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Performance Evaluation of Vertical Discs and Disc Coulters for Conservation Tillage in an Intensive Rice–Wheat Rotation System

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Abstract: As an advanced agricultural production technology, conservation tillage has been developed rapidly and adopted widely for many crops all over the world, but challenges remain with regard to dealing with excessive residues, especially for intensive rice–wheat rotation systems. Most studies to date have been based on a single type of tool and the indoor bin test to explore its performance. Accurate field test data on the tillage performance of different types of tools for conservation tillage are lacking in this area. In this study, five tillage tools were tested in a paddy field with plenty of crop residues to compare their performance. They were three vertical discs with plain disc (PD), notched disc (ND), and rippled disc (RD) and two disc coulters with plain disc coulter (PDC) and notched disc coulter (NDC). All five tools were tested using a specific field test rig at two different working depths of 70 and 100 mm. Tillage forces, straw cutting efficiency, soil disturbance width, and soil cutting depth were measured. The results showed that tool geometry and working depth had a significant impact on tillage performance. The vertical disc performed a higher average straw cutting efficiency, as well as lower tillage forces and lower soil disturbance width than the disc coulter. For straw handling and furrowing operations, RD had the highest straw cutting efficiency, moderate tillage force, and appropriate soil disturbance width among the five tools. For all five tools, the 100 mm working depth results in 40% higher draught force, 39% greater vertical force, and 18% higher straw cutting efficiency on average. For no-tillage seeding in the intensive rice–wheat rotation system, the RD would be a more suitable rotary tool for conservation tillage practice.

Keywords: conservation tillage; disc; straw cutting efficiency; soil disturbance; tillage force; working depth

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1. Introduction

Conservation tillage, an advanced agricultural tillage method, including less tillage and no-tillage, aims to reduce soil and water erosion, increase soil organic matter, improve soil structure, save production costs, and achieve sustainability of crop production [1–4]. Over the past decades, conservation tillage, thus, has been developed rapidly and adopted widely for many crops all over the world. However, challenges in dealing with excessive residue remain, especially for the intensive rice–wheat rotation system.

In the intensive rice–wheat rotation system conducted in East-China, high-yield agriculture leads to a larger number of residues left in the field after harvesting, which is detrimental to seeding operations, seed germination, and early plant growth [5,6]. The time for seedbed preparation in the transition period between crops is also very short, and it is based on the limited annual sunshine duration in the intensive rice–wheat rotation area [7]. Excessive residues in the field cause poor performance of soil-engaging tools, which affects the timely planting of the next crop [8]. Therefore, agricultural producers have been seeking well adapted and high-performance tillage tools to deal with the problems of excessive crop residues for no-tillage seeding operations [9].

Numerous types of soil-engaging tools are in use for conservation tillage, such as disc, hoe, chisel, and sweep for developing seed furrow and handling crop residues [10,11]. For dense residues cover conditions, the conventional soil-engaging tools for conservation tillage are various rotary tools (e.g., vertical discs and disc coulters) [9]. Each rotary tool can be classified by its geometry, such as plain-type, notched-type, and rippled-type [12]. Traditionally, vertical discs and disc coulters were on no-tillage planters as seed openers and straw-cutting tools [12]. During the operation of the planter, the rotary tools were used to cut the crop residue on the ground and develop furrow for seed placement [12]. The ultimate goal is to provide favorable field conditions for sowing operation and crop growth in an efficient manner [9]. However, tillage performances may be affected by different geometries of rotary tools and their operational parameters.

In the past few decades, numerous studies have been carried out to evaluate the effects of the geometrical and operational parameters of the rotary tools used for conservation tillage on tillage performance [13–16]. For example, soil tillage forces and straw cutting efficiency were significantly affected by the double disc diameter and working depth [8]; soil disturbance area and soil cutting force increased with the increase in disc diameter from 457 to 559 mm [9]. Compared with the eight-wave coulter, the soil disturbance width of the 13-wave coulter decreased by 17% [17]. A biomimetic disc, mimicking the mole rat's claw, can achieve 21.4% reduction in vertical resistance and 28.7% reduction in draught forces, as compared with the notched disc [18]. The working depth had a significant impact on the performance of the disc, and the deep tillage depth resulted in 5.1% higher residue mixing, 53.4% greater soil cutting forces, and 34.9% larger soil displacements, as compared to the shallow tillage depth [19]. Overall, previous studies have shown that the tillage performance was affected by the geometrical parameters (disc diameter, tool shape, cutting edge design, etc.), as well as operational parameters (working depth, working speed, residue conditions, etc.). Several indicators, including soil cutting forces [20], soil disturbance [21], straw cutting efficiency [8], residue incorporation [22,23], as well as fuel consumption efficiency [24], have also been suggested to assess the tillage performance.

Despite a large number of previous studies, a better understanding of the relationships existing between tillage performance and soil-engaging tools has not been elucidated, especially when excessive residues are left in the field after harvesting in intensive rice–wheat rotation systems. Most studies to date have been based on a single type of tool to explore its performance, and the comparison between different types of tools (such as vertical discs and disc coulters) was lacking. Earlier studies of residue cutting evaluation focused on the planting mode of one crop per-year, which is different from the intensive rice–wheat rotation system with excessive crop residues left of two crops per-year [9,17]. Thus, more tests on different types of rotary tools for conservation tillage in this area are still need to be carried out. Moreover, previous studies were mostly conducted in an indoor soil bin. Although the use of soil bin test could significantly save time and cost, it is still different from the actual field conditions. Indoor remolded soil significantly differs from the field soil, and the indoor straw conditions are different from the real field environment. Thus, more detailed field test data of performance evaluation of rotary tools for conservation tillage are also required.

The accurate field test data on the tillage performance and its affecting factors of rotary tools for conservation tillage are lacking in intensive rice–wheat rotation system. Therefore, our study investigated the tillage performance of rotary tools for conservation tillage in intensive rice–wheat rotation system under actual field conditions using a specific field test rig. The specific objectives include: (i) to evaluate the performance of five typical rotary tools for conservation tillage in terms of soil tillage forces, soil disturbance, and straw cutting, as well as (ii) to investigate the effects of working depth of vertical discs and disc coulters on tillage performance.

2. Materials and Methods

2.1. Site Description

The field experiments were conducted in November 2021 at a Research Farm of Nanjing Agricultural University, in Babaiqiao, Jiangsu Province, China (118°55′ E, 32°25′ N). In the rice—wheat rotation system, due to the large amount and toughness of the rice straw, it is more difficult to handle than wheat straw. Therefore, a paddy field with plenty of rice straws after the crop harvesting was used for the experiment, and the rice straw was selected as test straw. In this area, the second crop (wheat) was seeded using a drill seeder after harvesting rice crop, and the sowing amount is approximately 150 kg ha^{-1}. The soil of the experimental site was classified as a clay loam (38.86% clay, 39.84% silt, and 21.30% sand, respectively) [25]. The test site has been devoted to a rice–wheat rotation system for a long time. Soil moisture content and dry bulk density were determined by the gravimetric method [26]. The soil cone index was measured by a soil hardness instrument (TJSD-750, Zhejiang Top Instrument Co. Ltd., Hangzhou, China) [27]. Residue length and density were measured using the quadrat sampling method [28]. Table 1 shows the soil physical properties (i.e., cone index, soil moisture content, dry bulk density) at a depth of 0–15 cm and residue parameters (i.e., length, wet density, dry density) before tillage practices.

Table 1. Soil and residue parameters of the test site.

Type	Parameters	Value	Unit
Residue	Residue length	50–250	mm
	Wet density	8051 ± 812	kg ha^{-1}
	Dry density	3972 ± 379	kg ha^{-1}
	Moisture content (wet basis)	50.7	%
Soil	Dry bulk density	1.29	g cm^{-3}
	Moisture content	22.7 ± 2.1	%
	Cone index	1093 ± 164	kPa

2.2. Field Test Rig

The field experiment was carried out using a field test rig [29] developed at Nanjing Agricultural University, China (Figure 1). The test bench is 8 m long and 1.8 m wide, and it is carried on steel wheels through rails that allow it to move freely across experimental plots. It is equipped with a power transmission system, a multifunctional carriage unit, a lifting and lowering system, a traction system, a control system, and a data acquisition system. The carriage unit moves on twin guide rails with an adjusted speed, ranging from 0.05 to 1 m s^{-1}. One traction motor drives the carriage to move it forward and backward, and four lifting and lowering motors allow the carriage to move up and down. A 13.5 kW electric generator is used to provide power for the test rig, and all electrical components, such as motors, are controlled by a complex control system for power transmission. The vertical discs and disc coulters are mounted on a tool holder with an equal angle (perpendicular to the ground), and all operational parameters (e.g., working depth and forward speed) are adjusted and controlled precisely with a wireless control handle.

2.3. Description of the Tillage Tools

The straw cutting tools for conservation tillage, which were tested, are three vertical discs and two disc coulters, as shown in Figure 2. The three vertical discs have the same diameter (450 mm), but one is a plain disc (PD) with a smooth plane, one is a notched disc (ND) with 30 teeth, and the other is a ripple disc (RD) with 12 ripples. The two-disc coulters also have the same diameter (457 mm), but one is a conventional plain disc coulter (PDC), and the other is a notched disc coulter (NDC) with six teeth. The working width of the disc coulters was concavity. The material of all tools is 65 Mn steel, and the details of the main parameters of the five typical tillage tools are presented in Table 2.

Figure 1. Overview of the field test rig: 1. stand with a lifting and lowering motor, 2. power connection, 3. guide rail, 4. control system, 5. traction motor, 6. data acquisition computer, 7. data acquisition module, 8. electric generator, 9. electric cable, 10. control handle, 11. tool holder, 12. drawing chain, 13. carriage unit, 14. force sensor, 15. power screw and motor.

Figure 2. View of the five tillage tools tested.

Table 2. Detailed descriptions of vertical discs and disc coulters.

Parameters	Plain Disc	Notched Disc	Ripple Disc	Plain Disc Coulter	Notched Disc Coulter
Weight (kg)	3.8	3.66	3.86	4.8	2.7
External diameter (mm)	450	450	450	457	457
Number of teeth	—	30	12	—	6
Thickness (mm)	5	5	5	3.5	3.5
Working width (mm)	5	5	15	42	42

2.4. Experimental Design

Experiments were conducted to evaluate the performance of five typical rotary tools for conservation tillage in terms of soil tillage forces, straw cutting, and soil disturbance. Treatments were the ten combinations of the five different tools and two working depths

(70 and 100 mm). Each treatment was replicated three times in a completely randomized design. Therefore, a total of 30 field plots were used in the experiment, and each was 3 m long and 1 m wide. The forward speed and the amount of crop residues were set at 0.2 m s^{-1} and 8051 kg ha^{-1} for all the treatments. Considering the limitation of test bench length and operational safety, a relatively slow forward speed was selected, which was based on previous studies [8,10,14]. A constant forward speed was maintained using the field test rig. The straw in the field after harvesting by semi-feeding harvester is disorderly and not conducive to quantitative testing of straw cutting. Therefore, according to previous studies [8,18,22], the test straw was also applied using a similar unified treatment method. Firstly, the test straw parameters (i.e., length and density) were consistent with the straw parameters measured in the field. Then, before the test, the residues on the field surface were removed manually, and then the experimental straws were parallel and evenly spread on the plots.

2.5. Measurements

2.5.1. Tillage Forces

The force data was measured by a data acquisition system of the field test rig. As the tillage tool travelled with a multifunctional carriage unit, force signals were recorded through force sensors, and they were collected by a LabVIEW (National Instruments, Austin, TX, USA) program. In order to facilitate the data collection, the system used the Advantech Portable data acquisition module USB-4704-AE (Advantech Co., Ltd., Taipei, Taiwan). Acquired data were saved to a laptop computer in LabVIEW measurement format (LVM) at a rate of 500 Hz, and they were later converted to Microsoft Excel 2010 (Microsoft Corporation, Redmond, WA, USA) spreadsheets for processing. For each test, the average value of the force in the tillage process was used.

2.5.2. Straw Cutting Efficiency

Straw cutting efficiency is one of the essential indexes used in evaluating the performance of vertical discs and disc coulters for conservation tillage in intensive rice–wheat rotation systems. After each test, the laid straw was carefully collected and separated into cut and uncut straw for weighing. The straw cutting efficiency of tillage tools is determined by the collected straw before and after tillage, and it was calculated according to the equation proposed by Ahmad [10].

$$\text{Straw cutting efficiency } (\%) = \frac{\text{Weight of cut straw (g)}}{\text{Total weight of straw applied (g)}} \times 100\% \quad (1)$$

2.5.3. Soil Disturbance Width and Soil Cutting Depth

As shown in Figure 3a, the tillage tools travelled through the experiment ground. They not only cut the straw, but they also disturbed the soil. To facilitate measurement, the laid straw and the loosened soil were removed from the tillage plot to expose the seeding furrow. A pin-type soil furrow profiler [30] was used to measure the soil disturbance width and soil cutting depth, as shown in Figure 3b. The specific operation process is to first place the soil profiler across the furrow, and then the probe is slid downward until its bottom end contacts the furrow surface; and, then, digitize the reading of each probe using a camera to reproduce the furrow shapes.

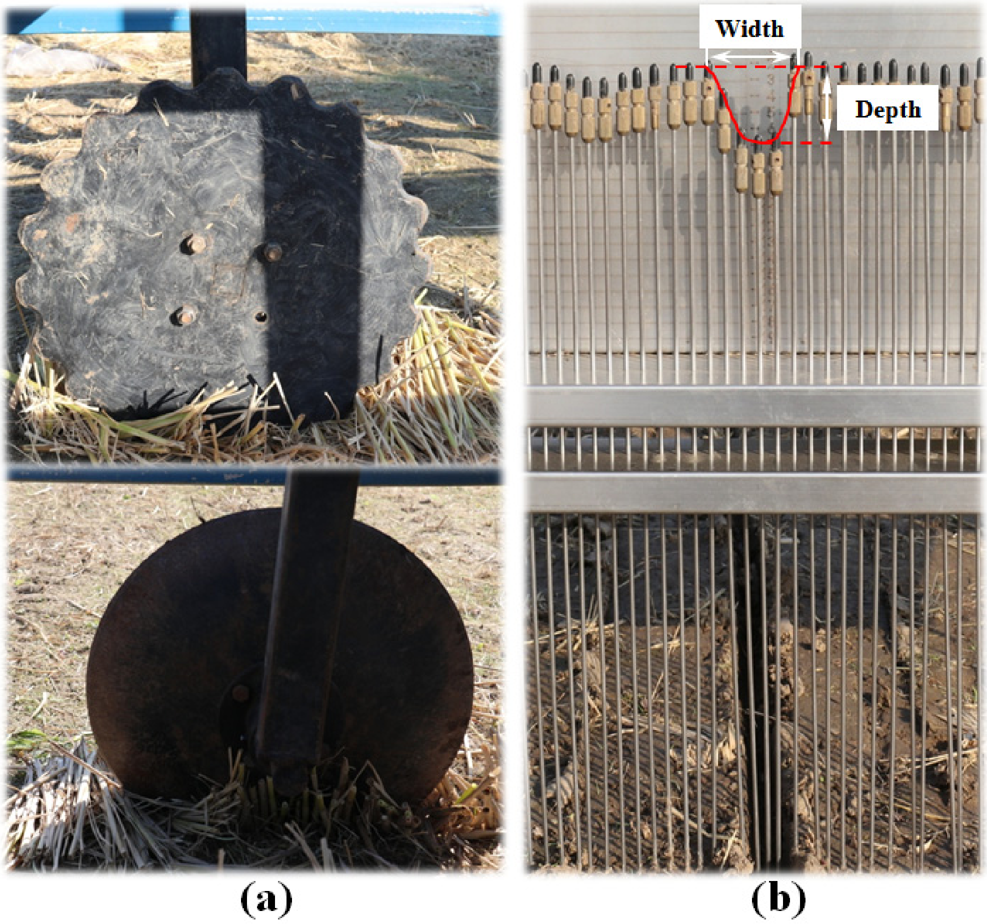

Figure 3. (**a**) The tillage tools working on the experimental plot; (**b**) a pin-type soil furrow profiler used to measure soil disturbance width and soil cutting depth.

2.6. Data Analysis

Statistical analysis by two-way factorial analysis of variance (ANOVA) was carried out using IBM-SPSS Statistics 22 software (IBM Corp., Armonk, NY, USA) at a 95% confidence interval. The LSD test was applied to find out a significant difference between the means and pairwise comparison at a 5% probability level. These factors included tool type, working depth, and the tools' interaction. The tool type and working depth were the main influencing factors when the interaction effects were not significant. To further investigate the differences between the two different groups of rotary tools (the vertical disc and disc coulter), the averages of three vertical discs and two disc coulters were also compared with the LSD test at a significance level of 0.05.

3. Results

The statistical analysis results indicated that none of the interaction effects were significant. Thus, in the following sections, the main effects of tool type and working depth on the tillage forces, straw cutting efficiency, soil disturbance width, as well as soil cutting depth, were introduced, and further differential statistical analysis between the vertical disc and disc coulter was also presented.

3.1. Tillage Forces

The measured draught force differed significantly among the tools and was also significantly affected by the working depth, as shown in Figure 4. The average draught force required by one vertical disc or disc coulter ranged from 261.5 to 531 N, which was averaged across the 70 and 100 mm working depths. Among five tools, ND and PD had the lowest draught force, while the PDC had the highest draught force. Further statistical analysis (Table 3) indicated that there was a significant difference between the average draught force of the disc and the disc coulter, and the disc coulter required a 44% higher draught force than the disc. The draught force of the same type of rotary tools was also statistically different. The RD required about 1.5-times more draught force than the ND and PD, on average, and the draught force of PDC was 78% higher than that of NDC. As for the depth effect, the draught force increased with the increase in working depth, and the 100 mm working depth required a 40% higher draught force than the 70 mm working depth, on average, among all five tools.

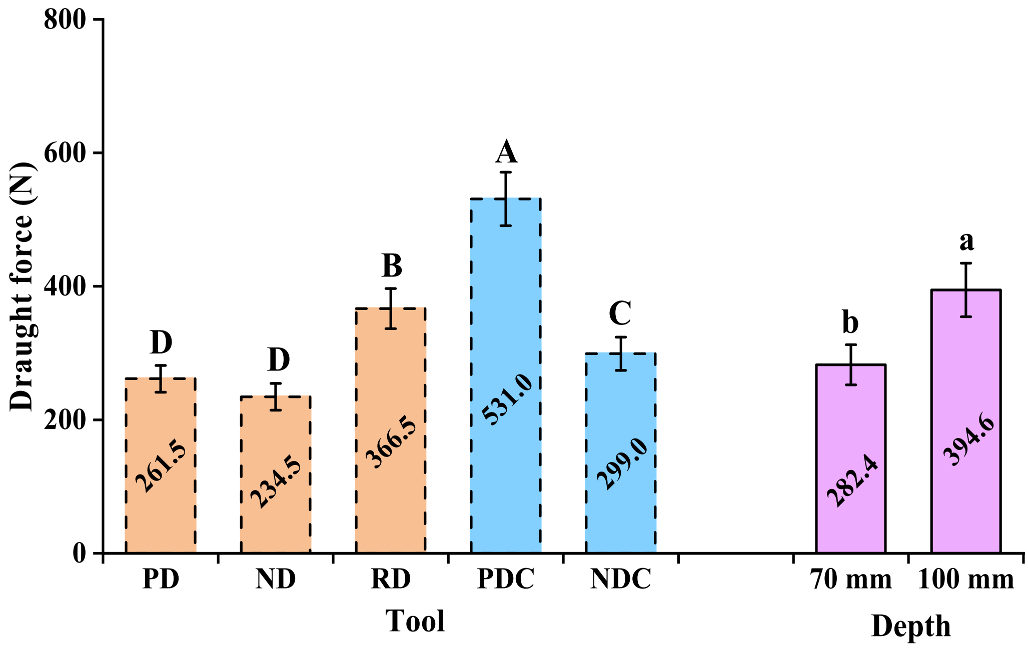

Figure 4. Draught force on different tillage tools (PD: plain disc; ND: notched disc; RD: rippled disc; PDC: plain disc coulter; NDC: notched disc coulter); the means followed by different letters are significantly different according to Duncan's multiple range test at the significance level of 0.05; differences among means of tillage tools are averaged across depths (n = 6), and, between tillage depths, they are averaged across tools (n = 15), which are indicated by different capital or lowercase letters, respectively, according to Duncan's multiple range test (p < 0.05).

Table 3. Draught force on different tillage tools (PD: plain disc; ND: notched disc; RD: rippled disc; PDC: plain disc coulter; NDC: notched disc coulter). The means followed by different letters are significantly different according to Duncan's multiple range test at the significance level of 0.05.

Type	Tools	Draught Force (N)		Average (mm)
		70 mm Working Depth	100 mm Working Depth	
Vertical discs	PD	212	311	287.5 b
	ND	194	275	
	RD	307	426	
Disc coulters	PDC	453	609	415.0 a
	NDC	246	352	

In terms of the vertical force, the difference was also significant among the tools, as shown in Figure 5. For all tillage tools, the range of average vertical force was from 361 to 709 N, which was averaged across the 70 and 100 mm working depths. PDC and PD had the highest and lowest vertical force among all tools, respectively. Further statistical analysis (Table 4) indicated that there was a significant difference between the average vertical force of the disc and the disc coulter, and the disc coulter required a 31% higher vertical force than the disc. Among the same types of tools, the vertical force of RD was 51.4% higher than that of ND and PD, on average, and the vertical force of PDC was 67% higher than that of NDC. Generally speaking, a larger working depth results in a higher vertical force for the five tools, which showed that the working depth is one of the most significant factors (Figure 5).

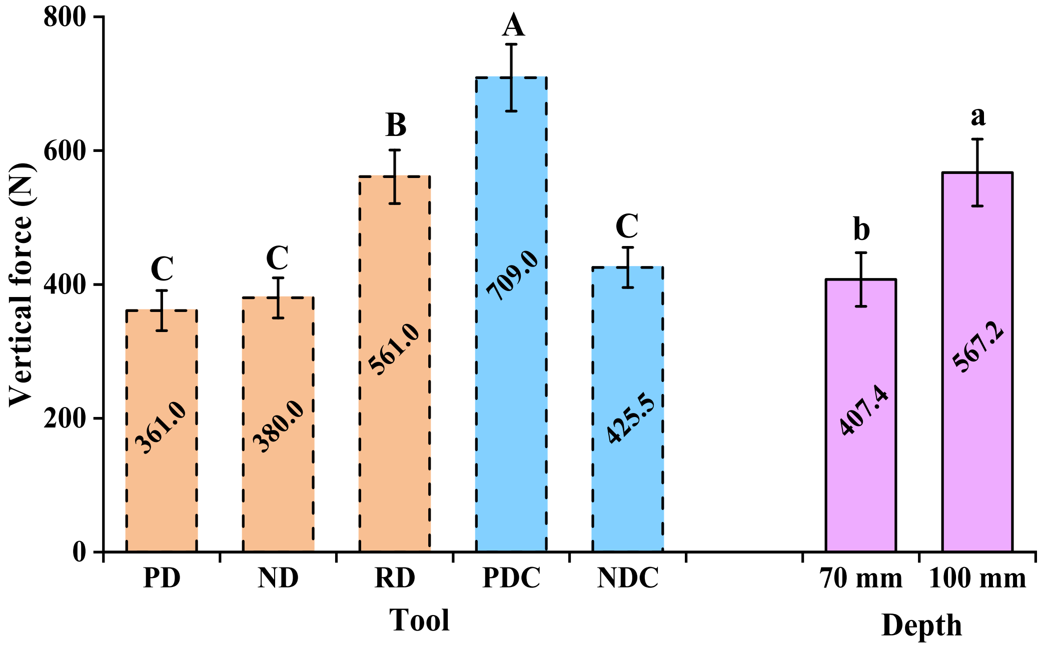

Figure 5. Vertical force on different tillage tools (PD: plain disc; ND: notched disc; RD: rippled disc; PDC: plain disc coulter; NDC: notched disc coulter); the means followed by different letters are significantly different according to Duncan's multiple range test at the significance level of 0.05; differences among means of tillage tools are averaged across depths (n = 6), and, between tillage depths, they are averaged across tools (n = 15), which are indicated by different capital or lowercase letters, respectively, according to Duncan's multiple range test ($p < 0.05$).

Table 4. Vertical force on different tillage tools (PD: plain disc; ND: notched disc; RD: rippled disc; PDC: plain disc coulter; NDC: notched disc coulter). The means followed by different letters are significantly different according to Duncan's multiple range test at the significance level of 0.05.

Type	Tools	Vertical Force (N)		Average (mm)
		70 mm Working Depth	100 mm Working Depth	
Vertical discs	PD	307	415	434.0 b
	ND	323	437	
	RD	458	664	
Disc coulters	PDC	616	802	567.3 a
	NDC	333	518	

3.2. *Straw Cutting Efficiency*

The tillage tools and working depth had a pronounced effect on the straw cutting efficiency, as shown in Figure 6. Across the 70 mm and 100 mm working depths, the RD had the highest average straw cutting efficiency (50.2%), while the NDC had the lowest average straw cutting efficiency (21.85%). The vertical discs had an average straw cutting efficiency of 47.15%, which was significantly higher than an average straw cutting efficiency of 25.48% for the disc coulters, as shown in Table 5. Among the three discs, the straw cutting efficiency of PD was 14% lower than that of ND, while the difference in straw cutting efficiency between ND and RD was not significant. Between the two disc coulters, the PDC had a higher straw cutting efficiency (33%) than NDC. For different types of tools, further statistical tests showed that there was a significant difference between the disc and disc coulter in average straw cutting efficiency, and the disc achieved about twice the straw cutting efficiency of that of the disc coulter. The straw cutting efficiency was significantly affected by working depth (Figure 6). The 100 mm working depth performed at 18% higher straw cutting efficiency than the 70 mm working depth, on average.

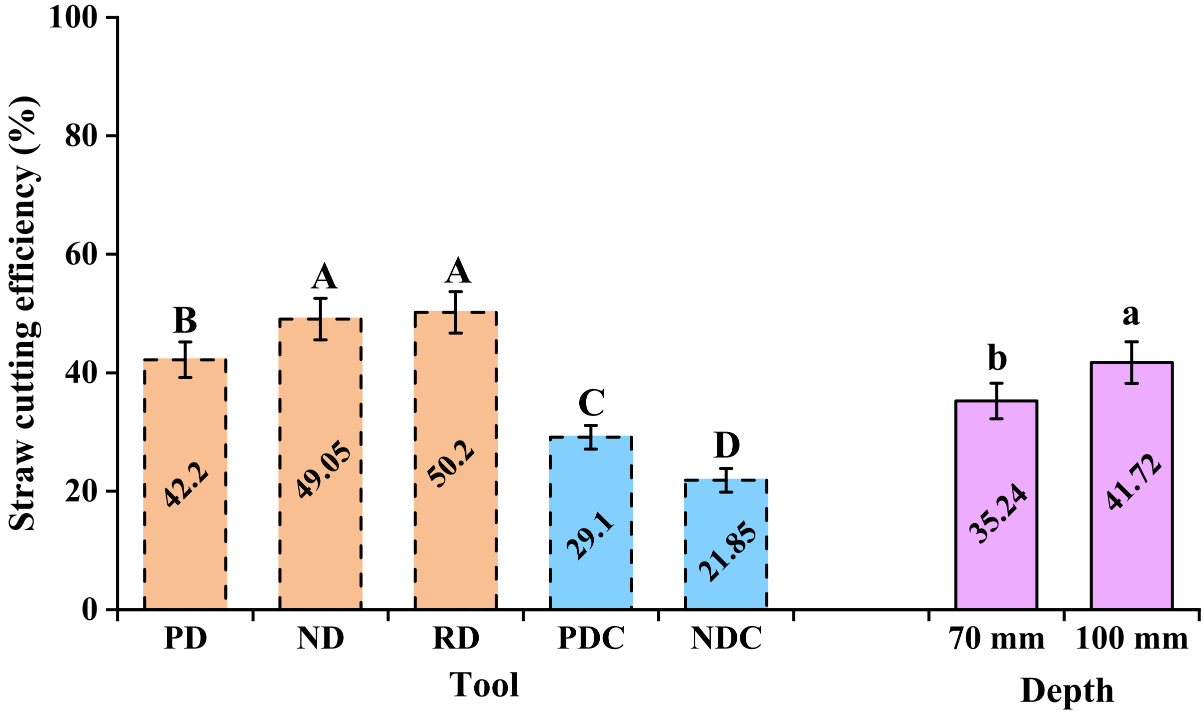

Figure 6. Straw cutting efficiency of different tillage tools (PD: plain disc; ND: notched disc; RD: rippled disc; PDC: plain disc coulter; NDC: notched disc coulter); the means followed by different letters are significantly different according to Duncan's multiple range test at the significance level of 0.05; differences among means of tillage tools are averaged across depths ($n = 6$), and, between tillage depths, they are averaged across tools ($n = 15$), which are indicated by different capital or lowercase letters, respectively, according to Duncan's multiple range test ($p < 0.05$).

Table 5. Straw cutting efficiency of different tillage tools (PD: plain disc; ND: notched disc; RD: rippled disc; PDC: plain disc coulter; NDC: notched disc coulter). The means followed by different letters are significantly different according to Duncan's multiple range test at the significance level of 0.05.

Type	Tools	Straw Cutting Efficiency (%)		Average (mm)
		70 mm Working Depth	100 mm Working Depth	
Vertical discs	PD	39.1	45.3	47.15 a
	ND	45.5	52.6	
	RD	47.9	52.5	
Disc coulters	PDC	25.4	32.8	25.48 b
	NDC	18.3	25.4	

3.3. Soil Disturbance Width and Soil Cutting Depth

The soil disturbance width differed significantly among the tools, while the difference in working depth in soil disturbance width was not significant, as shown in Figure 7. This may be due to varying tools having different working widths, resulting in a differing soil disturbance width among five tools. Across the 70 mm and 100 mm working depths, the PDC had the highest average soil disturbance width (55.65 mm), while PD had the lowest average soil disturbance width (6.6 mm). The disc coulters had an average soil disturbance width of 50.75 mm, which was significantly larger than the average soil disturbance width of 11.42 mm for the vertical discs, as shown in Table 6. Among the three discs, the soil disturbance width of RD was three times that of PD, while the difference in soil disturbance width between PD and ND was not significant. Between the two disc coulters, the PDC had higher soil disturbance width of 21.4% than NDC. In addition, increasing working depth had no significant effect on the soil disturbance width across all tillage tools. This may indicate that the geometry (working width) of tools has greater influence on the soil disturbance width than the working depth.

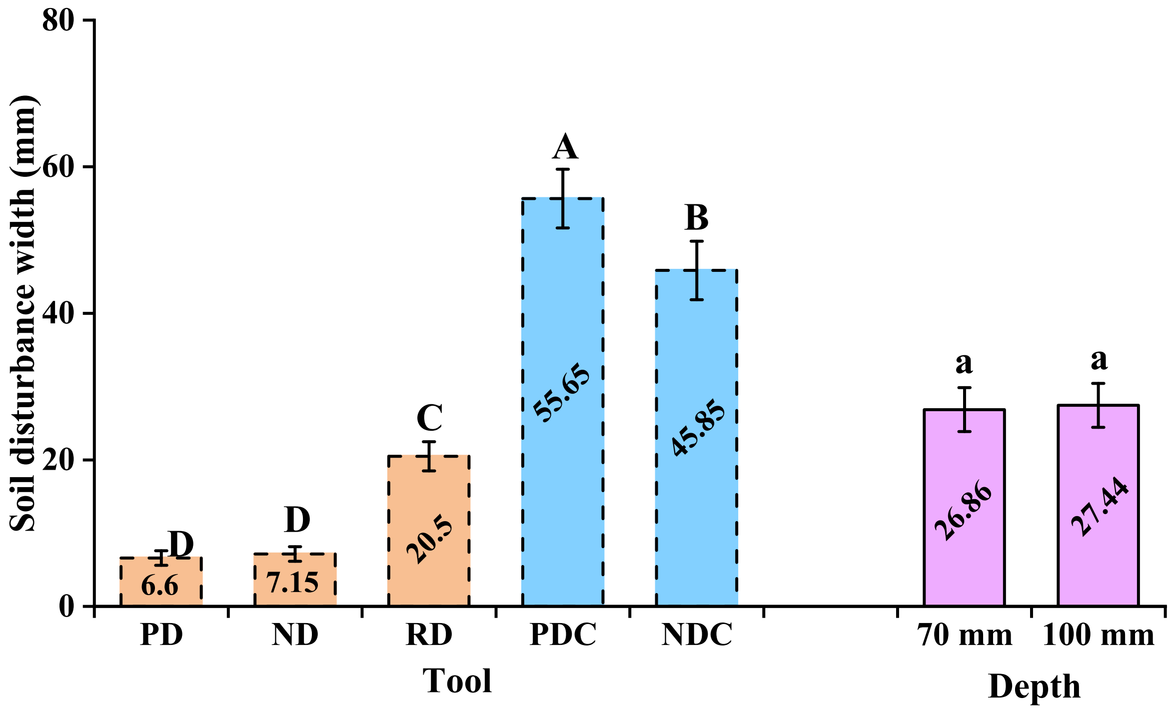

Figure 7. Soil disturbance width of different tillage tools (PD: plain disc; ND: notched disc; RD: rippled disc; PDC: plain disc coulter; NDC: notched disc coulter); the means followed by different letters are significantly different according to Duncan's multiple range test at the significance level of 0.05; differences among means of tillage tools are averaged across depths (n = 6), and, between tillage depths, they are averaged across tools (n = 15), which are indicated by different capital or lowercase letters, respectively, according to Duncan's multiple range test (p < 0.05).

Table 6. Soil disturbance width of different tillage tools (PD: plain disc; ND: notched disc; RD: rippled disc; PDC: plain disc coulter; NDC: notched disc coulter). The means followed by different letters are significantly different according to Duncan's multiple range test at the significance level of 0.05.

Type	Tools	Soil Disturbance Width (mm)		Average (mm)
		70 mm Working Depth	100 mm Working Depth	
Vertical discs	PD	6.5	6.7	11.42 b
	ND	7.1	7.2	
	RD	20.2	20.8	
Disc coulters	PDC	55.1	56.2	50.75 a
	NDC	45.4	46.3	

In terms of the soil cutting depth, the difference was significant only between the vertical discs and disc coulters, while the same type of tools had similar soil cutting depth, as shown in Figure 8. According to further statistical analysis (Table 7), compared to the disc coulters, the vertical discs could achieve better soil cutting depth at 70 mm and 100 mm working depths. The vertical discs had an average soil cutting depth of 83.4 mm, which was significantly larger than the average soil cutting depth of 76.75 mm. It was obvious to see that the soil cutting depth of all tillage tools increased with the increase in working depth.

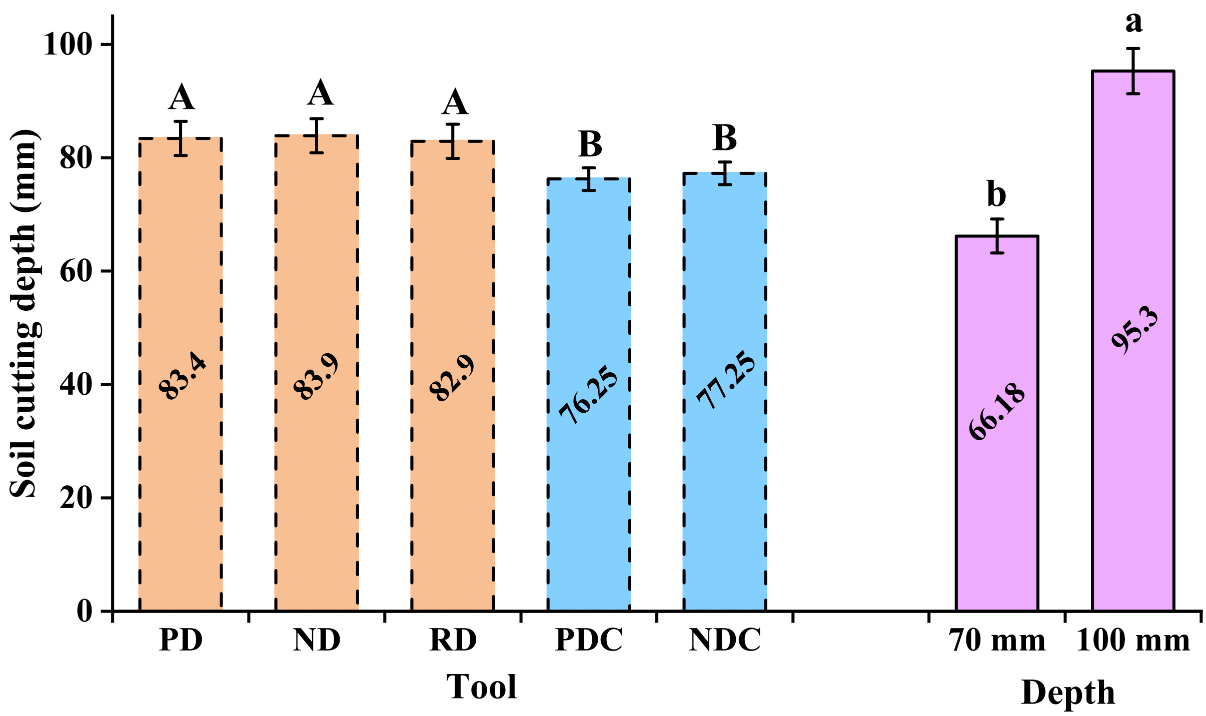

Figure 8. Soil cutting depth of different tillage tools (PD: plain disc; ND: notched disc; RD: rippled disc; PDC: plain disc coulter; NDC: notched disc coulter); the means followed by different letters are significantly different according to Duncan's multiple range test at the significance level of 0.05; differences among means of tillage tools are averaged across depths (n = 6), and, between tillage depths, they are averaged across tools (n = 15), which are indicated by different capital or lowercase letters, respectively, according to Duncan's multiple range test (p < 0.05).

Table 7. Soil cutting depth of different tillage tools (PD: plain disc; ND: notched disc; RD: rippled disc; PDC: plain disc coulter; NDC: notched disc coulter). The means followed by different letters are significantly different according to Duncan's multiple range test at the significance level of 0.05.

Type	Tools	Soil Cutting Depth (mm)		Average (mm)
		70 mm Working Depth	100 mm Working Depth	
Vertical discs	PD	68.6	98.2	83.4 a
	ND	69.1	98.7	
	RD	67.9	97.9	
Disc coulters	PDC	62.2	90.3	76.75 b
	NDC	63.1	91.4	

4. Discussion

Although not all performance evaluation indicators of five tillage tools had significant differences, the overall results showed that the geometrical parameters (such as number of teeth and width) and operational parameters (such as working depth) of disc tools for conservation tillage have an essential impact on tillage forces, straw cutting efficiency, soil disturbance width, and soil cutting depth. The vertical disc performed with a higher straw cutting efficiency, as well as lower tillage forces and soil disturbance width, than the disc coulter. The effect of working depth also performed an essential role in the tillage performance.

Comparing the force data with the vertical discs, the disc coulters required a higher draught force and vertical force. The average draught and vertical forces of the disc coulters were 44% and 31% higher than that of the vertical discs, respectively. This study results agreed with previous studies. Zeng and Chen [9] also found that that the fluted coulters had a 73% higher draft force than the rippled discs, on average. Typically, a wider tool creates a larger furrow, which would cause more soil disturbance, and this results in requiring a greater tillage force [9]. Apart from the RD, the two other vertical discs produced less draught and vertical forces than the disc coulters, and they should be a better choice for conservation practices requiring less soil disturbance. It was interesting to note that tools with higher draught forces also had high vertical forces, which was also found in a previous study [31]. The draught force and vertical force were associated with the contact area between the soil and tools, and the resistance increased with the increase in the contact area. The concavity of disc coulters and the waves of RD lead to a larger contact area, which resulted in higher tillage forces. The average vertical and draught forces required by one single tool range from 361 to 709 N and 261.5 to 531 N, respectively, which can be represented by the fact that vertical force was greater than draught force. This difference between vertical force and draught force may be related to contact area, soil conditions, straw status, as well as working parameters. This study also found that the tillage forces averaged across all five tools increased with the increase in working depth, which was similar to a previous study [19].

In terms of the rice residue handling, the rotary tools for conservation tillage were considered effective because the average straw cutting efficiency after tillage ranged from 21.85% to 50.2%. Similar residue cutting findings have been illustrated for conservation tillage in other crop residues, such as corn straw [32,33]. These results supported vertical discs, and disc coulters were effective residue cutting tools for conservation tillage. However, the straw cutting efficiency of different tools was significantly different, and the RD had the highest straw cutting efficiency. Zeng et al. [19] also found that the rippled disc was very aggressive in cutting residues, which resulted in less residue on the surface. Therefore, in terms of excessive residue, this phenomenon can result in poor seed placement, and it can slow seed germination [5,6]. The RD may be the most effective tool for conservation tillage practice in the intensive rice–wheat rotation system.

It was easy to conclude that the soil disturbance width increased with the working width of the tools. According to the ASABE standard, S477.1 [12], the disc coulters were regarded as wide tools, which indicated that they had wider soil disturbance than that of the vertical discs. In narrow disc tools, the RD had a significantly larger soil disturbance width as compared to PD and ND, which was attributed to its wider rippled cutting edge. Therefore, RD may be a compromise solution for no-tillage planters that require a certain furrow width for seed placement and less soil disturbance. The soil cutting depth results indicated that, under a working depth of 70 and 100 mm, the actual soil cutting depth of all five tillage tools was close to the working depth. However, the soil cutting depth of disc coulters was lower than that of vertical discs. This may be due to the lower straw cutting efficiency of disc coulters, resulting in excessive residue blocking the tool edge from cutting the soil downward. A controllable soil cutting depth would lead to a seedbed with consistent depth, which could be conducive to seeding operation and crop growth. In addition, a 100 mm working depth created a deeper soil cultivation layer, which can also reduce soil bulk density, improve water storage capacity, promote crop root growth, and increase crop yield [25].

For all five tools, compared to 70 mm depth, the 100 mm depth resulted in 40% higher draught force, 39% greater vertical force, and 18% higher straw cutting efficiency on average. Increasing the working depth from 70 mm to 100 mm resulted in a significantly increased portion of the tool in contact with soil, regardless of the disc type. The draught force increased with the increase in the contact area between the soil and the tool, according to the soil dynamics theory [34]. A deeper operation also requires greater vertical force to favor penetration into the soil. For all discs and coulters, the deeper working depth had a higher straw cutting efficiency than the shallow depth. This may be attributed to the fact that higher tillage forces from a deeper working depth are more conducive to cutting the straw.

The information obtained in this study is of great significance to the design and use of disc tools for conservation tillage in intensive rice–wheat rotary systems. The results not only strengthen the universal view on the purpose of different rotary tools, but they also quantify the differences in the performance of the vertical discs and disc coulters based on a paddy field with plenty of crop residues. In terms of straw cutting, RD was the most aggressive for residue handling among five tools. As a rotary tool with a larger working width, the disc coulters achieved greater soil disturbance. Similar to varying the geometrical parameters of rotary tools, varying working depth for conservation tillage will also have an essential impact on tillage performance. Therefore, it is necessary to select appropriate tillage tools and their operational parameters according to the specific requirements for conservation tillage practice in intensive rice–wheat rotary systems.

5. Conclusions

In this study, five typical rotary tools for conservation tillage in intensive rice–wheat rotation systems were evaluated in a paddy field to investigate their soil-engaging and residue-handling performance. The performance evaluation was conducted using a specific field test rig at two different working depths of 70 and 100 mm by measuring soil tillage forces, straw cutting efficiency, soil disturbance width, and soil cutting depth. The main conclusions of this study were as follows:

(i) The results indicated that tool geometry (such as number of teeth and width) had a significant impact on tillage performance. The vertical disc achieved a higher straw cutting efficiency, as well as lower tillage forces and soil disturbance width, than the disc coulter. For straw handling and furrowing operations, RD had the highest straw cutting efficiency, moderate tillage force, and appropriate soil disturbance width among the five tools.

(ii) The effect of working depth had an essential role in the tillage performance. For all five tools, compared to 70 mm depth, the 100 mm depth resulted in 40% higher draught force, 39% greater vertical force, and 18% higher straw cutting efficiency, on average. Another potential benefit of a deeper working depth was that it can reduce soil bulk density, improve water storage capacity, promote crop root growth, and increase crop yield.

(iii) Among the five tools, RD was the most effective tool for straw cutting in the intensive rice–wheat rotation system. The findings of this study can be used as a reference for the design and selection of non-tillage seeders and their components, which can be used for conservation tillage practice in this area.

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