DESIGN AND EXPERIMENT OF DEEP TOPDRESSING APPLICATOR FOR WINTER WHEAT
/
冬小麦深施追肥机的设计与试验

Huimin FENG[1], Jianhui NIE[2], Baohui XU[1], Yuming GUO*[3]
[1] Mechanical and Electrical Engineering Department, Yuncheng University, Yuncheng 044000, China;
[2]Intelligent Equipment Research Center, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China;
[3] College of Agricultural Engineering, Shanxi Agricultural University, Taigu 030801, China
Tel: +86-0354-6286869; E-mail: guoyuming99@sina.com
Corresponding author: Yu-ming Guo
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ABSTRACT
To achieve mechanized deep topdressing for winter wheat, the planting pattern of narrow and wide row spacing of (10+20) cm was proposed and the topdressing applicator was designed to implement deep topdressing in the 20 wide row. The numerical simulation was conducted to evaluate the soil disturbance of furrow opener, the precision fertilization control system was attached to improve the fertilization accuracy, the precision row alignment system was attached to furnish support for the operation between the rows, the field experiments were conducted to evaluate the performance of topdressing applicator and the effect of deep topdressing fertilization on grain yield and yield trait parameters after harvest. The simulation results showed that the double-disc furrow opener with parameters of disc diameter 350 mm, disc angle 10° and offset angle 25° caused the soil disturbance within the ± (5-15) cm range along with a heave less than 2 cm at a furrowing depth of 10 cm, the row alignment deviation values of guideline alignment and cross-track deviation under flat ground were mostly distributed within ±3 cm at a tractor speed of 3 km/h. The field experimental results indicated that at a working speed of 3 km/h, the topdressing applicator can accomplish 10 cm deep topdressing in the 20 cm wide row along with the row alignment deviation largely distributed with in ±5 cm, the GNs, TKW and grain yield were higher than broadcasting group, which verifies the feasibility of the planting pattern of (10+20) cm and the practicality of the deep topdressing applicator.

摘要
为实现冬小麦机械化追肥作业，本文提出了一种（10+20）cm 宽窄行种植在 20cm 宽行内追肥的作业模式，以此为依据设计了深施追肥机。通过离散元仿真分析了开沟器对于土壤的扰动作用，通过加装精量排肥系统提高施肥均匀性，通过加装对行作业系统提高深施肥作业对行精度，通过田间实验对作业方案和样机性能进行了验证。仿真结果表明，当双圆盘开沟器结构参数为：直径 350mm，圆盘夹角 10°，圆盘偏角 25°，在开沟深度为 10cm 时，土壤扰动范围为± (5-15) cm 且有低于 2cm 的土壤垄起；当作业速度为 3km/h，平地条件下追肥机具的对行作业偏差和接行作业偏差值基本分布在±3cm 内。田间追肥试验表明：作业速度为 3km/h，在宽窄行种植模式下追肥机可以实现在 20cm 宽行内进行 10cm 深施追肥作业且对行作业偏差基本分布在±5cm 内。深施追肥组小麦穗粒数、千粒重及小麦产量均高于表层撒施组，表明宽窄行模式下冬小麦机械化深施追肥方案可行。

INTRODUCTION
Topdressing winter wheat with fertilizer N is an important process to compositing for any deficiencies and giving wheat an extra boost to enhance winter wheat production and profitability *(Wang Y., 2020; Yang W., 2024*). The Nitrogen (*N*) fertilizer was reported as a crucial process of nutrient dynamics for plant growth (*Shen X., 2024*). Rational amount and suitable placement of N fertilizer were proposed to increase N utilization and improve the grain yield.

Broadcasting fertilization is the most common way for wheat topdressing, which is usually implemented by centrifugal disc spreader (*Assad Y., 2020*) or drones.

Huimin Feng, Lec. Ph.D., Eng.; Jianhui Nie, Engineer, Master, Eng.; Baohui Xu, Prof. Ph.D. Eng.; Yuming Guo, Prof. Ph.D. Eng.

However, the structural parameters of the spreading equipment and the operational parameters of these two fertilization methods exert substantial influence on fertilization uniformity, under specific operational conditions, the coefficient of variation (CV) values of fertilizer distribution can reach 10%-15% (*Ren W., 2021*). Additionally, for broadcasting, neither application can effectively reduce the total nitrogen application rate.

Fertilizer subsurface was studied to be an effective approach to realize high grain yield with moderate fertilizer amount, which also along with a superior fertilizer utilization rate *(Anurag P., 2020; Zhu W., 2023*). *Nkebiwe P. et al. (2016)* suggested that deep subsurface fertilizer placement may be an additional tool for the mitigation of negative consequences of increasingly frequent extreme weather events like high temperatures to improve the fertilizer utilization. *Liu T. et al., (2015*) studied deep Nitrogen placement can effectively decrease NH_3 volatilization and increase N utilization in no-tillage paddy fields.

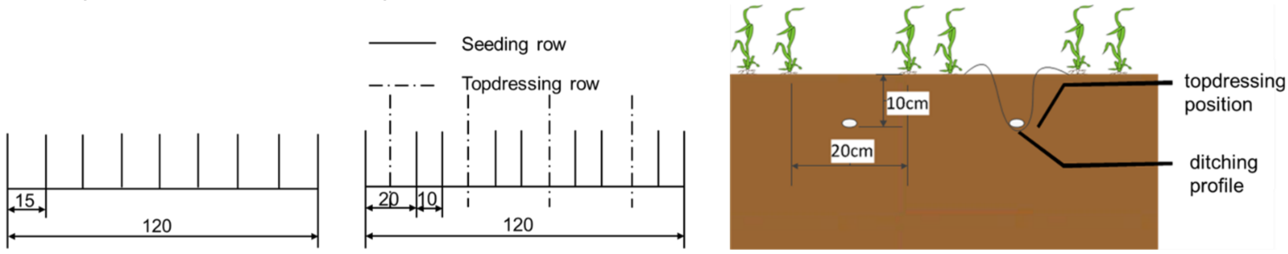
For winter wheat, the 15 cm uniform row spacing planting pattern makes topdressing impractical to mechanize deep fertilization during the green-up stage or jointing stage. To realize deep fertilization, adaptable inter-row spacing (*Guo M., 2015; Mabio C.,2016*) and ditch tools should be taken into consideration. MHDSR-NF combined with a furrower opener enables puddling, seeding, and fertilizer application operations simultaneously were designed to examine the effects of mechanical deep placement of fertilizer on N use efficiency (*Pan S. et al., 2017*). *Kargbo M. et al.* (*2016*) reported that deep fertilizer with precision hill-drilling machine in super rice has a higher efficiency and labor saving. A syringe through two tubules was used to place soil solution at 5 cm and 12 cm depths (*Wu M. et al., 2017*).

In summary, research on mechanized deep topdressing for winter wheat, few studies have analyzed planting row spacing and topdressing depth simultaneously as influencing factors to provide an effective and rational design of topdressing machine. Therefore, the objective of this study is to propose a planting pattern to apply deep topdressing for winter wheat. Based on an automatic navigation system and precision fertilization system, the applicator was designed to perform inter-row deep topdressing for winter wheat, which can apply nitrogen fertilizer to a specific depth between the seedling rows. Additionally, through experimental analysis, the operation performance of the deep topdressing applicator, as well as the impact of deep topdressing on grain yield and yield trait parameters were evaluated.

MATERIALS AND METHODS

Planting pattern and topdressing fertilization strategy

The traditional wheat planting method is drill seeding with an equal row spacing of 15 cm, based on the previous research (*Feng H. et al, 2017*), the narrow and wide row spacing of (10+20) cm was proposed to apply deep topdressing in the middle of 20 cm wide row, which can ensure that the wheat seeding density and the fertilizer amount are consistent with those in the traditional planting method. The schematic diagrams of planting method are shown in Fig. 1.



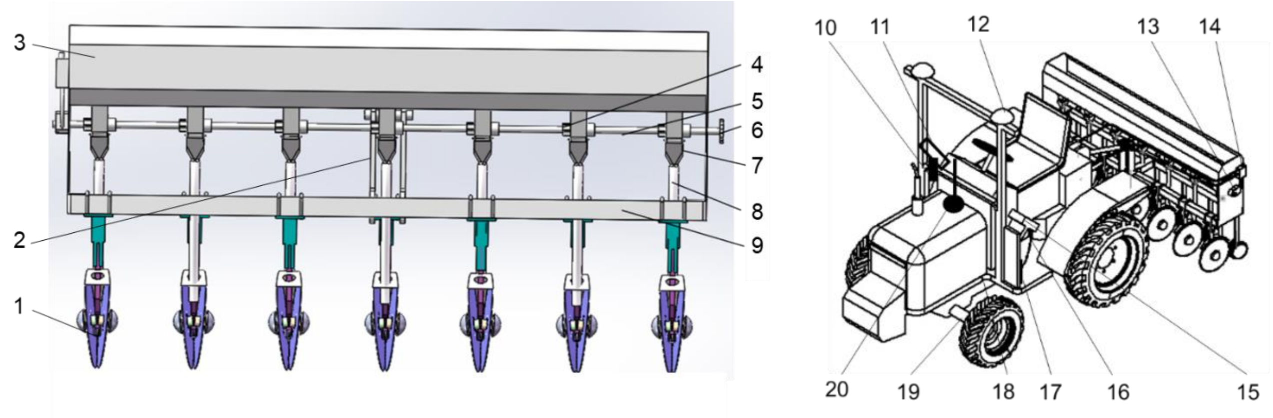
(a) uniform row spacing of 15 cm (b) row spacing of (10+20) cm (c) deep topdressing solution

Fig. 1 - The schemes of planting pattern and deep topdressing operation

Overall structure and working principle

The structure of the deep topdressing applicator is shown in Fig.2a, all the components are installed and fixed on the machine frame. The topdressing fertilization applicator is used in conjunction with a 14 - row wheat seeder, therefore, 7 sets of fertilizer metering devices of 30 cm interval were installed in a staggered front - to - back direction to realize deep topdressing application. The precision row alignment system was equipped to improve inter-row operation accuracy, which can effectively reduce cutting damage of the furrow opener to wheat roots as well as tire compaction damage to wheat seedlings, the precision fertilization control system was added to enhance uniform fertilizer distribution, the overall structure scheme is shown in Fig. 2b.

The row alignment system is composed of navigation terminal, RTK-GNSS controller, angular sensor, steering valve and other components; the fertilization control system is mainly composed of fertilization terminal, fertilization controller, hydraulic valve and motor.



(a) Schematic diagram of topdressing applicator (b) The overall structure of applicator

Fig. 2 - Overall design of topdressing applicator

(a) 1. Double - disc furrow opener; 2. Three-point hitch; 3. Fertilizer tank; 4. Fertilizer apparatus; 5. Fertilizer metering shaft; 6. Screw mechanism; 7. Fertilizer discharge box; 8. Fertilizer tube; 9. Machine frame

(b) 10. Fertilization controller; 11. Fertilization terminal; 12. RTK - GNSS antenna; 13. Hydraulic motor; 14. Electro - hydraulic valve; 15. Navigation terminal; 16. RTK - GNSS receiver; 17. Navigation controller; 18. Steering valve; 19. Angular sensor; 20. Radio antenna

The applicator is attached to tractor through a three-point hitch, the fertilization power is provided by the tractor's hydraulic system, the row alignment system and fertilization control system are separately installed on the tractor body, the hydraulic motor is connected to the fertilizer distribution shaft through a hexagonal shaft, the electro-hydraulic valve is installed on the side of the motor to shorten the hydraulic circuit and improve the operation efficiency.

Parameter design of furrow opener

The structural parameters of double-disc furrow opener were designed to evaluate the soil disturbance during deep topdressing operation, as shown in Fig.3. The main parameters studied are as follows: disc diameter D, disc angle θ and offset angle β (*Ye R., 2023*). The above structural parameters determine the position of the pinch point *m*.

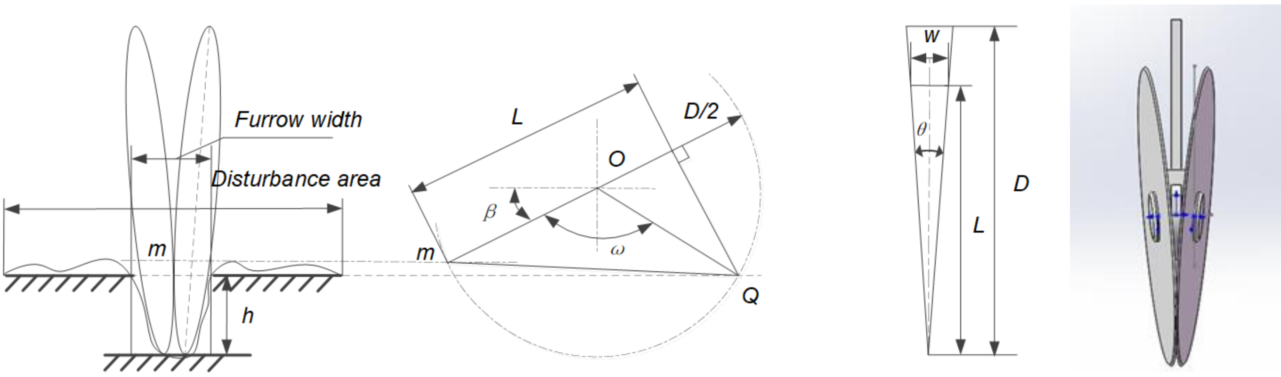


Fig. 3 - Structural parameters of double-disc furrow opener

Based on the structure scheme, the theoretical furrow width can be calculated as following:

$$\begin{cases} \omega = (90° - \beta) + \arccos(\dfrac{D/2 - h}{D/2}) \\ L = \dfrac{D}{2} + \dfrac{D}{2}\cos(180° - \omega) \quad 90° < \omega \le 180° \\ w = 2L\sin(\dfrac{\theta}{2}) \end{cases} \tag{1}$$

where: h is the depth of furrowing operation, mm; Q is the intersection point of the disc edge with the ground; *ω* is the angle between Q and the convergence point *m* at a certain depth, (°); L is the length of the projection of line *Qm* onto the diameter where the convergence point lies, mm; w is the furrow width, mm.

According to the requirements of the agricultural machinery design manual, four different parameter combinations in Table 1 were set up to conduct comparative analysis of disturbance effects of various furrow openers on soil, the SolidWorks and EDEM software were used to perform modeling and simulation process (*Wang Y., 2019*). The DEM parameters were classified as material, interaction and bond properties, the detailed descriptions of these properties are presented in Table 2. The soil disturbance area and the soil backfilling profile were selected as evaluation indicators to determine the final structural parameters of the double-disc furrow opener.

Table 1

The 4 sets parameters of double disc furrow opener

Type		**Parameter**		
		D / mm	**B / °**	**θ / °**
Double disc furrow opener	D_{disc1}	350	25	10
	D_{disc2}	350	15	10
	D_{disc3}	350	15	15
	D_{disc4}	300	15	10

Table 2

The properties parameters of DEM simulation

Parameter	**Value**
Soil density (kg·m^{-3})	2600
Steel density (kg·m^{-3})	7865
Soil shear modulus (MPa)	26
Steel shear modulus (MPa)	7.9×10^4
Soil Poisson's ratio	0.25
Steel Poisson's ratio	0.3
Particle-particle friction coefficient	0.6
Particle-steel friction coefficient	0.6
Soil restitution coefficient	0.6
Steel restitution coefficient	0.6
Particle-particle rolling friction coefficient	0.28
Particle-steel rolling friction coefficient	0.05

The precision fertilization control system

The precision fertilization control system has two major design requirements: one is to realize real-time control of the hydraulic motor rotational speed based on the tractor's driving speed, precisely regulate the rotational speed of the fertilizer distribution shaft to achieve the required control accuracy for the fertilizer application rate. The other one is to determine the optimal working length and rotational speed of the fertilizer apparatus based on the target fertilizer amount and the tractor's driving speed, thereby defining the fertilizer discharge per revolution of the apparatus to improve the uniformity of fertilizer application. Based on these requirements, the precision fertilization control system was designed.

The precision fertilization control system is shown in Fig. 4. The fertilization terminal obtains location information from the RTK-GNSS receiver and calculates the current driving speed of vehicle, and then determines the target rotational speed of hydraulic motor based on the fertilizer control model. The controller adjusts the opening degree of the valve according to the current signal output to regulate the flow through valve, which drives hydraulic motor to rotate, thus achieving precisely control over the rotational speed of hydraulic motor and fertilizer distribution shaft. Simultaneously, an encoder monitors the actual rotational speed signal of the hydraulic motor to form a closed-loop control circuit, the controller uses a PID algorithm to adjust system current in real time, fine-tuning the hydraulic motor speed to achieve accurate control of the fertilizer application rate. The apparatus parameters control method (*Feng H., 2020*) was used to improve fertilization uniformity.

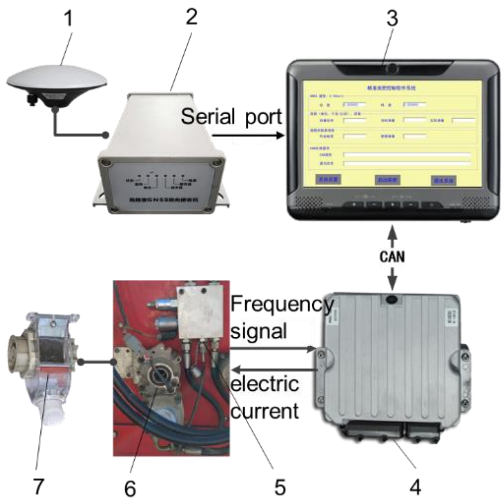


Fig. 4 - Precision fertilizer distribution control system

1. RTK - GNSS antenna; 2. RTK - GNSS receiver; 3. Fertilization terminal; 4. Fertilization controller; 5. Electro - hydraulic valve; 6. Hydraulic motor; 7. Fertilizer apparatus

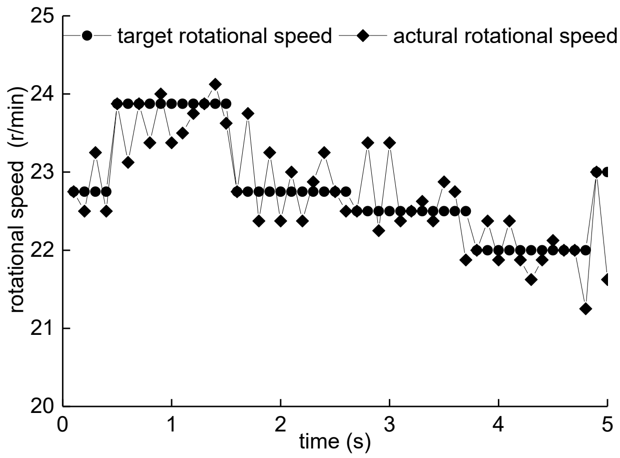


Fig. 5 - Control accuracy of rotational speed of hydraulic motor

The standard PID algorithm was used to calculate and control the rotational speed of the hydraulic motor in real - time. The control accuracy of the motor's rotational speed was analyzed in Fig. 5. Under dynamic conditions, the upper - computer sends a rotational speed command every 1 second at a tractor's forward speed of 5 km/h. The serial port sends back a command every 100 ms and records the rotational speed of motor. The results indicate that under dynamic conditions, the PID control system can complete the rotational speed adjustment within 0.2 seconds, the average control error of the motor's rotational speed is 1.52%, and the maximum control error is 10.2%. The results show that the system can meet the requirements of precisely fertilizer distribution.

Under the premise that fertilizer application rates remain consistent, the model of fertilizer amount was established by formula (2), and the target rotational speed of hydraulic motor is calculated using formula (3):

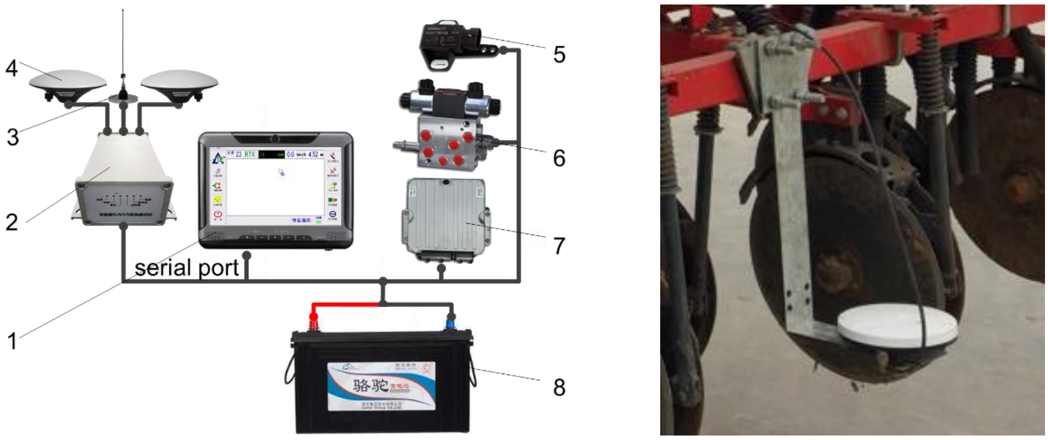
$$\begin{cases} \mathrm{d}S(t) = \dfrac{1000}{60} \times 10^{-4} V_G(t) W \mathrm{d}t \\ \mathrm{d}Q_0(t) = Q_0 \mathrm{d}S(t) \\ \mathrm{d}Q_0(t) = N_\mathrm{T} q R_0(t) \mathrm{d}t \end{cases} \tag{2}$$

$$R_0(t) = \frac{1000 V_G(t) W Q_0}{60 N_\mathrm{T} q} \times 10^{-4} \tag{3}$$

where: $S(t)$ is the operation area at time t, hm^2; $V_G(t)$ is the tractor's driving speed at time t, km/h; W is the operating width, m; Q_0 is topdressing amount per unit area, kg/hm^2; $Q_0(t)$ – topdressing amount at time t; $R_0(t)$ is the target rotational speed of hydraulic motor, r/min; q is the fertilizer discharge per revolution, kg/r; N_T is the amount of fertilizer tube.

The precision row alignment system

The precision row alignment system consists of a navigation control system, a steering control system, and an executive mechanism, as shown in Fig. 6(a). The target steering angle of the tractor's steering wheels is calculated in real - time by operation parameters and the tractor's driving speed measured and calculated by the GNSS, after receiving the steering command, the steering controller compares the target steering angle with the actual steering angle of the front wheels, and runs the PID control program to control the electro - hydraulic valve to drive steering. Due to the influence of tractor vibration and field flatness, the row-alignment accuracy of the topdressing applicator requires further testing, a GNSS antenna is installed at the middle position of the topdressing frame by using a right - angle fixing bracket to collect the machine's trajectory data, as shown in Fig. 6(b).

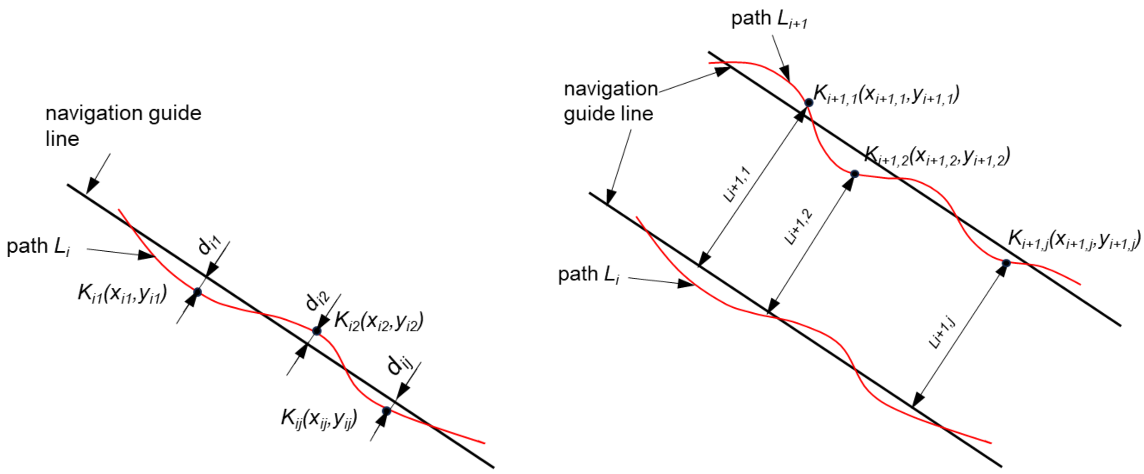


(a) Row alignment control system (b) Antenna installed on the applicator

Fig. 6 - Scheme of precision row alignment system

1. Navigation terminal; 2. RTK - GNSS receiver; 3. Radio antenna; 4. RTK - GNSS antenna; 5 Angular sensor; 6. Steering valve; 7. Navigation controller; 8. Power supply

The guidance alignment deviation and cross-track deviation were used to evaluate the row-alignment accuracy of the topdressing applicator, as shown in Fig.7.



(a) Guidance alignment deviation (b) Cross-track deviation

Fig. 7 - Schematic diagram of row alignment deviation

The equation of the navigation guide line can be obtained by converting the latitude and longitude of reference points on the guide line. The guidance alignment deviation d_{ij} is calculated by the lateral deviation from the sampling points on the machine trajectory to the navigation guide line, according to:

$$d_{ij} = \frac{A_i x_{ij} + B_i y_{ij} + C_i}{\sqrt{A_i^2 + B_i^2}} \tag{4}$$

The cross-track deviation $D_{i+1,j}$ is calculated by subtracting the operating width from the lateral deviation from the sampling points on the machine trajectory within the adjacent working width to the navigation guide line, according to:

$$D_{i+1,j} = \frac{A_i x_{i+1,j} + B_i y_{i+1,j} + C_i}{\sqrt{A_i^2 + B_i^2}} - W \tag{5}$$

The navigation accuracy of the tractor is an important factor affecting the row alignment accuracy of the topdressing applicator. When the driving speed is 5 km/h, three sets data of row alignment operation were processed and analyzed.

Field experimental design and treatments

The experiments were conducted to evaluated the operation performance at National Experiment Station for Precision Agriculture located in Changping, Beijing, China. The topdressing experiments were conducted in accordance with GB/T 20346.2—2006 *Fertilizing Machinery—Test Methods—Part 2: Inter-row Topdressing Machines* and JB/T 7864—2013 *Cultivator-Topdressing applicator*.

The wheat is planted in a wide-narrow row mode of (10+20) cm, with deep topdressing applied within the 20 cm wide rows at a depth of 10 cm, the uniform row planting of (15+15) cm with broadcasting topdressing was set as control group. Urea is used as the fertilizer, with a topdressing rate of 225 kg N ha^{-1} for all treatments (*Muhammad S., 2021*). The topdressing operation is conducted at a speed of 3 km/h, and each experiment group includes 3 replicate plots.

The trajectory data of topdressing applicator is recorded to analyze the row-alignment accuracy, the soil disturbance after topdressing is measured and analyzed to verify the effect of the double-disc opener on seedling area.

After harvest, the yield trait parameters were measured to evaluate the effect of deep topdressing on wheat yield, the spike number per unit area (SN), grain number per spike (GNs) and thousand grain weight (TGW) were measured by the average values of 10 random plants from each plot, and the grain weight per m^2 were obtained by weighing, wheats were manually harvested at mature stage from 3 representative unit areas (1 m^2). The Origin (OriginLab, USA) and SAS statistical Software (SAS Institute, USA) were used to process data analysis.

RESULTS AND DISCUSSIONS

The effects of structural parameters on soil disturbance

The DEM simulation results of *Ddisc3* were shown in Fig. 8, the moment with the largest soil disturbance area in each group was selected to determine the maximum soil disturbance range, the curve of the maximum disturbed soil range was determined by identifying the boundary where the particle velocity was zero. The soil backfill profile was determined by selecting the moment when the velocity of all particles was zero in each group. the comparative analyses of the maximum soil disturbance area and soil backfill profile were shown in Fig.8. The disturbance process for each cross-sectional soil layer lasted less than 2 seconds. The curve shape outside the ±15 cm range on the x-axis in the figure represents the initial shape of the soil bin, which has no impact on the soil disturbance analysis. The effect of soil heave caused by furrowing on seedlings was analyzed through the final soil backfill profile.

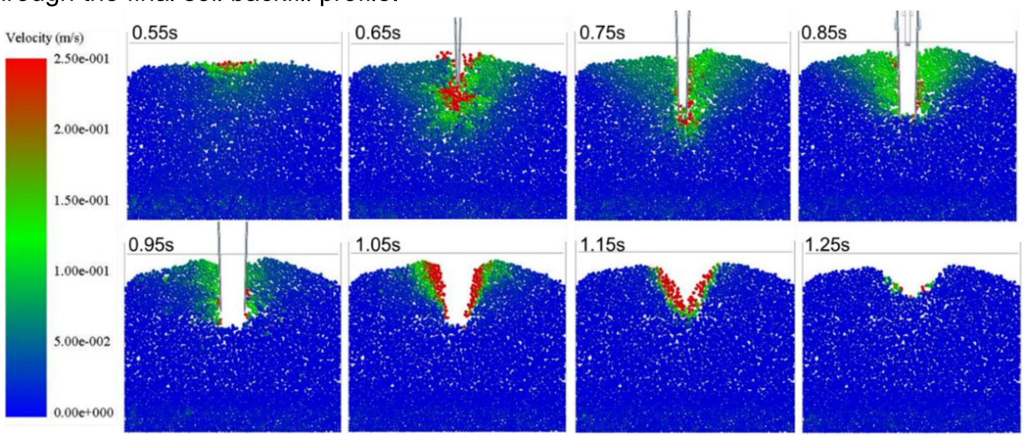
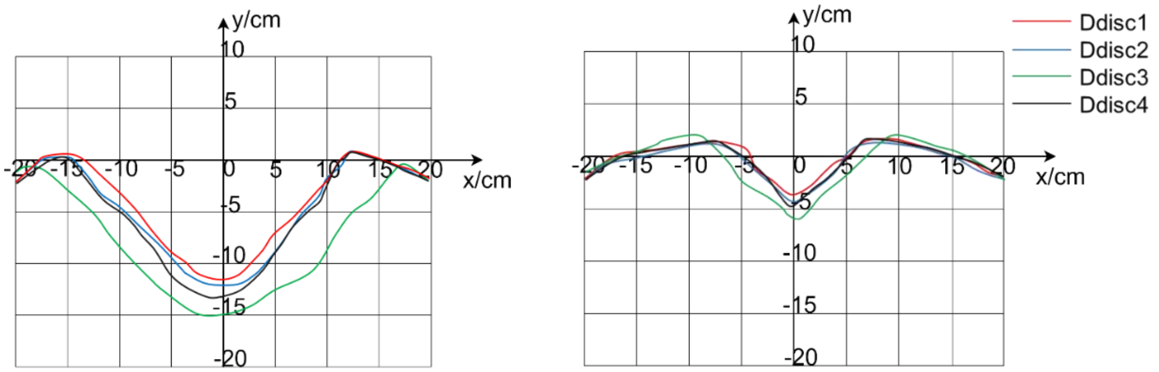


Fig. 8 - Soil disturbance process of double-disc opener

The simulation results of the soil disturbance area and soil backfill profile of four furrow openers are shown in Fig. 9. The soil disturbance area by opener $Ddisc3$ is significantly larger than 3 other types openers, thus, the comparation analyses were conducted for the other 3 groups. As can be seen in Fig. 9(a), when the furrowing depth is 10 cm, the soil disturbance ranges of the three groups are from - 15 cm to 15 cm, the disturbance ranges are not completely symmetrical which is due to the random errors during the soil particle generation process. Although the particles nearby the boundary were disturbed, the velocity of the particles is only about 0.05 m/s, and the duration of the disturbance process is less than 2 s, therefore, the soil cover impact of the furrow process on the wheat seedlings can be ignored.

As can be seen in Fig. 9(b), after the furrowing operation is completed, there is a soil heave within the ± (5-15) cm range on both sides of the ground, the height of the heave is less than 2 cm, and the highest point is within ±10 cm, which has minimal impact on the coverage of seedlings on both sides. Comparing the simulation results, Ddisc1 exhibits the smallest soil disturbance area and soil backfill profile.



(a) Soil disturbance area (b) Soil backfill profile

Fig. 9 - Soil disturbance area and soil backfill profile of four furrow openers

Combined with the formula 1, at a certain depth, for a given disc diameter D and included angle θ, as the offset angle β increases, the vertical position of pinch point decreases, thus leads to an increase in the theoretical furrow width; for a given disc diameter D and offset angle β, as the included angle θ decreases, the theoretical furrow width decreases.

Based on the above analysis, the parameters of the double-disc furrow opener are selected as follows: disc diameter D is 350 mm, disc angle θ is 10° and offset angle β is 25°, at a furrowing depth of 10 cm, the theoretical furrow width is calculated as 55.12 mm, which can avoid the furrow opener from cutting the wheat roots when the planting row spacing is greater than 20 cm.

The row alignment deviation analysis of topdressing applicator

The guidance alignment deviation distribution diagrams of tractor path and three sets of applicator paths were shown in Fig.10. As can be seen, the overall guideline alignment deviation of tractor path exhibits a normal distribution within ±1.5 cm, the overall guideline alignment deviations of row following (RF) paths exhibit a normal distribution and over 90% of deviations fall within ±3 cm, which can fully meet the accuracy requirements at an operating row width of 20 cm.

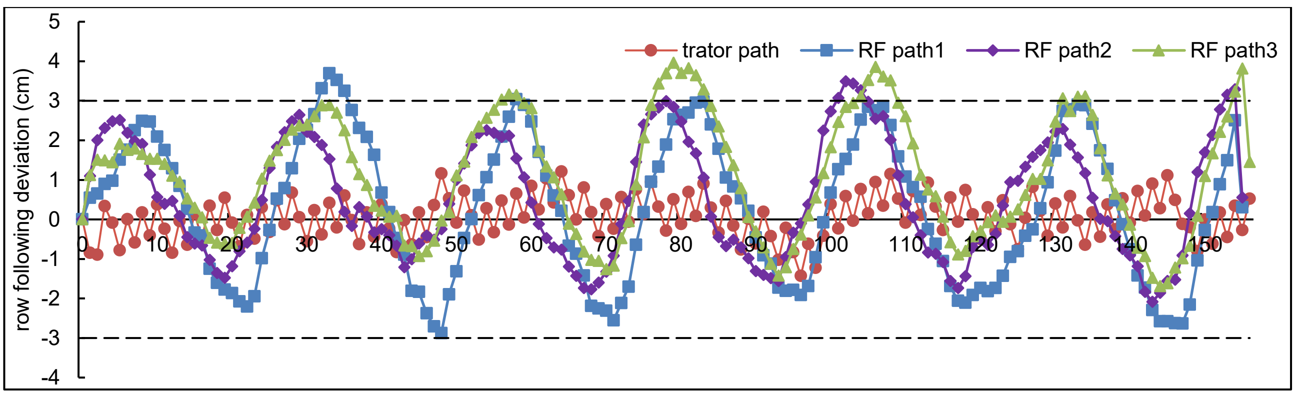
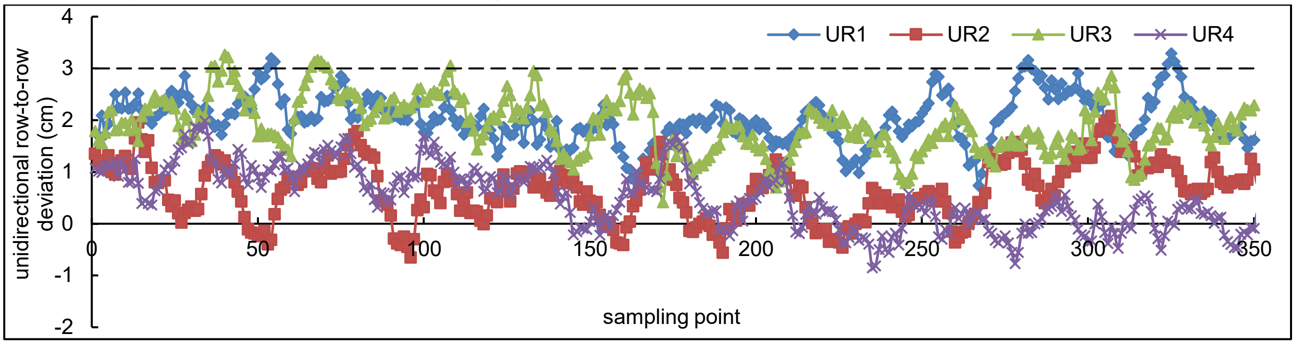
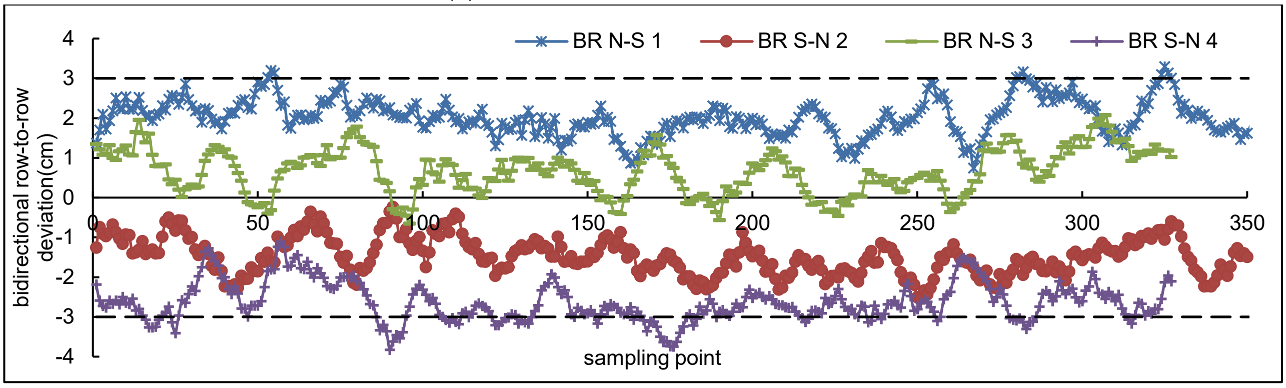


Fig. 10 - Guidance alignment deviation distribution of row following path

The cross-track alignment deviation includes unidirectional row-to-row deviation and bidirectional row-to-row deviation. At a driving speed of 3 km/h, the trajectory data of the topdressing applicator from 4 paths of unidirectional row-to-row operations and 4 paths of bidirectional row-to-row operations were analyzed respectively, the results were shown in Fig. 11.



(a) Unidirectional row to row deviation



(b) Bidirectional row to row deviation

Fig. 11 – Cross-track alignment deviation

As shown in Fig.11, the unidirectional row-to-row deviations exhibits certain fluctuations without an obvious normal distribution, and the tend to shift to one side of the guide line. In contrast, the bidirectional row-to-row deviations of the back-and-forth paths along the north-south direction are distributed on both sides of the navigation guide line. The distribution range of both cross-track deviations were essentially within ±3 cm. By comparison, the distribution of cross-track deviation shows a distinct bias, which can be attributed to machinery offset errors caused by row alignment calibration. Therefore, the cross-track deviation can be reduced by repeating the calibration process.

The results under field experiments

The field experiments and yield traits parameters measurement were carried out, as shown in Fig.12. Subsequently, the relevant experimental results were analyzed.

Fig. 12 – Field experiments

Soil disturbance under field condition

The furrow profile and soil disturbance range during topdressing furrowing at a depth of 10 cm were shown in Fig.13. The disturbance to the soil layers is a smooth inclined plane on both sides during furrowing, and it exhibits good soil backfilling due to the loose soil during topdressing period, which can effectively reduce damage to wheat roots and nitrogen volatilization.

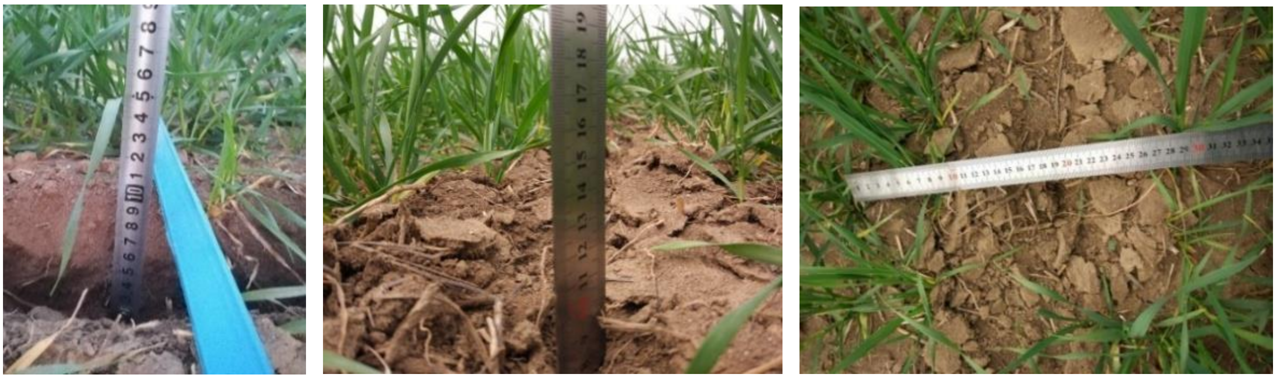


Fig.13 – Soil disturbance during topdressing furrowing at depth of 10 cm

Within the same furrow row, 10 points were randomly selected to measure the soil disturbance range, the farthest fracture point of the surface soil observed was selected as the boundary, and the results show that the surface soil disturbance range is between 27 and 31 cm. Due to the soil compaction, the movement of soil particles and disturbance range during actual furrowing operations differ from the simulation results, although the surface disturbance range increases, it did not form excessive soil heaving, resulting in a slight impact on seedling coverage.

Row alignment deviation of applicator under field condition

The trajectories data of 5 working paths were obtained to analyze the row alignment deviation of the topdressing applicator. Taking the first path navigation guide line as reference, the row alignment deviation of the first path and the cross-track deviation of the other four paths are analyzed. The deviations are calculated according to the formula (4) and (5), the results are shown in Fig. 14.

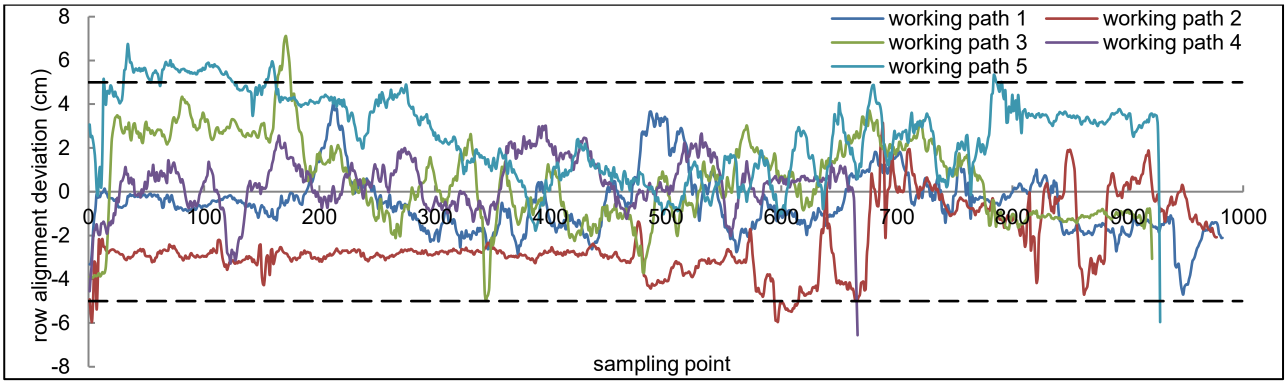


Fig. 14 - Row alignment deviation of 5 working paths

As can be seen in Fig. 14, the deviation ranges of the row alignment operation for the first working width to the fifth working width are -4.7~4.03 cm, -5.95~3.1 cm, -4.99~7.11 cm, -6.56~3.01 cm and -5.96~6.75 cm, respectively. The positive and negative deviations of the first working path are relatively evenly distributed, the largest cross track deviations of the working pass 2 and 4 are on the negative side of the coordinate axis, the largest cross track deviations of the working pass 3 and 5 are on the positive side of the coordinate axis, which is caused by the difference of steering direction. Except for a few data points with excessively large deviations, the row alignment deviations of the topdressing machine were basically distributed within the range of ±5 cm, this result can meet the requirements of mechanized deep topdressing operations.

During topdressing, the flatness of the field has a significant impact on the operational stability of the topdressing applicator. When carrying out the operation, the working speed of the tractor can be adjusted according to the soil flatness to decrease the row alignment deviation caused by vibration.

Effect of deep topdressing on grain yield and yield trait parameters of winter wheat

The grain yield (GY) and yield trait parameters after harvest in the two groups are comparatively analyzed, including spike number per unit area (SN), grain number per spike (GNs) and thousand grain weight (TGW). The results are presented in table 3.

Table 3

The grain yield and yield trait parameters of two groups

	SN/units	GNs/units	TGW/g	GY/kg·ha-2
Experimental group	317	35.23	45.11	4075.75
Control group	321	34.3	42.75	3544.5

The GNs, TWG and GY values of the experimental group are higher than the control group, the theoretical grain yield of experimental group is about 500 kg higher than the control group, which has a similar conclusion with the *He Y. (2020)* study that deep topdressing treatment could significantly improve the grain yield of winter wheat. The results show that deep topdressing application is beneficial to the wheat heading and grain filling, which can increase the wheat yield to a certain extent.

CONCLUSIONS

This study provided a feasible solution to the problem of mechanized deep topdressing application of winter wheat, and the main conclusions are as follows.

(1) The planting pattern of (10+20) cm row spacing were proposed, the topdressing applicator attached precision fertilization control system and precision row alignment system was designed to implement deep topdressing fertilization in the 20 cm wide row.

(2) The DEM simulations were performed to evaluate the soil disturbance of double disc furrow opener at a furrowing depth of 10cm. The results showed that with a disc diameter D of 350 mm, a disc angle θ of 10° and an offset angle β of 25°, the opener caused minimal soil disturbance within a range of approximately ± (5-15) cm, with a soil backfill heave of less than 2 cm.

(3) The row alignment accuracy of topdressing applicator was analyzed by guideline alignment deviation and cross-track alignment deviation. At an operation speed of 3 km/h, the deviation values were basically distributed within ±3 cm under flat ground conditions.

(4) Under field conditions, the topdressing applicator was validated as effective, achieving 10 cm deep topdressing within the 20 cm row spacing. The resulting soil disturbance had a negligible effect on seedling coverage, and the row alignment deviations were generally distributed within ±5 cm at an operating speed of 3 km/h. Yield analysis indicated that mechanized deep topdressing positively influenced both the yield trait parameters and the overall grain yield.

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