

# Field Investigation of Straw Length, Stubble Height and Rotary Speed Effect on the Dispersion and Burying of Residue

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## Research Article

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# Abstract

High-yielding agriculture leads to plenty of residues left in the field after harvest, which not only makes seeding operations difficult, but also decreases residue decomposition rate. Thus, it is necessary to incorporate some residue into the soil by tillage operations. Providing the relation between tillage operations and residue incorporation, and establishing a mathematical model plays an important role in residue management and the design of tillage machinery. In order to obtain detailed data on the interaction between crop residue and tillage operations, an electric and multi-functional field testing bench with precise parameter control was developed to perform residue incorporation characteristics of rotary tillage, and investigated straw length, rotary speed and stubble height effect on the dispersion and burying of residue. Three experimental factors affecting residue incorporation performance were studied, i.e. six lengths of straw (30-150 mm), four heights of stubble (50-200 mm), and three rotary speeds (240-320 rpm). Chopped straw and stubble with certain sizes were prepared for the test, and measure the dispersion uniformity and burying rate of residue after rotary tillage. The results indicated that straw length, stubble height, and rotary speed all impact residue incorporation quality. The dispersion uniformity and burying rate of residue decreased with the increase of straw length and stubble height; Lower rotary speed parameter buried lesser residue and dispersed worse uniformity than higher one; It is suggested that farmers determine the straw length and stubble height at the stage of harvest according to the burying rate and dispersion uniformity of residue.

## Background

As a carrier of material, energy and nutrient, crop residues are a valuable renewable biological resource<sup>1-3</sup>, and suitable for fertilizer, fodder, and bedding materials<sup>4-6</sup>. When crop residues are returned to the field as fertilizer, it can not only solve the environmental problems caused by straw burning, but also increase soil organic matter and fertility, improve soil pore structure and promote crop growth<sup>7-11</sup>. However, the position of residue distribution in the field has a great impact on the accumulation rate of organic matter<sup>12</sup>. Plenty of residues accumulated on the ground after harvest, which not only makes seeding operations difficult, but also decreases residue decomposition rate<sup>13-14</sup>. While residue incorporated into the soil is conducive to the complete contact between residue and microorganism for increasing residue decomposition rate and can greatly reduce the consumption of chemical fertilizer in the field<sup>15-16</sup>. Meanwhile, the proper residue decomposition rate to supply fertilizer nutrients for crop growing in time depends largely on the uniformity of residue dispersion<sup>17</sup>. Therefore, one way of efficient utilization of residue is to evenly incorporate residue into soil by tillage operation.

In the intensive rice-wheat rotational farming carried out in East-China, grain yield is increased year by year. High-yielding agriculture leads to plenty of residues left in the field after harvesting<sup>18</sup>. A large amount of residue mulching on the ground will make sowing operation difficult and lead to slower residue decomposition. Therefore, a common way is to cut the residue into a proper length and then incorporate the residue uniformly into the soil by tillage operation<sup>19</sup>. That is, some crop residue must be incorporated into the soil<sup>20-21</sup>. Implementing soil tillage can realize the residue incorporation for fertilization utilization<sup>22</sup>. However, residue incorporation quality varies widely due to differences in residue length, tillage tools, forwarding speed, and soil type<sup>23-24</sup>. For example, short residue length is conducive to residue incorporation to acquire a better burying rate in sweep tillage<sup>25</sup>; The application of a trash-board could improve the residue burying and displacement performance in plough tillage<sup>26</sup>; Deeper tillage depth and higher speed could increase straw burying<sup>27</sup>. Hence, providing the relation between tillage operations and residue incorporation, and establishing a mathematical model plays an important role in residue management and the design of tillage machinery.

Over the past decades, many studies have been conducted to explore how tillage operation parameters and residue conditions affect the effect of residue returning. Liu et al.<sup>13</sup> used a straw tracing method to study the movement of residue in sweeping operation, and the results showed that the residue length and forward speed could impact straw displacement and burying. Fang et al.<sup>19</sup> found that kinematic parameter has a significant effect residue burying in rotary tillage operation, and the results indicated that higher kinematic parameters could obtain better residue burying quality. Zeng and Chen<sup>28</sup> used the discrete element method to develop a tool-residue interaction model for simulating the process of residue incorporation operation. The results showed that increasing the speed is conducive to increase soil and residue displacement, and residue burying rate. Unfortunately, all the above experimental studies were carried out in an indoor soil bin. Although the benefits of the soil bin test are well known, there are many limitations in the experimental conditions. Such as the influence of stubble factor on residue incorporation cannot be implemented in the test, and there are also some differences between indoor remolded soil and field soil. So data are still lacking of the interactions between crop residue and tillage operations under field test conditions. In addition, more detailed studies of the dispersion state of residue after incorporated into the soil, as well as residue incorporation characteristics of rotary tillage are required.

Although the importance of a better understanding of the dispersion state of residue after incorporated into the soil has been emphasized by a number of authors<sup>29-31</sup>, technical methods to quantify the dispersion position of residue was limited. Davut and Kamil<sup>30</sup> use stratified sampling method to obtain the residue information in different soil layers, but cannot quantify the position of each straw after incorporated into the soil. In contrast, our study quantifies the dispersion uniformity of residue after tillage by using the residue spatial coordinate digitizer, and explores for the first time tillage operation parameters effect on the dispersion state of residue. In addition, we also developed a electric and multi-functional field testing bench to obtain sufficient field test data under precise control conditions, as well as to comprehensively understand the effect of tillage operation on residue incorporation. In order to provide the mathematical relation between tillage operations and residue incorporation, this study was designed to: (i) develop a multi-functional field testing bench and use it to perform residue incorporation characteristics of rotary tillage (ii) investigate the effect of straw length and stubble height on residue dispersion and residue burying on field condition, and, (iii) the effect of rotary speed on the residue incorporation quality.

## Materials And Methods

**Site description.** In November 2020, the experiments were conducted in the Babaiqiao, Nanjing Agricultural University, Jiangsu Province, China (118°55'E 32°25'N). The tillage test was carried out in the field after the rice crop harvesting in autumn. The soils in the field were clay loam with yellow-brown colour, under rice-wheat rotations. Before the start of experiments, soil physical properties (cone index, moisture content, bulk density) and residue parameters (length, height, wet density) were measured and the results presented in Table 1.

**Table 1.** Soil properties and straw parameters of experimental site.

Parameter	Value	
Soil	Texture	Clay loam ( 21.20, 39.67 and 38.96% sand, silt and clay, respectively )
	Cone index	635, 1000, 987 kPa at 5, 10, and 15 cm depths, respectively
	Moisture content	22.6, 23.4, 24.8% at depth of 0-5, 5-10 and 10-15 cm, respectively
	Dry bulk density	1.29 g cm <sup>-3</sup>
Residue	Straw length	0-15 cm
	Stubble height	0-20 cm
	Wet density	8012 kg ha <sup>-1</sup>
	Dry density	3943 kg ha <sup>-1</sup>

**Description of the test bench and tillage tool.** An electric and multi-functional field testing bench with precise parameter control was developed for this study. Its main features include a movable carriage, rotary tiller, traction motor, lifting motor, electric generator, power distribution box, and control system. The rectangular steel tubes of various sizes were welded to construct an 8000 mm long and 2000 mm wide test bench (Fig. 1). The movable carriage is transported on twin lead rails with an adjustable speed at 0.05-1 m s<sup>-1</sup>. A traction motor and four lifting motors drive the carriage to move forward and backward, and up and down, respectively. The test bench was powered by a 13.5kW electric generator, and there was a complex control system to complete power transmission and operation control.

A 225-mm-rotary radius C-type blade (IT225) was selected for its widespread application in the annual rice-wheat rotating fields managed in East China regions. The blades are fixed on the rotary tiller, and move with the movable carriage (Fig. 2). The moveable carriage in the test bench was equipped with a 6.3 kW drive motor for driving the rotary blades to rotate, and the rotary speed of the rotary tiller was adjustable from 0 to 600 rpm. The tillage depth, rotation rate, and forward speed are easy to adjust through a wireless control handle.

**Residue preparation.** Before the field test, straw length, stubble height, and the amount of residue after rice harvest were observed and measured. The straw lengths were found to range from 30-150mm, and the stubble heights ranged from 50 to 200 mm. The amount of total residue was 8012 kg ha<sup>-1</sup>. In this study, we want to determine an appropriate straw length and stubble height for residue incorporating. Therefore, the straw lengths of 30, 50, 75, 100, 125, and 150 mm, and stubble height of 50, 100, 150, and 200 mm were selected for the experiments. The stem of rice residues was collected from field and chopped into specific lengths with a chip cutter, and then laid evenly under the test plots after being dyed red (for better observation) with spray paint (Fig. 3a). There are two ways of residue preparation; one is to lay the straw on the soil face after stubble removal (Fig. 3b), and the other is to cut the stubble to the required height with a pair of scissors and then lay the straw on the soil face (Fig. 3c). The amount of residue laid in the two ways was identical, which was 8012 kg ha<sup>-1</sup>, to simulate the actual field state after harvesting.

**Experimental design.** In this study, three experiments were carried out to investigate the effect of residue parameters (straw chopping length and stubble height) and rotary speed on residue burying and residue spatial dispersion. The purpose of experiment 1 was to study the effect of straw chopping length on residue incorporation by rotary tillage. The data of residue burying and residue spatial dispersion was acquired using rotary tillage with the six straw lengths. A rotary tillage operation with the rotary speed of 280 rpm and forward speed of 0.5 m s<sup>-1</sup> was implemented in the experiment.

The purpose of experiment 2 was to explore the effect of stubble height on residue burying and residue spatial dispersion using the four straw mixtures. Residue mixture 1 (M1) consisted of 50 mm high stubble and 50 mm long chopping straw. Residue mixture 2 (M2) consisted of 100 mm high stubble and 50 mm long chopping straw. Residue mixture 3 (M3) included 150 mm high stubble and 50 mm long chopping straw and residue mixture 4 (M4) comprised 200 mm high stubble and 50 mm long chopping straw. Each mixture had 8012 kg ha<sup>-1</sup> of residue cover, and the operation parameters were the same as in experiment 1.

The purpose of experiment 3 was to investigate the effect of rotary speed on residue burying and residue spatial dispersion. The straw length of 50 mm, forward speed of 0.5 m s<sup>-1</sup>, and three rotary speeds of 240, 280, and 320 rpm were selected in this experiment. The tillage depth was 100 mm in all three tests, and each test was repeated three times. There were 39 field plots in three experiments, and each 2 m long and 0.5 m wide.

**Measurements.** *Residue burying.* The burying of residue is one of the important indexes to evaluate the quality of residue incorporation. The higher burying rate of residue implies a better quality of residue incorporation. The burying rate of residue was calculated using Eqs. (1) proposed Fang et al.<sup>19</sup>

$$N = \frac{m_q - m_h}{m_q} \times 100\% \quad (1)$$

Where  $m_q$  (kg) is the total weight of residue before tillage and  $m_h$  (kg) is the total weight of residue after tillage.

*Residue dispersion.* A) Sample collection and measurement. In the process, samples of soil-residue mixture were collected from the surface after rotary tillage, and the residue spatial coordinates were measured. Considering the average depth of the soil layer after tillage was about 150 mm, we made many steel sampling frames with dimensions of 300×300×150 mm. For collecting our sample, a sampling frame was placed in the middle of the tilled area and the knocked it utterly into the soil layer with a steel hammer. Finally, the sample of soil-residue mixture was taken out after a steel tray was embedded to the root of the sampling frame (Fig. 4a). After all samples were collected in this way, they were taken back to the laboratory for further measurement and analysis.

A residue spatial coordinate digitizer was developed to measure the residue spatial position and obtain the data of residue dispersion uniformity. It is mainly composed of four parts: an arc scale, a horizontal scale, a vertical scale and a pillar (Fig. 4b). The horizontal scale and vertical scale are fixed on the pillar, and above them is the arc scale. In the horizontal direction, the arc rotation arc and horizontal distance can be measured by rotating the horizontal scale along the pillar and moves along the slider. In the vertical direction, we also can obtain the vertical distance according to the slider position in the vertical scale. Because there was less residue bending after tillage since experimental materials were the main stalk of paddy residue with high moisture content and short length, so it was reasonable to use the coordinates of the residue head and tail instead of the position of the whole residue. Therefore, the digitizer is reliable to ascertain the location of the residue by measuring the coordinates of residue.

B) Analysis of residue dispersion. Firstly, the residue absolute coordinates were saved in the \*. IBL format (a coordinate point file format) and inputted into the 3D software Pro/Engineer 5.0 (PTC, America) to create the 3D model of residue dispersion automatically (Fig. 5a). Secondly, a multi-scale segmentation of the 3D model of residue spatial dispersion was conducted to analyze the uniformity of residue dispersion. The model was not only divided with a 50 mm length scale in the depth direction (Fig. 5b), but also segmented with a 50× 50×50 mm cube scale in the overall direction (Fig. 5c). Finally, the total length of residue in each segment area was calculated by the 3D software.

The uniformity of residue dispersion could be accurately analyzed by the coefficient of variation of residue total length ( $C_V$ ) in each segment area, and the smaller the  $C_V$ , the more uniform the residue dispersion, which implies the better quality of residue dispersion. The calculation of  $C_V$  was shown in Eqs. (2)

$$C_V = \frac{S_D}{A_r} \times 100\% \quad (2)$$

Where  $S_D$  is the standard deviation of residue total length and  $A_r$  is the average value of residue total length.

The 3D model of residue spatial dispersion was segmented into three layers on average in the depth direction, namely the upper layer (UL), the middle layer (ML), and the lower layer (LL). Total length of all residues in each layer under different treatments was calculated, and then the proportion of residue in each layer was analyzed to evaluate the uniformity of residue spatial dispersion in the depth direction. A higher proportion of straw in ML and LL implies better residue dispersion in the depth direction. The 3D model of residue spatial dispersion was further divided into 108 small cubes in the overall direction, where the size of each cube was 50× 50×50 mm. The  $C_V$  in each cube was analyzed to evaluate the uniformity of residue dispersion. It could easily be judged that the better quality of residue dispersion in the overall direction was that the smaller  $C_V$  in each cube.

**Data analysis.** The data were subjected to statistical analysis by one way factorial analysis of variance (ANOVA) using IBM-SPSS Statistics 22 software (IBM Corp., Armonk, N.Y., 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.

## Results

**Effect of straw length on residue burying and dispersion.** *Residue burying.* According to the experimental results, residue burying rate decreased with straw length, and showed a nonlinear logarithmic relation (Fig.6). The results showed that most of the residue could be buried in the soil by rotary tillage in the length range of straw from 30 to 150 mm. However, there were great differences in residue burying rate with different straw chopping lengths after rotary tillage. Under the straw length of 30 mm, there was a good burying effect, and the burying rate was as high as 94.5%. Yet, there was an unfavorable burying effect under 125 and 150 mm, and the burying rate was only 78.2% and 76.2%, respectively. Therefore, short residue is more conducive to residue incorporation than long residue.

*Residue dispersion.* The total length and proportion of residue in each layer at different straw chopping lengths are listed in Table 2. The results indicated that the longer the residues were, the more difficult it was to incorporate into the soil by rotary tillage. The proportion of residue in the ML and LL decreased gradually with the increase of straw chopping length. The proportions of residue in the UL under the straw length of 125 and 150 mm were 42.3% and 47.3%, respectively. Almost half of the residue was distributed in the sowing depth layer with 0-50mm, which potentially would cause straw overhead wheat seeds (straw hair pinning) and blocking of the sowing tools (furrow openers, coulters, etc.). So, these two treatments are not suitable for high quality seeding operations. In contrast, the uniformity of residue spatial dispersion under the straw length of 30 and 50 mm were better in all three layers, and the proportion of residue in the LL were 34.7% and 32.4%, respectively, which was conducive to residue decomposition and wheat sowing. In addition, the proportion of residue under the straw length of 125 and 50 mm in the LL were only 17.5% and 11.9%, respectively, and most of the residue was distributed in the UL and ML. This finding indicates that the long residue was not easy to be incorporated in the BL and the main reason was that long residue had a small moving distance in the depth direction after rotary tillage.

**Table 2.** Total length and proportion of residue in each layer at different straw chopping lengths.

Layer, mm	The total length of residue, mm						The proportion of residue, mm					
	30	50	75	100	125	150	30	50	75	100	125	150
UL(0-50)	1081	1274	1501	1575	1650	1815	23.2c	28.3c	35.2a	38.1a	42.3a	47.3a
ML(0-100)	1965	1764	1580	1542	1568	1568	42.1a	39.3a	37.1a	37.3a	40.2a	40.8b
LL(0-150)	1617	1458	1181	1017	683	456	34.7b	32.4b	27.7b	24.6b	17.5b	11.9c

Means for each factor in the same column followed by the same letter are not significantly different at  $P > 0.05$  as tested by LSD.

The quality of residue dispersion could be evaluated comprehensively through further divide the 3D model of residue into small cubes in the overall direction. The quality of residue dispersion in the overall direction under different straw lengths was as shown in Fig.7. The results indicated that with the increase of straw length, the  $C_V$  in each cube was increased gradually. The  $C_V$  in each cube under the straw length of 30 and 50 mm were lower, 72.9% and 73.1%, respectively. In contrast, the  $C_V$  in each cube under the straw length of 150 mm was the highest, 92.6%. According to these experimental results, it was suggested that the long residue should be chopped into the short residue as far as possible by the harvester while considering low energy consumption, which could improve the spatial dispersion quality of residue after rotary tillage.

**Effect of stubble height on residue burying and dispersion.** *Residue burying.* Fig. 8 shows the relation of burying rate and four residue mixtures. The height of stubble had a significant impact on the residue burying. With the increase of stubble height, the residue burying rate decreased gradually with the same straw chopping length. Under the stubble height of 50 and 100 mm, there was a high burying effect, and the burying rate in M1 and M2 were 90.2% and 86.2%, respectively. However, there was an unfavourable burying effect under the stubble height of 150 and 200 mm, and the burying rate in M3 and M4 were only 80.7% and 78.2%, respectively. For four residue mixtures used under rotary tillage condition, the stubble height of 100 mm was a dividing point. When stubble height was less than 100 mm, there was a high burying rate for residue incorporating into the soil by rotary tillage, and suitable for high quality seeding operations. It is recommended to reduce the stubble height during harvester operation in order to obtain a high burying rate after straw incorporation by rotary tillage.

*Residue dispersion.* Table 3 compares the total length and proportion of residue in each layer at four residue mixtures. As discussed in previous sections, when stubble was higher than 100 mm, it was difficult to incorporate the residue into the soil by rotary tillage. It appears that the proportion of residue in the ML and LL decrease with increasing stubble height. The percentage of residue in the UL under the M3 and M4 were 40.4% and 44.2%, respectively. More than 40% of the residue was dispersed in the sowing depth layer with 0-50 mm, which was not conducive to the subsequent sowing operation. However, under the M1 and M2, there were more residues could be incorporated into the deep soil, and the proportion of residue in the ML and LL were 71.2% and 66.4%, respectively. This finding indicates that high stubble was not easy to be incorporated in the soil, and also affect the burying of chopping straw. It was suggested that the stubble height should be kept as low as possible during harvesting, which could improve the quality of residue incorporation after rotary tillage.

**Table 3.** Total length and proportion of residue in each layer at different residue mixtures.

Layer, mm	The total length of residue, mm				The proportion of residue, mm			
	M1	M2	M3	M4	M1	M2	M3	M4
UL (0-50)	1302	1502	1663	1813	28.8 c	33.6 b	40.4 a	44.2 a
ML (50-100)	1721	1717	1495	1589	38.1 a	38.4 a	36.3 a	38.7 b
LL(100-150)	1494	1251	958	704	33.1 b	28.0 c	23.3 b	17.1 c

Means for each factor in the same column followed by the same letter are not significantly different at  $P > 0.05$  as tested by LSD.

In order to further accurately quantify the dispersion of residue incorporated into the soil, the 3D model of residue was divided into small cubes in the overall direction. Fig. 9 shows the quality of residue dispersion in the overall direction under different residue mixtures. The results indicated that the  $C_V$  in each cube was increased with the increasing stubble height. The  $C_V$  in each cube under the M1 and M2 were lower, 73.2% and 75.5%, respectively. But when the stubble height was 150 and 200 mm, there was an unfavourable effect on the uniformity of residue dispersion. The  $C_V$  in each cube under the M4 was the highest, 87.1%. It was suggested that the stubble height should be kept lower than 100 mm, and the straw length should not be longer than 50 mm. Under this condition, people could obtain a relatively high quality of residue incorporation after rotary tillage.

**Effect of rotary speed on residue burying and dispersion.** *Residue burying.* The straw length of 50 mm was selected to explore the effect of rotary speed on residue burying, and results of burying rate at the three rotary speeds are shown in Fig.10 a. The results indicated that higher rotary speed buried residue than the lower one. For the rotary speed of 320 rpm, there was about 92.3% of residue incorporated into the soil after tillage. At the rotary speed of 240 rpm, the percent of burying residue was decreased to 86.7%. The main reason is that under high-speed rotary tillage, on the one hand, the straw can easily to move downward into the soil y the action of rotary blades, on the other hand, the resulting small clod is easier to bury residue.

**Figure 10.** Percent of burying rate and  $C_V$  after tillage at the rotary speeds of 240, 280, and 320 rpm. (a) burying rate at three rotary speeds, (b)  $C_V$  at three rotary speeds. Means for each factor followed by the same letter are not significantly different at  $P > 0.05$  as tested by LSD; the error bars are standard deviations of means.

*Residue dispersion.* Total length and proportion of residue in each layer at different rotary speeds are listed in Table 4. The results indicated that proportion of residue in the ML and LL increased with the increasing rotary speed. The percent of residue in the UL at the rotary speed of 320 rpm was the lowest, 25.7%, which was conducive to the subsequent sowing operation. In contrast, for the rotary speed of 240 rpm, the proportion of residue in the UL increased 6.5%, and was more likely to cause residue overhead wheat seeds. However, with the increase of rotary speed, the energy consumption of rotary tillage will also increase, so a balance between rotary speed and residue incorporation needs to be found.

**Tab 4 - Total length and proportion of residue in each layer at different rotary speeds.**

Layer, mm	The total length of residue, mm			The proportion of residue, mm		
	240	280	320	240	280	320
UL (0-50)	1413	1301	1204	32.2 b	28.8 c	25.7 c
ML (50-100)	1617	1723	1839	36.8 a	38.1 a	39.3 a
LL (100-150)	1362	1495	1641	31.0 b	33.1 b	35.0 b

Means for each factor in the same column followed by the same letter are not significantly different at  $P > 0.05$  as tested by LSD.

The quality of residue dispersion in the overall direction at different rotary speeds was shown in Fig. 10b. The results showed that the  $C_V$  in each cube was decreased slightly with the increasing rotary speeds. The  $C_V$  value in each cube at the rotary speed of 240 rpm was the biggest, 76.4%. For the rotary speed of 280 and 320 rpm, The  $C_V$  values were lower, 73.2%, and 72.8%, respectively. There is an increased trend in the quality of residue dispersion from the rotary speed of 240 to 280 rpm, but there are no significant trend changes from the rotary speed of 280 to 320 rpm. The main reason is that the rotary blades could mix residue and soil well when the rotary speed is larger than 280 rpm.

## Discussion

Residue burying and dispersion are affected by many factors, such as tillage tools, stubble height, residue length, and tillage operation parameters. Soil bin studies carried out by previous research workers showed that shorter residue had a positive effect on increase straw burying rate and improve residue dispersion quality<sup>25,30</sup>, and the field experiments carried out in our study also obtained the similar results. In addition, it was also found that slower operation speed will decrease residue incorporation, which is similar to Fang et al.<sup>19</sup> How residue conditions and tillage operations impact residue incorporation was difficult to investigate through tractor field operation due to too many uncontrollable variables. Although the experimental factors are easy to control, soil bin experiments are also difficult to fully simulate the actual complex field conditions. Thus, an electric and multi-functional field testing bench was developed to perform residue incorporation characteristics of rotary tillage. Compared with soil bin tests, experiments conducting in the field will be more accurate to study the experimental factors affecting residue burying and dispersion. In this study, a new field test approach for promoting exploration in complex field conditions was introduced, and the first data of straw length, stubble height, and rotary speed effect on residue burying and dispersion was provided. These data would be very important for establishing mathematical model between tillage operations and residue incorporation, so as to provide guidance for residue management and the design of tillage machinery.

## Conclusion

Field experiments were conducted to study the effects of straw length, stubble height, and rotary speed on residue burying and dispersion. A field testing bench was developed to perform residue incorporation characteristics of rotary tillage at different straw lengths, stubble heights, and rotary speeds. Conclusions drawn were as follows:

- (i) Straw length and stubble height had a significant effect on residue burying and dispersion. The burying rate and spatial dispersion quality of residue decreased with the increase of straw length and stubble height. The residue incorporation quality of 30 mm straw length was better than other treatments, and the burying rate and  $C_V$  were 94.5%, and 72.9%, respectively. There was an excellent residue incorporation quality at 50 mm stubble height, and the burying rate and  $C_V$  were 90.2% and 73.2%, respectively.

(ii) Lower rotary speed buried less residues and dispersed worse uniformity than the higher one. Compared to the value at 240 rpm, the percent of burying residue could be increased by 5.6% at 320 rpm.

(iii) Straw length, stubble height, and rotary speed all impact residue incorporation quality. It is suggested that farmers determine the straw length and stubble height at the stage of harvest according to the burying rate and dispersion uniformity of residue. Higher speed of rotary tillage (320 rpm) is recommended as higher speed can increase burying and dispersion quality of residue.

## Declarations

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## Author contributions

Conceptualization, G.X.; data acquisition and analysis, G.X., Y.X. and Q.D.; funding acquisition, Y.H. and Q.D.; writing—original draft, G.X. and Y.X.; writing—review and editing, G.X. Q.D. and Y.H. . All authors have read and agreed to the published version of the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

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## Figures

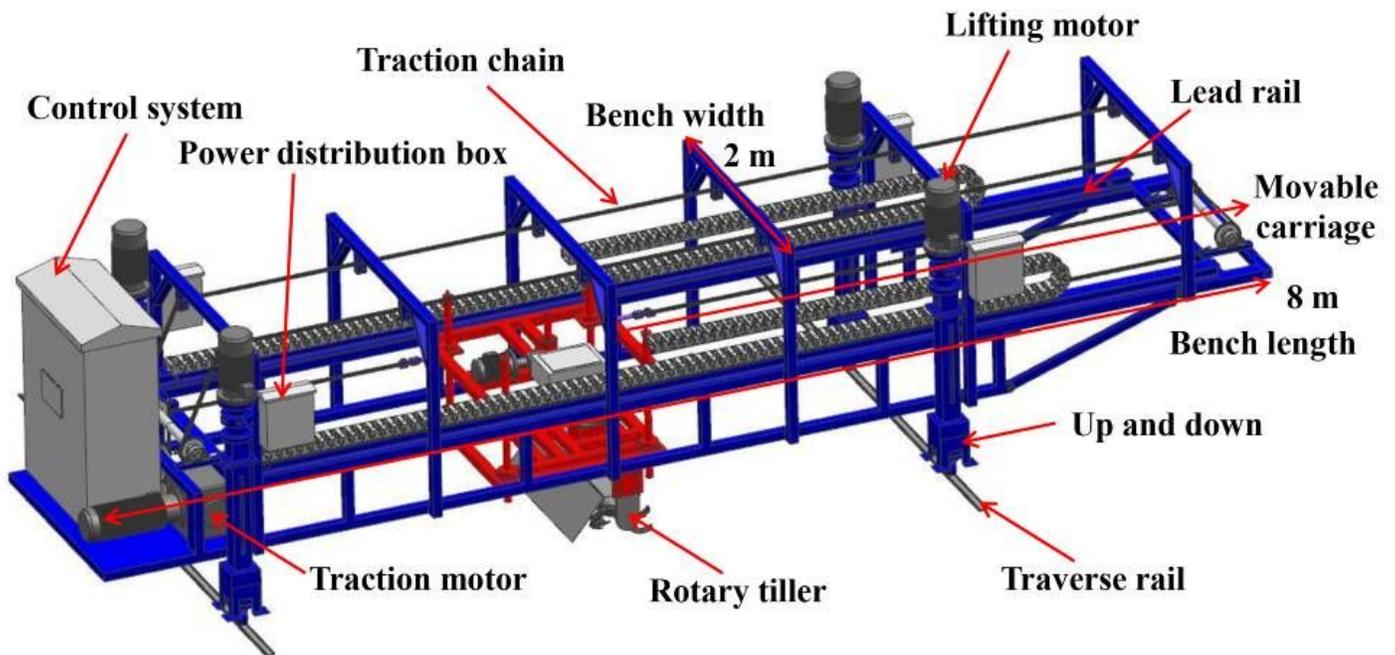


Figure 1

Schematic structure of field testing bench

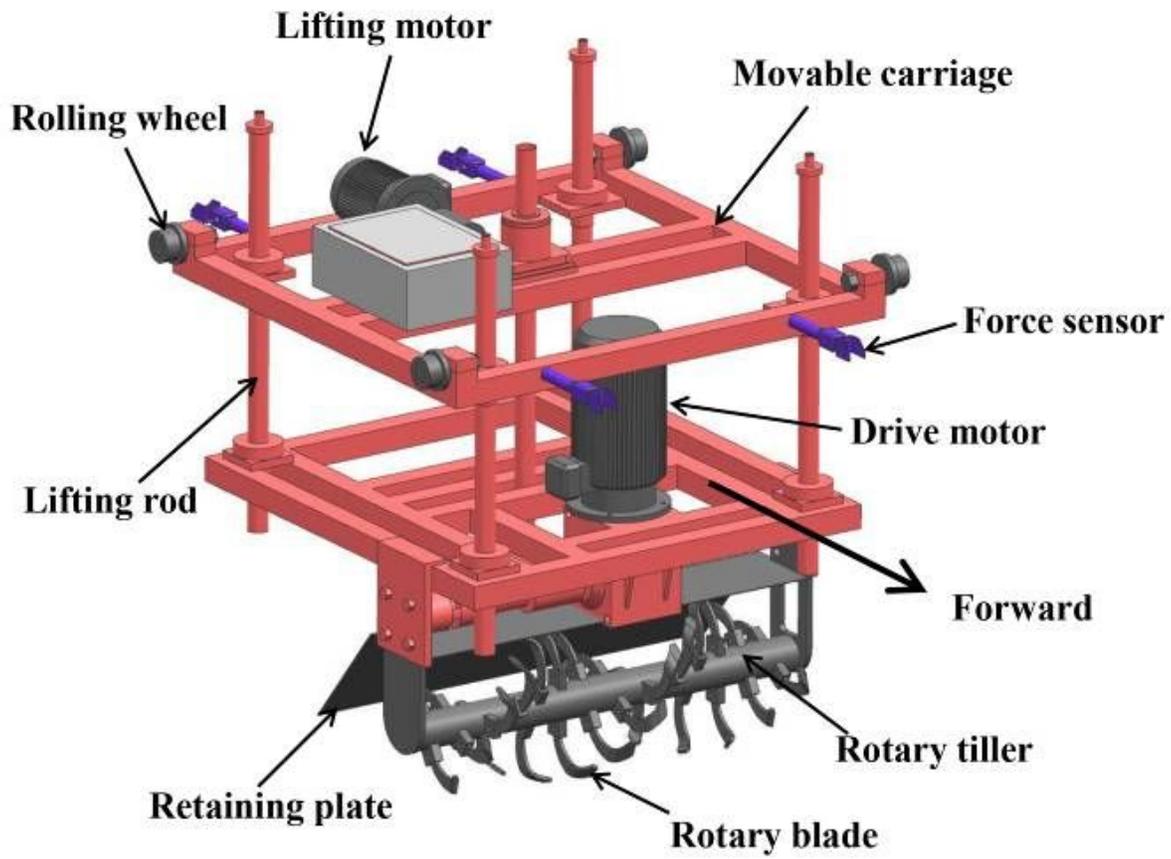
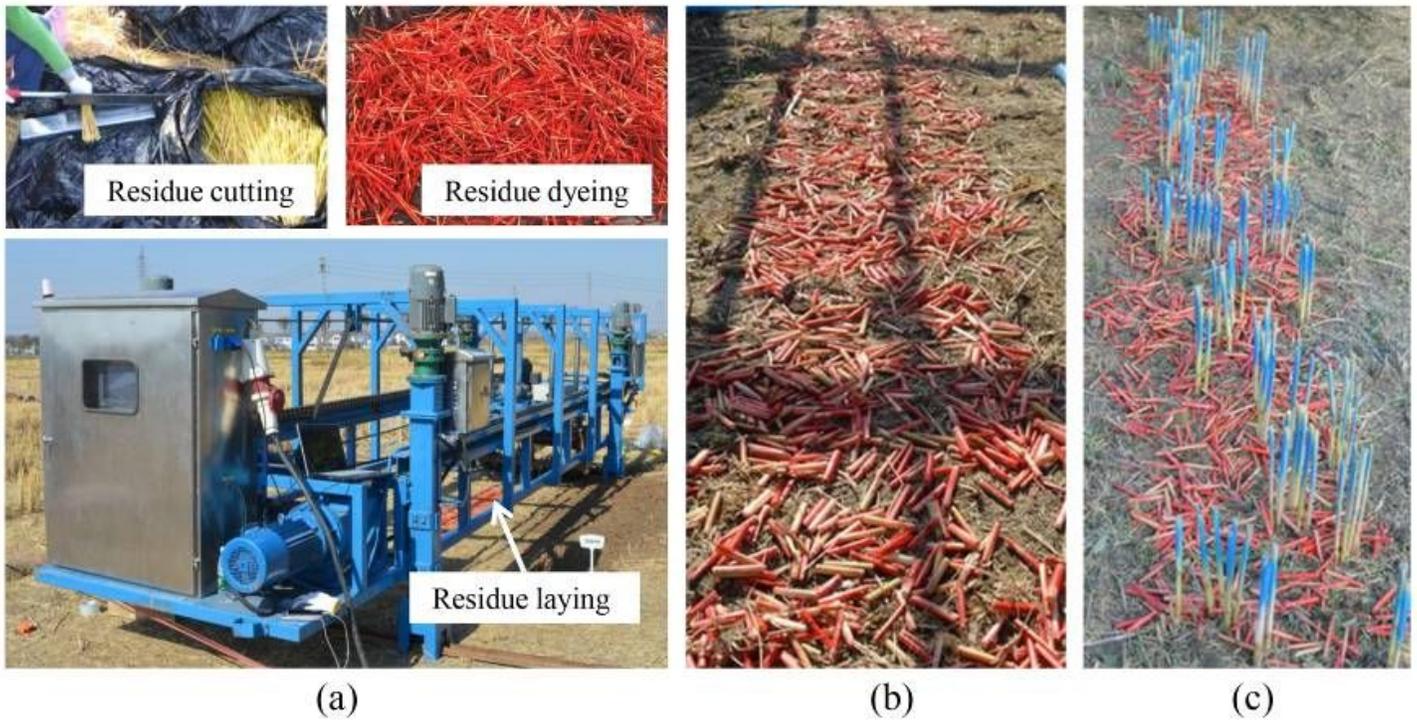


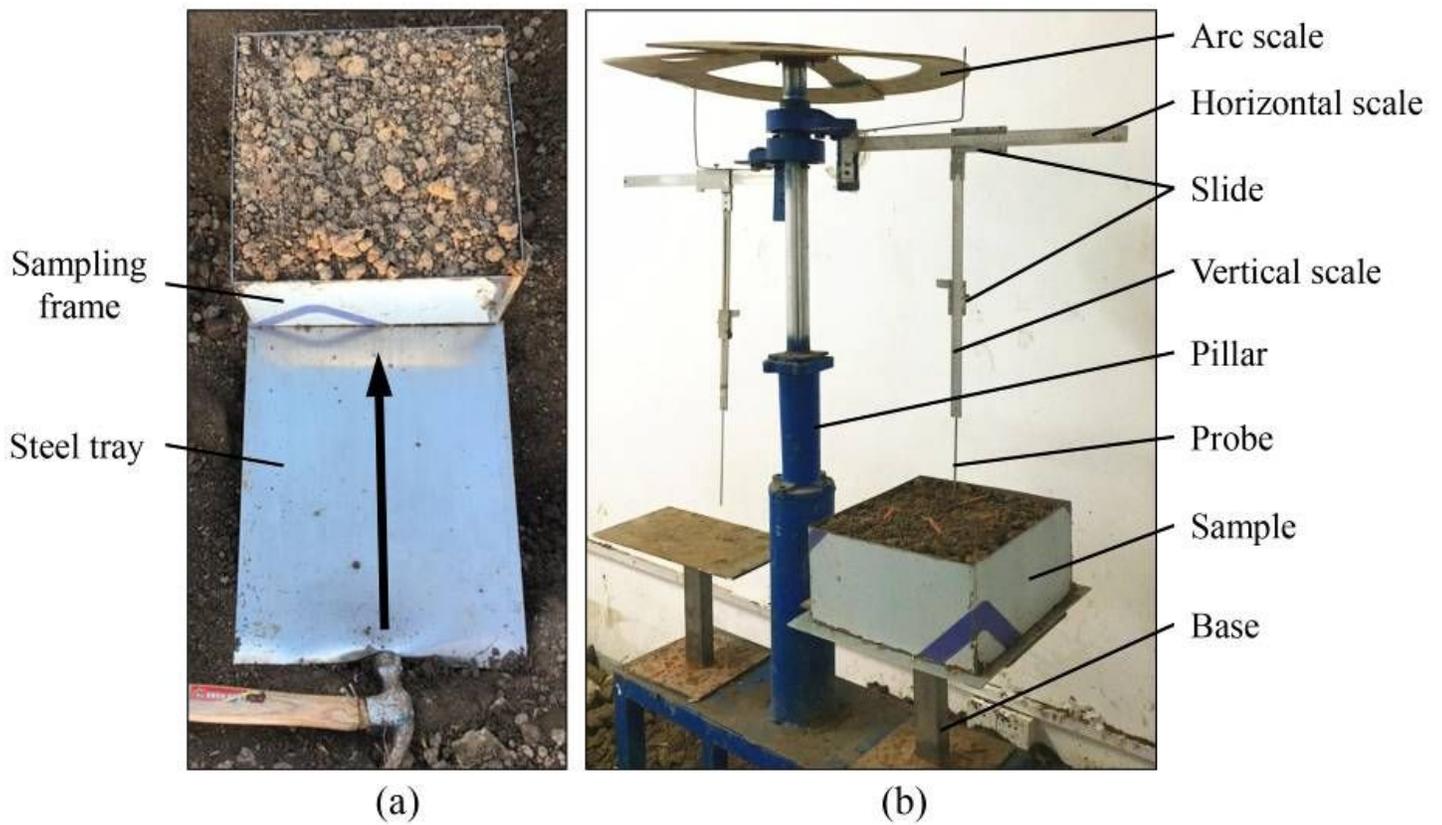
Figure 2

Schematic structure of movable carriage and rotary tiller.



**Figure 3**

Residue preparation. (a) Residue treatment, (b) Straw lay on the soil face. (b) Straw and stubble lay on the soil face.



**Figure 4**

Sample collection and measurement. (a) Sample collection of the soil-residue mixture, (b) Measurement of residue spatial coordinates.

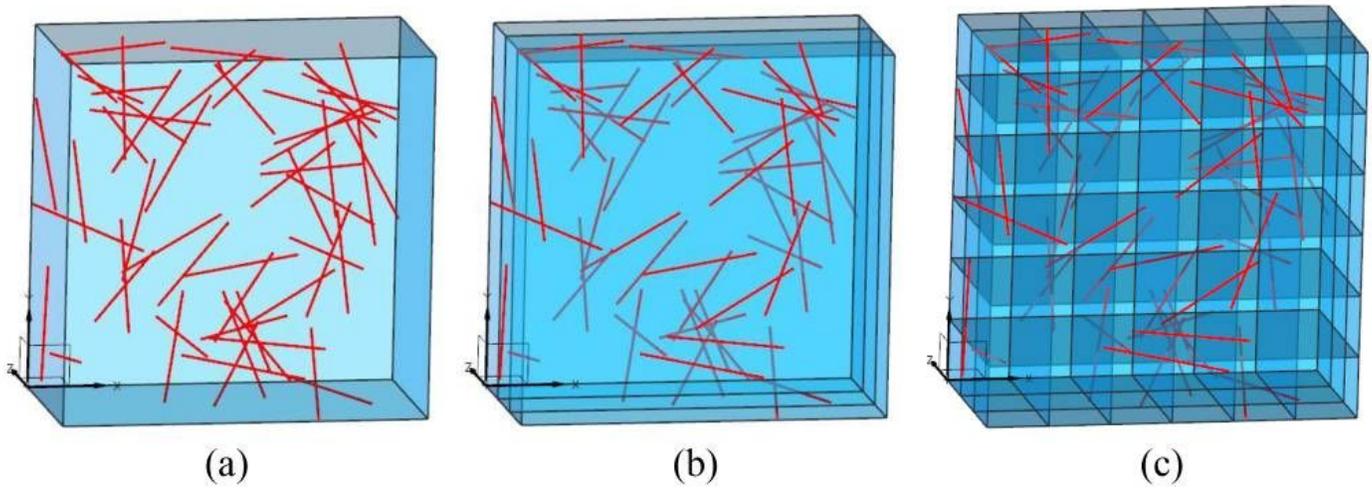


Figure 5

Reconstruction and segmentation of residue dispersion model in 3D software. (a) Residue dispersion model, (b) Model segmentation in the depth direction, (c) Model segmentation in the overall direction.

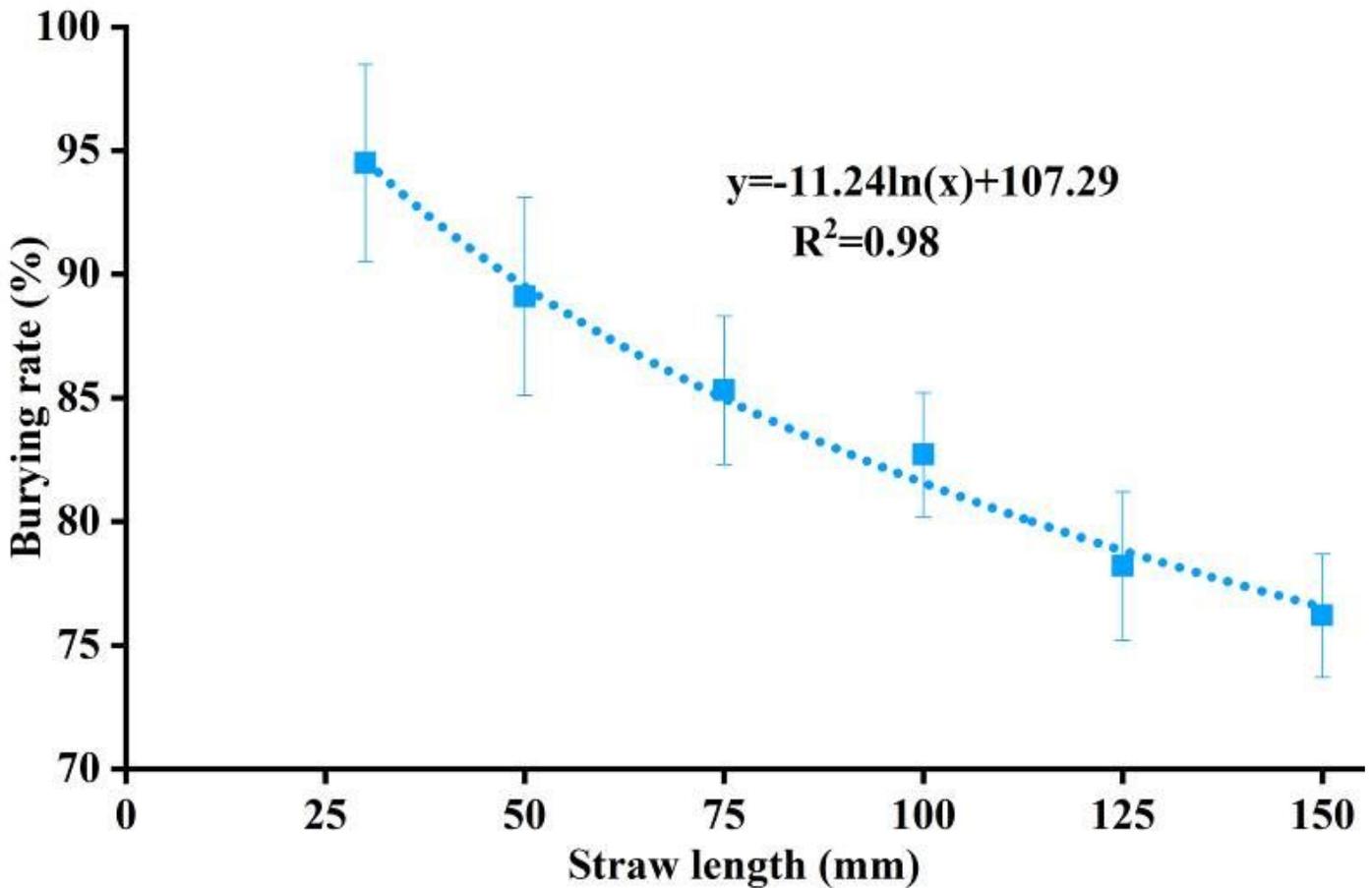


Figure 6

Burying rate at different straw lengths.

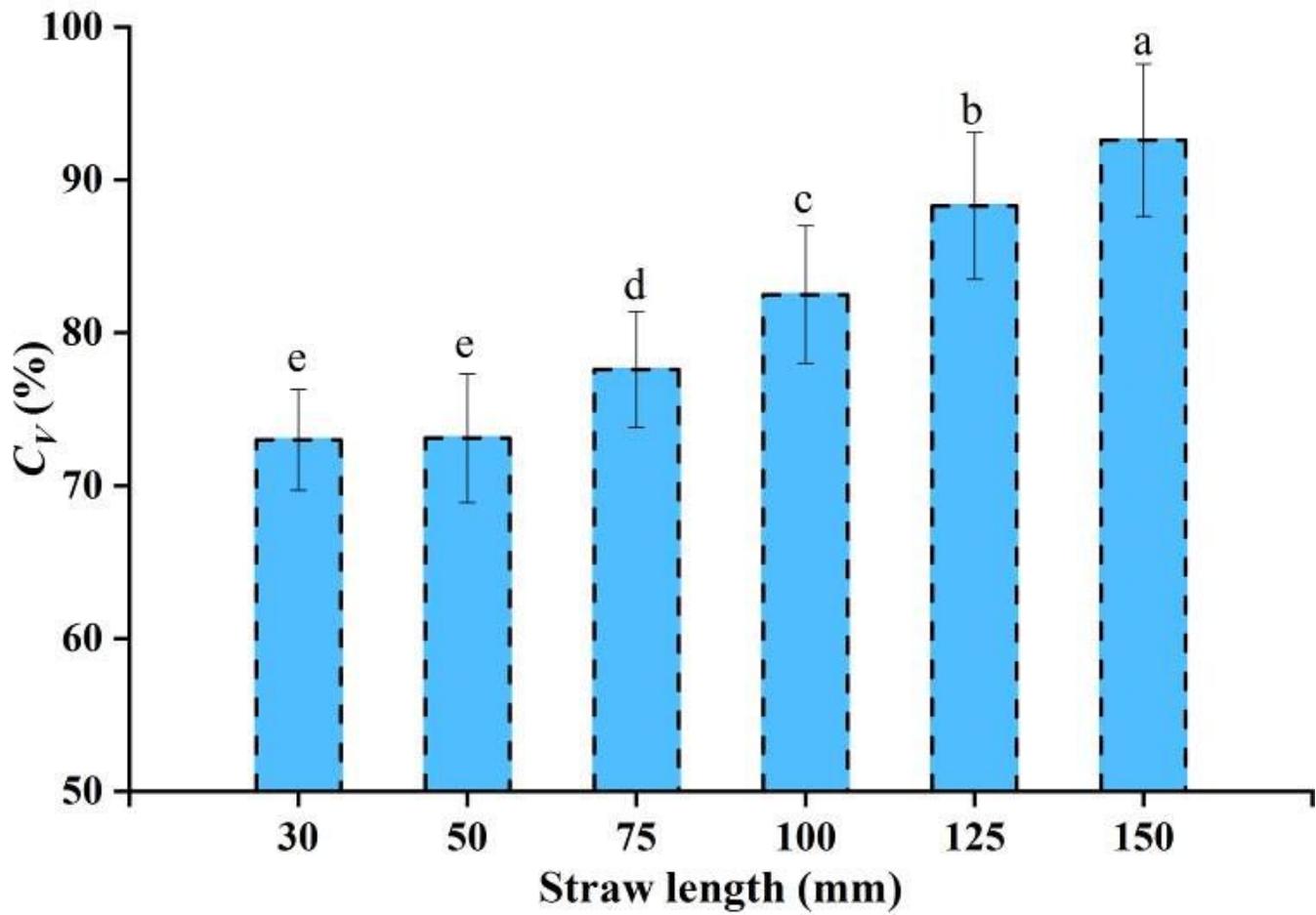


Figure 7

Residue dispersion quality in the overall direction under different straw lengths. Means for each factor followed by the same letter are not significantly different at  $P > 0.05$  as tested by LSD; the error bars are standard deviations of means.

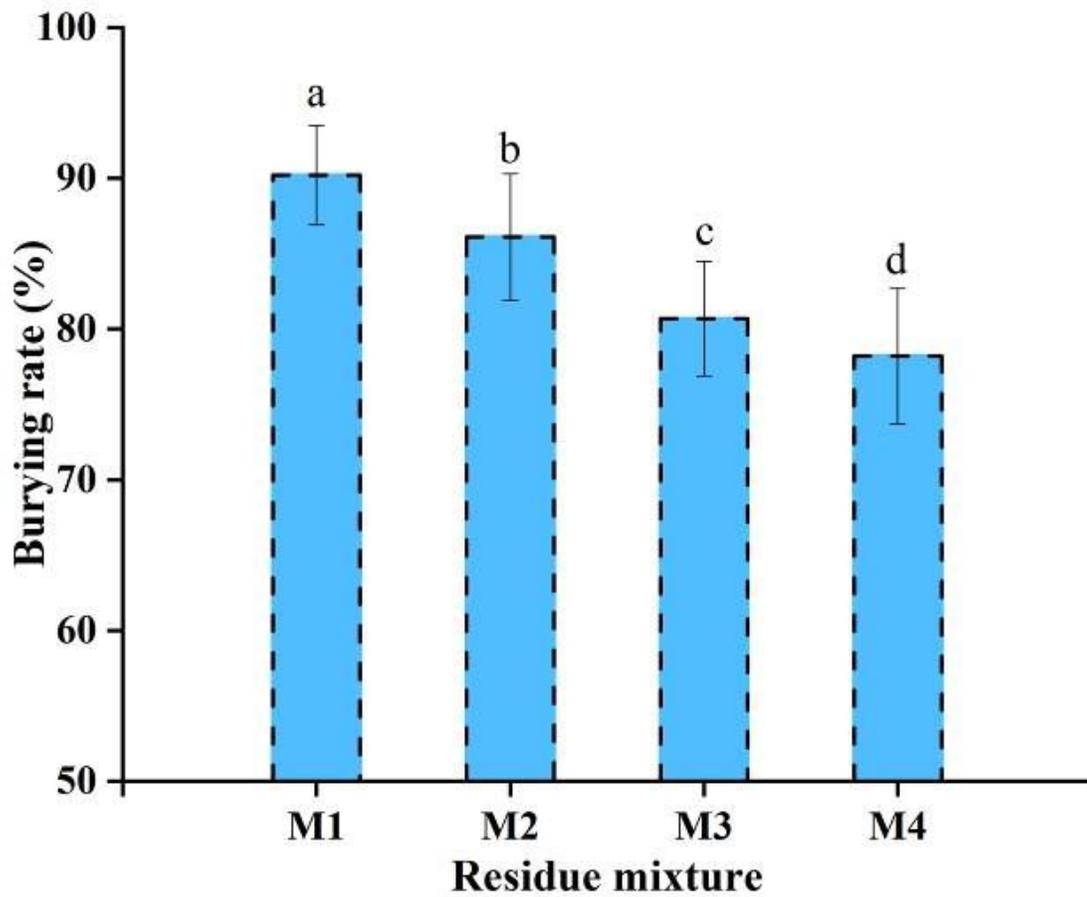


Figure 8

Relation of residue mixture and burying rate. Means for each factor followed by the same letter are not significantly different at  $P > 0.05$  as tested by LSD; the error bars are standard deviations of means.

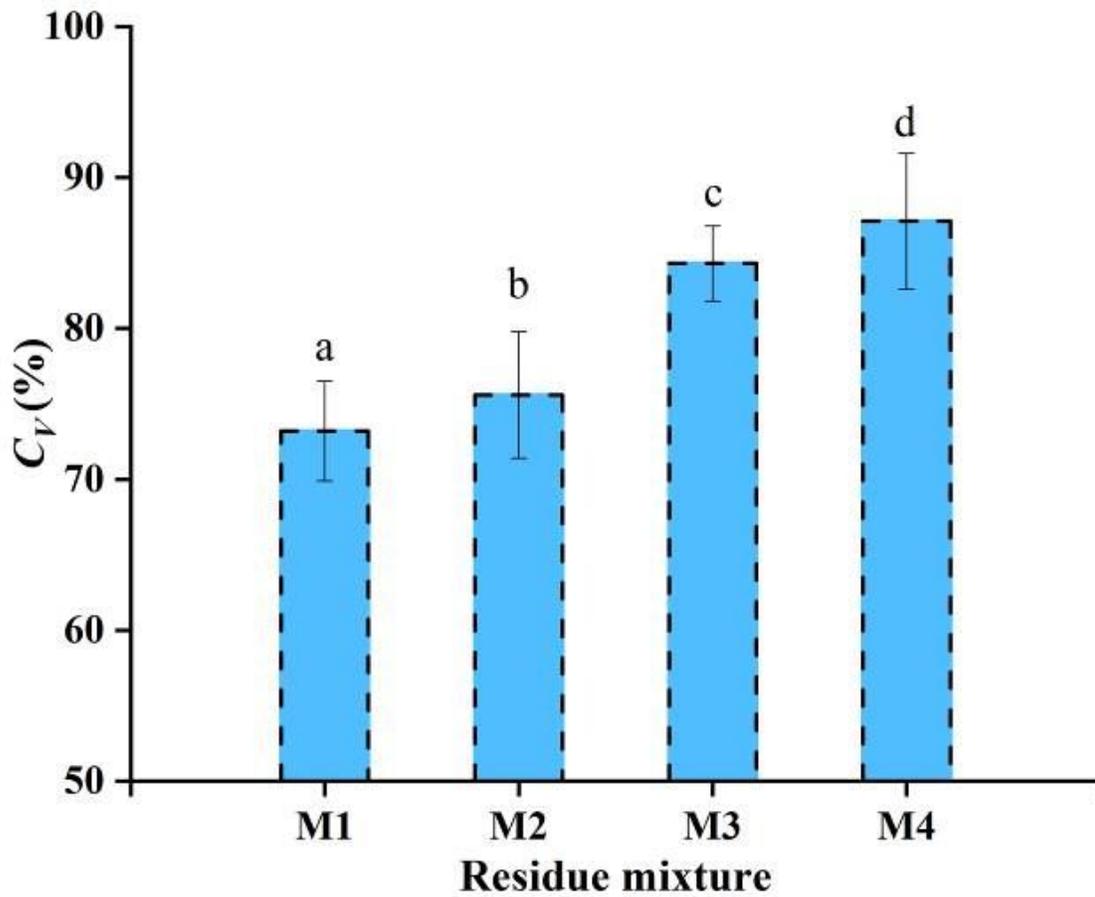
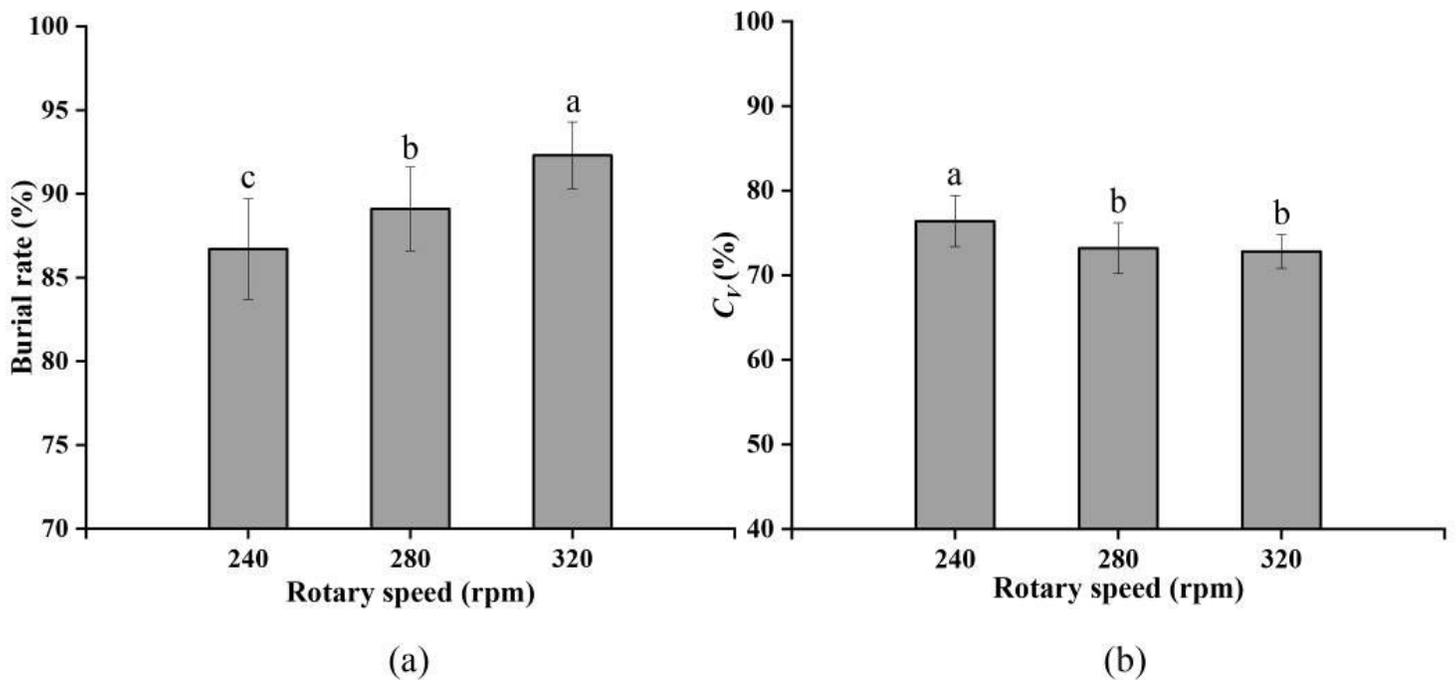


Figure 9

Residue dispersion quality in the overall direction under different residue mixtures. Means for each factor followed by the same letter are not significantly different at  $P > 0.05$  as tested by LSD; the error bars are standard deviations of means.



## Figure 10

Percent of burying rate and CV after tillage at the rotary speeds of 240, 280, and 320 rpm. (a) burying rate at three rotary speeds, (b) CV at three rotary speeds. Means for each factor followed by the same letter are not significantly different at  $P > 0.05$  as tested by LSD; the error bars are standard deviations of means.