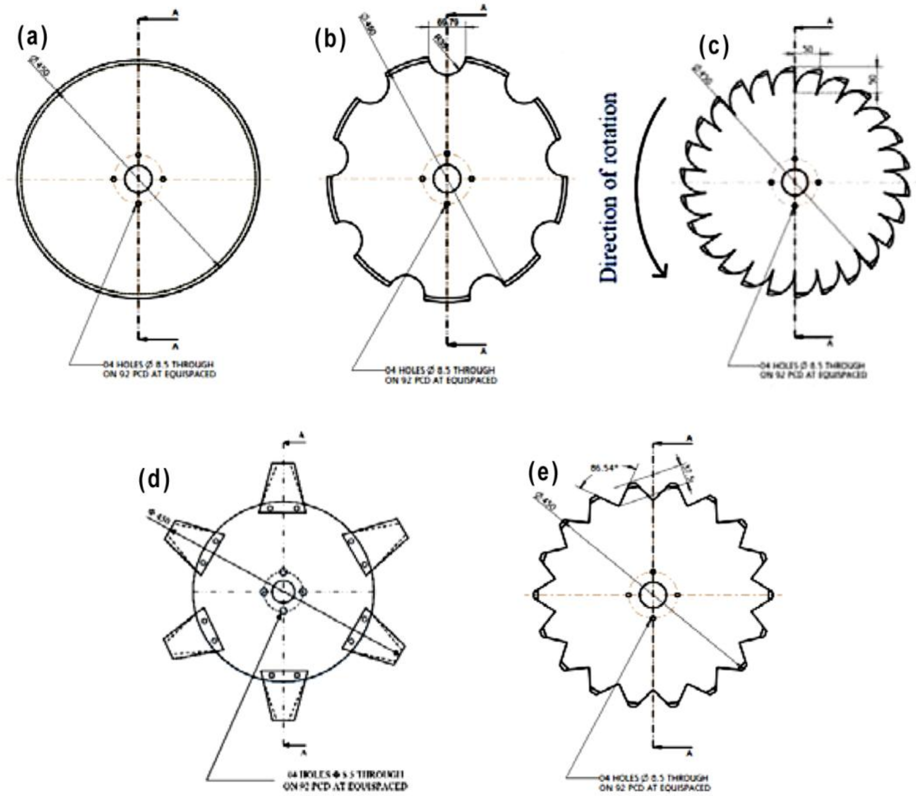

Fig. 1 — Drawing of different disc coulters used in residue cutting system

Fig. 2 — Disc coulter and press wheels mounted on the shafts of residue cutting system

only) was tried to operate in soil bin under powered mode through an electric motor and chain sprocket power transmission system. However, it could not be operated under powered mode even with one coulter due to less torque capacity of the motor. Moreover, with this arrangement, residue could not be held by side press wheels at the cutting point as it lies much ahead to the centreline of the shaft. Considering these problems and to ensure simultaneous holding and cutting actions on the loose residue, two press wheels (material: polypropylene, dia: 250 mm, spacing: 20 mm) were mounted on the front shaft as shown in Fig. 2 (a) and developed residue cutting system equipped with only one disc coulter at rear shaft along with side press wheels was tested under free rolling condition in soil bin by switching off the electric motor. The residue cutting system was attached to the carriage as presented in Fig. 2 (b). The indoor soil bin contained a stationary soil bin, soil processing trolley, linear movement transmission system, carriage and test rig. The soil bin was filled with black cotton soil (sand 19.2%, slit 27.6% and clay 52.3%) having 1.37 g·cc^{-1} bulk density and 30.6% field capacity.[26]

Soil Bin and Test Rig

The soil bin contained a stationary bin (5 m length, 2.1 m width and 1 m deep), soil processing trolley, carriage, test rig, linear movement transmission system, power transmission unit, instrumentation setup, and data recording unit. Both sides of soil bin were equipped with top rails to facilitate the linear motion of soil processing trolley and residue cutting system on the track. The soil processing trolley was equipped with rotary tiller, leveler and roller used for tilling, leveling and compacting the soil, respectively, during the test bed preparation. The vertical positions of these units were set with the help of hydraulic cylinder. The carriage was attached to soil processing trolley with the help of rectangular bars and mounting plates. The test rig i.e. residue cutting system was fixed to carriage using mounting plates. A hydraulic type cone penetrometer was also mounted on the carriage to measure the soil strength. Residue cutting system with different components of carriage and soil processing trolley is presented in Fig. 3. The soil processing trolley and residue cutting system were linearly moved on the test bed through the rails with a preferred forward speed by selecting the suitable combination of gear box joined with input shaft of a revolving drum, which was connected to the soil processing trolley through a chain and sprocket drive. Soil processing trolley, residue cutting system and hydraulic system were operated using the control box located outside the bin.

Performance Evaluation of Residue Cutting System

The developed residue cutting system fitted with each disc coulter was tested in soil bin to assess its performance on penetration depth, width of cut, soil disturbance and residue cutting of different crops. The tests were performed in soil bin at different forward speeds (0.56, 0.83 and 1.11 m·s^{-1}) under rice, wheat and maize residues for medium to heavy residue load conditions (i.e. 8 t·ha^{-1} for rice and wheat and 16 t·ha^{-1} for maize). The maximum forward speed of 1.11 m·s^{-1} was fixed according to recommendation of Jat *et al.* (2010), who reported to limit the forward speed within 1.11–1.38 m·s^{-1} to avoid slippage and uneven crop stand.[27]

Speed Measurement

The forward speed of carriage was measured using a laser displacement sensor (Make: SICK AG, Germany, model: DT500, supply voltage: 10–30 VDC, output: 4–20 mA, measuring range: 0.2–30 m, accuracy: ± 3 mm) and time counter in data logger.

Soil Moisture and Bulk Density

The soil moisture affects the penetration depth, soil disturbance and energy requirement of seeding and planting implements. Therefore, to avoid the effect of soil moisture on performance parameters, it was maintained within 16.8–18.4% (db). The moisture content of soil and crop residues were measured by placing the samples in hot air oven at 110°C for 24 h and weighing them on electronic balance according to Indian Standard (IS: 2720 (Part II)-2010). After each treatment, bulk density of soil was measured using core cutter (dia: 51 mm, length: 74.5 mm) and electronic weighing balance. In the entire experiment, bulk density of the soil was found in the range of 1.49–1.57 g·cc^{-1}.

Soil Penetration Resistance

The penetration resistance of soil is an important parameter, which affects sinkage phenomenon, soil

1 Rotary tiller
2 Motor for rotary tiller unit
3 Hydraulic cylinder for leveler
4 Leveler
5. Hydraulic motor
6 Chain for linear motion of soil processing trolley
7 Rails
8 Roller
9 Carriage
10 Hydraulic cylinder for cone penetrometer
11 Residue cutting system
12 Disc coulter with side press wheels
13 Press wheels mounted at front shaft

Fig. 3 — Residue cutting system with different components of carriage and soil processing trolley

Table 2 — Experimental plan for testing of residue cutting system

Sl. No.	Independent parameters			Dependent parameters
	Coulter type	Residue type	Forward speed, m·s^{-1}	
1	Plain coulter	Rice, wheat and maize	0.56, 0.83 and 1.11	Penetration depth, top width, soil disturbance and residue cutting
2	Notched coulter			
3	Star wheel coulter			
4	Curved teeth coulter			
5	Cutter bar blade coulter			

disturbance, energy requirement, residue cutting and hairpining characteristics. To eliminate the effect of penetration resistance on performance characteristics of disc coulters, cone index of soil was maintained within 1600 ± 100 kPa throughout the experiment. It was measured using a cone penetrometer fitted with double S type load cell (Make: IPA Pvt. Ltd., model: DS 032HO, capacity: 300 kg, rated output: 1.5 ± 0.01 mV·V^{-1}, repeatability: ± 0.05%, output resistance: 350 ± 2 Ω and operating temperature: 5 to 70°C). The data from load cell were fed to data logger, which displayed cone index (CI) - depth curve on the screen.

Soil Disturbance

The minimal soil disturbance is the key requirement for CA. The soil disturbance was calculated in terms of cross-sectional area of slit opened by the coulter, which was considered in V shape. With each run, penetration depth and top width were measured at three different locations and soil disturbance was calculated. In this study, mean values of penetration depth, top width and soil disturbance have been reported.

Residue Cutting

Effective residue cutting is essential for proper seed-soil contact, improved germination and well establishment of crop. To measure the residue cutting, initial weight of residue for a specific patch area was measured, which was then placed on the soil surface across the plane of cutting. After running coulter over the residue, uncut residue was carefully taken out and its weight was measured. The residue cutting percentage was calculated using the following equation:

$$\text{Residue cutting, \%} = \left(1 - \frac{\text{weight of uncut residue}}{\text{intial weight of residue}}\right) \times 100$$

Experimental Procedure for Testing of Residue Cutting System

The residue cutting system with each disc coulter was tested under no-till condition in soil bin subjected to forward speeds of 0.56, 0.83 and 1.11 m·s^{-1} with crop residue of rice, wheat and maize. Initially, soil was pulverized to a depth of 12 cm with the help of rotavator unit followed by leveling operation by scrapper. After this, soil was compressed (CI: 1600 ± 100 kPa) with hydraulically operated roller to simulate soil conditions under CA. The residue of rice (avg. mc = 12.31%, wet basis (wb)) and wheat (avg. mc = 27.45%, wb) weighing 240 g each was spread on a patch of 0.3 m × 1 m representing residue load of 8 t·ha^{-1}. In case of maize, residue (avg. mc = 73.17%, wb) having 640 g weight was spread on a patch of 0.4 m × 1 m simulating residue load of 16 t·ha^{-1}. The performance parameters i.e. penetration depth, top width, soil disturbance and residue cutting were measured by performing the experiments as per experimental plan given in Table 2. The experimental data were statistically examined to investigate the effect of disc coulter type, residue type and forward speed on soil disturbance and residue cutting.

Table 3 — Measuring range and uncertainty of different parameters

Parameters	Measuring range	% Uncertainty
Distance	0.2–30 m	± 0.1
Time counter	—	± 0.1
Width	0.1–15 cm	± 1
Depth	0.1–15 cm	± 0.5
Weight	0.1–500 g	± 0.1
Cone index	3–9000 kPa	± 0.2
Soil disturbance	—	± 1.2
Residue cutting	0–100%	± 0.3

Uncertainty Analysis

The measurement in each parameter carries some amount of uncertainty, which needs to be quantified. Such uncertainties are caused by systematic and random errors and play an important part in results analysis of the experiment. The measuring range and uncertainty of different parameters are given in Table 3. The overall uncertainty in the present study was found to be ±1.69%.

$$\text{Overall uncertainty (\%)} = \sqrt{(U_X^2 + U_T^2 + U_W^2 + U_D^2 + U_{Wt}^2 + U_{CI}^2 + U_{SD}^2 + U_{RC}^2)}$$

where, U_X is uncertainty of distance; U_T is uncertainty of time; U_W is uncertainty of width; U_D is uncertainty of depth; U_{Wt} is uncertainty of weight; U_{CI} is uncertainty of cone index; U_{SD} is uncertainty of soil disturbance and U_{RC} is uncertainty of residue cutting.

Data Analysis

The experimental data were statistically analyzed using PROC GLM in SAS 9.3 at a significance level of 5% ($\alpha = 0.05$). Tukey's multiple comparison test was also carried out to find out the effect of each independent parameter on soil disturbance and residue cutting at each level.

Results and Discussion

Penetration Depth

The penetration depth of coulter is an important parameter, which plays a key role in seeding or planting depth of disc furrow openers. The planting depth affects seed-soil contact, seed germination and crop stand.[28,29] The penetration depth of different disc coulters at selected forward speeds under different crops residues is depicted in Table 4. In the entire experiment, penetration depth of all disc coulters was found in the range of 5−10 cm. Among the disc coulters, penetration depth of cutter bar blade disc coulter was higher over other disc coulters possibly due to better movement of soil after striking of blade in response to enough space between two consecutive blades. The effect of speed on penetration depth was not conclusive, which might be due to narrow range of selected speeds in this study. In general, penetration depth of disc coulters was lower under maize residue as compared to other crops residue. It was due to presence of thick maize stalks between soil surface and press wheels, which did not allow the disc coulters to penetrate to a pre-set level (10 cm).

Top Width of Cut

The width of cut should be as minimal as possible i.e. just enough for direct seeding of crops under no-till condition. The top width of slits opened by disc coulters with different speeds and crop residues is presented in Table 5. The hairpining phenomenon i.e. tendency of residue being inserted into soil without cutting affects the top width of slits.[30,31] As compared to other crops residue, maize residue favoured the lesser width of cut due to proper cutting and lesser flexibility of maize stalks over rice and wheat residues, thereby lessening the problem of hairpining. Overall, star wheel type disc coulter performed well in terms of lesser and more uniform width of cut at all forward speeds under different crop residues.

Soil Disturbance

The minimum soil disturbance is one of the key requirements for conservation agriculture. The ANOVA results of soil disturbance are presented in Table 6. All independent parameters i.e. coulter type, residue type and speed, and their interaction showed significant effects on the soil disturbance. The soil disturbance of disc coulters with different test speeds and crop residues is shown in Table 7. It is evident from the results that the minimum soil disturbance (3.96 cm^2) was observed for star wheel disc

Table 4 — Penetration depth of disc coulters with different test speeds and crop residues

Coulter type	Rice residue			Wheat residue			Maize residue		
	Speed, $m \cdot s^{-1}$								
	0.56	0.83	1.11	0.56	0.83	1.11	0.56	0.83	1.11
Star wheel type disc	8.2^{a}	7.5^{a}	7.2^{b}	8.2^{ab}	5.7^{a}	6.2^{a}	6.8^{ab}	8.1^{b}	5.7^{a}
Plain disc	9.0^{b}	8.7^{a}	8.8^{b}	7.5^{a}	7.7^{ab}	9.0^{bc}	5.0^{a}	4.5^{a}	7.5^{b}
Cutter bar blade type disc	10.4^{c}	9.0^{a}	5.0^{a}	10.0^{b}	10.0^{b}	10.0^{c}	9.2^{b}	9.5^{b}	9.0^{c}
Notched disc	9.9^{c}	8.0^{a}	8.4^{b}	7.2^{a}	7.0^{a}	7.2^{ab}	6.5^{ab}	8.2^{b}	5.5^{a}
Curved teeth type disc	7.7^{a}	6.8^{a}	7.5^{b}	7.7^{a}	7.9^{ab}	7.8^{abc}	6.0^{ab}	9.2^{b}	8.7^{c}

Note: All data are in cm; numbers with different letters without any common letter in a column are statistically significant ($\alpha = 0.05$)

Table 5 — Width of cut by disc coulters with different test speeds and crop residues

Coulter type	Rice residue			Wheat residue			Maize residue		
	Forward speed, $m \cdot s^{-1}$								
	0.56	0.83	1.11	0.56	0.83	1.11	0.56	0.83	1.11
Star wheel disc coulter	1.2^{a}	1.0^{a}	1.0^{a}	1.0^{a}	1.2^{a}	1.5^{a}	1.3^{ab}	0.7^{a}	1.4^{a}
Plain disc coulter	1.2a	5.0^{bc}	3.2^{b}	2.2^{a}	2.7^{ab}	1.8^{a}	1.1^{a}	1.0^{a}	0.8^{a}
Cutter bar blade disc coulter	4.5^{d}	3.8^{b}	4.2^{b}	1.9^{a}	1.7^{a}	1.7^{a}	1.2^{ab}	0.7a	0.8^{a}
Notched disc coulter	3.6^{c}	5.3^{c}	4.7^{b}	4.8^{b}	3.6^{bc}	3.3^{ab}	0.9^{a}	0.9^{a}	0.8^{a}
Curved teeth disc coulter	3.0^{b}	5.7^{c}	3.3^{b}	4.3^{b}	5.0^{c}	4.7^{b}	1.7^{b}	2.0^{b}	2.3^{b}

Note: All data are in cm; numbers with different letters without any common letter in a column are statistically significant ($\alpha = 0.05$)

Table 6 — ANOVA results of soil disturbance with different disc coulters, test speeds and crop residues

Source	SS	DF	MS	F-value	p-value
Model	5532.0	44	125.73	22.70	<0.001
Intercept	12543.28	1	12543.28	2264.46	<0.001
Coulter type	1516.17	4	379.04	68.43	<0.001
Residue type	2113.78	2	1056.89	190.80	<0.001
Speed	72.45	2	36.23	6.54	0.002
Coulter type × Residue type	976.71	8	122.09	22.04	<0.001
Coulter type × Speed	356.81	8	44.60	8.05	<0.001
Residue type × Speed	130.82	4	32.71	5.90	<0.001
Coulter type × Residue type × Speed	365.25	16	22.83	4.12	<0.001
Error	498.53	90	5.54	—	—
Total	18573.81	135	—	—	—

R^2 = 0.917 (adjusted R^2 = 0.877), SS = Sum of squares, DF = degree of freedom, MS = Mean square

Table 7 — Soil disturbance of disc coulters with different test speeds and crop residues

Coulter type	Rice residue			Wheat residue			Maize residue			Overall mean
	Speed, m·s^{-1}									
	0.56	0.83	1.11	0.56	0.83	1.11	0.56	0.83	1.11	
Star wheel disc coulter	4.79^{a}	3.98^{a}	3.68^{a}	4.08^{a}	3.29^{a}	4.63^{a}	4.54^{a}	2.64^{a}	3.97^{a}	3.96^{a}
Plain disc coulter	5.21^{a}	21.71^{b}	14.0^{bc}	8.08^{b}	10.38^{abc}	8.25^{a}	2.75^{ab}	2.25^{a}	2.89^{a}	8.39^{b}
Cutter bar blade disc coulter	23.48^{d}	17.25^{b}	10.67^{ab}	9.33^{b}	8.5^{ab}	8.33^{a}	5.35^{b}	3.48^{a}	3.75^{a}	10.02^{b}
Notched disc coulter	18.05^{c}	21.57^{b}	19.54^{c}	17.38^{c}	12.88^{bc}	12.63^{ab}	3.13^{ab}	3.78^{a}	2.12^{a}	12.34^{c}
Curved teeth disc coulter	11.50^{b}	19.29^{b}	12.42^{bc}	16.08^{c}	19.82^{c}	18.12^{b}	4.92^{ab}	9.17^{b}	10.11^{b}	13.49^{c}
Mean soil disturbance at 0.56, 0.83 and 1.11 m·s^{-1} speed	9.24^{A}	—	—	—	10.67^{B}	—	—	—	9.01^{A}	—
Overall mean		13.81^{C}			10.78^{B}			4.32^{A}		

Note: All data are in cm^2; numbers with different letters without any common letter in a column and numbers with different capital letters in a row are statistically significant (α = 0.05)

coulter followed by plain (8.39 cm^2), cutter bar blade (10.02 cm^2), notched (12.34 cm^2) and curved teeth (13.49 cm^2) disc coulters. However, under maize residue, plain disc coulter performed well in terms of lesser soil disturbance for all test speeds. These results of present study are in line with findings of Sawant *et al.* (2016), who reported lesser soil disturbance for plain rolling coulter (dia: 360 mm) coupled with double disc furrow openers over furrow openers without coulter, when operated in soil bin under maize residue.[22] Overall, the test speeds of 0.56 and 1.11 m·s^{-1} resulted in lesser soil disturbance as compared to 0.83 m·s^{-1} speed. Among the residue type, maize residue favoured the lesser soil disturbance due to better cutting as a result of lower shear strength (6−12 MPa) and higher bending strength (bending force 40−459 N) over rice and wheat residues, thereby reducing the hairpining tendency and soil disturbance.[32,33] However, such mechanical properties depend upon stem diameter and moisture content.[29] The soil disturbance was higher under rice residue as compared to wheat due to more flexibility i.e. lesser bending strength of rice residue (4−10 MPa) over wheat residue (9−19 MPa), thereby increasing the hairpining tendency and soil disturbance.[34–36]

Residue Cutting

Residue cutting is the most important parameter, which reflects how efficiently residue cutting system works. The ANOVA results of residue cutting are shown in Table 8. Coulter type, residue type and their interaction with each other, and speed produced significant effect on cutting of different residues. Crop residue cutting of various disc coulters at selected test speeds is presented in Table 9. Disc coulter type and crop residue had significant effect on residue cutting. The highest mean residue cutting (98.15%) was achieved with star wheel disc coulter followed by notched (84.12%), curved teeth (75.82%), plain (62.91%) and cutter bar blade (52.12%) disc coulters. The effect of operational speeds on residue cutting was not significant (p>0.05), which might be due to narrow range of operational speeds in contrast to findings of Sarauskis *et al.* (2013), who reported that straw cutting increased with coulter speed.[19] Among the crop residues, the maximum residue cutting (84.44%) was observed for maize residue followed by rice (74.38%)

Table 8 — ANOVA results of residue cutting with different disc coulters, speeds and crop residues

Source	SS	DF	MS	F-value	p-value
Model	83392.45	44	1895.28	10.99	<0.001
Intercept	747422.41	1	747422.41	4335.06	<0.001
Coulter type	35504.81	4	8876.20	51.48	<0.001
Residue type	9041.77	2	4520.88	26.22	<0.001
Speed	1050.42	2	525.21	3.046	0.052
Coulter type × Residue type	25690.76	8	3211.34	18.63	<0.001
Coulter type × Speed	4110.24	8	513.78	2.98	0.005
Residue type × Speed	1858.64	4	464.66	2.70	0.036
Coulter type × Residue type × Speed	6135.82	16	383.49	2.22	0.009
Error	15517.15	90	172.41	—	—
Total	846332.01	135	—	—	—

$R^2 = 0.843$ (adjusted $R^2 = 0.766$)

Table 9 —Residue cutting (%) by disc coulters with different test speeds and crop residues

Coulter type	Rice residue			Wheat residue			Maize residue			Overall mean
	Speed, m·s^{-1}									
	0.56	0.83	1.11	0.56	0.83	1.11	0.56	0.83	1.11	
Star wheel disc coulter	100.0^{a}	100.0^{b}	100.0^{c}	100.0^{c}	91.67^{d}	97.92^{d}	100.0^{b}	93.75^{b}	100.0^{b}	98.15^{e}
Plain disc coulter	100.0^{a}	79.17^{ab}	20.83^{a}	33.33^{a}	34.72^{a}	19.44^{a}	100.0^{b}	78.65^{b}	100.0^{b}	62.91^{b}
Cutter bar blade disc coulter	69.44^{a}	68.06^{ab}	62.5^{b}	59.72^{ab}	54.17^{b}	50^{ab}	45.83^{a}	25.52^{a}	33.85^{a}	52.12^{a}
Notched disc coulter	81.94^{a}	72.22^{ab}	73.61^{bc}	69.44^{a}	81.94^{cd}	84.72^{cd}	93.23^{b}	100.0^{b}	100.0^{b}	84.12^{d}
Curved teeth disc coulter	57.92^{a}	63.61^{a}	66.39^{bc}	66.67^{b}	66.67^{bc}	65.28^{bc}	95.83^{b}	100.0^{b}	100.0^{b}	75.82^{c}
Mean residue cutting at 0.56, 0.83 and 1.11 m·s^{-1} speed	78.22^{A}				74.01^{A}				71.64^{A}	
Overall mean		74.38^{B}			65.05^{A}			84.44^{C}		

Note: Numbers with different letters without any common letter in a column and numbers with different capital letters in a row are statistically significant ($\alpha = 0.05$)

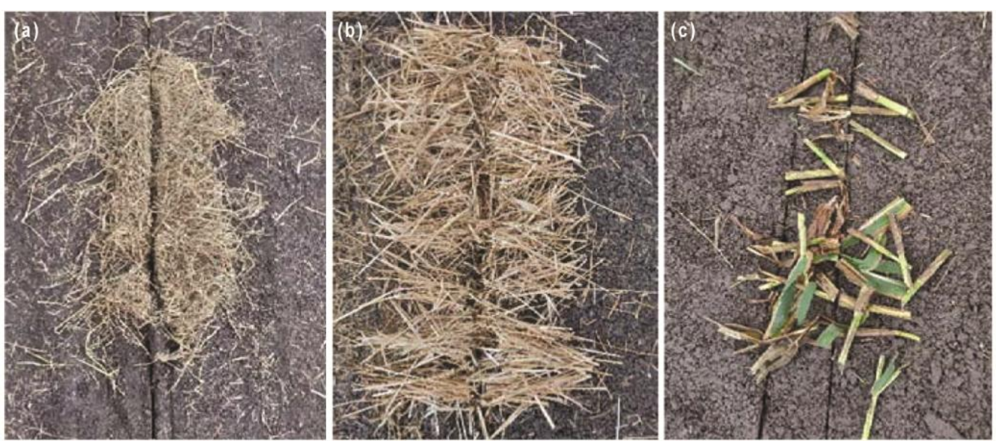

Fig. 4 — Rice, wheat and maize residues with 100% cutting

and wheat (65.05%) residues. The straw cutting performance is affected by mechanical properties (tensile, shear and bending strengths) and moisture content of straw.[31] The maize stalks hold lesser shear strength (6–12 Mpa), which are easier to cut.[29] Moreover, shear strength is negatively correlated to moisture content.[37] In present study, moisture content of maize stalks was 73.17% (wb), which might be the reason for reduced shear strength and easier cutting of maize residue. The results of present study are contradict to findings of Choi & Erbach (1986), who reported that shearing of corn stalks by rolling coulter increased with decrease in moisture content of corn stalk.[38] In present study, lesser cutting of wheat residue may be attributed to its higher shear strength over rice residue, which requires more force for cutting action.[35] Rice, wheat and maize residues with 100% cutting are presented in Fig. 4.

Conclusions

The performance of residue cutting system with various disc coulters was evaluated under zero-till condition in soil bin using different forward speeds and crop residues. All disc coulters were able to reach to typical sowing depth of major crops. The intermediate forward speed caused higher soil disturbance as compared to other test speeds. The residue of maize crop favored the minimal soil disturbance followed by wheat and rice residues. The least soil disturbance was observed for star wheel disc coulter under all crop residues. In the experiment, no effect of speed on residue cutting was observed possibly due to narrow selected range of speed. The results suggested that maize residue was easier to cut, while wheat residue showed difficulty in cutting. The best performance in terms of residue cutting was observed for star wheel disc coulter along with minimal soil disturbance, suggesting its suitability in machines used for seeding operation under conservation agriculture. The integration of star wheel disc coulter with double disc furrow openers could be an effective approach for direct seeding of crops under anchored as well as loose residue covered fields in conservation agriculture. However, it requires further studies for validation of such system under field conditions.

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