Experimental and numerical investigations of the impacts of separating board and anti-blocking mechanism on maize seeding

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Abstract

Maize seeding is greatly affected by improper seed placement and poor planter performance under a no-tillage mechanisation system. To overcome the issue, we explored the impact of separating board and anti-blocking mechanism (0, 1/4, 1/2, 2/3, 3/4, and 1 type) on maize seeding under different forward speeds (3, 5, 7 km/h) and rotational speeds (260, 400, 530, 740 rpm), where the performance metrics included the mass of straw coiled, seeding height, emergence rate, soil mound depth, straw movement, and straw clearance. The study results show that separating board helps to increase forward and side displacements of the straw, which avoids localized accumulation of straw around the anti-blocking mechanism. The straw clearance rate of the anti-blocking mechanism with a separating board is greater than that without the separating board. Therefore, the 2/3 type anti-blocking mechanism with a separating board is recommended for maize seeding at a forward speed of 5 km/h and a rotational speed of 400 rpm.

Introduction

Huang-Huai-Hai Plain locates in semi-arid and semi-humid regions of China and has a significant share of 51% in national maize and wheat yields (Fang *et al.,* 2015). Maize follows wheat crop in Huang-Huai-Hai Plain, resulting in wheat straw cover in the fields before maize seeding. This straw cover increases organic material, which ultimately raises crop yield (Zhang *et al*., 2014; Thierfelde *et al*., 2015; Zhang *et al*., 2015) and conserves moisture and reduces soil erosion (Wang *et al.,* 2000; Melland *et al.,* 2016). However, more and more straws are thrown away or open burning at will, causing an enormous waste of resources and a series of problems, such as atmospheric pollution and traffic interruption (Fang *et al.,* 2017). Apart from these, there are some problems associated with maize seeding as clogging in the seed placement system and restricting planter performance (Yang *et al.,* 2016).

Studies have been conducted to address these challenges by chopping straw residue in front of the planter, pushing the residues sideways during furrow opening, and burying residues in a strip ahead of the furrow opener. Recently, anti-blocking systems were developed, which cut the straw (Fallahi and Raoufat, 2008; Chen *et al*., 2016) and placed it along sideways (Raoufat and Matbooei, 2007; Gao *et al.,* 2014; Wang *et al.*, 2017). In addition, the existence of a separating board, was first introduced and discussed in the research of Gao *et al*. (2014).

The efficiency of such systems is usually characterised by the trafficability of machines, seed placement rate, and seedling emergence. However, the straw movement needs to be studied during the interaction of straw and anti-blocking mechanism. There are various types of straw movement, such as rotation, deflection, collision and recoil, and even throwing like slant and linear moving straw trajectory (Liao, 2005). Fluid mechanics can explain such straw movement behaviour, but the approach cannot quantify the displacement of straw (Gu *et al.*, 1994; Gao, 2014). Nevertheless, it represents the importance of straw displacement during straw-tool interaction (Conte *et al.*, 2011). The tracer method was employed by Liu *et al.* (2007 and 2010) at different forward speeds concluding that the forward speed significantly affects straw displacement. Similar results were reported by Mari *et al.* (2014), Farid Eltom *et al.* (2015), Fang *et al.* (2016a and 2016b), and Niu *et al.* (2019), where the straw movement was studied by using different tillage tools under controlled conditions and verified by simulation with discrete element method (DEM).

The specific objectives of this paper include: i) straw movement caused by round roller-claw anti-blocking mechanism with and without separating board installed under a controlled soil bin condition; ii) straw burial related to the anti-blocking mechanism with and without separating board installed via numerical simulation; iii) performance of the round roller-claw anti-blocking mechanism under a field condition.

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Materials and methods

Description of anti-blocking mechanism

In this study, a round roller-claw anti-blocking mechanism of steel was installed on maize planter and used for maize seeding under no-tillage conditions. Six different anti-blocking mechanisms were designed based on the percent of claw height accounted for the total round roller-claw height and named as 0, 1/4, 1/2, 2/3, 3/4, and 1 type. These treatments were tested with and without a separating board installed, composed of two flat panels to guide straw movement during planting, as shown in Figure 1.

Experiment site and setup

Soil bin experimental setup

The experiments were conducted in the soil bin at the Soil-Plant-Machinery System Laboratory of Shandong Academy of Agricultural Machinery Sciences, Shandong, P.R. China. The dimensions of the soil bin are 60×2.5×1 m (length×width×depth) filled with enough soil that can facilitate testing of maize planter without side effects and variability. The experimental straw was obtained from Zhangqiu district of Jinan, Shandong, China; its average moisture content was kept constant at 18.60% during the experiments. The straw mulching cover was maintained at 916.95 g/m^2. The soil density was managed at 1.70 g/cm^3 with a soil hardness of 0.96 MPa. The average moisture content of 0-5 cm soil layer was 10.07%, whereas, in 5-10 cm soil depth was 13.51%.

A round roller-claw anti-blocking mechanism was installed on the maize planter (Model # 2BYSF-3) and driven by a PTO shaft installed on the soil bin. The experimental equipment used in the study is shown in Figure 2. The movement of straw was monitored with a high-speed photography system comprised of a camera (Photron FASTCAM UX50), laptop (Thinkpad T490), support mechanism, and light source (Nanguan 27W).

Simulation setup

The anti-blocking mechanism and straw interaction was modelled using EDEM (Version-2018, DEM Solutions Ltd., Edinburgh, Scotland). The hard-sphere model was used to simulate soil, and the diameter of the spherical surface was set to 10 mm. The spheres of 3-mm radius and 5-mm space between the centres of adjacent ones were used to simulate the straw, and three lengths, 36 mm, 76 mm, and 116 mm, respectively, were generated. There were 60,000 soil particles and 2400 straw particles used for simulation. The primary material and interaction parameters used in the simulation are quoted from the previous work (Fang *et al.*, 2016b) and shown in Table 1. The simulation model is shown in Figure 3.

Field experimental setup

The experiment was conducted at Zhangqiu district, Jinan city, Shandong province of China. Wheat was previously harvested, leaving behind straw with an average height of 25 cm. The straw mulching cover was 932.65 g/m^2, with an average moisture content of 18.61%. The soil bulk density was 1.70 g/cm^3, the average moisture content was 10.32 % in the upper 5 cm layer and was 13.62% in the next 5 cm soil depth, whereas soil hardness was 1.01 MPa. A maize planter (Model # 2BYSF-3) with the former mentioned anti-blocking mechanism was used.

Measurements

Straw movement

Straw applied in the soil bin over an area of 1 m wide and 20 m in length. Five different groups of straw with different colours and marks were used as straw tracers. The lateral tracers with marks in two ends were placed perpendicular to the direction of the machine forward speed, and the longitudinal ones without marks were placed parallel to the forward direction. A local coordinate system was adopted to record the straw movement, so the initial X coordinates of all straw tracers were 0. For the three groups of straw tracers that laid in the anti-blocking mechanism's operation centre line, the initial Y coordinates were 0.

In comparison, the other two groups of straw tracers were arranged laterally 30 mm away from the operation centre line of the anti-blocking mechanism. All tracers were placed in the way shown in Figure 4, and the central coordinates of each group of straw were also illustrated. Straw displacements were calculated

Table. 1 Simulation parameters.

Type	Parameters	Values
Soil intrinsic parameters	Density Poisson ratio Shear modules	1.85 g/cm^3 0.38 1×10^6 Pa
Straw intrinsic parameters	Density Poisson ratio Shear modules	0.241 g/cm^3 0.4 1×10^6 Pa
Steel intrinsic parameters	Density Poisson ratio Shear modules	7.865 g/cm^3 0.3 7.9×10^{10} Pa
Soil- soil contact parameters	Recovery coefficient Static friction coefficient Rolling friction coefficient	0.6 0.6 0.4
Soil-steel contact parameters	Recovery coefficient Static friction coefficient Rolling friction coefficient	0.6 0.6 0.05
Straw-steel contact parameters	Recovery coefficient Static friction coefficient Rolling friction coefficient	0.3 0.3 0.01

by the absolute difference between the original and final positions.

Straw clearance rate

The quadrat was fabricated with inner dimensions of 300-mm length and 120-mm width to collect residue mass data (Figure 5). A hand-operated scissor was used to cut residue that resided along the inner perimeter line of the sampling area. The straw clearance rate was calculated by following Eq. (1):

$$B = \frac{(A_1 - A_2)}{A_1} \times 100\% \tag{1}$$

Where B is the straw clearance rate in %, A_1 is the weight of straw before seeding in the sampling area in g, and A_2 is the weight of straw after planting in the sampling area in g.

Coiled straw measurement

The straw coiled on the opener and anti-blocking mechanism was taken off and weighed as a mass of coiled straw (Fang *et al.,* 2018).

Soil mound depth

The V-shaped soil surface profile with a depression along the centre of the opener path and two mounds on the sides, is typical for seed furrows (Vamerali *et al.*, 2006), shown in Figure 6. As an indication of soil disturbance after seeding, the soil mound depth was defined by the height from the soil surface to the top of the mound.

Seedling emergence

The number of seedlings in a length of 5 m at random positions was selected to calculated seedling emergence by Eq. (2):

$$C = \frac{Q_s}{Q_c} \times 100 \tag{2}$$

Where C is seedling emergence in %, Q_s is the actual number of seedling emergence, Q_c is the number of planting seed.

Seedling height

On the 15th day after seeding, 10 maize plants were selected at random positions to measure their height from the soil horizon to the highest point of maize in the natural state. The average height of 10 maize plants was the seedling height.

Experimental design and statistical analysis

Firstly, the soil bin experiments were conducted under different forward and rotational speeds to observe the straw movement. Secondly, numerical simulation was done to study the straw burial behaviours with and without the separating board installed. Finally, the performance of different anti-blocking mechanisms was tested in the field.

Each treatment was replicated three times in a randomised complete block design (RCBD). Significant differences detection of results was done by variance analysis and Duncan test using SPSS software (ver. 20, SPSS, Inc., Chicago, IL, USA), and significance level of 0.05.

Results and discussion

Comparison between the experimental and simulated results

The soil bin experimental results showed that the mass of straw coiled was 7.14 g with a separating board installed for a controlled straw-covered condition. The result was compared with that of the field, and the relative error was 30.70%. The field experimental result was higher due to the wet root of wheat coiled on the anti-blocking mechanism, resulting in a higher value of 10.30 g.

The DEM numerical simulated results showed that the straw clearance rate was 97.4% while the field result was 82.4%, and the relative error was 18.20% for the mechanism with separating board installed. Meanwhile, the straw clearance rate in the simulation was 92.3%, the field result was 86.7%, and the relative error was 6.46% for the mechanism without separating board installed. The numerical results were more significant than those of the field, and the relatively little error inferred that the simulation model could be used to analyse such a seeding process.

Straw movement and clearance

Straw movement is a significant index on the performance of the anti-blocking mechanism and finally affects seeding passing ability. When no separating board was installed, straw displacement was 370 mm for forward displacement and 255 mm for side displacement. These values with separating board installed were 844 and 298 mm for forward and side displacements. The increase of straw displacements, especially for forward displacement, revealed the guiding effect of the separating board. Figure 7 depicted that the separating board helps to increase the straw's lat-

Table 2. The working performance of the anti-blocking mechanism.

The type of anti-blocking mechanism	With separating board				Without separating board			
	Mass of coiled straw	Soil depth mound	Seedling emergence rate	Height of seedling	Mass of coiled straw	Soil mound depth	Seedling emergence rate	Height of seedling
0	23.09 ± 1.45^{a}	96.11 ± 1.11^{ab}	82.46 ± 4.64^{b}	169.50 ± 11.90^{a}	22.46 ± 5.71^{a}	93.89 ± 3.09^{a}	80.70 ± 3.51^{bc}	168.67 ± 5.95^{a}
1/4	10.35 ± 0.96^{b}	81.11 ± 5.88^{b}	91.23 ± 1.75^{ab}	165.50 ± 1.32^{a}	11.12 ± 2.54^{a}	62.22 ± 9.88^{c}	89.47 ± 0.00^{ab}	163.33 ± 3.06^{a}
1/2	9.83 ± 1.31^{b}	87.22 ± 8.73^{b}	89.47 ± 3.04^{ab}	172.17 ± 7.07^{a}	12.81 ± 5.59^{a}	85.56 ± 4.34^{ab}	89.47 ± 0.00^{ab}	177.33 ± 3.68^{a}
2/3	10.30 ± 0.18^{b}	99.44 ± 1.47^{ab}	94.74 ± 3.04^{a}	179.50 ± 9.09^{a}	15.32 ± 2.37^{a}	86.67 ± 11.71^{ab}	98.25 ± 1.75^{a}	176.33 ± 5.73^{a}
3/4	8.50 ± 0.81^{b}	83.89 ± 12.26^{b}	91.23 ± 1.75^{ab}	168.17 ± 7.97^{a}	18.37 ± 6.98^{a}	66.11 ± 4.34^{bc}	78.95 ± 5.26^{c}	175.33 ± 2.62^{a}
1	17.54 ± 4.02^{a}	117.22 ± 14.02^{a}	92.90 ± 1.98^{a}	167.83 ± 9.71^{a}	17.29 ± 3.57^{a}	79.44 ± 6.76^{abc}	80.70 ± 4.64^{bc}	176.50 ± 11.59^{a}

[a-c]Different lowercase letters in the same column, indicate a significant difference ($P<0.05$) between the treatments.

eral and forward displacement, which avoids localized accumulation of straw around the anti-blocking mechanism.

The straw clearance characteristic represents the moving behaviour of the straw group in a specific area, so it might be more suitable to describe straw side movement in studying the performance of the anti-blocking mechanism. The straw clearance characteristic with and without separating board installed was shown in Figure 8. The straw moved like a fluid at the effect of a round roller without a separating board installed, but some of the straw pushed away from the seeding line returned, as shown in Figure 8A. The straw backfill phenomenon was not so evident while the separating board was used, as shown in Figure 8B. The straw moved along the

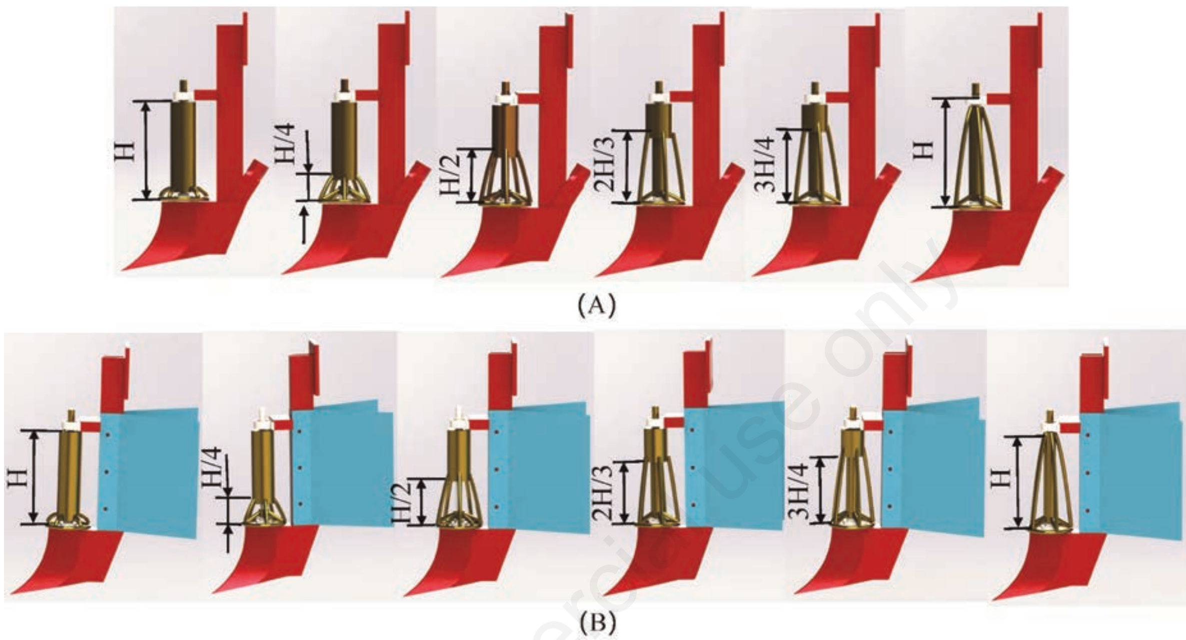

Figure 1. The six different round roller-claw anti-blocking mechanisms of (A) without separating board installed, (B) with separating board installed.

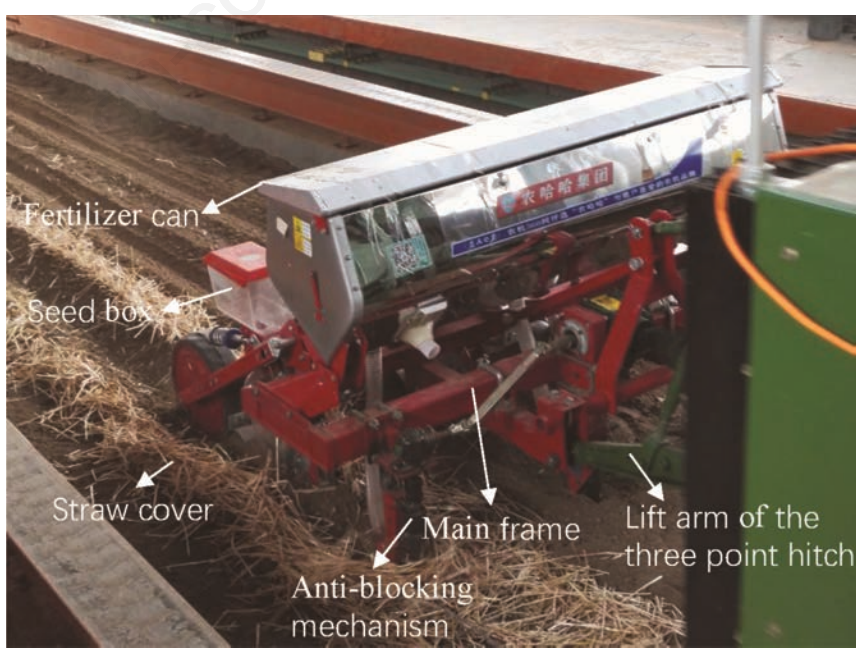

Figure 2. Soil bin and testing equipment.

separating board after the round roller's effect and continued to move away from the seeding line at the guidance effect of separating board. The straw clearance rate of 2/3 type anti-blocking mechanism with separating board was 97.4%, while the value without board installed was 92.3% as the mechanism was operated at a forward speed of 5 km/h and rotational speed of 400 rpm. It proved again that the separating board could reduce straw backfill.

Working performance of different types of anti-blocking mechanism

The working performance of the anti-blocking mechanism was evaluated by mass of coiled straw, soil mound depth, seedling emergence, and seedling height, and the results of variance analysis are shown in Table 2.

Since the wheat straw is bendable and easy to coil on rotating parts of the agricultural machine during the working process, the separating board was designed to guide the straw to move along the board, reducing the chances of straw coiling as shown in Figure 9. The effect of getting rid of coiled straw was more obvious with 1/2, 2/3, and 3/4 types structures; the average reducing ratio was 65.11%. To 0, 1/4, and 1 type structures, there were no significant differences ($P<0.05$) between the anti-blocking mechanism with and without the separating board installed. Although, the type of round roller-claw with separating-board installed significantly ($P=0.001$) affected the mass of coiled straw, there were significant differences ($P<0.05$) for the mass of coiled straw between 1 type

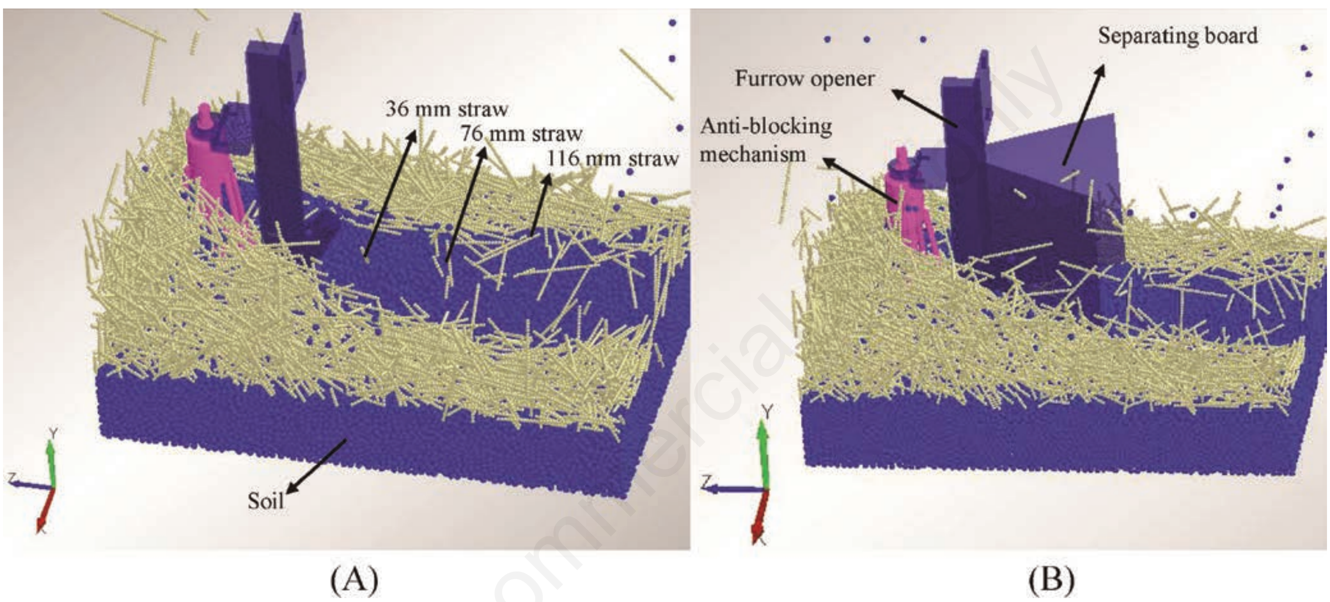

Figure 3. Simulation model of the working process of anti-blocking mechanism (A) without separating board installed; (B) with separating board installed.

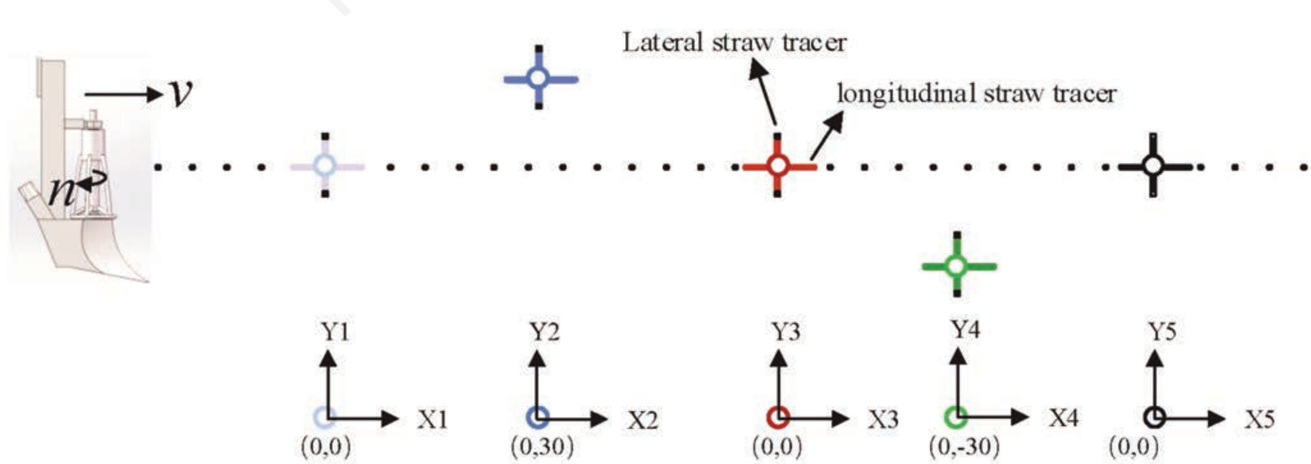

Figure 4. Schematic view of tracer placements in soil bin.

structure and the others type structures except for the 0-type structure type (P=0.061). Especially, the mass of coiled straw was extremely high at 0 type structure no matter whether the separating-board was installed or not. The mass of coiled straw of 0 type structure was significantly higher ($P<0.05$) than those of 1/4, 1/2, 2/3, and 3/4 types with separating-board installed. The missing claw of 0 type structure might be the main cause for the claw could throw away the straw wound on it while rotated high.

The seedling height varied from 165.5 to 179.5 mm for the structure with separating board, while those without separating board varied from 163.3 to 177.3 mm (Figure 10). The difference of the structure with separating board between the maximum and minimum seedling height was higher than that of the structure without separating board. However, there were no significant differences ($P>0.05$) for seedling height with the different anti-blocking mechanism structure no matter whether the separating-board was installed or not. Therefore, the 1/2 and 2/3 type structure would be recommended if the seedling height was considered.

Higher values of soil mound depth typically correspond to better performance of soil disturbance, which is suitable for seedling emergence (Figure 11). The anti-blocking mechanism with the installed separating board had larger soil mound depth because the board was installed on the same basis with round roller-claw. In addition, the outstretched separating board, separated the soil and straw to both sides; reducing the soil and straw backfill. As a result, after being dealt with an anti-blocking mechanism with a separat-

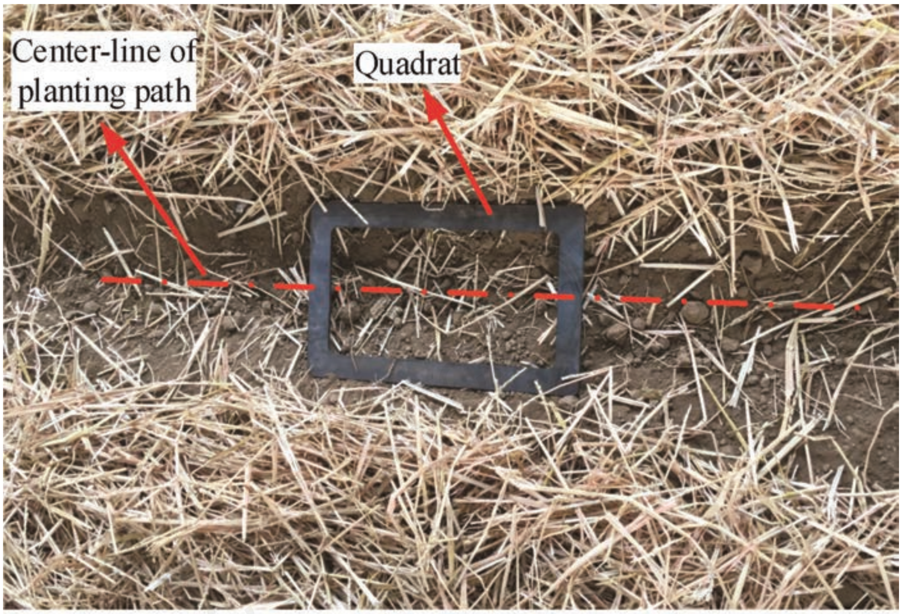

Figure 5. Photo of the quadrat in the plot.

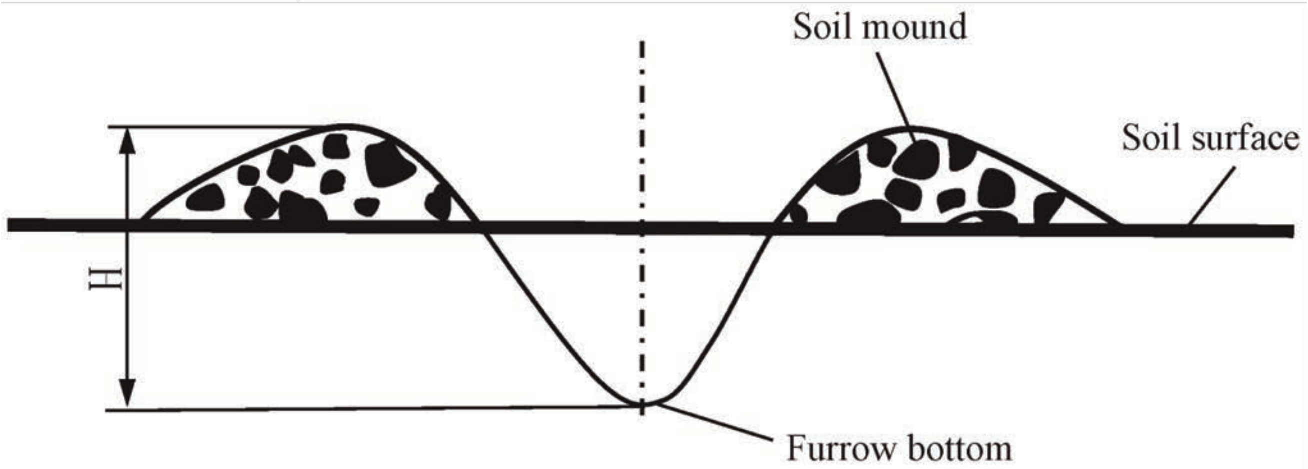

Figure 6. The V-shaped soil surface profile after seeding.

ing board installed, the soil condition was more suitable for seedling emergence. Thus, the seedling emergence rate variations were consistent with those of soil mound depth except the 0-type round roller-claw anti-blocking mechanism. There were no significant differences (P>0.05) for soil mound depth with the different anti-blocking mechanism structure no matter whether the separating-board was installed or not. However, the type of round roller-claw significantly (P=0.009) affected the seedling emergence without separating board installed, the seedling emergence of 2/3 type structure was the highest, but there was no significance between 2/3 type structure and 1/4 type structure (P=0.083), 2/3 type structure and 1/2 type structure (P=0.083).

The maximum value of seedling emergence was obtained by a 2/3 type round roller-claw anti-blocking mechanism for both structures with and without separating board installed. Accordingly, the 2/3 type round roller-claw anti-blocking mechanism was found suitable for the structure coiled the less straw but attained the higher seedling emergence and seedling height.

Effect of working parameters on coiled straw

The 2/3-type anti-blocking mechanism was recommended after compressive consideration of straw coiled, seedling height, and seedling emergence rate. So, the mentioned type was further investigated under different working parameters of forward speed and rotational speed, as shown in Figure 12.

The mass of the coiled straw was the highest at the forward speed of 3 km/h while the rotational speed was 260 rpm; it might be because of the straw backfill. Straw backfill like that of soil

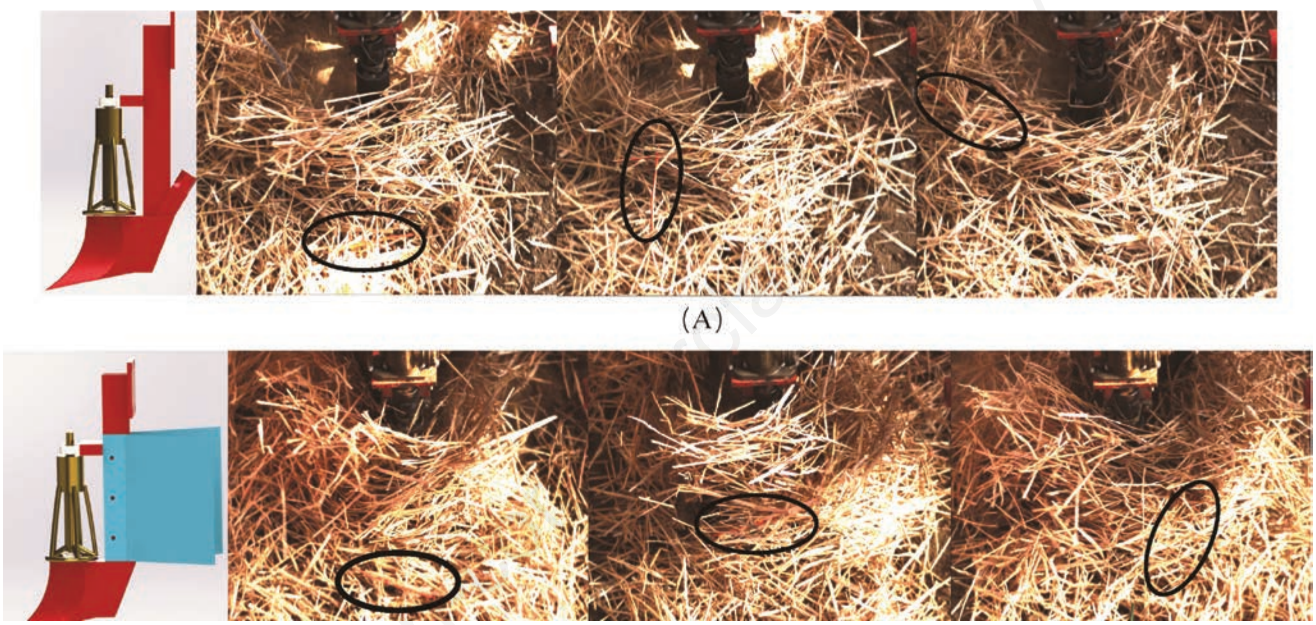

Figure 7. The movement of straw tracer (A) without separating board; (B) with separating board.

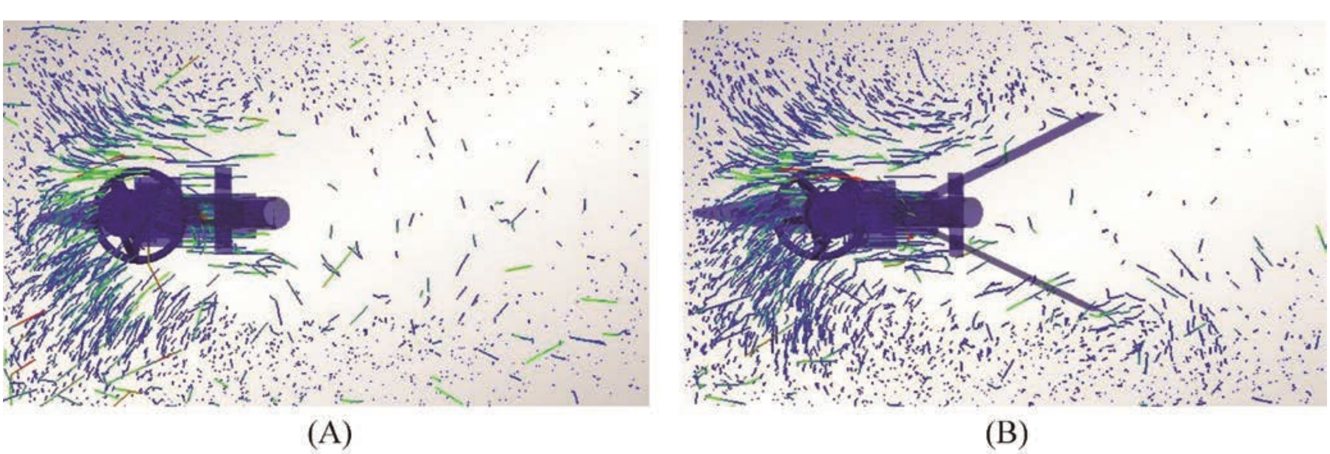

Figure 8. The straw clearance behaviour (A) without separating board; (B) with separating board.

backfill, usually occurred at lower speed conditions because this condition cannot supply a lot of energy to throw straw away. When the rotational speed was higher than 260 rpm, the mass of the coiled straw increased with increasing forward speed just because the forward speed was fast so that the straw could not be thrown out in a short time. The phenomenon was more evident when forward speed increased from 5 to 7 km/h. Moreover, the variation trend with the forward speed of coiled straw was similar at the rotational speed of 400, 530, and 740 rpm. It meant that the increase of rotational speed would enhance working efficiency but not lead to the much augment of coiled straw mass; however, the increase of rotational speed will lead to the increase of energy.

The variance analysis results showed that the rotational speed had no significant effect ($P>0.05$) on the mass of the coiled straw. Besides, there were significant differences ($P<0.05$) in the mass of coiled straw with different forward speeds, excepting forward speeds between 3 and 5 km/h. Thus, taking working efficiency, energy consumption, and mass of coiled straw into account, the optimal working parameters of the anti-blocking mechanism with separating board was the forward speed of 5 km/h and rotational speed of 400 rpm.

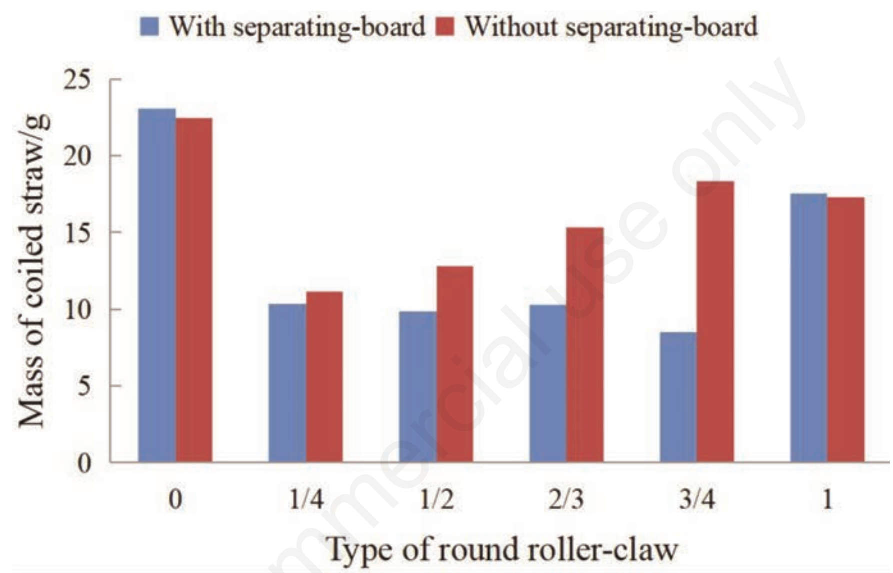

Figure 9. The mass of coiled straw varied with the type of round roller claw.

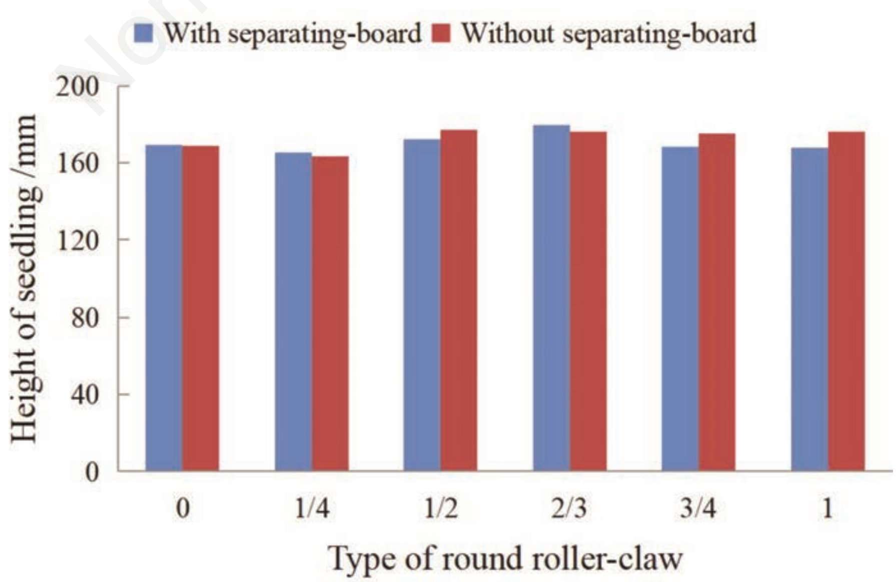

Figure 10. The height of the seedling varied with the type of round roller claw.

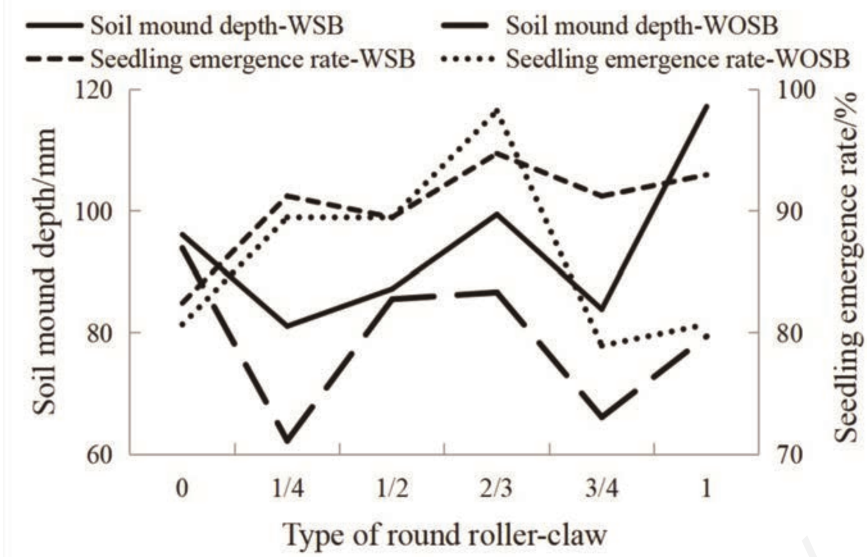

Figure 11. The correlation of soil mound depth and seedling emergence of different types of anti-blocking mechanism. WSB, with separating board; WOSB, without separating board.

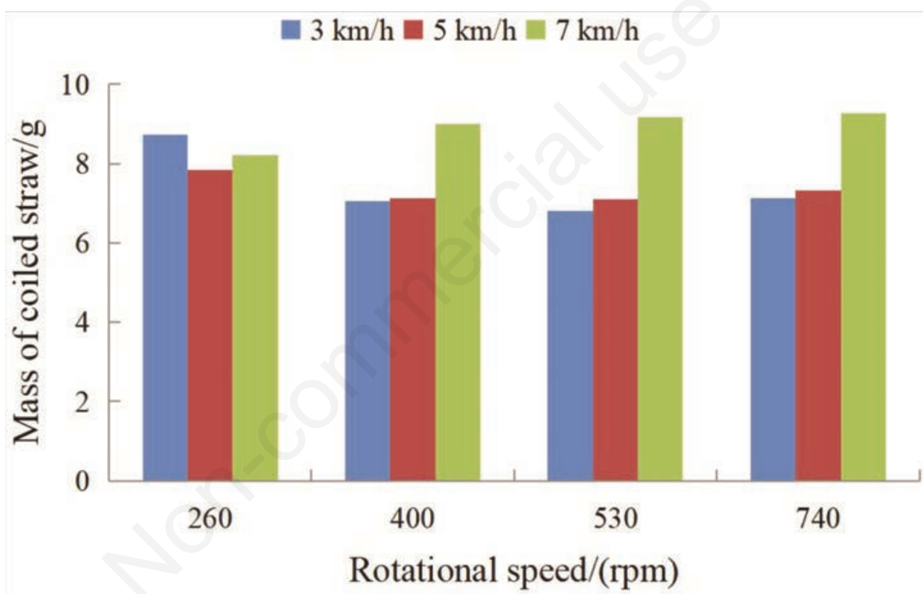

Figure 12. The mass of coiled straw under different working parameters.

Conclusions

In this study, the soil bin experiment, numerical simulation, and field experiment were conducted to investigate the effect of the separating board, working parameters on the performance of the row cleaning mechanism. It was concluded that separating board was found effective with a straw clearance rate of 82.4%, but it also made a denser layer of straw in front of the planter. The simulation results supported the application of a separation board which reduces the backfill of straw. Meanwhile, the optimal working parameters of the anti-blocking mechanism with separating board were forward speed of 5 km/h and rotational speed of 400 rpm with 2/3 type anti-blocking mechanism based on the mass of straw coiled, seedling height, soil mound depth, and seedling emergence rate under circumstanced conditions.

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