sustainability

MDPI

Article

Comparative Performance of Various Disc-Type Furrow Openers in No-Till Paddy Field Conditions

Fiaz Ahmad [1,2], Ding Weimin [1,*], Ding Qishou [1,*], Abdur Rehim [3] and Khawar Jabran [4]

1 College of Engineering, Nanjing Agricultural University Jiangsu Province, Nanjing 210031, China; engrfiaz@yahoo.com
2 Department of Agricultural Engineering, Bahauddin Zakariya University, Multan 60800, Pakistan
3 Department of Soil Science, Bahauddin Zakariya University, Multan 60800, Pakistan; abdurrahim@bzu.edu.pk
4 Department of Plant Protection, Faculty of Agriculture and Natural Sciences, Duzce University, Duzce 81060, Turkey; khawarjabran@duzce.edu.tr
* Correspondence: wmding@njau.edu.cn (D.W.); qsding@njau.edu.cn (D.Q.)

Received: 14 March 2017; Accepted: 22 June 2017; Published: 29 June 2017

Abstract: Different furrow openers are required to be evaluated for their suitability to manage rice straw for direct planting of wheat in paddy fields. This study was carried out to assess the straw-cutting ability and draft requirements of four different disc-type furrow openers (notched, toothed, smooth-edge single disc, and double disc) in no-till paddy fields. The openers were attached to an in-field traction rig equipped with S-type load cells, and tested using three operating depths of 30, 60, and 90 mm, and three traveling speeds of 0.1, 0.2, and 0.3 m s^{-1}. Vertical and horizontal forces acting on the openers were observed using LabVIEW software based data acquisition system. The results of this study indicated that the furrow opener type, operating depth, and speed significantly influenced the horizontal and vertical forces, as well as straw-cutting ability of the furrow openers. The highest draft and vertical force were noted for double disc-type furrow openers. The mean straw-cutting efficiency of notched, toothed, and smooth-edge single disc and double disc furrow openers were 12.4, 46.2, 11.4, and 78.5%, respectively. The double disc furrow opener (DD) produced the lowest level of hair-pinned straw and had the highest straw-cutting efficiency with a value of 88.6% at 90 mm operating depth, and therefore had the best performance in comparison with other furrow openers.

Keywords: conservation tillage; crop residue; disc furrow opener; draft; straw-cutting efficiency; paddy field

1. Introduction

Tillage operations are aimed at improving the physical properties of soil for achieving enhanced crop production. Continuous application of conventional tillage and burning of crop residue decline soil fertility [1], that ultimately reduces soil productivity [2]. Soil organic carbon (SOC), water holding capacity, nutrient flow, and biological life are negatively affected by conventional tillage due to the degradation of soil structure [3,4]. Maintenance of soil health and energy-efficient technologies are essential for sustainable crop production [5]. Conservation tillage is recognized as a low-cost and energy-efficient tillage system for crop production [6,7].

Conservation tillage activities are preferred because of their advantages in improvement of soil structure and water and soil conservation by incorporation of crop residues near the soil surface [8]. Further, this has positive impacts on the soil micro-flora and micro-fauna [9]. Conservation tillage is abroad term that often includes no-tillage and shallow surface tillage (minimum tillage) [10,11]. Crop reaction to tillage systems is dissimilar because of the composite connections between weather, tillage-induced soil edaphic, and crop requirements [12]. For that reason, the suitability of conservation tillage systems is required to be locally assessed before adoption of conservation tillage practices.

Zero tillage provides the greatest input use efficiency, the lowest energy consumption, and maximum net benefit to farmers [13–16]. Soil physical and chemical properties are improved by conservation tillage practices, however, interference of rice crop residue during sowing operations for wheat crops leads to non-uniform plant stand, which constrains the adoption of zero tillage practices [17]. Owing to its unique soil structure, paddy fields have complex failure patterns and draft force requirements [18]. Moreover, edaphic constraints and deterioration of the soil environment appears because of puddling in paddy fields [19,20]. For precise, direct sowing practices, effective paddy residue handling during crop sowing is required [21].

For seed placement and handling of crop residue, a number of furrow openers such as disc, hoe, and chisel types are used in zero tillage. Disc furrow openers are used both as an effective soil-engaging tool for seed drilling, and a straw-cutting tool. In comparison with hoe-type furrow openers, soil disturbance of disc-types is minimal [22,23]. In general, disc-type furrow openers used in zero tillage are classified as smooth-type, toothed-type, and notched-type, and either single or double-disked [24].

Bianchini and Magalhaes [6] concluded that toothed and notched disc openers have higher crop residue cutting performance than that of the smooth disc openers in sugarcane fields. In general, the majority of previous studies evaluated the effectiveness of furrow openers in terms of seed distribution pattern [25–28], soil physical properties, and crop emergence [29–33] under low moisture conditions. Some other studies aimed to optimize the performance of furrow openers in zero tillage, concentrating on the soil–tool interactions [6,34,35]. In general, soil–tool interactions are expressed in terms of forces arising at the soil–tool interface (draft and vertical forces) and soil particles displacement [36]. Energy efficiency of the tool can be achieved through optimization of the tool configurations and operating conditions. The straw-cutting ability and force requirements of various disc-type furrow openers in direct-sowing paddy fields following rice-wheat cropping pattern is still to be elucidated.

Disc-type furrow opener capability (force requirement and straw-cutting efficiency) is influenced by soil characteristics (moisture content, texture, and resistance expressed as cone index), residue level, furrow opener geometry, and rotational speed of the opener [34]. The dynamic performance of disc coulters on soil covered with straw was investigated by Endrerud [37], and it was concluded that straw cover affects the disc opener penetration depth. In other studies [6,38], tooth-type disc openers expressed better performance compared to smooth-type single disc furrow openers in terms of sugarcane residue-cutting ability and vertical force requirements. The performance of furrow openers (such as straw-cutting ability) could be influenced by operating conditions. For instance, the cutting ability was increased with increasing working speed of the opener [39]. The shearing percentage of crop residue increases with the sharpness of coulters and soil strength, while speed ratio influences the residue-cutting performance [40].

In no-till paddy fields, furrow openers have operational issues and generally exhibit a stumpy residue-cutting ability due to soil-straw conditions. A furrow opener pushes the residue into soil without cutting, and causes the hair-pinning of straw, thus, the uncut straw reduces soil-seed contact. Therefore, in no-till paddy fields, enhancement of straw-cutting efficiency of furrow openers is still a challenge for researchers. The present study was aimed at comparing the performance of double disc with smooth-edge, notched and toothed single disc furrow openers in no-till paddy fields, in terms of draft and vertical force requirements and, especially, straw-cutting ability.

2. Materials and Methods

2.1. Experimental Area Description

The clay loam soil texture at the experimental site was found to contain 38.9% sand (>0.2 mm), 39.8% silt (0.2–0.002), 21.3% clay (<0.002 mm), and 3.2% soil organic matter. Experiments were executed in a paddy field after the rice crop harvesting at Jangpu Agricultural Farm, Nanjing Agricultural University, in December 2013. The rice–wheat cropping pattern was followed at the experiment field for a long time.

2.2. Measurements of Soil Properties

Soil physical properties (moisture content, bulk density) were determined by collecting 24 undisturbed soil samples (3 cm long and 5 cm diameter) at random from the experimental field prior to the commencement of the experiment. The soil was weighed before and after oven-drying at 105 °C for 24 h to quantify the bulk density and dry basis soil moisture content [35,41]. Cohesion, internal friction angle, and shear strength were determined using direct shear box apparatus [42]. Soil surface penetration resistance (cone index) was measured up to a depth of 10 cm with a digital penetrometer (TJSD-750, Zhejiang Top Instrument Co. Ltd, China) from ten random spots in the experimental area. The soil physical and mechanical properties are presented in Table 1.

Table 1. Soil physical and mechanical properties.

Soil Parameter	Value
Bulk density	1.28 g cm^{-3}
Wet density	1.7 g cm^{-3}
Soil texture	Clay loam
Moisture content	33.3%
Internal friction angle	12.7°, 7.7°, 8.5° at depth of 0–2, 4–6 and 8–10 cm.
Soil cohesion	42.1, 52.1, and 61.7 kPa at depth of 0–2, 4–6 and 8–10 cm.
Soil cone index	682, 1280, 1000, 1185, 1212 kPa at 0, 2.5,5, 7.5, and 10 cm depth.

2.3. Specifications ofTest Rigand Disc Furrow Openers

Four various types of furrow openers (smooth, toothed, and notched single disc, and smooth-edge double disc—hereafter referred to as double disc—with an external diameter of 450 mm) were selected for the tests (Figure 1). Single discs were installed vertically as to have no inclined angle, whereas for double disc openers, each disc had a 7° inclined angle. The details of the main parameters of the furrow openers are presented in Table 2. Furrow openers were tested in the paddy field by using a test rig designed and developed in the Key Laboratory of Intelligent Agricultural Equipment of Jiangsu province, Nanjing (Figure 2). The main aim of designing the test rig (used in the field conditions for the experiment) was to control the operating conditions of the tools and to avoid tractor tire compaction in the field. The test rig consisted of a tool moving frame/trolley, a tool hitching frame, a power source, two load transducers named as LSR-2A (2KN, Shanghai, Zhendan Sensor and Instrument Factory, China) for measuring draft and vertical forces, and a data acquisition system. One load cell was attached between the trolley rings and a wire was used to pull the opener for horizontal force, and the other one was fixed between the hitching frame and a depth-controlling rod for the vertical force measurements. These transducers were calibrated before running the tests. To run the data acquisition system (computer and sensors) a battery was used, whereas, in order to operate the furrow openers, power was supplied by power take-off (PTO) of a two-wheel tractor.

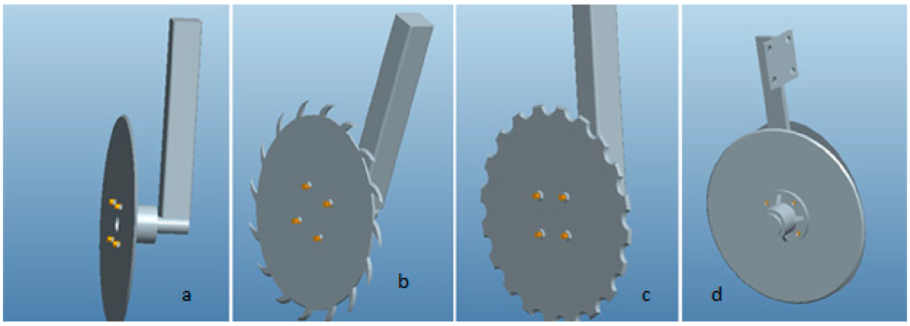

Figure 1. 3D view of furrow openers: (**a**) smooth-edge single disc; (**b**) tooth-type; (**c**) notched-type; (**d**) smooth-edge double disc.

Table 2. Detailed descriptions of furrow openers.

Parameters	Single Disc	Notched-Type	Toothed-Type	Double Disc
Weight with connecting rod (kg)	10.68	10.4	10.74	19.96
Weight of connecting rod (kg)	6.88	6.88	6.88	-
Weight of disc (kg)	3.8	3.52	3.86	-
Thickness (mm)	5	5	5	5
External diameter (mm)	-	450	450	450
Internal diameter (mm)	-	420	390	-
Notch height (mm)	-	15	30	-
Number of notches per teeth	-	20	16	-
Distance between consecutive teeth (mm)	-	-	5.2	-
Edge thickness (mm)	1.25	2	1.51	1.25
Disc inclined angle (degrees)	0	0	0	7

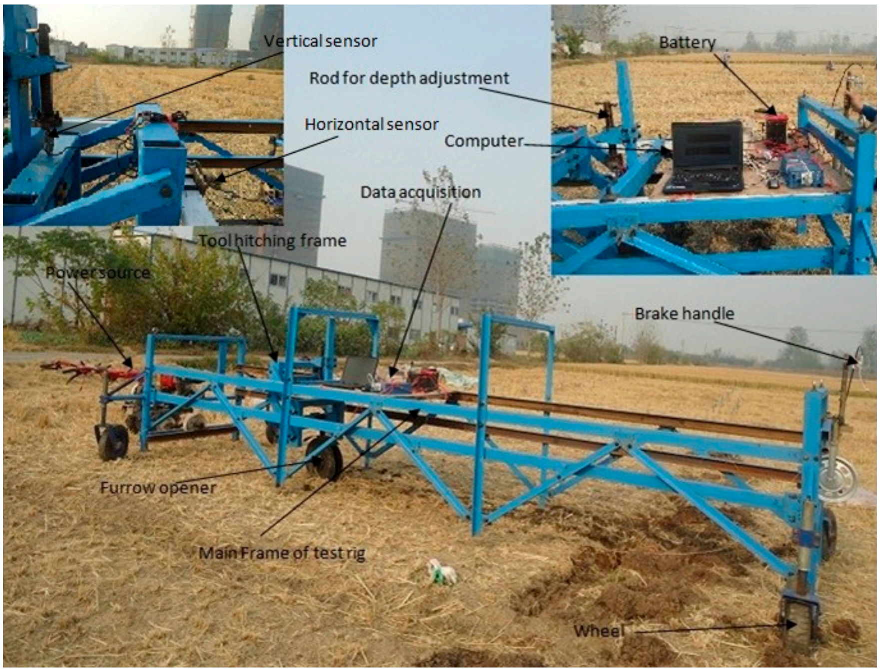

Figure 2. Test rigalong with data aqusition system.

2.4. Test Procedure

A randomized complete block design with three-way factorial arrangements (4 × 3 × 3) was followed to carry out the study. Four different types of furrow openers (toothed, notched, smooth-edge single disc, and smooth-edge double disc) were tested at three operating depths (30, 60, and 90 mm) and three traveling speeds (0.1, 0.2, and 0.3 m s^{-1}). The selected travelling speeds were a little low as there was no option for higher speed with field test rig. The working depth was measured from the edges of notches and teeth for notched and tooth-type furrow openers, respectively. Each test was replicated three times. A deep furrow perpendicular to the tool was dug to secure and measure the operating depth of the tool. The tool was first adjusted in the furrow according the required depth. As the depth of the furrow was more than the required depth, before operation of the tool it was in the air and did not touch the ground surface. The straw-cutting efficiency of the furrow openers was determined following Kushwaha et al. [34], Magalhães et al. [38], and Bianchini and Magalhães [6]. Firstly, the stubbles were cut to clean the soil surface, leaving the roots in the soil. Then 200 g m^{-2} of freshly harvested straw was uniformly spread in front of the furrow opener under no-till conditions following similar methodology as adopted in previous studies. The average length of the straw was 43 cm. A hitching frame with a depth-adjustable screw rod was attached to the furrow openers and then fixed to the trolley; the trolley had the ability to move freely on the main frame of the rig (Figure 3).

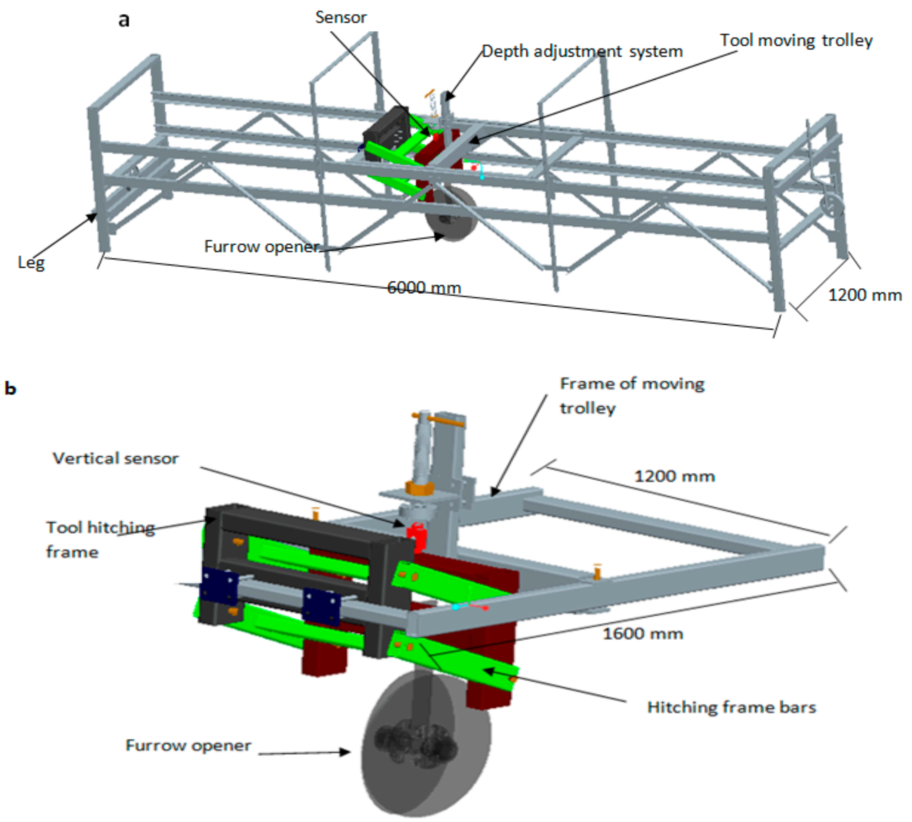

Figure 3. (**a**) ProE 3D view of test rig; (**b**) ProE 3D view of a furrow opener attached to a hitching frame and movable trolley.

2.5. Data Recording

The data acquisition system consisted of software and hardware components. The software program used in this study was the LabVIEW (National Instruments, Austin, TX, USA) programming test system, and hardware was composed of a data acquisition card, signal amplifier, computer, battery, and inverter. To assist the data collection, a USB-4711A Advantech bus multifunction data acquisition card was attached with the system. The data acquisition card, with 12 bits per channel, had a maximum sampling frequency of 150 kHz, and 16 single-ended or eight differential combination analog inputs.

The LabVIEW two-channel data acquisition system was applied to record the draft and vertical force signal data (Figure 4A,B). The millisecond voltage data was recorded in EXCEL spreadsheet format.

A digital camera (Canon, Canon Inc., Beijing, China) was used to record straw and soil cutting patterns. The snapshots were recovered from recorded videos and analyzed. Furthermore, the laid straw was carefully collected and separated into cut and uncut straw for weighing, to determine the straw-cutting capacity of the furrow openers. Equation (1) was used to calculate the straw cutting efficiency:

$$\text{Straw Cutting Efficiency } (\%) = \frac{\text{Weight of Cut Straw}}{\text{Total weight of Straw Applied}} \times 100 \quad (1)$$

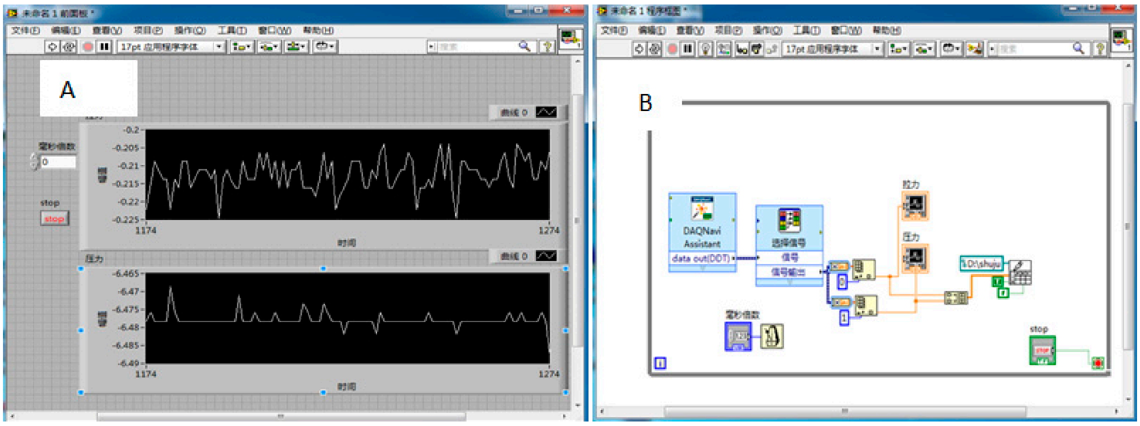

Figure 4. (**A**) LabVIEW data acquisition front panel; (**B**) LabVIEW data acquisition block.

2.6. Data Analysis

To analyze the data, analysis of variance (ANOVA) was executed using the Statistix Statistical Software Package (version 8.1, Analytical Software, Tallahessee, FL, USA). When the F-test indicated statistical significance at the $p = 0.05$ probability level, treatment means were separated by the least significant difference ($LSD_{0.05}$) test [43].

3. Results and Discussion

Statistical mean values of draft, vertical force, and straw-cutting efficiency for all treatments are presented in Table 3. Further, at the plastic phase of the paddy field (moisture content of 33.3%), a typical variation of forces (draft and vertical) on the double disc furrow opener has been presented in Figure 5. The vertical force line shows that as the furrow opener's disc touched the soil surface, resistance appeared.

Table 3. Mean values of draft, vertical force, and straw-cutting efficiency.

Factor	Levels	Draft (N)	Vertical Force (N)	Straw Cutting Efficiency (%)
Furrow Opener	Smooth-type	481.3 ^{b}	923 ^{c}	11.4 ^{d}
	Toothed-type	421.0 ^{c}	903.7 ^{c}	46.2 ^{b}
	Notched-type	444.3 ^{c}	1105.3 ^{b}	12.4 ^{c}
	Double disc	737.3 ^{a}	1533.9 ^{a}	78.5 ^{a}
Operating Depth (mm)	30	284.2 ^{a}	722.5 ^{a}	28.3 ^{c}
	60	470.3 ^{b}	1025.8 ^{b}	38.7 ^{b}
	90	808.5 ^{c}	1601.1 ^{c}	44.4 ^{a}
Travelling Speed (m s^{-1})	0.1	427.9 ^{a}	943.6 ^{a}	34.3 ^{c}
	0.2	519.8 ^{b}	1114.4 ^{b}	36.3 ^{b}
	0.3	615.30 ^{c}	1291.4 ^{c}	40.7 ^{a}

Means for each factor in the same column followed by the same superscript are not significantly different at $p < 0.05$ as tested by LSD.

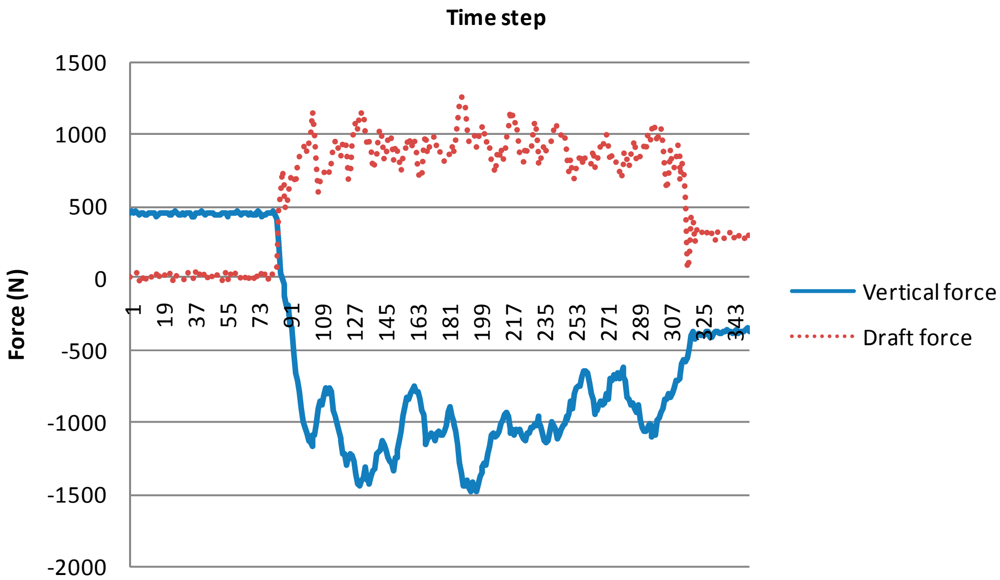

Figure 5. Typical variation, with distance, of the draft and vertical forces acting on a double disc opener.

3.1. Draft Force (Fh) Requirement of Furrow Openers

The results indicated that the influences of operating depth traveling speed and furrow opener type on the draft force in no-till paddy fields were significant. The interaction effects of depth × furrow opener type, furrow opener type × speed, depth × speed, and depth ×furrow opener × speed on the draft force were also significant. The test results indicated that the double disc furrow opener showed significantly higher draft force than the other type of disc openers for all operating depths and speeds. The comparison among discs indicated that the drafts of toothed and notched single disc openers did not differ significantly from each other, whereas, drafts of smooth and notched single disc openers were significantly different at 30, 60, and 90 mm depths (Table 4). At a 90 mm operating depth, toothed single disc furrow openers expressed the lowest draft force requirement, whereas double disc furrow openers exhibited the highest draft force requirement. The higher draft force of the double disc opener concurs with existing soil failure and cutting theories [44], which elaborate that tillage tools with greater cutting wideness require higher draft force. Likewise, Darmora and Pandey [45] also concluded, on the basis of results of evaluation of seven different furrow openers, that opener width affected the draft force. Hasimu and Chen [35] reported that the winged hoe-type openers showed higher draft force and specific draft requirements than other hoe-type openers. In soil bin conditions, Kushwaha et al. [34] also observed the raise in draft force with depth for disc-type (smooth, notched, and serrated) furrow openers. Chaudhuri [24] analyzed different seed openers and found that with increasing operating depth, draft force on tillage tools also increases. The draft force results are in agreement with Bianchini and Magalhães [6] who reported that horizontal draft forces ranged from 0.94 to 1.36 kN for smooth-type, 0.32 to 0.5 kN for toothed-type, and 0.6 to 0.78 kN for notched-type single disc furrow openers, when cutting sugarcane residue at 80 mm and 100 mm operating depths, respectively.

The mean values of the effect of speed and the furrow opener type on draft force are presented in Table 5. The lowest draft force was observed at the speed of 0.1 m s^{-1} for toothed-type furrow openers, while the highest draft force was achieved for double disc furrow openers operating at 0.3 m s^{-1} speed (Table 5). Kushwaha et al. [34] observed the increase in draft force with the increase in rotation speed of coulters. The speed of the tool may help the tool to penetrate soil, thus increasing the draft force, while high penetration may also be responsible for higher soil vertical resistance acting on the opener.

Table 4. Effect of furrow opener × depth interaction on draft and vertical forces for furrow openers working at various depths in no-till paddy fields.

Furrow Opener	Draft (N)			Vertical Force (N)		
	30 mm	60 mm	90 mm	30 mm	60 mm	90 mm
Smooth-Type	266.9 [h]	450.7 [e]	726.4 [b]	660.5 [a,b]	875.5 [d]	1241.0 [f]
Toothed-Type	218.2 [j]	390.7 [f]	654.2 [c]	589.3 [a]	826.1 [c,d]	1295.6 [f]
Notched-Type	238.6 [h,j]	416.4 [e,f]	678.0 [c]	757.2 [b,c]	1072.8 [e]	1486.0 [g]
Double Disc	413.3 [g]	623.3 [d]	1175.2 [a]	883.1 [d]	1336.7 [f]	2381.8 [h]

Means for each parameter followed by the same superscript are not significantly different at $p \leq 0.05$, as tested by LSD.

Table 5. Effect of furrow opener × speed interaction on draft and vertical forces for furrow openers working at various speeds in no-till paddy fields.

Furrow Opener	Draft (N)			Vertical Force(N)		
	0.1 m s^{-1}	0.2 m s^{-1}	0.3 m s^{-1}	0.1 m s^{-1}	0.2 m s^{-1}	0.3 m s^{-1}
Smooth-Type	394.86 [h,j]	468.56 [e,f]	580.6 [c]	825.7 [a]	931.7 [b,c]	1011.6 [c,d]
Toothed-Type	354.11 [j]	409.55 [g,h]	499.3 [d,e]	811.2 [a]	894.1 [a,b]	1005.8 [c,d]
Notched-Type	364.19 [j]	440.74 [f,g]	528.10 [d]	863.3 [a,b]	1081.1 [d]	1371.5 [e]
Double Disc	598.53 [c]	760.15 [b]	853.13 [a]	1274.2 [e]	1550.7 [f]	1776.7 [g]

Means for each parameter followed by the same superscript are not significantly different at $p \leq 0.05$, as tested by LSD.

3.2. Vertical Force Performance (Fv) of Furrow Openers

Upward vertical force was significantly influenced by furrow opener type, operating depth, and speed according to the analysis of the variance. The highest vertical draft force was noted for double disc furrow openers, followed by notched-type, toothed-type, and smooth-type single disc furrow openers, respectively. Previously, a similar working behavior was noted for smooth-type, toothed-type, and notched-type single disc furrow openers in sugarcane residue conditions [6]. Kushwaha et al. [34], Magalhães et al. [38], and Choi and Erbach [40] also found variations of vertical force with changes in opener type and diameter.

The interaction effect between operating depth and the furrow opener type was significant (Table 4). The results indicated that increasing the operating depth increased the soil vertical resistance acting on the furrow opener. The penetration resistance increases in lower layers of soils because of hardpan in paddy fields, developed as a result of puddling [7,20,46]. Bianchini and Magalhães [6] recorded the range of vertical forces as 3.54 to 3.72 kN for smooth-type, 2.12 to 2.26 kN for notched-type, and 1.24 to 1.65 kN for toothed-type single disc furrow openers at the operating depths of 80 and 100 mm, respectively, for sugarcane residue. At 30 mm depth, toothed-type single disc showed the lowest vertical force, whereas, double disc furrow openers expressed the highest vertical force at 90 mm operating depth.

The influence of the interaction between furrow opener type and working speed on vertical force is presented in Table 5. Double disc furrow openers showed the highest vertical force of 1776.7 N at the speed of 0.3 m s^{-1}, whereas toothed-type single disc demonstrated the lowest vertical force of 811.2 N at the speed of 0.1 m s^{-1}. Kushwaha et al. [34] concluded similar results and found that vertical force increased with the speed of the disc-type furrow openers. The work of Magalhães et al. [38] incicatedthat the vertical load requirement for toothed disc tool penetration at 70 mm operating depth varied between 1.5 to 2.1 kN in soil covered by sugarcane residue. The emergence rate is also affected by penetration depth. Karayel and Šarauskis [28] concluded that at downward forces of 1150 and 1400 N of the furrow opener, the emergence percentage of maize was highest because of having the best sowing uniformity. The high sowing uniformity ultimately leads to the highest crop emergence and yield.

3.3. Straw Cutting Efficiency of Various Disc-Type Furrow Openers

The straw used for the test had a moisture content of 41.4%. The statistical results showed that the effects of furrow opener type, operating depth, and traveling speed on the straw-cutting efficiency in no-till paddy fields were significant. The interaction effects of depth × furrow opener, furrow opener × speed, depth × speed, and depth × furrow opener × speed on straw-cutting efficiency were significant. Toothed-type furrow openers showed the second best straw-cutting performance among all four furrow opener types under test conditions with mean values of 33.0, 46.9, and 58.7% at operating depths of 30, 60, and 90 mm, respectively. However, we observed the issue of straw-rolling due to the backward-pushing action of the teeth. The notched-type single disc opener showed a straw-cutting capacity with mean values of 9.9, 10.4.0, and 13.7% at operating depths of 30, 60, and 90 mm (Figure 6), respectively. Notched-type furrow openers nearly had efficiency similar to the smooth-type single disc furrow openers. Notched-type and smooth-type single disc furrow openers pushed the straw into the paddy field (straw hair-pinning), which might reduce crop emergence due to decreased soil-seed contact.

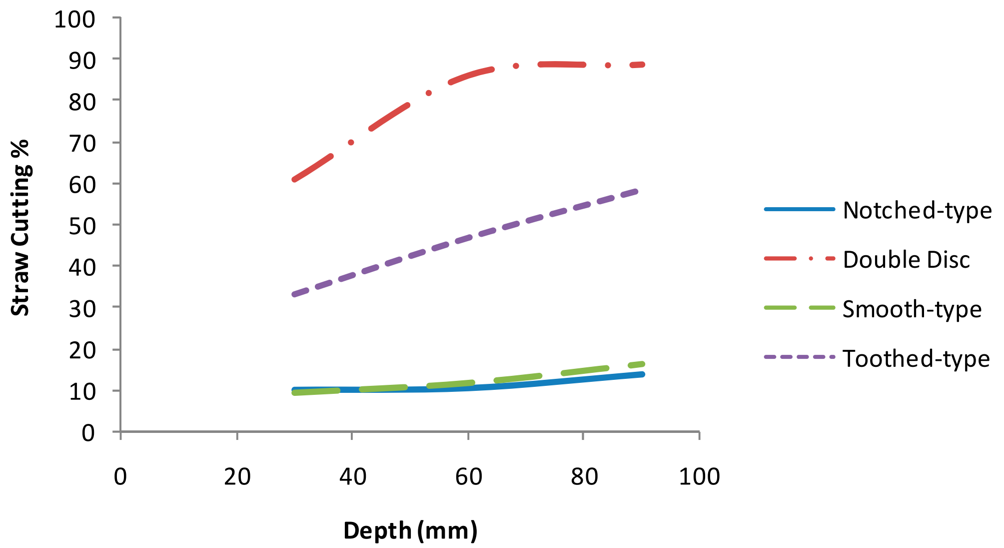

Figure 6. Changes in straw-cutting efficiency with operating depth for different furrow openers.

As observed in the case of double disc openers, the straw was cut due to the application of tensile force on the straw and soil (Figure 7). Paddy soils are mostly sticky soils [18]. Therefore, hairpinning phenomena was observed less in double disc furrow openers, and they showed the highest straw-cutting efficiency. Straw-cutting performance is also affected by straw mechanical properties such as tensile, shear, and bending strengths [34]. The moisture content of straw also affects the mechanical properties of the straw [47]. The dependence of straw-cutting on moisture content has been reported by researchers [39] previously.

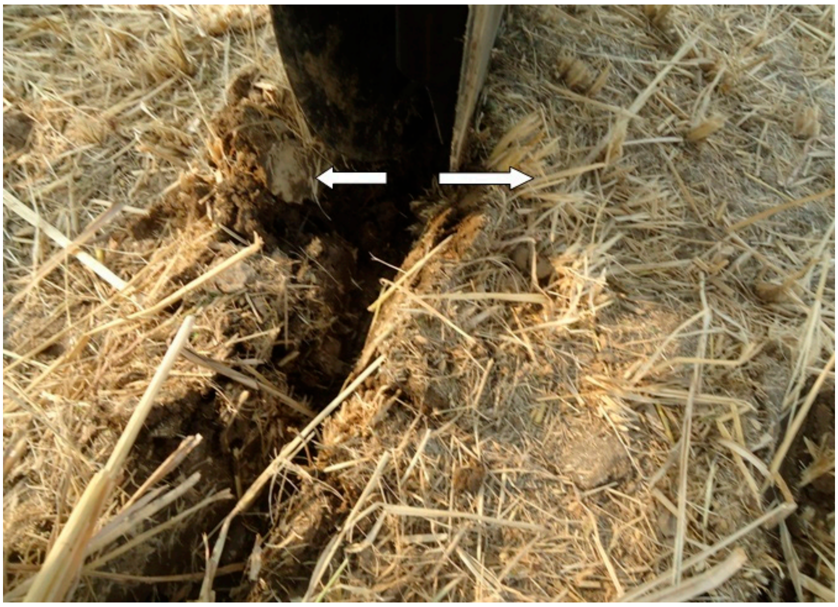

Figure 7. Soil failure and a furrow opened by a double disc opener.

From the results, it can be concluded that straw-cutting efficiency in paddy fields can be increased by increasing tensile action through increased disc incline angles, along with the bending and shearing actions of cutting tillage tools. The design and development of further tillage and straw-cutting tools should focus on the magnitude of tensile force exerted by the tool on soil and straw in no-till paddy fields, because bending forces appear to cause hair-pinning rather than cutting of straw in paddy soils which have high moisture content. Previous studies [6,34] concluded that straw in front of smooth-type single disc furrow openers was cut by a simple shearing and rolling-action, whereas, the soil acts like a cutting board for a knife. This means that if the soil does not offer adequate support to hold the straw in position during the cutting process, the straw ultimately bends, and soil permits the uncut straw to get pushed into the soil due to the compressive load from the furrow opener. Straw-cutting efficiency is further affected by straw moisture content. When straw has high moisture content, it is easy to push the straw into the soil without it being cut. In the present study, hair-pinning was facilitated due to these reasons: (1) the paddy field was in the plastic phase; and (2) the straw had high moisture content (41.4%). Thus, it was easy for smooth-type, toothed-type, and notched-type single disc furrow openers to fold the straw and push it into the furrow. The observed results related to smooth-type, notched-type, and toothed-type single disc furrow openers are also in agreement with the findings of Bianchini and Magalhães [6], who concluded that toothed-type furrow openers provided higher sugarcane residue cutting efficiency than notched-type and smooth-type single disc openers. Smooth-type single disc openers produced nearly114% more hairpinned sugarcane residue than that obtained from notched-type openers. Magalhaes et al. [38] compared the performance of different sizes of toothed-type openers and observed that toothed-type openers with a diameter of 711 mm left 26 g m^{-1} of uncut sugarcane residue, which was significantly higher than the amount of uncut residue presented by 508 and 610 mm diameter toothed-type furrow openers.

The straw-cutting efficiency of smooth-type, toothed-type, and notched-type single disc, and double disc furrow openers at different traveling speeds is shown in Figure 8. Straw-cutting efficiency increased with an increase in operating speed. Straw-cutting efficiencies ranged from 11.2 to 13.8% for the smooth-type, from 11.1 to 11.5% for the notched-type, from 42.5 to 49.9% for the toothed-type single disc, and from 72.4 to 87.4% for double disc furrow openers, as the speed changed from 0.1 to 0.3 m s^{-1}, respectively.

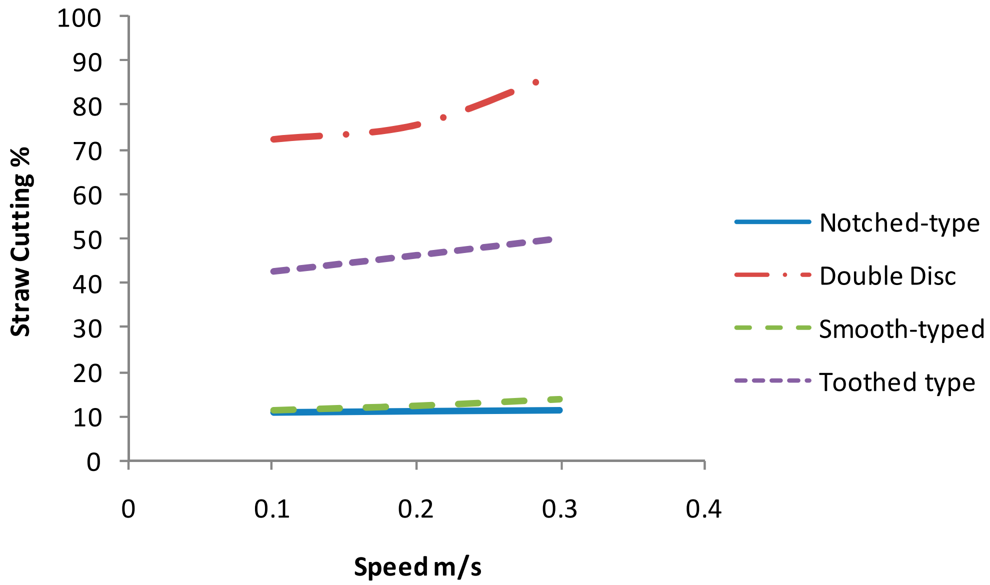

Figure 8. Changes in straw-cutting efficiency with traveling speed for different furrow openers.

The influence of operating depth on furrow opener crop residue-cutting efficiency at different speeds has been presented in Figure 9. Notched-type openers had better straw-cutting performance than that of smooth-type single disc furrow openers. Figure 10 shows straw-cutting performance by the notched-type, toothed-type, smooth-type single disc, and double disc furrow openers. It can be observed from this figure that the straw was cut where the double disc furrow opener passed over the straw (Figure 10d) because the straws were completely segmented, whereas the smooth-type and notched-type single disc openers pushed the straw into the soil and caused hair-pinning (Figure 10a,c).

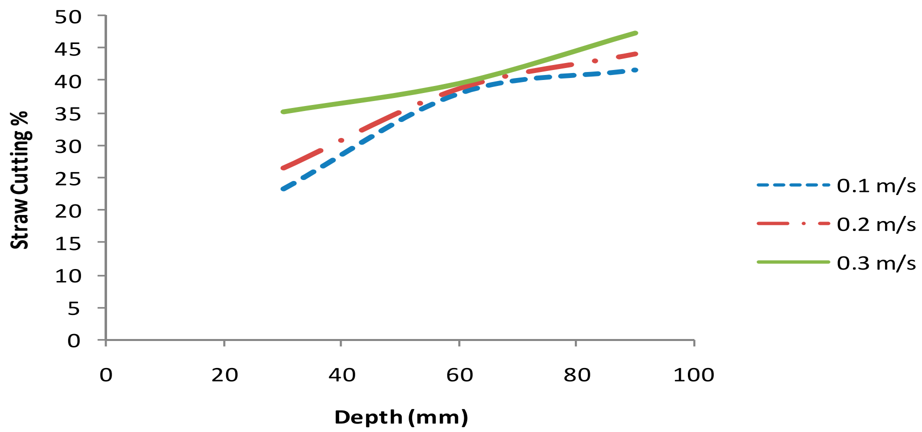

Figure 9. Effect of operating depth and traveling speed on straw-cutting.

The toothed-type single disc opener rolled the straw over itself and demonstrated lower straw cutting performance comparable with the double disc furrow opener (Figure 10b). Sarauskis et al. [39] reported that higher capacity of straw cut was observed at maximum speeds (speed ratio $\lambda > 1.27$ and $\lambda = 1.5$) of an active disc coulter than by an inactive disc coulter ($\lambda = 1.0$). It was reported that inactive disc coulters ($\lambda = 1.0$) cut approximately 30% of winter wheat straw with natural moisture content ($mc = 10.1\%$) and only 12% of humid straw ($mc = 22.3\%$). The results from the present study showed the double disc furrow opener as an efficient straw-cutting device in no-till paddy fields.

Figure 10. Straw cutting performance of (**a**) notched-type opener; (**b**) toothed-type; (**c**) smooth-type single disc; and (**d**) double disc furrow openers.

4. Conclusions

Appropriate furrow openers are required for direct-drill sowing of wheat in no-till paddy fields covered by rice straw and stubble. In this research, force requirements and straw-cutting efficiency of four furrow openers (notched, toothed, smooth single disc, and double disc) were measured at different operating depths and speeds. Force requirements and straw-cutting efficiency were considerably influenced by the operating depth, opener-type, and speed. Double disc and smooth-type single disc furrow openers had the highest and lowest straw-cutting efficiencies, respectively. The draft and vertical forces for double disc and toothed-type single disc furrow openers were the highest and lowest, respectively, whereas the straw-cutting efficiency of toothed-type single disc furrow openers was only 58% of that of double disc furrow openers. In no-till paddy soils, it can be concluded that the double disc furrow opener had optimum efficiency in view of straw-cutting efficiency and less hair-pinning, in comparison with the single disc (smooth, notched, and toothed)-type furrow openers. It is recommended that, in paddy field conditions, the best tool for no-till direct seeding is the double disc furrow opener. Therefore, the present study was helpful in the appropriate selection of a furrow opener as a direct-drill machine and its implications in paddy fields. Moreover, non-disc-type furrow openers should be compared with disc-type furrow openers, and sowing uniformity should be determined at field level using computer simulations.

Acknowledgments: This manuscript represents a portion of Ph.D. research by the first author. Thanks to the HEC, Pakistan for providing Ph.D. Scholarship to the first author. Additionally, work was sponsored by the National Science and Technology Support Program (2013BAD08B04) and the State Key Special Program of Soil Fertility Improvement and Cropping Innovation for High-Yield Efficiency in Rice Cropping Areas (2016YFD0300900).

Author Contributions: Fiaz Ahmad, Ding Weimin, Ding Qishou and Abdur Rahim conceived and designed the experiments; Fiaz Ahmad and Ding Qishou performed the experiments; Fiaz Ahmad, Abdur Rahim and Khawar Jabran analyzed the data. All authors contributed to write paper. All authors have revised and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Montgomery, D.R. Soil erosion and agricultural sustainability. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 13268–13272. [CrossRef] [PubMed]
2. Murphy, C.A.; Foster, B.L.; Ramspott, M.E.; Price, K.P. Effects of cultivation history and current grassland management on soil quality in northeastern Kansas. *J. Soil Water Conserv.* **2006**, *61*, 1–10.
3. Farooq, M.; Flower, K.C.; Jabran, K.; Wahid, A.; Siddique, K.H.M. Crop yield and weed management in rainfed conservation agriculture. *Soil Tillage Res.* **2011**, *117*, 172–183. [CrossRef]
4. Lal, R. Tillage effects on soil degradation, soil resilience, soil quality, and sustainability. *Soil Tillage Res.* **1993**, *27*, 1–8. [CrossRef]
5. Marcela, Q. Effect of Conservation Tillage in Soil Carbon Sequestration and Net Revenues of Potato-Based Rotations in the Colombian Andes. Master's Thesis, University of Florida, Gainesville, FL, USA, 2009.
6. Bianchini, A.; Magalhães, P.S.G. Evaluation of coulters for cutting sugar cane residue in a soil bin. *Biosyst. Eng.* **2008**, *100*, 370–375. [CrossRef]
7. Farooq, M.; Nawaz, A. Weed dynamics and productivity of wheat in conventional and conservation rice-based cropping systems. *Soil Tillage Res.* **2014**, *141*, 1–9. [CrossRef]
8. Lahmar, R. Adoption of conservation agriculture in Europe. *Land Use Policy* **2010**, *27*, 4–10. [CrossRef]
9. Zhang, S.; Li, Q.; Lü, Y.; Sun, X.; Jia, S.; Zhang, X.; Liang, W. Conservation tillage positively influences the microflora and microfauna in the black soil of Northeast China. *Soil Tillage Res.* **2015**, *149*, 46–52. [CrossRef]
10. Derpsch, R.; Franzluebbers, A.J.; Duiker, S.W.; Reicosky, D.C.; Koeller, K.; Friedrich, T.; Sturny, W.G.; Sá, J.C.M.; Weiss, K. Why do we need to standardize no-tillage research? *Soil Tillage Res.* **2014**, *137*, 16–22. [CrossRef]
11. Sprague, M.A.; Triplett, G.B. *No-Tillage and Surface-Tillage Agriculture: The Tillage Revolution*; Wiley: New York, NY, USA, 1986.

12. Boone, F.R. Weather and other environmental factors influencing the crop responses to tillage and traffic. *Soil Tillage Res.* **1988**, *11*, 283–324. [CrossRef]
13. Gupta, R.; Seth, A. A review of resource conserving technologies for sustainable management of the rice-wheat cropping systems of the Indo-Gangetic plains (IGP). *Crop Prot.* **2007**, *26*, 436–447. [CrossRef]
14. Erenstein, O.; Laxmi, V. Zero tillage impacts in India's rice-wheat systems: A review. *Soil Tillage Res.* **2008**, *100*, 1–14. [CrossRef]
15. Erenstein, O.; Farosoq, U.; Malik, R.K.; Sharif, M. On-farm impacts of zero tillage wheat in South Asia's rice-wheat systems. *Field Crops Res.* **2008**, *105*, 240–252. [CrossRef]
16. Jabran, K.; Farooq, M.; Hussain, M.; Dogan, M.N.; Yasin, M.; Aulakh, A.M. Aerobic rice in reduced tilled fields fetches higher yield and net economic returns. Proceedings of 3rd International Conference 'Frontiers in Agriculture', Dankook University, Cheonansi, Korea, 3–5 October 2012.
17. Carter, M.R. A review of conservation tillage strategies for humid temperate regions. *Soil Tillage Res.* **1994**, *31*, 289–301. [CrossRef]
18. Tagar, A.A.; Ji, C.; Ding, Q.; Adamowski, J.; Chandio, F.A.; Mari, I.A. Soil failure patterns and draft as influenced by consistency limits: An evaluation of the remolded soil cutting test. *Soil Tillage Res.* **2014**, *137*, 58–66. [CrossRef]
19. Farooq, M.; Basra, S.M.A. Resolving the edaphic conflict in rice-wheat system. In Proceedings of the 14th Australian Agronomy Conference, Global Issues Paddock Action, Adelaide, Australia, 21–25 September 2008.
20. Farooq, M.; Basra, S.M.A.; Asad, S.A. Comparison of conventional puddling and dry tillage in rice-wheat system. *Paddy Water Environ.* **2008**, *6*, 397–404. [CrossRef]
21. Carter, M.R. Soil quality for sustainable land management: Organic matter and aggregation interactions that maintain soil functions. *Agron. J.* **2002**, *94*, 10–18. [CrossRef]
22. Janelle, L.; Tessier, S.; Lague, C. *Seeding Tool Design for No-Tillage Conditions in North-Eastern America*; ASAE: St. Joseph, MI, USA, 1995.
23. Parent, G.; Tessier, S.; Allard, G.; Angers, D.A. *Seedbed Characteristics for Forages and Cereals with No-Tillage in the Northeast*; ASAE: St. Joseph, MI, USA, 1993.
24. Chaudhuri, D. Performance evaluation of various types of furrow openers on seed drills—A review. *J. Agric. Eng. Res.* **2001**, *79*, 125–137. [CrossRef]
25. Chen, Y.; Tessier, S.; Irvine, B. Drill and crop performances as affected by different drill configurations for no-till seeding. *Soil Tillage Res.* **2004**, *77*, 147–155. [CrossRef]
26. Doan, V.; Chen, Y.; Irvine, B. Effect of residue type on the performance of no-till seeder openers. *Can. Biosyst. Eng.* **2005**, *47*, 229–235.
27. Karayel, D.; Özmerzi, A. Comparison of vertical and lateral seed distribution of furrow openers using a new criterion. *Soil Tillage Res.* **2007**, *95*, 69–75. [CrossRef]
28. Karayel, D.; Šarauskis, E. Effect of down force on the performance of no-till disc furrow openers for clay-loam and loamy soils. *Agric. Eng.* **2011**, *43*, 16–24.
29. Doan, V.; Chen, Y.; Irvine, B. Effect of oat stubble height on the performance of no-till seeder openers. *Can. Biosyst. Eng.* **2005**, *47*, 237–244.
30. Vamerali, T.; Bertocco, M.; Sartori, L. Effects of a new wide-sweep opener for no-till planter on seed zone properties and root establishment in maize (*Zea mays*, L): A comparison with double-disk opener. *Soil Tillage Res.* **2006**, *89*, 196–209. [CrossRef]
31. Iqbal, M.; Muneer, A.M.; Hussain, K.A.; Umair, M. Evaluation of the energy efficientzone disk drill for sowing of wheat after harvesting paddy crop. *Int. J. Agric. Biol.* **2012**, *14*, 633–636.
32. Muneer, A.M.; Iqbal, M.; Miran, S. Evaluation of three seed furrow openers mounted on a zone disk tiller drill for residue management, soil physical properties and crop parameters. *Pak. J. Agric. Sci.* **2012**, *49*, 349–355.
33. Altikat, S.; Celik, A.; Gozubuyuk, Z. Effects of various no-till seeders and stubble conditions on sowing performance and seed emergence of common vetch. *Soil Tillage Res.* **2013**, *126*, 72–77. [CrossRef]
34. Kushwaha, R.L.; Vaishnav, A.S.; Zoerb, G.C. Performance of powered-disc coulters under no-till crop residue in the soil bin. *Can. Agric. Eng.* **1986**, *28*, 85–90.
35. Hasimu, A.; Chen, Y. Soil disturbance and draft force of selected seed openers. *Soil Tillage Res.* **2014**, *140*, 48–54. [CrossRef]

36. Conte, O.; Levien, R.; Debiasi, H.; Sturmer, S.L.K.; Mazurana, M.; Muller, J. Soil disturbance index as an indicator of seed drill efficiency in no-tillage agrosys-tems. *Soil Tillage Res.* **2011**, *114*, 37–42. [CrossRef]
37. Endrerud, H.C. Dynamic performance of drill coulters in a soil bin. *J. Agric. Eng. Res.* **1999**, *74*, 391–401. [CrossRef]
38. Magalhães, P.S.G.; Bianchini, A.; Braunbeck, O.A. Simulated and Experimental Analyses of a Toothed Rolling Coulter for Cutting Crop Residues. *Biosyst. Eng.* **2007**, *96*, 193–200. [CrossRef]
39. Sarauskis, E.; Masilionyte, L.; Romaneckas, K.; Kriauciuniene, Z.; Jasinskas, A. The effect of the disc coulters forms and speed ratios on cutting of crop residues in no-tillage system. *Bulg. J. Agric. Sci.* **2013**, *19*, 620–624.
40. Choi, C.H.; Erbach, D.C. Cornstalk residue shearing by rolling coulter. *Trans. Am. Soc. Agric. Eng.* **1986**, *29*, 1530–1535. [CrossRef]
41. Blake, G.R.; Hartge, K.H. *Methods of Soil Analysis: Part 1. Physical and Mineralogical Methods*; American Society of Agronomy and Soil Science Society of America: Madison, WI, USA, 1986.
42. Fredlund, D.G.; Vanapalli, S.K. *Methods of Soil Analysis: Part 4. Physical Methods*; Soil Science Society of America: Madison, WI, USA, 2002.
43. Steel, R.G.D.; Torrie, J.H.; Dickey, D.A. *Principles and Procedures of Statistics: A Biometric Approach*, 3rd ed.; McGraw Hill Book Co., Inc.: New York, NY, USA, 1996.
44. McKyes, E. *Soil Cutting and Tillage*; Elsevier: New York, NY, USA, 1985.
45. Darmora, D.P.; Pandey, K.P. Evaluation of performance of furrow openers of combined seed and fertiliser drills. *Soil Tillage Res.* **1995**, *34*, 127–139. [CrossRef]
46. Kukal, S.S.; Aggarwal, G.C. Puddling depth and intensity effects in rice-wheat system on a sandy loam soil: I. Development of subsurface compaction. *Soil Tillage Res.* **2003**, *72*, 1–8. [CrossRef]
47. Tavakoli, H.; Mohtasebi, S.S.; Jafari, A. Physical and mechanical properties of wheat straw as influenced by moisture content. *Int. Agrophys.* **2009**, *23*, 175–181.