Effect of soil surface roughness on emergence rate and yield of mechanized direct-seeded rapeseed based on 3D laser scanning

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Abstract: The quality of seedbed after sowing such as soil surface roughness is one of the key factors affecting the seedling emergence of rapeseed, which ultimately affected crop yield. However, the effect of soil surface roughness on seedling emergence and yield of rapeseed is still unclear. In this study, field experiments at the experimental site of Jianli and Shayang were carried out. Three treatments were designed: relative slow (M1), medium (M2), and fast (M3) forward speed of the unit. Soil surface roughness measured by a 3D laser scanner, seed quantity of the seeder, emergence rate and yield of rapeseed were determined to investigate the soil surface roughness effect on emergence rate and yield of rapeseed. The results showed that as the forward speed of the unit increased, the compartment surface became rougher. Compared with the M1 and M2 treatments, soil surface roughness under the M3 treatment increased by 36.5% and 9.8%, respectively. The actual seed quantity of the seeder under different treatments ranged from 3 806.56 to 4 158.18 g/hm^2. The average error rate of the actual and theoretical seed quantity was less than 5%, which met the operational quality requirements for seeding rapeseed crops. As the forward speed of the unit increased, the actual seed quantity of the seeder gradually increased while the emergence rate and yield of rapeseed decreased. The seed quantity under the M3 treatment increased by 6.9% and 4.7%, while the emergence rate of rapeseed decreased by 3.3% and 2.0%, and the yield decreased by 23.2% and 13.1%, compared with the M1 and M2 treatments, respectively. Correlation analysis indicated that emergence rate and yield of rapeseed were negatively influenced by soil surface roughness. Considering rapeseed emergence rate, seed yield, and economic benefits, the M1 treatment was recommended. But considering the factor that the M1 treatment may reduce the unit operation efficiency, and thus resulting in lower cost of production, M2 could be recommended in actual farming. The results of this study laid a theoretical foundation for analyzing the relationship between the seedbed surface quality and seedling emergence and yield.

Keywords: mechanized direct-seeder, soil surface roughness, rapeseed, seed emergence rate, yield
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1 Introduction

Rapeseed (*Brassica napus* L.), the most important oil crop, has omnifarious value of feed, green manure, vegetables, energy, tourism, and nectar source. Over the past five years, the annual global rapeseed planting area has averaged 34.80 million hm^2[1]. China has accounted for 19.2% of the global rapeseed production; however, its planting area is somewhat decreasing[1]. Notably, more than 90% of Chinese production is winter rapeseed, which is primarily located in the Yangtze River Basin[2]. Therefore, stabilizing rapeseed planting and increasing rapeseed output in this region is important for ensuring edible oil plants and promoting national economic development.

Mechanized direct-seeding is an effective method of cultivating rapeseed that can improve production efficiency, reduce costs, increase profits, and can promote rapeseed planting[3,4]. Influenced by soil texture and soil moisture conditions in the Yangtze River Basin, the quality of the seedbed surface after mechanized direct-seeding is a key factor affecting rapeseed seedling emergence, which ultimately affects the construction of high-yield and high-efficiency rapeseed population and yield formation[5]. As previously reported, rapeseed is a small shallow-seeded crop[6]. The sowing depth should be controlled within 20 mm when performing mechanized seeding in the middle and lower reaches of the Yangtze River[7]. A depth greater than 30 mm does not favor seedling establishment and final yield[6]. Therefore, proper seedbed arrangement and sowing depth control are beneficial for producing uniform rapeseed emergence after sowing, improving the subsequent seedling rate, and promoting the balanced development of rapeseed population.

Soil surface roughness is widely used to assess the hydrological and erosive behavior of soils[8,9], and few researchers have used this parameter to quantitatively evaluate seedbed surface quality[7]. Nevertheless, the traditional contact measurement method is still used to measure seedbed surface roughness[10]. This measurement data cannot accurately reflect true surface conditions due to its insufficient sample size. With the development of surface observation technology, non-contact surface elevation measurement methods such as laser measurement[7] and photogrammetry[11], which

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can achieve high-precision surface height measurement without disturbing the original surface, have been widely applied in agricultural farming. For instance, Eitel et al.[12] evaluated the feasibility of applying three-dimensional laser scanning technology to study the influence of surface roughness on runoff erosion of grassland river channels. Li et al.[13] used a three-dimensional laser scanning test and a cellular automata soil erosion model to explore the soil surface roughness under different slope gradients expressed as slope erosion. Liu et al.[7] acquired three-dimensional soil surface roughness data in mechanized direct-seeded rapeseed farmland using a measuring device based on laser radar scanning technology. Zheng et al.[14] estimated soil surface roughness of bare soils by combining optical and radar data.

To date, no data have been published analyzing the effect of soil surface roughness on rapeseed emergence rate and yield. Therefore, the qualitative and quantitative correlation between these three parameters is still unclear. It is hypothesized that the worse the seedbed surface quality, the lower the seedling emergence rate and crop yield. In the present study, changes in soil surface roughness, emergence rate and yield of winter rapeseed, coupled with seed quantity of the seeder were monitored at the experimental site of Jianli and Shayang located in the Yangtze River Basin. The objectives of this work were to evaluate seedbed surface quality (expressed as soil surface roughness) under different forward speeds of the unit and to further investigate how seedbed surface quality affects the emergence rate and yield of rapeseed. The results provide a theoretical basis and technical support for improving the cultivated land surface structure and sowing quality.

2 Materials and methods

2.1 Site description

Field experiments were conducted from October 2020 to May 2021 at Jianli (29°48′47″N, 113°01′14″E) and Shayang (30°43'14"N, 112°18'3"E) in Hubei Province, central China (Figure 1). The preceding crops before the experiment at Jianli and Shayang were soybean and rice, respectively. The experimental site of Jianli and Shayang was characterized by a subtropical monsoon climate with an average annual precipitation of 1226 mm and 1150 mm, and an average annual temperature of 16.3°C and 16.5°C, respectively. The top-soil (0-20 cm) was sandy loam with soil bulk density of 1.41 g/cm^3 and 1.39 g/cm^3, total N content of 1.185 g/kg and 1.365 g/kg, total P content of 0.884 g/kg and 0.844 g/kg, total K content of 4.546 g/kg and 4.572 g/kg at Jianli and Shayang, respectively.

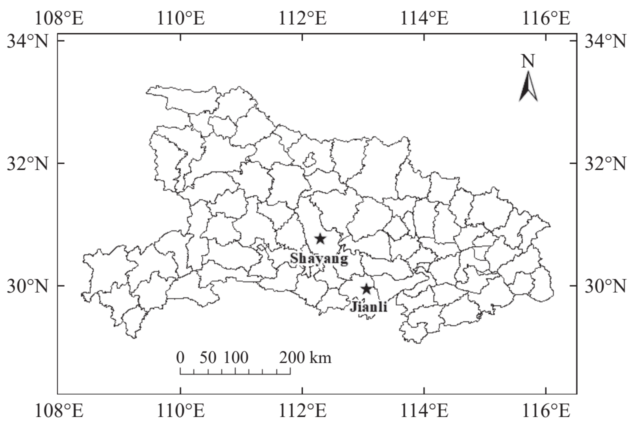


Figure 1 Location of the experimental site of Jianli and Shayang

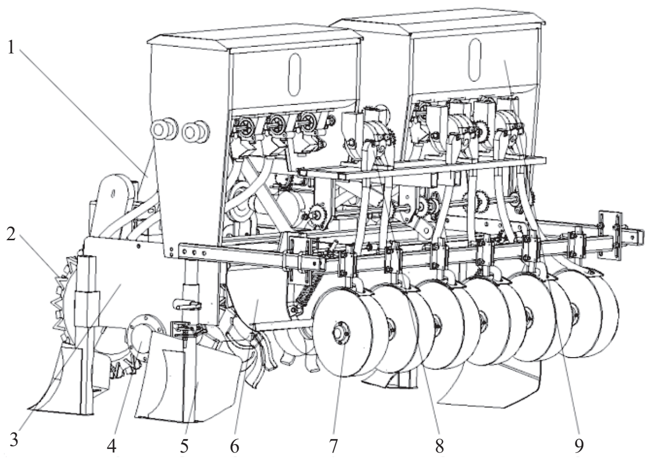
2.2 Experimental material and design

2.2.1 Experimental material

Seeds of widely cultivated rapeseed cultivar ‘Huayouza 62’, which were produced by Hubei Guoke High-tech Co., Ltd., were used in this study.

The rapeseed specific slow-release fertilizer ‘Yishizhuang’ developed by Huazhong Agricultural University and produced by Hubei Yishizhuang Agricultural Science and Technology Co., Ltd. was used. The total nutrient of fertilizer was ≥40.0%, with N, P_2O_5, K_2O, and medium trace elements (B, Ca, Mg, Zn, and S) at 25%, 7%, 8%, and 5%, respectively.

The 2BFQ-6 type combined rapeseed seeder developed by Huazhong Agricultural University was used as the test machine to complete the operations of ditching, rotary tillage, precision sowing, fertilization, and covering at one time. The direct-seeding machine (expressed as ‘seeder’ in the following section) was composed of a three-point suspension device, a profiling-driven ground wheel, a main frame, a rotary tillage device, a ditching device, a leveling plate, a double-disc opener, a seed-metering device, and a fertilizer device (Figure 2).



1. Three-point suspension device 2. Profiling-driven ground wheel 3. Main frame 4. Rotary tillage device 5. Ditching device 6. Leveling plate 7. Double-disc opener 8. Seed metering device 9. Fertilizer device

Figure 2 2BFQ-6 type combined rapeseed seeder

In the field, the seeder was connected to a tractor through a three-point suspension device, and the tractor was used to pull the seeder forward (Figure 3). Meanwhile, border ditching devices opened ditches on both sides. The profiling-driven ground wheel moved along with the unit, and the fertilizer and seed-metering devices worked through the chain drive under the action of ground friction. The fertilizer discharged from the fertilizer device was channeled to the surface through fertilizer pipes. The rotary tillage device was driven by the output shaft of the tractor through the universal coupling to realize rotary tillage ground preparation. At the same time, the rotary tillage device mixed the surface fertilizer into the seedbed, the surface of which was leveled by a leveling plate. The seed was then discharged from the seed-metering device into the seed trench drawn by the double-disc opener of the seed tube. These components were operated together to precisely seed the fields[15]. The main working parameters of the seeder are listed in Table 1.

2.2.2 Experimental design

A single-factor test was performed according to the forward speed of the unit, with three relative gradient levels: slow, medium,

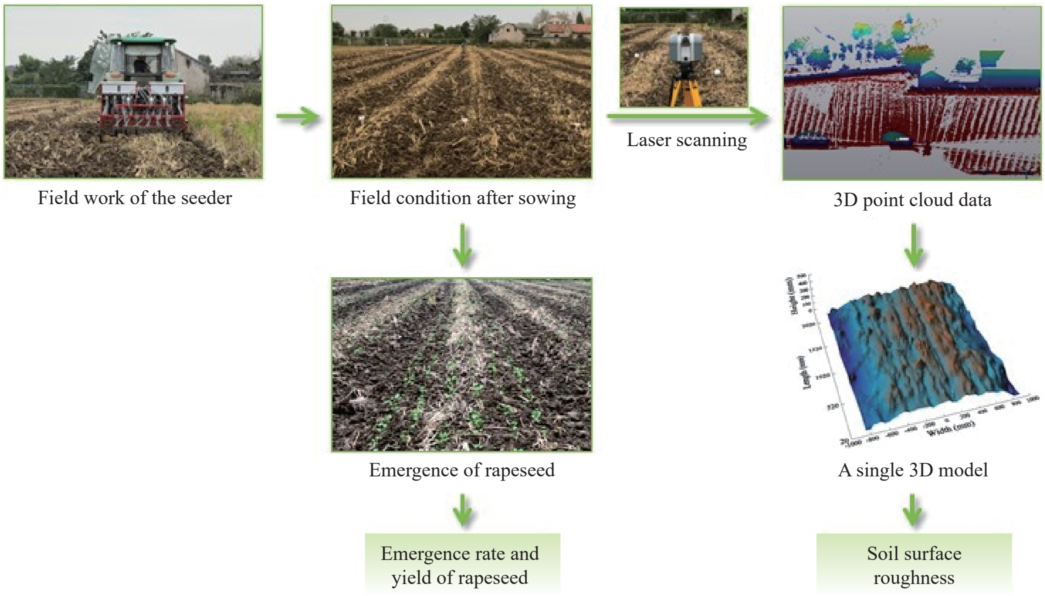


Figure 3 General procedure workflow

Table 1 Main working parameters of 2BFQ-6 type combined rapeseed seeder

Parameter	Value
Whole machine quality/kg	800
Dimension/m	2.3×2.0×1.5
Work breadth/m	2
Seeder type	Combined positive and negative air pressure precision seed platter
Number of holes in the type of planter	50
Wheel diameter/cm	50
Planting rows	6
Seeding depth/mm	10-20
Upper ditch width/cm	25-35
Bottom ditch width/cm	10-15
Ditch depth/cm	20-25

and fast, denoted as M1, M2, and M3, respectively. Three treatments were included in total. In this study, a Dongfanghong-954 tractor and a John Deere JD5-954-1 tractor were used as supporting power at Jianli and Shayang, respectively. The relative slow forward speeds were 2.17 km/h and 2.0 km/h, the relative medium forward speeds were 3.36 km/h and 2.5 km/h, and the relative fast forward speeds were 4.15 km/h and 3.6 km/h, at Jianli and Shayang, respectively. The velocity parameters were calculated by measuring the time required for the seeder to travel a certain distance.

Three replicates were performed for each treatment using a randomized design. One compartment was used as a repetition. The effective area for the sampling and testing of each compartment (excluding the operation area of the seeder start and stop section) was 30 m^2 (15 m×2 m). The rapeseed crops were sown on October 23, 2020, and October 25, 2020, and harvested on May 2, 2021, and May 3, 2021, at Jianli and Shayang, respectively. When sowing, the fertilizer was applied synchronously via mixed mechanical application. The amount of slow-release fertilizer was 450 kg/hm^2 with no top-dressing, according to fertilizer recommendations proposed by the Department of Agriculture and Rural Areas of Hubei Province. Other field managements were conducted according to local practices.

2.3 Measurement index and methods

2.3.1 Soil water content

Soil sample cores from 0 to 10 cm were taken to measure soil water content through a diameter gauge on the day of emergence determination (Jianli: 37 DAS, Shayang: 34 DAS, DAS indicates days after sowing). Three cores were obtained from each replicate and mixed as soil samples for the replicate. Soil water content was measured by oven-drying at 105°C for 12 h.

2.3.2 Soil surface roughness

A 3D laser scanner model Trimble TX8 (Trimble RealWorks Software, USA) was used to acquire the 3D point cloud data of the soil surface (Figure 3). The scanner is characterized by a high scanning speed at 1 million measuring dots per second and can capture objectives with a scanning range of 340 m. The range measurement noise is less than 1 mm. And, the scanner is equipped with a laser beam diameter of 6-10-34 mm@10-30-100 m, a field-of-view angle of 360°×317°, and a built-in HDR camera (10 million pixels, full field of view).

In field trials, the scanner was mounted on an industrial tripod (Figure 3). The tripod-mounted scanner was placed on the east, west, south, and north side of the compartment and aligned so the soil surface would fall roughly in the scanning window. A total of 4 scans were taken for each compartment. Five targets were placed on the scene to locate the scans. Only the points derived from the laser were used in the analysis, with no accompanying photographs[16].

Soil surface roughness was characterized by the root mean square height (RMSH)[7], which reflected how the soil height deviated from the average height. The smaller the RMSH value, the smoother the surface. Due to the high spatial heterogeneity of the seedbed surface, the roughness calculation was significantly affected by the scale of the calculation area. To explore the changing law of surface roughness at different scales, we defined the local RMSH (locRMSH). In practice, we randomly selected the local surface elevation data in the measurement area through the rectangular window and analyzed the local variation characteristics of the random surface roughness. The locRMSH was calculated as follows:

$$\text{locRMSH} = \sqrt{\frac{1}{(X_l - X_f)\times(Y_l - Y_f)}} \times \sqrt{\sum_{c=X_f}^{X_l} \sum_{r=Y_f}^{Y_l} \left[z(x_c, y_r) - \bar{z}\right]^2} \quad (1)$$

where, X_l is the index of the last column; X_f is the index of the first column; Y_l is the index of the last row; Y_f is the index of the first row; c is the column index; r is the row index; $z(x_c, y_r)$ is the height value of the position (x_c, y_r); and $\bar{z}$ is the average of $z(x_c, y_r)$.

For one-dimensional discrete data, the RMSH was calculated as follows:

$$\text{RMSH} = \sqrt{\frac{\sum_{i=1}^{n}[z_i - \bar{z}]^2}{n-1}} \quad (2)$$

where, n is the number of sampling points; z_i is the height value of the i-th sampling point; and $\bar{z}$ is the average height value.

The elevation data was obtained with a sampling interval of 150 mm and a section thickness of 20 mm, along with the direction of the length of the compartment surface of the rapeseed direct seeder, which was used as measurement data to calculate the stability coefficients of seed bed and seed-ditch depth according to the following equation:

$$\begin{cases} U = \left(1 - \dfrac{\sigma}{\overline{W}}\right) \times 100\% \\ \sigma = \sqrt{\dfrac{\sum_{j=1}^{n}\left(W_j - \overline{W}\right)^2}{n-1}} \\ \overline{W} = \dfrac{\sum_{j=1}^{n} W_j}{n} \end{cases} \quad (3)$$

where, U is the stability coefficient of seed bed (or seed-ditch depth), %; σ is the standard deviation of seed bed (or seed-ditch depth), mm; $\overline{W}$ is the average value of seed bed (or seed-ditch depth), mm; W_j is the seed bed (or seed-ditch depth) of j-th sections, mm; and n is the number of measured sections.

2.3.3 Emergence rate of rapeseed

In this study, the transmission ratio from the ground wheel of the seeder to the seed-metering device was 1:1.156. The theoretical plant spacing and the theoretical seed quantity of the seeder can be calculated by the following equation[17]:

$$\begin{cases} H_r = \dfrac{\pi D(1+\delta)}{it} \\ Q = \dfrac{10^7 Kitq}{B\pi D(1+\delta)} \end{cases} \quad (4)$$

where, H_r is the theoretical planting spacing, mm; Q is the theoretical seed quantity, g/hm²; D is the wheel diameter, mm; δ is the wheel slip rate, 0.02-0.05; i is the transmission ratio; t is the number of seed-metering holes; K is the number of seeding rows of the direct-seeding machine; q is the thousand-seed-weight of the rapeseed seeds, g; B is the width of the direct-seeding machine, mm.

Calculated by Equation (4), the H_r ranged from 27.72 to 28.54 mm, and the Q varied from 3805.82 to 3917.76 g/hm². In addition, the amount of seeding from the direct-seeding device was measured using the weighing method, after which the actual seed quantity was calculated.

The seedling emergence was recorded on 37 DAS and 34 DAS at Jianli and Shayang, respectively. The emergence rate (the ratio of the emergence number to the actual total number of seeds) was calculated. Along the forward direction of the unit, the distance between adjacent plants in each row was measured with tape. The distribution law of rapeseed plant spacing was analyzed, after which the actual plant spacing was determined.

2.3.4 Crop yield

At harvest, plants at a size of 1.25 m² (1.12 m×1.12 m) were selected from each replicate to determine yield components, including branch numbers per plant, pod numbers per plant, seed numbers per pod, 1000-seed weight, and harvest population density. The seed yield was determined after the plants were sun-dried and threshed.

2.3.5 Economic benefits

The economic benefit was calculated using the following equation:

$$\begin{cases} \text{Economic benefits} = \text{Total output} - \text{Total input} \\ \text{Total output} = \text{Yield} \times \text{Market price} \\ \text{Total input} = \text{Agricultural inputs} + \text{Other inputs} \end{cases} \quad (5)$$

Rapeseed market price was 4.796 CNY/hm². Agricultural inputs referred to rapeseed seed (80 CNY/hm²), fertilizer (2.15 CNY/hm²), and pesticides (267 CNY/hm²). Other inputs referred to mechanical seeding fees (1482.3 CNY/hm²) and agronomic management and harvest fees (5720.4 CNY/hm²).

2.4 Statistical analyses

Data were compiled and analyzed using Microsoft Excel 2010 (Microsoft Corporation, New Mexico, USA). Variance analysis and correlation analysis were identified using SPSS Statistics 22.0 (SPSS Inc. Chicago, IL, USA), and the differences were considered significant when α=0.05. Figures were plotted in OriginPro 9.0 software (OriginLab Corporation, Northampton, MA, USA) and Surfer 11.0 (Golden Software, Inc, Colorado, USA).

3 Results

3.1 Climate condition and soil water content

Daily air temperature and precipitation at the two experimental sites fluctuated over time (Figure 4). Total precipitation at Jianli (527.7 mm) was approximately 1.29 times greater than that of Shayang, where the mean maximum and minimum temperatures were 0.98 and 1.05, respectively.

As listed in Table 2, soil water content at Jianli was relatively greater than that of Shayang, increasing by an average of 17.8%. At the two experimental sites, soil water content decreased as the unit forward speed increased. Compared with the M2 and M3 treatments, soil water content under the M1 treatment increased by 3.2% and 7.4%, respectively. However, treatment effects on soil water content were not significant (p>0.05).

3.2 Soil surface roughness

The unit forward speed had an obvious effect on soil surface roughness. Compared with the bottom of the ditch, the relative height of the compartment at Jianli after the seeder operation was 216.37 mm, 212.69 mm, and 200.29 mm, under the M1, M2, and M3 treatments, respectively; where Shayang was 288.21 mm, 253.66 mm and 244.30 mm, respectively (Figure 5). As the forward speed of the unit increased, the compartment surface became rougher (Table 2). Compared with the M1 and M2 treatments, soil surface roughness expressed as RMSH under the M3 treatment increased by 29.7% and 3.8% at Jianli, respectively, and increased by 43.3% and 14.8% at Shayang, respectively (p<0.05).

To further clarify how the unit forward speed affects the quality

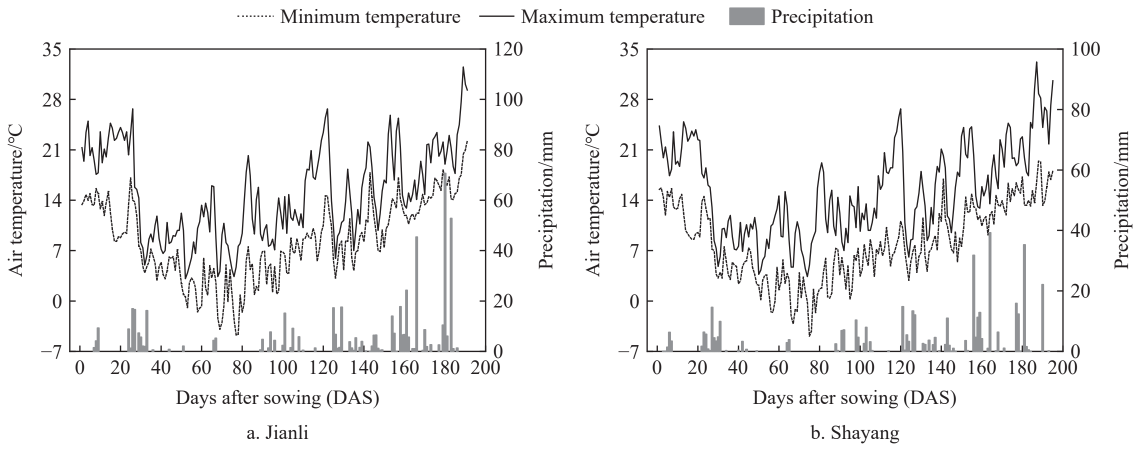
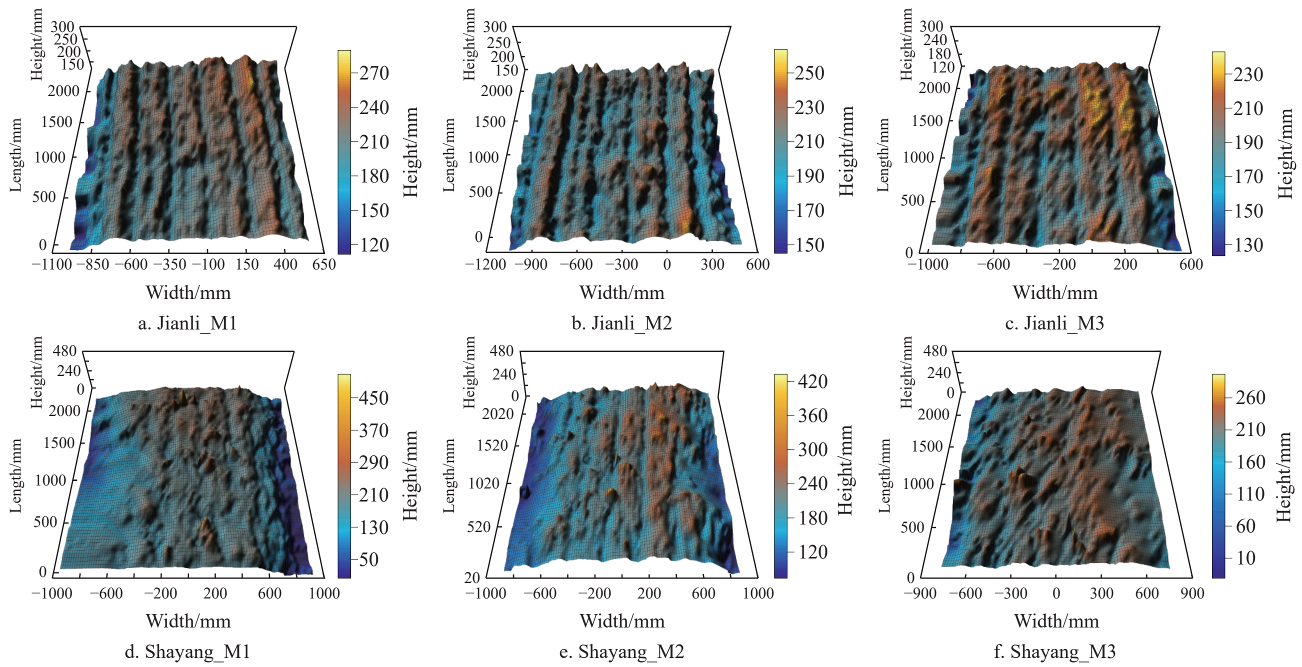


Figure 4 Changes of air temperature and precipitation at Jianli and Shayang

Table 2 Soil water content, soil surface roughness, seed quantity, and emergence rate of rapeseed under different treatments at Jianli and Shayang

Experimental site	Treatment	Soil water content/%	soil surface roughness/mm	Seed quantity/g·hm^{-2}	Emergence rate/%
Jianli	M1	30.4^a	12.83^b	3889.27^a	87.3^a
	M2	29.7^a	16.03^a	3995.81^a	85.5^a
	M3	28.6^a	16.64^a	4158.18^a	83.2^a
Shayang	M1	26.1^a	17.30^c	3806.56^a	53.5^a
	M2	25.1^a	21.61^b	3858.10^a	53.2^a
	M3	24.1^a	24.80^a	4065.00^a	52.4^a

Note: M1, M2, and M3 indicate the relative slow, medium, and fast forward speed of the unit, respectively. Different lowercase letters in the same column at each experimental site indicate significant differences among treatments.



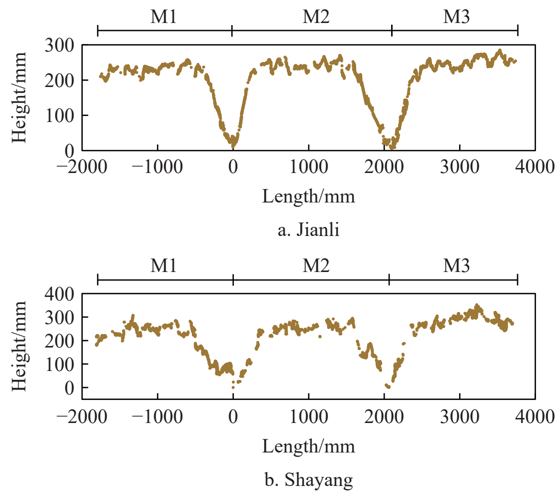
Note: M1, M2, and M3 indicate the relative low, medium, and fast forward speed of the unit, respectively.

Figure 5 Three dimensional digital model of seedbed surface at Jianli and Shayang

of the compartment surface and the ditch, the measuring section along with the direction of the length of the seeder's compartment surface was analyzed. As shown in Figure 6 and Figure 7, the average width of the seed bed was 1.48 m with >90% stability coefficient, while the average depth of the seed-ditch was 19.32 mm with >70% stability coefficient. All these results met the quality requirements of the planter operation (Table 1) and provided a suitable seedbed for the emergence and subsequent growth of rapeseed crops. Meanwhile, a roughly "V"-shaped ditch was identified (Figure 6). Different degrees of soil backflow were observed at the two experimental sites, which was more obvious at Shayang.

3.3 Seed quantity of the seeder

The actual seed quantity of the seeder ranged from 3889.27 to 4158.18 g/hm^2 and from 3806.56 to 4065.00 g/hm^2 at Jianli and Shayang, respectively (Table 2), which exceeded the theoretical value to a certain extent. While, the average error rate of the actual and theoretical seed quantity was 4.2% and 2.7% at Jianli and



a. Jianli

b. Shayang

Note: M1, M2, and M3 indicate the relative low, medium, and fast forward speed of the unit, respectively.

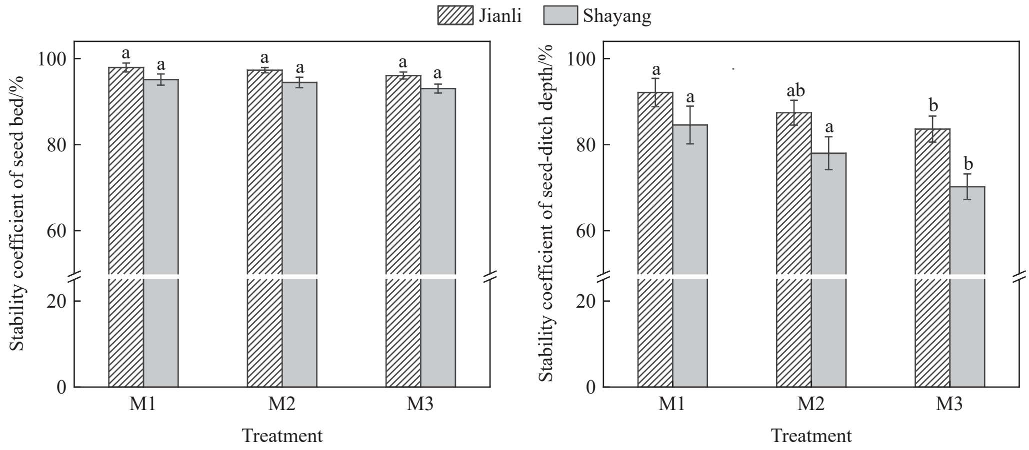
Figure 6 Surface contours under different treatments at Jianli and Shayang

Shayang, respectively. In addition, the actual seed quantity of the seeder gradually increased as the unit forward speed increased (M1<M2<M3, Table 2). The seed quantity under the M3 treatment increased by 6.9% and 4.7% compared with the M1 and M2 treatments, respectively. However, treatment effects on seed quantity of the seeder were not significant (p>0.05).

3.4 Emergence rate of rapeseed

The experimental site had a significant effect on the emergence rate of rapeseed (Table 2). The emergence rates in paddy fields (Shayang) were significantly lower than that of upland (Jianli), with an average reduction of 31.6%. As the forward speed of the unit increased, the emergence rate of rapeseed gradually decreased. Compared with the M1 and M2 treatments, the emergence rate of rapeseed under the M3 treatment decreased by 3.3% and 2.0%, respectively. However, the effects did not significantly differ (p>0.05). Correlation analysis indicated that the emergence rate of rapeseed was positively impacted by soil water content and was negatively influenced by RMSH (Figures 8a and 8b).

An exponential distribution of plant spacing frequency was



a. Stability coefficient of seed bed

b. Stability coefficient of seed-ditch depth

Note: M1, M2, and M3 indicate the relative low, medium, and fast forward speed of the unit, respectively. Bars with different letters represent significant differences among treatments at p<0.05.

Figure 7 Stability coefficients of seed bed and seed-ditch depth under different treatments at Jianli and Shayang

observed (Figure 9). To accurately obtain the plant spacing, the data of each row measured in the experiment were superimposed, and the total exponential distribution ($y=\lambda e^{-\lambda x}$) was fitted. At Jianli, the λ was 0.220, 0.228, and 0.233, and the expected value of the actual plant spacing was 4.54 cm, 4.39 cm, and 4.29 cm, under the M1, M2, and M3 treatments, respectively. At Shayang, the λ was 0.140, 0.145, and 0.148, and the expected value of the actual plant spacing was 7.14 cm, 6.92 cm, and 6.77 cm, under the M1, M2, and M3 treatments, respectively. According to the theoretical and actual plant spacing, the theoretical plant spacing correction coefficient of the seeder was 1.503-1.637 and 2.371-2.577 at Jianli and Shayang, respectively. This result provides a reference for improving the design of the seeder, including the number of holes in the seed-metering device, the diameter of the ground wheel, and the transmission ratio.

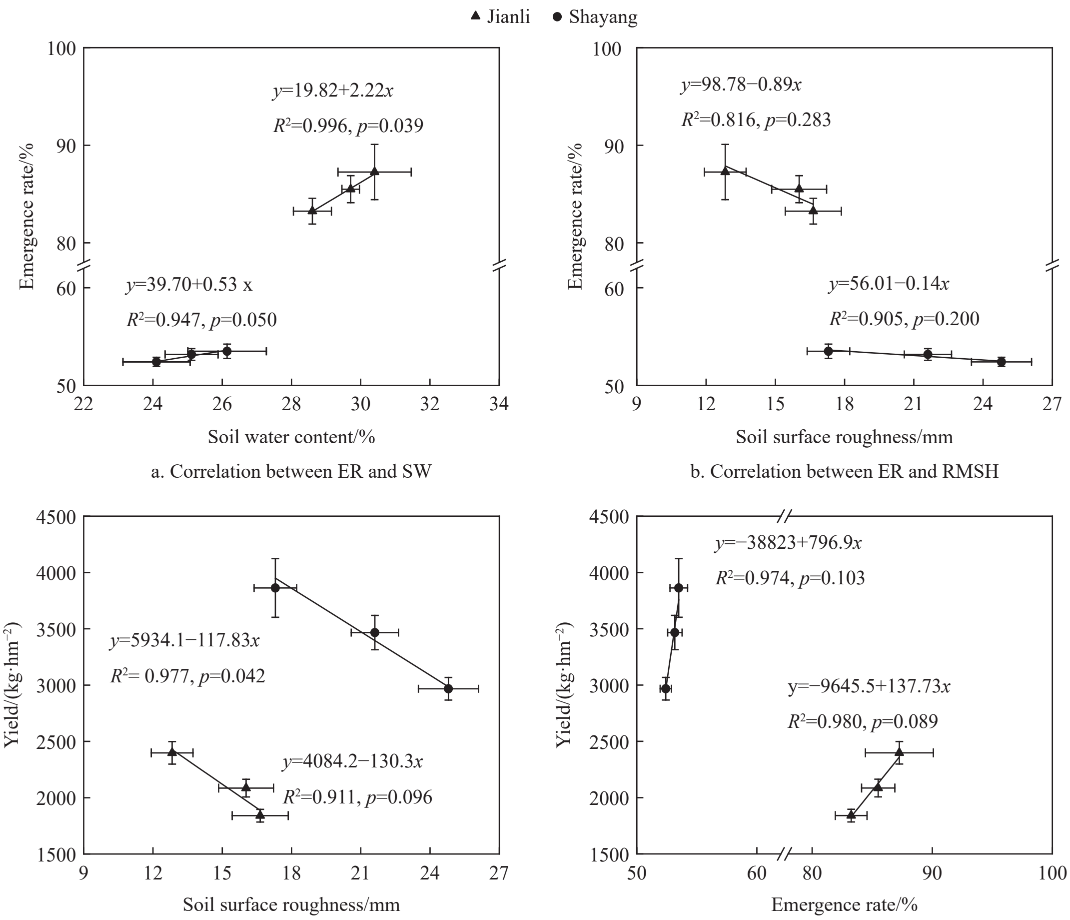
3.5 Rapeseed yield

Rapeseed yield and its related components were strongly affected by the experimental site and forward speed of the unit (Table 3). Yield components (e.g., branch number per plant, pod number per plant, seed number per pod, 1000-seed weight) at Shayang were relatively greater than that of Jianli except for the harvest population density, which ultimately resulted in a 62.8% increase in rapeseed yield. Compared to the M3 treatment, M1 and M2 treatments significantly improved the branch number per plant, pod number per plant, and seed number per pod at Jianli and significantly increased pod number per plant at Shayang. While, other components between treatments at each experimental site were not significant.

As the forward speed of the unit increased, the rapeseed yield gradually decreased. Compared with the M1 and M2 treatments, yield under the M3 treatment decreased by 23.2% and 13.1%, respectively. Treatment effects were significantly different (p<0.05). Correlation analysis indicated that the rapeseed yield was negatively impacted by RMSH and was positively influenced by the emergence rate (Figures 8c and 8d).

3.6 Economic benefits

The changing trend of the economic benefits under different treatments (Table 4) was similar to that of emergence rate (Table 2) and seed yield (Table 3). The highest economic benefits occurred in the M1 treatment, which, on average, were 1.727 and 25.451 times greater than those in M2 and M3, respectively. Therefore, M1 was the proper treatment when rapeseed was mechanized in production.



a. Correlation between ER and SW

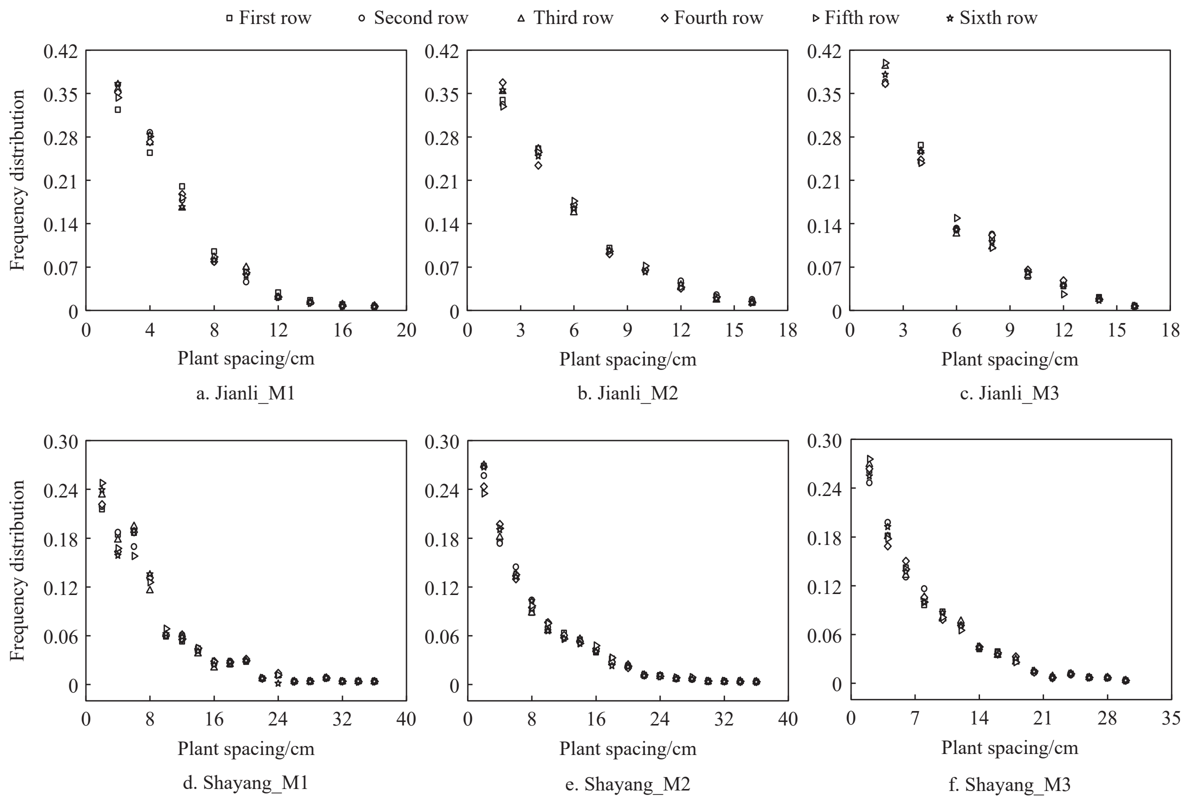
b. Correlation between ER and RMSH

c. Correlation between yield and RMSH

d. Correlation between yield and ER

Note: ER, SW, and RMSH indicate emergence rate, soil water content, and soil surface roughness, respectively.

Figure 8 Correlations of emergence rate with soil water content and soil surface roughness, and the effects of soil surface roughness and emergence rate on yield



a. Jianli_M1

b. Jianli_M2

c. Jianli_M3

d. Shayang_M1

e. Shayang_M2

f. Shayang_M3

Note: M1, M2, and M3 indicate the relative low, medium, and fast forward speed of the unit, respectively.

Figure 9 Plant spacing frequency distribution of each row under different treatments at Jianli and Shayang

Table 3 Yield components and yield of rapeseed under different treatments at Jianli and Shayang

Experimental site	Treatment	Branch numbers per plant	Pod numbers per plant	Seed numbers per pod	1000-seed weight/g	Harvest population density/ ($\times10^4$ hm^{-2})	Yield (kg·hm^{-2})
Jianli	M1	4.2^a	120.6^a	19.83^a	4.303^a	41.07^a	2398.10^a
	M2	3.6^b	94.0^b	19.74^{ab}	4.168^a	42.86^a	2085.28^b
	M3	2.8^c	66.8^c	19.62^b	4.066^a	44.05^a	1840.19^c
Shayang	M1	5.3^a	213.0^a	20.00^a	4.531^a	28.57^b	3862.14^a
	M2	5.2^a	197.8^a	19.95^a	4.500^a	29.76^b	3465.96^a
	M3	5.2^a	149.4^b	19.81^a	4.424^a	33.33^a	2967.33^b

Note: M1, M2, and M3 indicate the relative slow, medium, and fast forward speed of the unit, respectively. Different lowercase letters in the same column at each experimental site indicate significant differences among treatments.

Table 4 Economic benefits under different treatments at Jianli and Shayang (CNY·hm^{-2})

Experimental site	Treatment	Total output	Agricultural input	Other input	Total input	Economic benefits
Jianli	M1	11 501.74^a	1545.64^a	7202.70^a	8748.34^a	2753.40^a
	M2	10 001.40^b	1554.16^a	7202.70^a	8756.86^a	1244.53^b
	M3	8825.92^c	1567.15^a	7202.70^a	8769.85^a	56.06^c
Shayang	M1	18 523.61^a	1539.02^a	7202.70^a	8741.72^a	9781.89^a
	M2	16 623.44^a	1543.15^a	7202.70^a	8745.85^a	7877.59^b
	M3	14 231.92^b	1559.70^a	7202.70^a	8762.40^a	5469.52^c

Note: M1, M2, and M3 indicate the relative slow, medium, and fast forward speed of the unit, respectively. Different lowercase letters in the same column at each experimental site indicate significant differences among treatments.

But from the viewpoint of increasing operation efficiency, M2 could be recommended.

4 Discussion

4.1 The impact of the unit forward speed on soil surface roughness

Soil surface roughness is an important index for characterizing soil surface microgeomorphology, which directly impacts crop planting. Accurately measuring soil surface roughness is of great significance to the realization of precision agriculture. However, little research has been performed on soil surface roughness in farmland fields, especially the use of high precision and high efficiency measuring instruments. In our study, a 3D laser scanner was used to acquire the 3D point cloud data of soil surface under different forward speeds of the unit. The results showed that the relative height of the compartment surface at Shayang (244.30-288.21 mm) was greater than that of Jianli (200.29-216.37 mm, Figure 5), which could be related to factors such as the unit forward speed, soil texture, and field conditions. In this experiment, the lower forward speed of the unit at Shayang made the soil finer and thicker. A paddy-upland rotation planting pattern at Shayang was commonly used. Rice stubble and floating grass from previously planted crops increased soil porosity and plow layer thickness[18], which increased the relative height of the compartment surface. As the forward speed of the unit increased, the compartment surface became rougher (expressed as RMSH, Table 2). This is because as the unit moved more slowly, the cutting pitch of the rotary tiller was smaller[19], which was more conducive to finely crushing and uniformly mixing the soil. This produced a smoother surface. Meanwhile, as the unit moved more slowly, the soil was leveled and compacted for a longer period, further smoothing the surface.

As previously reported[20], the 2BFQ-6 type combined rapeseed seeder uses the front and back plow to open the furrow. The front plow breaks the soil and turns the furrow, while the back plow clears and reshapes the furrow. These two plows eventually form a complete furrow. In this study, the ditch was roughly "V"-shaped. Different degrees of soil backflow were observed at the two experimental sites, and a more obvious phenomenon was observed at Shayang (Figure 6). This phenomenon is likely because Shayang was a paddy field, which had a higher soil water content before sowing (Jianli vs Shayang = 27.8% vs 30.0%). The presence of straw residue before planting made the soil stickier and heavier, increasing the cohesive force between soil particles. The back plow stuck to clay and congested soil, leading to changes in the geometric shape of the plow body touching the soil. This resulted in an unstable trench shape, making it hard to adequately clear and shape the ditch. Therefore, reducing the forward speed of the unit is an effective method of improving the rotary tillage quality of direct-seeding machines in the field.

4.2 The impact of the unit forward speed on seed quantity of the seeder

The seed quantity of the seeder is theoretically influenced by the wheel diameter, wheel slip rate, number of seed-metering holes, and transmission ratio[17]. Also, seed quantity is influenced by the negative pressure of sucking seed, vibration, and forward speed of the seeder[15,21]. In our study, the actual seed quantity of the seeder (Table 2) was mostly greater than the theoretical value. This is primarily because, in the field experiment, the planter fan worked within the rated speed, and the negative suction pressure was relatively high, leading to greater seed reabsorption on the seeding hole and a higher reseeding index. The lower seed quantity at Shayang than at Jianli (Table 2) was closely related to the working performance of the tractor and the field conditions. On the one hand, the difference in PTO speed of the rear output shaft of the tractor resulted in higher negative seed suction pressure generated by the fan at Jianli than at Shayang, which increased the seed suction of the upper hole on the seed plate, resulting in a higher seed quantity. On the other hand, a previous study demonstrated that the slip rate increased as soil water content increased[22]. In this study, soil water content before sowing was higher at Shayang. The ground wheel easily slipped during the field operation of the seeder, increasing the slip rate. Meanwhile, heavy clay soil can increase the thickness of the soil on the rim of the wheel, indirectly increasing the wheel diameter. As previously reported[17], the seed quantity was inversely proportional to the slip rate of the ground wheel and the diameter of the ground wheel. Therefore, the increased slip rate and ground wheel diameter in our experimental conditions resulted in a lower seed quantity. Although differences between the theoretical and actual seed quantity existed, the average error rate was less than 5.0%, which met the operational quality requirements for seeding rapeseed crops[23]. This indicates that the seeder had strong adaptability in both upland and paddy fields.

The forward speed of the unit affects the working speed of the fan in the pneumatic system, the adsorption of the seed, the slip rate of the ground wheel, and the vibration of the machine[15]. All of these factors have an important role in the seed quantity of the seeder. In our study, the actual seed quantity of the seeder gradually increased as the unit forward speed increased (Table 2). This could be because increases in the operating speed of the unit would vibrate the whole machine, improving the filling performance of the seed-metering device and increasing the negative pressure of the fan. All of these ultimately increased the seed quantity of the seeder. Therefore, to achieve a stable seed quantity of the seeder under different forward speeds, a voltage stabilizing device should be installed on the fan, and the correction coefficient of seed quantity stability should be considered.

4.3 The impact of the unit forward speed on emergence rate and yield of rapeseed

The emergence of seedlings from soil was the combined result of several processes: seed germination, shoot elongation to reach the soil surface, radicle elongation to ensure water uptake, and seedling survival when encountering obstacles in soil were important factors[24]. Other than the above emergence processing factors, seed sowing depth and compartment surface quality were the key factors affecting the seedling rate of rapeseed[25]. Nevertheless, the response of emergence rate of rapeseed to soil surface quality is unclear. In our experiment, the emergence rate of rapeseed (Table 2) was within the range of 45%-69% reported by Zuo et al.[6]. The emergence rate of rapeseed gradually decreased as the forward speed of the unit increased (Table 2). This is likely due to the changes in seed sowing depth and compartment surface, which are affected by the quality of rotary tillage and the stability of the double-disc trenching depth of the seeder. The higher forward speed of the unit has been shown to have greater soil surface roughness (Table 2), increasing or decreasing sowing depth. When the seeding is too shallow, the rape seedlings can burn at high temperatures or freeze at low temperatures, resulting in the missing seedling. When the seeding is too deep, the topsoil ability of the rape seedlings is weak and can easily result in nutrient depletion, making it difficult to emerge. In summary, as the unit worked faster, the compartment surface was rougher, and the rapeseed seedlings decreased. This result was similar to our correlation analysis (Figure 8b). To meet the current requirements of a high-speed, high-quality, and high-efficiency seeder, the influence of surface quality on the emergence rate of rapeseed needs to be further verified.

Values of rapeseed yield in our study (Table 3) were greater[26,27] or lower[28] than those of previous research using the same amount of nitrogen fertilizer. The reason for the difference could be due to the cultivar[29], planting density[30], fertilizer source[31], and hydrothermal conditions[32]. Additionally, as the forward speed of the unit increased, rapeseed yield gradually decreased (Table 3). This trend was strongly influenced by the coarse soil surface quality, the lower emergence rate of rapeseed (Table 2, Figure 8), and the inhibited yield components (e.g., branch number per plant, pod number per plant, seed number per pod, 1000-seed weight, Table 3) at higher unit forward speeds. Based on the results of emergence rate, seed yield, and economic benefits of rapeseed in the present study, the M1 treatment is the optimal unit operation speed in rapeseed production. However, after considering that the M1 treatment can reduce the unit operation efficiency, and thus resulting in lower cost of production, the M2 treatment is also a good choice in actual farming.

5 Conclusions

(1) A 3D laser scanner was used to measure soil surface roughness in this study. The results indicated that as the forward speed of the unit increased, the compartment surface become rougher. Compared with the relative slow and medium unit forward speed treatments, soil surface roughness under the relative fast unit forward speed treatment increased by 36.5% and 9.8%, respectively.

(2) The actual seed quantity of the seeder under different forward speeds ranged from 3806.56 to 4158.18 g/hm^2. The average error rate of actual and theoretical seed quantity was less than 5%, which met the operational quality requirements for seeding rapeseed crops. The actual seed quantity gradually increased as the unit forward speed increased. The seed quantity under the relative fast unit forward speed treatment increased by 6.9% and 4.7% compared with the relative slow and medium unit forward speed treatments, respectively.

(3) The emergence rate and yield of rapeseed gradually decreased as the forward speed of the unit increased. Compared with the relative slow and medium unit forward speed treatments, the emergence rate decreased by 3.3% and 2.0%, and yield decreased by 23.2% and 13.1%, under the relative fast unit forward speed treatment, respectively. Considering the emergence rate, seed yield, economic benefits, and unit operation efficiency, the relative medium unit forward speed treatment could be recommended in actual farming.

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