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Experimental Study on the Soil Conditions for Rapeseed Transplanting for Blanket Seedling Combined Transplanter

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Abstract: To address the lack of available information on the soil physical conditions suitable for rapeseed blanket-shaped seedling transplanting, as well as the lack of protocols for the optimisation of soil tillage components in the utilisation of an integrated rapeseed blanket seedling combined transplanter, the physical parameters of different soil conditions and their impact on the growth of rapeseed after transplanting were investigated in this study. The aim was to determine the suitable soil physical parameters for rapeseed blanket-shaped seedling transplanting. First, the changes in soil firmness, soil bulk density, and soil moisture content during the installation of the rapeseed blanket seedling combined transplanter were tested and analysed, providing preliminary data for subsequent research. Using the variables of soil firmness and soil moisture content in the micro-environment around the roots and stems (30–50 mm) after rapeseed seedling transplantation and indicators such as the survival rate, root diameter, seedling height, and dry weight, an experiment on the growth of rapeseed blanket-shaped seedlings was conducted based on the furrow cutting transplanting principle. The results indicated that during the initial stage of rapeseed transplanting, the soil moisture content significantly influenced the vitality of the rapeseed plants. Under a high soil moisture content, the typically lengthy seedling period was shortened, and the effect on vitality was good, with minimal influence from the soil firmness. After seedling establishment, the rapeseed growth was significantly affected by the soil firmness. When the soil moisture content was less than 20%, increasing the soil firmness to 500 kPa was beneficial for moisture retention and rapeseed seedling growth. At a soil moisture content ranging from 20 to 25%, a soil firmness of 400 kPa was most suitable for both rapeseed vitality and late-stage growth. When the soil moisture content exceeded 25%, reducing the soil firmness to 300 kPa was beneficial for rapeseed growth, as an excessively high moisture content may lead to soil compaction, affecting seedling development. This study provides a theoretical basis for optimizing the design of soil tillage components in the application of an integrated rapeseed blanket seedling combined transplanter and for the high-yield management of rapeseed after transplanting.

Keywords: rapeseed; soil physical conditions; transplanter; soil working components

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1. Introduction

Rapeseed is a major oilseed crop in China and one of the primary sources of high-quality edible vegetable oil [1–5]. The main rapeseed cultivation areas in China are concentrated in the Yangtze River basin, where the prevalent cropping pattern involves a rotation of rice and oilseed. Approximately 30% of these areas experience a significant decline in yield due to delayed rice harvesting, resulting in the inability to sow rapeseed in a timely manner [6–8]. Seedling cultivation and transplantation are effective measures for addressing the tight crop rotation timing for rapeseed, compensating for the insufficient length of growing periods, and are crucial strategies for ensuring stable and high yields [9–11]. Given that rapeseed is a field crop with a high planting density, it requires efficient transplanting methods. Mechanical transplanting in rice stubble fields, which are characterised by heavy soil and abundant residual straw, poses considerable challenges [12–14].

In response to the challenge of mechanically transplanting rapeseed in rice stubble fields with a large amount of straw litter and heavy soil, a research team led by Wu Chongyou at the Agricultural Mechanization Research Institute of the Ministry of Agriculture and Rural Affairs has proposed, after more than 10 years of exploration, the transplanting principle of cutting rapeseed blanket-shaped seedling into blocks and inter-row insertions. The authors developed an integrated rapeseed blanket seedling combined transplanter [15–17]. This multipurpose machine can complete the processes of rotary ploughing, stubble burying, seedbed creation, seedbed surface levelling and slitting, substrate cutting, seedling pick-up, planting into furrows, and covering with soil. This has demonstrated a high efficiency, good operational quality, and strong adaptability to different types of soil, showcasing excellent prospects for widespread applications. However, observations of the growth and development of rapeseed after machine transplanting have revealed significant differences caused by varying soil compaction levels of the ridges and the furrows, leading to slowed growth and even stunted seedling development. To investigate this issue, here, a study was conducted on the soil conditions in the micro-environment around the roots and stems (30–50 mm radius) and at a soil depth of 100 mm after rapeseed transplantation, as shown in Figure 1. The aim of this study was to investigate the suitable soil conditions for the mechanical transplantation of rapeseed blanket-shaped seedlings, providing reference information for the optimisation of rapeseed transplanters and high-yield management after transplantation.

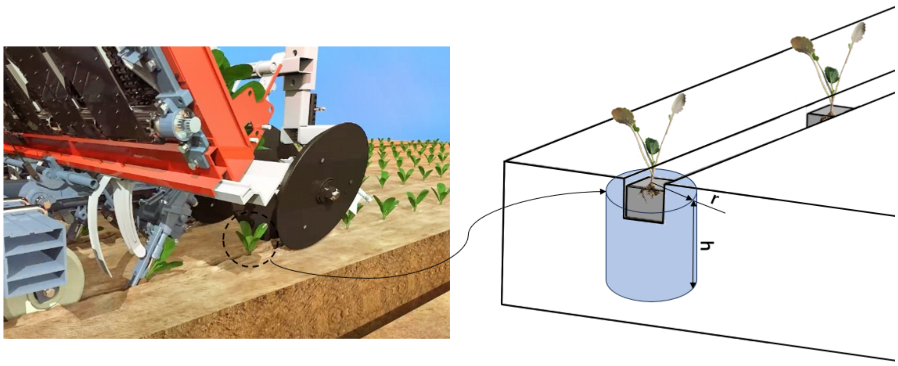


Figure 1. Microenvironmental soil conditions around roots and stems of rapeseed plants after transplantation. (h) Depth. (r) Radius.

2. Materials and Methods

2.1. Introduction to the Joint Transplantation Operation of Rapeseed Blanket-Shaped Seedlings

The operational process of the rapeseed blanket seedling combined transplanter mainly includes the processes of rotary ploughing, stubble burying, seedbed creation, seedbed surface levelling and slitting, substrate cutting, seedling pick-up, planting into furrows, and covering with soil. Different states and regions of soil firmness and moisture during the operation of the transplanter on the soil were measured, including in a plot before rototilling (PBR), uncompacted surfaces after rototilling (USAR), compacted surfaces after rototilling (CSAR), planting furrows cut into compacted surfaces (PFCICS), and after soil covering and compaction (SCAC).

In general, during the operation of the transplanter, soil undergoes sequential mechanical loosening and compaction. Mechanical loosening is characterised by relative decreases in soil bulk density and firmness, along with a relative increase in soil moisture content. In contrast, mechanical compaction manifests as increases in soil bulk density and firmness, concurrently leading to a reduction in soil saturated hydraulic conductivity. These processes are integral to agricultural machinery operations, where mechanical compaction involves rearranging soil particles to create a more compact structure, while mechanical loosening leads to the formation of a relatively loose soil structure. Despite their contrasting effects, both mechanical compaction and loosening induce changes in the overall soil structure [18–25]. Therefore, compression tests were conducted on soils with different moisture levels to observe the variations in soil moisture content, soil firmness, and soil bulk density. The aim of this approach was to further identify the soil physical parameters that require in-depth study and provide a robust reference for designing experimental schemes for subsequent trials involving the cutting and transplanting of rapeseed blanket-shaped seedlings.

2.2. Soil Physical Parameters

To characterise the soil physical conditions for rapeseed transplanting, soil compaction tests were conducted. On 7 June 2023, soil samples were collected from rice stubble fields in Rongfeng village, Wuxing District, Huzhou city, Zhejiang Province, China. Soil configuration and testing were conducted at the laboratory of the Agricultural Mechanization Research Institute of the Ministry of Agriculture and Rural Affairs. The experimental instruments used included a TJSD-750 soil firmness tester (Zhejiang Top Instrument Co., Ltd., Hangzhou, China), an AC-9140A Electric heating blast drying oven (Wujiang Aocheng Oven Equipment Co., Ltd., Suzhou, China), a CX-12000 electronic scale (Nancheng Changxie Electronic Products Factory, Dongguan, China), and a universal material testing machine.

2.2.1. Soil Preparation

Prior to the experiment, a particle sieve was used to screen out the larger straw residue and stones. Furthermore, an electronic moisture metre was used to rapidly measure the initial soil moisture content. Subsequently, accounting for the initial soil moisture content, soil samples with water content levels of 10%, 15%, 20%, 25%, and 30% were prepared. When a given sample needed to have its moisture level reduced to achieve the necessary water content level, the original soil was placed in a well-ventilated environment to gradually evaporate the moisture from it. The soil moisture content was frequently measured using an electronic moisture metre until the target value was achieved. To increase the water content of soil samples, the original soil was uniformly mixed with a certain amount of water, ensuring even water infiltration into the soil. The amount of water that was subsequently added was then adjusted to achieve the desired soil moisture content. Again, the soil moisture content was frequently measured using an electronic moisture metre until the required level was reached, after which the soil was stored and labelled in a sealed bag.

2.2.2. Soil Compression Test

Before the experiment, buckets were individually filled with the soils prepared at different moisture contents to ensure uniform and compact soil filling and to avoid large air pockets. Subsequently, the buckets were placed on the universal testing machine, as illustrated in Figure 2.

Using a universal material testing machine, a soil compaction test was conducted with a force range from 0 to 1000 N at a compaction speed of 60 mm/s. To assess soil rheological behaviour during the test, the maximum pressure at which the behaviour occurred was recorded. Subsequently, new soil compaction tests were conducted based on this maximum pressure, ensuring a minimum of 5 sets of test data. After each force application, the soil firmness was measured at a depth of 50 mm below the compression point, and the data were recorded using a soil firmness metre. Furthermore, soil samples were taken from the compressed points using a soil ring knife. These samples were labelled and measured. Finally, the soil samples were placed in an electric hot air oven for 8 h at 105 °C, dried, and then weighed to calculate the soil bulk density. To ensure the accuracy of the test results, two measurements were taken for both soil firmness and soil bulk density at the same pressure, and the average value was calculated.

Figure 2. Soil compaction test.

2.3. Transplanter Operation Soil Parameter Assessment

The purpose of this experiment was to detect and analyse the changes in soil parameters during combined transplanter operation for rapeseed blanket-shaped seedlings. This study provides a reference basis for designing experimental schemes on soil conditions for subsequent experiments involving the furrow cutting and transplanting of rapeseed blanket-shaped seedlings. On 24 August 2023, soil tests were conducted on samples collected from the rice stubble fields of Rongfeng village, Wuxing District, Huzhou city, Zhejiang Province, before and after the operation of the rapeseed blanket seedling transplanter. The experimental machine used was a 2ZGK-6 model rapeseed blanket seedling combined transplanter (National Machinery Heavy Industry (Changzhou) Excavator Co., Ltd., Changzhou, China), as shown in Figure 3. The experimental instruments used included a TJSD-750 soil firmness instrument (Zhejiang Top Instrument Co., Ltd., Hangzhou, China), an AC-9140A electric hot air drying oven (Wujiang Aocheng Oven Equipment Co., Ltd., Suzhou, China), and a CX-12000 electronic scale (Nancheng Changxie Electronic Products Factory, Dongguan, China).

Figure 3. 2ZGK-6 model rapeseed blanket seedling combined transplanter. The identifier is the manufacturer's logo for this device.

2.3.1. Measurement of Soil Firmness

Following the GB/T5262-2008 standard [26], a five-point method was employed to determine the soil firmness measurement positions. The measurements were taken using a soil firmness instrument at various stages of the rapeseed blanket seedling transplanter operation. These stages included the PBR, USAR, CSAR, PFCICS, and SCAC stages. During the measurement, each point was measured in layers 100 mm below the soil surface, with layer intervals of 25 mm. The final results for each layer were calculated as the arithmetic average.

2.3.2. Measurement of Soil Moisture Content and Soil Bulk Density

The sampling positions were determined using the five-point method outlined in GB/T5262-2008. The soil was sampled using a ring knife at the various stages of the operation, including the PBR, USAR, CSAR, PFCICS, and SCAC stages. However, for the USAR stage, due to the relatively large gaps between soil particles, the soil was incidentally compacted during sampling with a ring knife. Therefore, it was not possible to measure soil bulk density using the ring knife. The soil moisture content and soil bulk density for the other operational stages were calculated using Equations (1) and (2).

The equation for calculating the relative soil moisture content was

$$W\% = \frac{W_2 - W_3}{W_2 - W_1} \tag{1}$$

where $W\%$ is the soil moisture content, W_1 is the weight of the lead box (g), W_2 is the weight of the aluminium box with the original soil (g), and W_3 is the weight of the aluminium box with the dried soil (g).

The equation for calculating the soil dry bulk density was

$$\rho_b = \frac{W_3 - W_1}{V} \tag{2}$$

where ρ_b is the soil dry bulk density in g/cm^3, W_1 is the weight of the lead box (g), W_3 is the weight of the aluminium box with the dried soil (g), and V is the volume of the soil sampling ring in cm^3. In this experiment, the soil sampling ring had a volume (V) of 100 cm^3.

2.4. Experimental Study on the Soil Conditions Suitable for Furrow Cutting and Transplanting

To investigate the influence of soil parameter changes in the micro-environments around the roots and stems (30–50 mm radius) on the growth of rapeseed after the transplantation of the rapeseed blanket-shaped seedlings, soil condition experiments for furrow cutting and transplanting of rapeseed blanket-shaped seedlings were conducted on 10 September 2023 in the experimental field of the Agricultural Mechanization Research Institute of the Ministry of Agriculture and Rural Affairs in Nanjing, Jiangsu Province, and on 30 September 2023 in the rice stubble fields of Hexin village, Liyang city, Changzhou, Jiangsu Province. The experimental machine used was the 2ZGK-6 model rapeseed blanket seedling combined transplanter (National Machinery Heavy Industry (Changzhou) Excavator Co., Ltd., Changzhou, China),. The experimental instruments used included a TJSD-750 soil firmness instrument (Zhejiang Top Instrument Co., Ltd., Hangzhou, China), DHS-20A electronic moisture analyser (Shanghai Jinghai Instrument Co., Ltd., Shanghai, China), CX-12000 electronic scale (Nancheng Changxie Electronic Products Factory, Dongguan, China)., and DL90150 digital Vernier calliper (Deli Group Co., Ltd., Ningbo, China).

2.4.1. Soil Preparation

For the experiment, soils with moisture contents of 15%, 20%, 25%, and 30% were prepared. Soil was collected from the experimental plots. First, the larger straw residue and stones were removed using a sample sieve. After screening, the soil was stored in sealed bags, and the original soil moisture content was rapidly measured using an electronic moisture analyser. This facilitated the subsequent adjustments of soils with different moisture content levels to account for the original soil moisture content. For soils requiring a decrease in moisture content, the original soil was placed in a well-ventilated environment to allow for the gradual evaporation of soil moisture. Conversely, for soils requiring an increase in moisture content, a specific amount of water was uniformly mixed into the original soil until the target moisture content was reached.

2.4.2. Seedbed Preparation

Seedbed preparation involved processes such as furrow opening, laying the preprepared soil into the furrows, levelling the furrow ridges, and cutting the slits (i.e., square-bottomed planting furrows). In this experiment, mechanical operations, including rotary tillage and furrow opening, were employed to ensure that the soil firmness of the experimental area, which was 50 mm below the surface after ploughing, was less than 50 kPa.

Subsequently, furrows were made with a width of 250 mm and a height of 150 mm, as depicted in Figure 4a. After furrow opening, soils with different moisture content levels were preprepared and laid in the furrows, as shown in Figure 4b. The furrow ridges were pressed using wooden boards, as illustrated in Figure 4c. Following furrow opening, the soil firmness within the furrow was controlled using the depth of the furrow-opening board and a soil firmness tester, as demonstrated in Figure 4d. Based on the results of the study on the soil physical characteristics for rapeseed blanket-shaped seedling transplantation, the soil firmness at the furrow bottom needed to be kept at 300 kPa, 400 kPa, and 500 kPa. If the soil firmness at the furrow bottom did not meet the requirements, the soil was ploughed again prior to furrow opening until the soil firmness of the furrow bottom met the experimental requirements.

(**a**) (**b**)

Figure 4. *Cont.*

(**c**) (**d**)

Figure 4. Seedbed preparation processes. These are listed as follows: (**a**) furrow opening; (**b**) laying the preprepared soil into the furrows; (**c**) levelling of the furrow ridges; (**d**) final slits (square-bottomed planting furrows).

2.4.3. Seedling Sampling and Measurement

In accordance with the requirements for cultivating rapeseed seedlings [27], the seedlings were prepared before transplantation by cutting the rapeseed blanket seedlings with a knife. Single seedlings on individual substrate blocks were selected to ensure that each substrate block was intact and uniform in size, as illustrated in Figure 5.

Figure 5. Morphological characteristics of rapeseed seedling plants. (h) Seedling height. (d) Stem diameter.

Then, 40 seedling blocks were randomly selected as samples. The height of the seedlings was measured using a calliper. After the measurements were taken, the roots of the rapeseed seedlings were cleaned to ensure that there was no substrate residue. Subsequently, the rapeseed seedlings were dried, after which their weights were sequentially measured and recorded.

2.4.4. Transplantation and Covering

The screened rapeseed seedlings were subsequently transplanted into the bottoms of the furrow slits with different soil conditions. Then, the seedling root areas were covered with soil with the same moisture content as the soil at the bottom of the furrow slit. This process was used to avoid damaging the soil firmness at the bottom of the furrow slits.

2.4.5. Seedling Management and Observation

No water or fertiliser was applied for one week after transplanting. To address the issue of rainy days, a shelter structure was constructed in advance to ensure good protection from rain. The growth of the rape plants was observed every day for the different soil conditions, images were taken as records, and insect pest control was also performed.

2.4.6. Post-Transplantation Statistics

One week after transplantation, the vitality of the rapeseed seedlings was statistically recorded under different soil conditions. After two weeks, the soil firmness was measured for the various moisture content conditions. The growth of the rapeseed blanket seedlings was observed and statistically analysed during the initial stages of transplantation. The weight of the seedlings was recorded after drying.

3. Results and Discussion

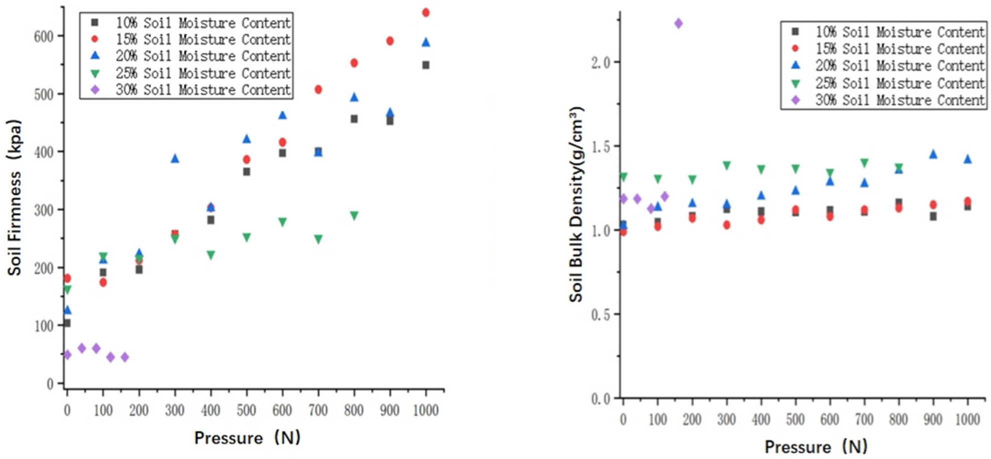
3.1. Soil Physical Parameters

The results of the soil compression test are shown in Table 1.

Table 1. Soil compression test results.

Pressure	Soil Moisture Content									
	11.09%		16.07%		21.30%		24.58%		31.25%	
	Soil Firmness	Soil Bulk Density	Soil Firmness	Soil Bulk Density	Soil Firmness	Soil Bulk Density	Soil Firmness	Soil Bulk Density	Soil Firmness	Soil Bulk Density
(N)	**(kpa)**	**(g/cm^3)**	**(kpa)**	**(g/cm^3)**	**(kpa)**	**(g/cm^3)**	**(kpa)**	**(g/cm^3)**	**(kpa)**	**(g/cm^3)**
0	103.5	1.03	181	0.99	124.5	1.025	163	1.32	49	1.185
40									60.5	1.185
80									60	1.127
100	191	1.045	174	1.02	212	1.135	219.5	1.31		
120									45	1.2
160									45	2.23
200	196.25	1.08	212	1.07	223	1.155	215.5	1.305		
300	257	1.125	257	1.03	386	1.15	250	1.39		
400	281.75	1.11	303	1.06	302.5	1.2	223	1.365		
500	365	1.105	386	1.12	420	1.23	253.5	1.37		
600	397.25	1.115	416	1.08	461.5	1.285	280	1.345		
700	399.25	1.11	507	1.12	397.5	1.275	250	1.405		
800	456	1.16	553	1.13	492	1.355	291	1.375		
900	452.5	1.08	591	1.15	466	1.445				
1000	549	1.14	640	1.17	587	1.415				

The experimental data from the soil compaction test in Table 1 were processed and are visualised in Figure 6. At 10% soil moisture, the soil withstood pressures exceeding 1000 N. In this range, the soil firmness ranged from a minimum of 103.5 kPa to a maximum of 549 kPa, with the soil bulk density ranging from a minimum of 1.03 g/cm^3 to a maximum of 1.16 g/cm^3. At 15% soil moisture content, the soil withstood pressures greater than 1000 N. The soil firmness ranged from a minimum of 181 kPa to a maximum of 640 kPa, while the soil bulk density ranged from a minimum of 0.99 g/cm^3 to a maximum of 1.17 g/cm^3. At 20% soil moisture content, the soil withstood pressures greater than 1000 N. The soil firmness varied from a minimum of 124.5 kPa to a maximum of 587 kPa, and the soil bulk density ranged from a minimum of 1.025 g/cm^3 to a maximum of 1.445 g/cm^3. At 25% soil moisture content, the soil withstood a maximum pressure of approximately 800 N. The soil firmness ranged from a minimum of 163 kPa to a maximum of 291 kPa, while the soil bulk density ranged from a minimum of 1.305 g/cm^3 to a maximum of 1.405 g/cm^3. Finally, at 30% soil moisture content, the soil withstood a maximum pressure of approximately 160 N. The soil firmness ranged from a minimum of 49 kPa to a maximum of 60.5 kPa, and the soil bulk density ranged from a minimum of 1.185 g/cm^3 to a maximum of 2.23 g/cm^3.



(**a**) (**b**)

Figure 6. Soil compression test results. These are listed as follows: (**a**) soil firmness; (**b**) soil bulk density.

The results of the correlation analysis between soil firmness and soil bulk density at different moisture levels was performed using the Pearson Correlation Coefficient, and the results are presented in Table 2.

Table 2. Correlation analysis between soil firmness and soil bulk density.

Soil Moisture Content			Soil Firmness	Soil Bulk Density
11.09%	Soil firmness	Pearson Correlation	1	0.751 **
		Significance (Two-Tailed)		0.008
		Number of Cases	11	11
	Soil bulk density	Pearson Correlation	0.751 **	1
		Significance (Two-Tailed)	0.008	
		Number of Cases	11	11
16.07%	Soil firmness	Pearson Correlation	1	0.934 **
		Significance (Two-Tailed)		0.000
		Number of Cases	11	11
	Soil bulk density	Pearson Correlation	0.934 **	1
		Significance (Two-Tailed)	0.000	
		Number of Cases	11	11
21.30%	Soil firmness	Pearson Correlation	1	0.894 **
		Significance (Two-Tailed)		0.000
		Number of Cases	11	11
	Soil bulk density	Pearson Correlation	0.894 **	1
		Significance (Two-Tailed)	0.000	
		Number of Cases	11	11

Table 2. *Cont.*

Soil Moisture Content			Soil Firmness	Soil Bulk Density
24.58%	Soil firmness	Pearson Correlation	1	0.574
		Significance (Two-Tailed)		0.106
		Number of Cases	9	9
	Soil bulk density	Pearson Correlation	0.574	1
		Significance (Two-Tailed)	0.106	
		Number of Cases	9	9
31.25%	Soil firmness	Pearson Correlation	1	−0.528
		Significance (Two-Tailed)		0.361
		Number of Cases	5	5
	Soil bulk density	Pearson Correlation	−0.528	1
		Significance (Two-Tailed)	0.361	
		Number of Cases	5	5

** The correlation is significant at the 0.01 level (Two-Tailed).

At soil moisture contents of 11.09%, 16.07%, and 21.30%, the soil firmness exhibited a highly significant correlation with the soil bulk density. Notably, the correlation was the strongest at 16.07% soil moisture content, reaching 0.934. At 24.58% soil moisture content, the soil firmness and soil bulk density exhibited a positive correlation, but the correlation was not significant. At 31.25% soil moisture content, the soil firmness and soil bulk density exhibited negative correlations, but these correlations were not significant. The corresponding linear equations are as follows:

$$\begin{cases} y_1 = 2640.9x_1 - 2573.3 \\ y_2 = 2768.5x_2 - 2621.4 \\ y_3 = 975.93x_3 - 842.632 \\ y_4 = 615.12x_4 - 594.41 \\ y_5 = -8.6988x_5 + 63.951 \end{cases} \quad (3)$$

where y_1 and x_1 represent the soil firmness and soil bulk density under 10% soil moisture content conditions, y_2 and x_2 represent the soil firmness and soil bulk density under 15% soil moisture content conditions, y_3 and x_3 represent the soil firmness and soil bulk density under 20% soil moisture content conditions, y_4 and x_4 represent the soil firmness and soil bulk density under 25% soil moisture content conditions, and y_5 and x_5 represent the soil firmness and soil bulk density under 30% soil moisture content conditions.

The experimental results indicated that as the soil moisture content increased, the maximum pressure that the soil could bear decreased. Additionally, under constant soil moisture content conditions, there was a correlation between the soil firmness and soil bulk density. This implies that for subsequent experiments, it is possible to proceed with either the soil moisture content and soil bulk density approach or the soil moisture content and soil firmness approach. However, soil firmness is easier to determine and measure compared to soil density. Therefore, in this experiment, the subsequent main focus of the study was the physical soil parameters of moisture content and firmness. The specific indicators for soil moisture content and firmness were determined based on the results from the assessment conducted during the operation of the transplanting machine.

3.2. Transplanter Operation Soil Parameter Assessment

3.2.1. Soil Firmness Analysis

The results from the assessment of surface soil firmness before and after soil cultivation, at the furrow bottom, and after SCAC by the rapeseed blanket-shaped seedling transplanter are presented in Table 3.

Table 3. Soil firmness assessment results before and after transplanter operation.

Measurement Depth (mm)	Soil Firmness (kpa)				
	PBR	USAR	CSAR	PFCICS	SCAC
25	480.17	26.98	332.92	344.83	284.25
50	555.92	33.69	408.08	393.00	312.08
75	609.50	68.54	437.17	428.92	317.08
100	701.83	82.54	444.83	486.50	326.0

The processed data from Table 3 are illustrated in Figure 7.

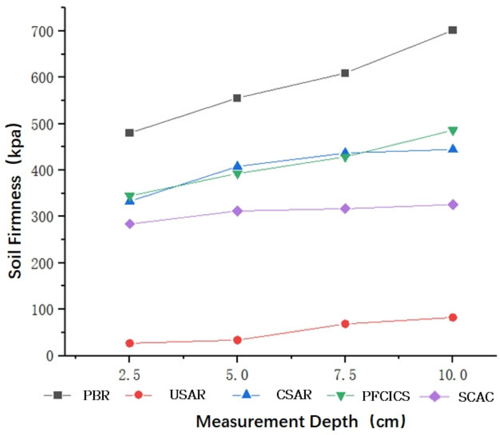


Figure 7. Soil firmness under different soil conditions before and after transplanting.

In the rice stubble fields, the soil firmness generally increased with increasing measurement depth. Before the operation of the transplanter, the soil firmness at the PBR stage exhibited the most significant increase. At a depth of 25 mm, the corresponding soil firmness was 480.17 kPa, and at a depth of 100 mm, the corresponding soil firmness reached 701.83 kPa, which represents an increase of 221.66 kPa. After the operation of the transplanter, the soil firmness at the USAR stage decreased to a range of 26.98~82.54 kPa. This can be attributed to the increased gaps between the soil particles during the rototilling process, which reduces the compaction of the soil. After transplanting, both the ridges formed with the actively driven furrow levelling and cutting roller and at the furrow bottom formed by the convex circular ring on the levelling roller exhibited a trend of increasing soil firmness. The soil firmness of the ridges increased by 110.91 kPa, and the maximum increase in the furrow soil firmness was 141.67 kPa. The SCAC device, through its pushing action, closed the planting furrows (seam closing), and during this process, the soil around the transplanted rapeseed plants was compacted, resulting in an increase in soil firmness, with the smallest increase being 41.75 kPa. Additionally, at depths of 50 mm and 75 mm, the soil firmness at the furrow bottom after transplanting was slightly lower than the soil firmness at the CSAR stage. This may have been due to the disruption of the soil structure caused by the machine after furrow cutting transplanting. At 25 mm, the soil firmness in the PFCICS was greater than the soil firmness in the CSAR, primarily because the furrow was initially formed with a significant penetration force. At 100 mm, the soil firmness in the PFCICS was greater than the soil firmness in the CSAR, mainly due to the greater depth of furrow penetration compared to the ridge depth.

3.2.2. Soil Moisture Content and Soil Bulk Density Analyses

The calculated results for the soil moisture content and soil bulk density under different conditions before and after the operation of the transplanter are presented in Table 4.

Table 4. Soil bulk density and soil moisture content under different conditions before and after operation.

Soil Physical Parameters	PBR	CSAR	PFCICS	SCAC
Soil bulk density/kpa	1.34	1.19	1.35	1.28
Soil moisture content	22.73%	24.73%	24.80%	25.35%

The experimental results revealed changes in the soil moisture content before and after the operation of the rapeseed blanket seedling combined transplanter. Prior to operation, the soil moisture content was 22.73%, while after operation, the average soil moisture content increased to 24.96%, representing a relative increase of 2.23% compared to the moisture content before operation. The main reason for this change was the significant evaporation of surface soil moisture before machine operation, while after machine operation, the lower soil layer was rotary tilled to the surface, leading to a relative increase in the soil moisture content.

There were significant changes in the soil bulk density before and after the operation of the transplanter. The average bulk density of the soil before machine operation was 1.34 g/cm^3, indicating that the soil was relatively compacted before machine operation. After machine operation, the average bulk density of the compacted surface soil was 1.19 g/cm^3, indicating an increase in the gaps between soil particles, resulting in a relative decrease in soil bulk density. In contrast, the average bulk density of the soil in the PFCICS was 1.35 g/cm^3. This is mainly due to the compression cutting method used for planting in furrows, which leads to the compact accumulation of soil particles, thereby increasing the soil bulk density. The soil average bulk density after the SCAC stage was 1.28 g/cm^3. This is because SCAC causes the soil at the edge of the furrow to be squeezed into the furrow, increasing the gaps between soil particles and reducing the soil bulk density.

In this experiment, soil operations were conducted using a rapeseed seedling combined transplanter in a rice stubble field. Soil parameters such as the soil firmness, soil bulk density, and soil moisture content were tested. The results at a moisture content ranging from 22.73% to 25.35%, within the 30–50 mm range, are as follows:

The average soil firmness before rototilling in the plot was 555.95 kPa, and the soil bulk density was 1.34 g/cm^3. The USAR had an average soil firmness of 408.08 kPa, and the soil bulk density was 1.19 g/cm^3. The PFCICS had an average soil firmness of 393.00 kPa and a soil bulk density of 1.35 g/cm^3. After SCAC, the average soil firmness was 312.08 kPa, and the soil bulk density was 1.28 g/cm^3.

The soil firmness changes were as follows: The soil firmness decreased by 93.94% from before rototilling to the USAR stages. The soil firmness increased by 1111.3% from the USAR to the CSAR stages. The soil firmness decreased by 3.7% from the CSAR to the PFCICS stages. The soil firmness decreased by 20.59% from the PFCICS to the SCAC stages.

The physical parameters of the soil before and after the operation of the rapeseed blanket seedling combined transplanter were also evaluated. Additionally, based on the results of this experiment, the specific experimental values for soil moisture content in the rapeseed blanket seedling furrow-cut transplanting soil conditions were 15%, 20%, 25%, and 30%, while for soil firmness, the values were 300 kPa, 400 kPa, and 500 kPa.

3.3. Experimental Study on the Soil Conditions Suitable for Furrow Cutting and Transplanting

The main morphological parameters of the rapeseed blanket seedlings before furrow cutting transplanting are shown in Table 5.

After two weeks of transplanting rapeseed blanket plants, the soil firmness was measured under different soil moisture content conditions. The measurement results are presented in Table 6.

Table 5. Key morphological parameters of rapeseed blanket seedling before transplanting.

Experiment	Parameter	Maximum Value	Minimum Value	Average Value	Standard Deviation
Experiment 1 (Nanjing)	Seedling Height/mm	100	80	86.9	6.62
	Stem Diameter/mm	2.62	1.66	2.23	0.26
	Dry Weight/g	0.111	0.059	0.088	0.018
Experiment 2 (Liyang)	Seedling Height/mm	113	85	99.1	8.28
	Stem Diameter/mm	2.5	1.7	2.03	0.23
	Dry Weight/g	0.142	0.067	0.097	0.022

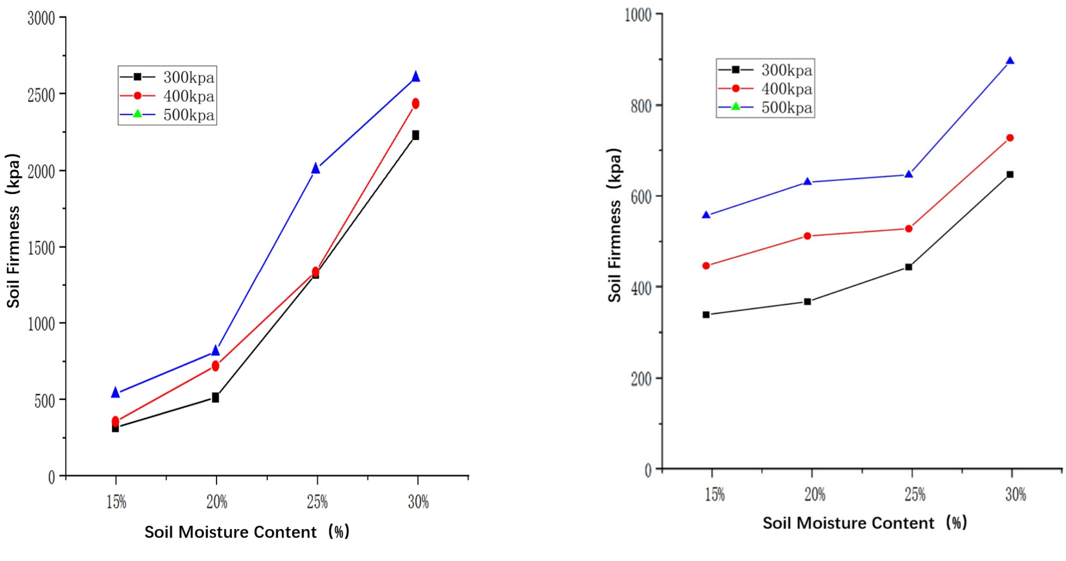
Table 6. Statistical analysis of soil firmness two weeks after transplanting rapeseed blanket seedlings with different soil moisture contents.

Experiment	Soil Moisture Content	Soil Firmness/kpa		
		300	400	500
Experiment 1 (Nanjing)	15%	311.25	350.25	534
	20%	508.5	717.5	810.5
	25%	1323.25	1339	2015.75
	30%	2242.25	2451	2620.25
Experiment 2 (Liyang)	15%	353.33	456.67	562.67
	20%	381.00	519.67	633.33
	25%	454.00	535.00	648.67
	30%	649.67	727.00	888.67

The data from Table 6 were processed and visualised, as shown in Figure 8, revealing an overall significant upwards trend in soil firmness two weeks after the transplantation of rapeseed blanket seedlings. Furthermore, under the initial high soil moisture content and firmness conditions, there was a more pronounced increase in soil firmness during the later stages.

The growth status of the rapeseed blanket seedlings two weeks after transplantation under different soil conditions are visualised in Figure 9.

The specific growth statistics are presented in Table 7.



(**a**) (**b**)

Figure 8. Changes in soil firmness two weeks after transplanting rapeseed blanket seedlings under Different soil moisture contents. These are listed as follows: (**a**) Experiment 1 (Nanjing); (**b**) Experiment 2 (Liyang).

Table 7. Statistical analysis of initial growth characteristic parameters after rapeseed transplantation under different soil conditions.

Experiment	Soil Moisture Content	Soil Firmness (kpa)	Survival Rate	Stem Diameter (mm)	Seedling Height (mm)	Dry Weight (g)
Experiment 1 (Nanjing)	15%	300	53.3%	2.29	102.5	0.105
		400	60%	2.06	108.33	0.162
		500	60%	2.59	146.11	0.310
	20%	300	100%	2.19	139.67	0.260
		400	100%	2.64	168.07	0.450
		500	100%	2.64	192	0.453
	25%	300	100%	2.35	158	0.341
		400	100%	2.08	137.2	0.232
		500	100%	2.07	101.67	0.183
	30%	300	100%	1.90	94.8	0.149
		400	100%	1.92	95.93	0.141
		500	100%	1.85	83.87	0.137
Experiment 2 (Liyang)	15%	300	13.3%	1.70	81	0.079
		400	20%	2.05	115	0.125
		500	6.7%	1.95	117.5	0.1715
	20%	300	13.3%	2.15	105.5	0.132
		400	60%	2.22	130.5	0.35
		500	66.7%	2.11	149.3	0.363
	25%	300	86.7%	1.77	137.5	0.2123
		400	86.7%	1.72	109.5	0.1633
		500	73.3%	1.71	99.3	0.139
	30%	300	100%	1.75	114.8	0.2113
		400	80%	1.84	114.7	0.189
		500	80%	1.73	122.1	0.1737

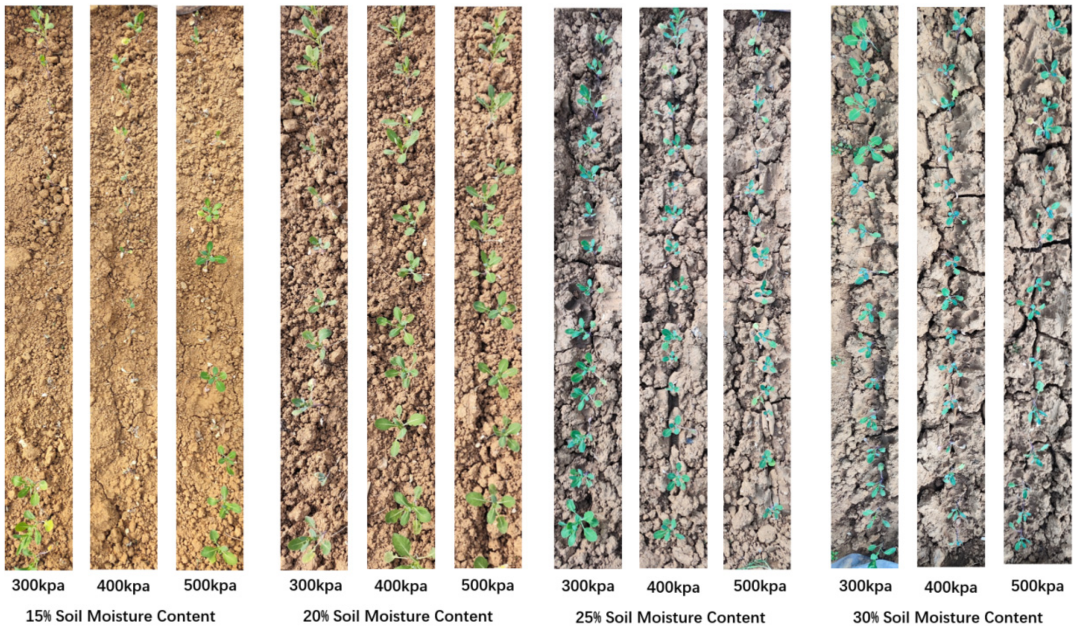
According to Table 7, the four sets of data for the survival rate, root diameter, seedling height, and dry weight were subjected to dimensionless processing and averaging [28], with the following calculation equations:

$$Y_{ij} = \frac{x_{ij}}{\frac{1}{n}\sum_{i=1}^{n} x_{ij}} \quad (4)$$

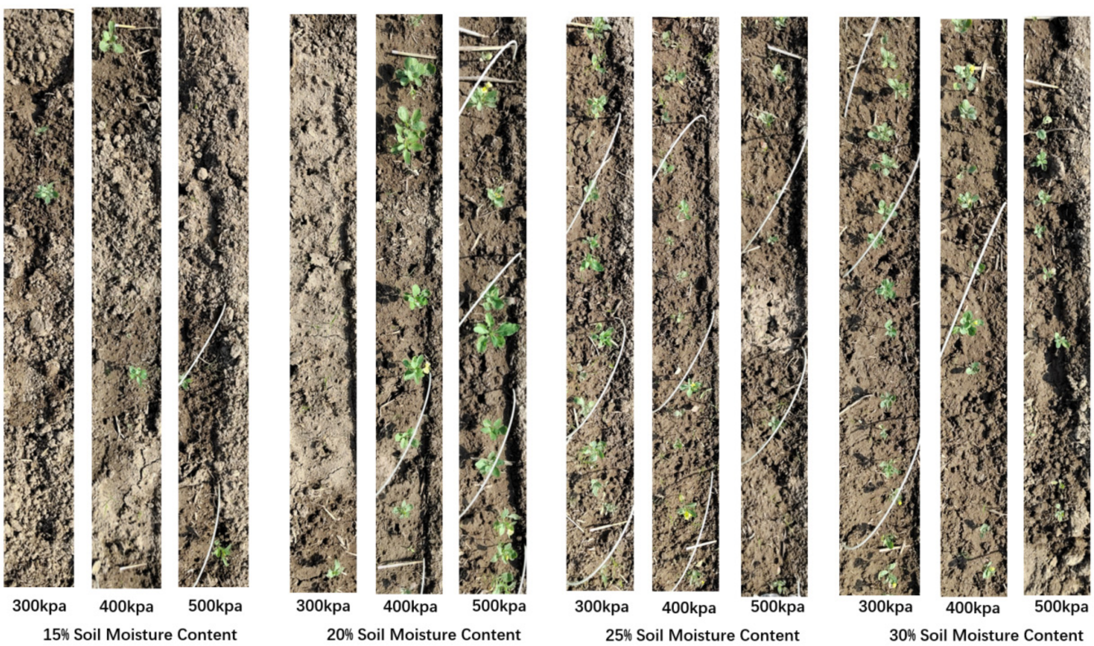
where Y_{ij} represents the dimensionless value after averaging for the i-th observation in the j-th group, x_{ij} represents the original value for the i-th observation in the j-th group before averaging, and n is the sample size for each group. The dimensionless values of the survival rate, stem diameter, seedling height, and dry weight were subsequently fitted after averaging. The fitted data served as the growth values after transplanting for rapeseed blanket seedlings, and the following equation was used:

$$Y = 0.1x_1 + 0.2x_2 + 0.3x_3 + 0.4x_4 \quad (5)$$

where Y represents the growth value of the rapeseed blanket seedlings, x_1 is the stem diameter; x_2 is the survival rate; x_3 is the seedling height; and x_4 is the dry weight. The results of two separate experiments are shown in Table 8. Under the condition of 20% moisture content, the initial growth of rapeseed after transplanting was optimal at 500 kPa soil firmness. In contrast, at moisture levels of 25% and 30%, the initial growth of the rapeseed blanket seedlings after transplanting was relatively better at 300 kPa soil firmness. However, at a 15% moisture content, the initial growth performance of the rapeseed after transplanting was not ideal at all the soil firmness levels.



(**a**)



(**b**)

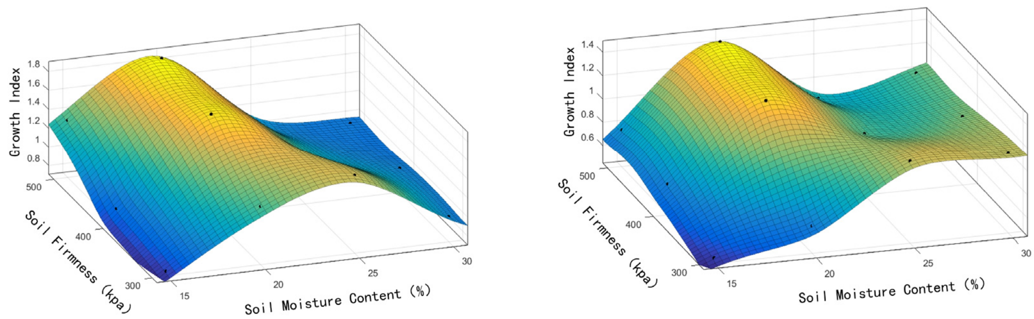
Figure 9. Growth statuses of rapeseed blanket seedlings two weeks after transplantation under different soil conditions. These are listed as follows: (**a**) Experiment 1 (Nanjing); (**b**) Experiment 2 (Liyang).

The data were processed and visualised, as shown in Figure 10. Within the moisture content range of 15–30%, the optimal soil firmness decreased with an increasing soil moisture content. Therefore, under higher soil moisture levels, soil firmness can be expected to be reduced. Under different soil firmness conditions, the growth of rapeseed seedlings initially increased, and then decreased with an increasing soil moisture content. At a soil firmness of 300, the growth value was highest at 25% moisture content. At soil firmness levels of 400 and 500, the growth value was highest at 20% moisture content.

Table 8. Statistical summary of growth values in the initial stage after rapeseed blanket seedling transplantation under different soil conditions.

Soil Moisture Content	Soil Firmness (kpa)	Experiment 1 (Nanjing) Growth Values	Experiment 2 (Liyang) Growth Values
15%	300	0.76	0.49
	400	0.90	0.71
	500	1.32	0.76
20%	300	1.32	0.68
	400	1.78	1.34
	500	1.85	1.43
25%	300	1.53	1.15
	400	1.25	0.97
	500	1.06	0.86
30%	300	0.97	1.13
	400	0.96	1.03
	500	0.92	0.99

By observing and comparing the early growth of seedlings under different soil conditions after the transplantation of the rapeseed blanket seedlings, it was found that following transplantation, the soil moisture content had a significant initial impact on the growth performance. This primarily influenced the vitality of the rapeseed plants; the higher the soil moisture content was, the shorter the slow growth seedling period was, and the better the vitality of the rapeseed plants were after transplantation. However, an excessively high soil moisture content was not necessarily advantageous. After the transplantation of rapeseed, soil firmness had a considerable impact on late-stage growth. Specifically, when the soil moisture content was less than 20%, increasing the soil firmness to 500 kPa was beneficial for moisture retention and the growth of the rapeseed plants. At a soil moisture content ranging from 20 to 25%, a soil firmness of 400 kPa was most suitable for ensuring the vitality of rapeseed plants and subsequent growth. When the soil moisture content exceeded 25%, reducing the soil firmness to 300 kPa was beneficial for rapeseed growth. Excessive levels of moisture can lead to soil compaction, with the result that the rapeseed root systems are unable to penetrate the soil, affecting growth, as illustrated in Figure 11.



(**a**) (**b**)

Figure 10. Growth of rapeseed blanket seedlings during the initial transplanting stage under different soil conditions. These are listed as follows: (**a**) Experiment 1 (Nanjing); (**b**) Experiment 2 (Liyang).

Figure 11. After soil compaction, the rapeseed root system is unable to penetrate the soil.

Soil compaction refers to a phenomenon in which the soil particles are compacted due to pressure, resulting in a dense soil structure. Soil compaction reduces the soil's porosity, affecting soil aeration and water permeability, and thereby adversely affecting the growth of plant roots. The physical properties of soil and plant growth are intricately linked to the occurrence of soil compaction [29–32]. By comparing the growth of the rapeseed roots under different soil conditions during the early stages of transplanting, it was observed that when the soil was not compacted, the roots penetrated the soil well, absorbed nutrients, and exhibited good development, as shown in Figure 12a. However, after soil compaction, the rapeseed roots were unable to penetrate the soil layer, could only grow along the compacted furrow bottom, and were unable to absorb nutrients from the soil. This ultimately resulted in poor rapeseed growth, as illustrated in Figure 12b. Moreover, the higher the soil moisture content and firmness were, the more severe the soil compaction was in later growth stages, and the more significant the inability of the rapeseed roots to penetrate the soil was.

(**a**) (**b**)

Figure 12. The impact of soil compaction on the growth of rapeseed roots after transplanting. The soil types are listed as follows: (**a**) noncompacted soil; (**b**) compacted soil.

4. Conclusions

This study experimentally investigated the impact of changes in soil physical conditions within the micro-environment around roots and stems (30–50 mm) after the transplantation of rapeseed blanket seedlings on the growth of rapeseed plants. Suitable soil physical parameters were identified for the post-transplantation growth of rapeseed blanket seedlings, providing a theoretical basis for the design optimisation of the soil tillage components to be used when operating the rapeseed seedling transplanter and for the field management of rapeseed after transplantation. This study aimed to create favourable soil conditions for the growth and development of rapeseed after transplanting. The main conclusions are as follows:

1. To identify the primary soil physical parameters affecting growth after mechanical transplanting with the rapeseed seedling transplanter, the relationships between the soil moisture content, soil firmness, and soil bulk density were studied through soil plate penetration tests. A correlation between soil firmness and soil bulk density was established, allowing for analysis and the determination that the key soil physical parameters for subsequent research are primarily the soil moisture content and soil firmness.
2. To understand the impact of the combined transplanter operation on soil, the changes in soil firmness, soil bulk density, and soil moisture content before and after the operation were detected and analysed. The results indicated that the transplanter operation process had a compacting effect on the soil. Based on these findings, the soil parameters were determined for subsequent rapeseed seedling furrow cutting transplanting experiments: soil moisture contents of 15%, 20%, 25%, and 30% and soil firmness values of 300 kPa, 400 kPa, and 500 kPa.
3. To explore the suitable soil parameters for rapeseed seedling transplantation, the micro-environment around the roots and stems (30–50 mm) was selected to study the impact of changes in the soil physical parameters on rapeseed growth. Based on the results of Conclusions (1) and (2), growth experiments with rapeseed blanket seedlings were conducted using the furrow cutting transplanting principle. These findings indicate that at the early stages after rapeseed transplantation, the soil moisture content significantly influences rapeseed vitality. As the soil moisture content increased, the slow-growing seedling period shortened, and the effect on vitality improved. In contrast, the influence of soil firmness was relatively small during this period. In the later stages of growth after seedling establishment, soil firmness had a greater impact. Specifically, when the soil moisture content was less than 20%, increasing the soil firmness to 500 kPa was beneficial for moisture retention and the growth of rapeseed plants. At a soil moisture content ranging from 20 to 25%, a soil firmness of 400 kPa was most suitable for ensuring rapeseed vitality and late-stage growth. When the soil moisture content exceeded 25%, reducing the soil firmness to 300 kPa was beneficial for rapeseed growth, but excessively high soil firmness and moisture contents may lead to soil compaction, affecting rapeseed seedling development.
4. In general, the soil moisture content in rice stubble fields was typically greater than 25%. Therefore, the objective should be to reduce soil firmness by improving and optimising the design of soil working components. This approach aims to create favourable soil conditions for the growth of rapeseed plants after transplanting using the rapeseed blanket seedling transplanter.

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References

1. Yin, Y.; Wang, H. Achievement, Problem and Scientific Policy of Rapeseed Industry Development in China. *J. Agric. Sci. Technol.* **2012**, *14*, 1–7.
2. Zhang, Y.; Zhang, H.; Leng, S.; Ni, J.; Zuo, Q.; Yang, G.; Fang, Y. Suitable sowing date of rapeseed blanket seedlings. *Chin. J. Oil Crop Sci.* **2020**, *42*, 210–215.
3. Hu, Y.; Gu, J.; Guo, J. Factors Influencing Mechanized Production and Harvesting Methods for Rapeseed. *J. Agric. Mech. Res.* **2020**, *42*, 179–182.
4. Hu, Q.; Wei, H.; Yan, Y.; Zhang, X.; Liu, L.; Shi, J.; Zhao, Y.; Qin, L.; Chen, C.; Wang, H. Rapeseed Research and Production in China. *Crop J.* **2017**, *5*, 127–135. [CrossRef]
5. Zuo, Q.; Liu, J.; Shan, J.; Zhou, J.; Wang, L.; Yang, G.; Leng, S.; Liu, H. Carbon and Nitrogen Assimilation and Partitioning in Canola (*Brassica napus* L.) in Saline Environment. *Commun. Soil Sci. Plant Anal.* **2019**, *50*, 1700–1709. [CrossRef]
6. Wu, C.; Yi, Z. Selection of the Full Mechanization Technology Route for Rapeseed in China. *J. Chin. Agric. Mech.* **2009**, *02*, 3–6.
7. Wang, Y.; Lu, J.; Li, X.; Li, J.; Liu, P.; Xu, W.; Yang, Y. Study on Nitrogen Fertilizer Effects and Optimum Fertilizer Rates for Transplanting and Direct-Seeding Rapeseed. *Sci. Agric. Sin.* **2011**, *44*, 4406–4414.
8. Wu, C.; Zhu, C.; Zhang, M.; Zhang, C. Key Points of Rapeseed Mechanized Production Technology. *Agric. Equip. Technol.* **2012**, *38*, 20–21.
9. Yuan, W.; Wu, C. Analysis of the Current Situation and Development Trend of Rapeseed Transplanting Machinery in China. *J. Chin. Agric. Mech.* **2007**, *06*, 61–63.
10. Zuo, Q.; Wang, L.; Zheng, J.; You, J.; Yang, G.; Leng, S.; Liu, J. Effects of Uniconazole Rate on Agronomic Traits and Physiological Indexes of Rapeseed Blanket Seedling. *Oil Crop Sci.* **2020**, *5*, 198–204. [CrossRef]
11. Ma, N.; Li, Y.; Hu, Q.; Li, J.; Li, G.M.; Zhang, C.L. Research of Agronomic Techniques for Mechanical Production of Winter Rape (*Brassica napus* L.) in South China. *Chin. J. Oil Crop Sci.* **2010**, *32*, 451–456.
12. Jiang, L. Study on the Mechanism and Optimization of Mechanical Transplanting of Rapeseed Blanket Seedlings. Master's Thesis, Anhui Agricultural University, Hefei, China, 2019.
13. Zuo, Q.; You, J.; Wang, L.; Zheng, J.; Li, J.; Qian, C.; Lin, G.; Yang, G.; Leng, S. A Balanced Sowing Density Improves Quality of Rapeseed Blanket Seedling. *Agronomy* **2022**, *12*, 1539. [CrossRef]
14. Labra, M.-H.; Struik, P.-C.; Calderini, D.-F.; Evers, J.B. Leaf Nitrogen Traits in Response to Plant Density and Nitrogen Supply in Oilseed Rape. *Agronomy* **2020**, *10*, 1780. [CrossRef]
15. Wu, J.; Tang, Q.; Yuan, W.; Wang, S.; Wu, C. Design and Parameter Optimization of Ditching and Compacting Parts of Rapeseed Carpet Seedling Transplanter. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 46–53.
16. Jiang, L.; Tang, Q.; Wu, J.; Yu, W.; Zhang, M.; Jiang, D.; Wei, D. Design and Test of Seedbed Preparation Machine before Transplanting of Rapeseed Combined Transplanter. *Agriculture* **2022**, *12*, 1427. [CrossRef]
17. Wu, C.; Feng, J.; Wu, J.; Li, D.; Li, X.; Shu, J.; Wang, K. Comprehensive Testing and Analysis on Working Effects of the Rape Transplanters. *J. Chin. Agric. Mech.* **2023**, *44*, 1–5.
18. Ungureanu, N.; Croitoru, Ş.; Biriş, S.; Voicu, G.; Vlăduţ, V.; Selvi, K.Ç.; Boruz, S.; Marin, E.; Matache, M.; Manea, D.; et al. Agricultural soil compaction under the action of agricultural machinery. *Simp. Aktual. Zadaci Meh. Poljopr.* **2015**, *1*, 31–42.
19. Zhou, P. Influence of Deep Tillage on Soil Structure and Water Utilization in Wheat-Corn Double Cropping Fields. Master's Thesis, Shandong Agricultural University, Taian, China, 2020.
20. Jia, M.; Huang, L.; Li, Q.; Zhao, J.N.; Zhang, Y.J.; Yang, D.L.; Wang, H. Effects of tillage methods on physico-chemical and microbial characteristics of farmland soil and nutritional quality of wheat. *J. Plant Nutr. Fertil.* **2022**, *28*, 1964–1976.
21. Zhou, Y.; Lu, B. Effects of Agricultural Machinery Compaction on Soil Physical Properties. *J. Chin. Agric. Mech.* **2018**, *39*, 66–70.
22. Gao, A.; Zhang, X.; Wang, Y.; Huang, X.; Han, Z. Experimental Study on the Influence of Mechanical Compaction on Soil Structure in Different Types of Alfalfa Fields. *For. Mach. Woodwork. Equip.* **2019**, *47*, 53–58.
23. Keller, T.; Maria, S.; Tino, C.; Horn, R.; Or, D. Historical Increase in Agricultural Machinery Weights Enhanced Soil Stress Levels and Adversely Affected Soil Functioning. *Soil Tillage Res.* **2019**, *194*, 104293. [CrossRef]
24. Zhou, Y.; Liu, N.; Yu, L.; Lu, B.; Zhang, W.; Liu, X. Soil Mechanical Compaction and Its Effect on Crop Growth. *Chin. Agric. Sci. Bull.* **2022**, *38*, 83–88.
25. Ren, L.; Wang, L.; Lin, L.; Zhang, B. The Progress and Prospect of Soil Compaction by Agricultural Machinery in Arable Land: A Review. *Acta Pedol. Sin.* **2023**, *60*, 610–626.

26. *GB/T 5262-2008*; General Provisions for the Determination of Test Conditions for Agricultural Machinery. China Standards Press: Beijing, China, 2009.
27. Wang, Z.; Leng, S.; Zhang, Y.; Liu, L.; Shi, J.; Zhao, Y.; Qin, L.; Chen, C.; Wang, H. Research Progress on Seedling Transplanting Technology of Rapeseed Blanket-like Seedlings. *Jiangsu J. Agric. Sci.* **2023**, *39*, 1247–1255.
28. Li, L.; Guo, Y.; Yi, P. Analyzing the Principles for Choosing Dimensionless Methods. *J. Syst. Manag.* **2016**, *25*, 1040–1045.
29. Mada, D.; Ibrahim, S.; Hussaini, I. The effect of soil compaction on soil physical properties southern adamawa state agricultural soils. *Int. J. Eng. Sci.* **2013**, *2*, 70–74.
30. Tu, Z.; Feng, W.; Xu, T. Analysis of Soil Compaction Causes and Its Effect on Crop Water Absorption. *Shaanxi J. Agric. Sci.* **2020**, *66*, 71–73.
31. Augustin, K.; Kuhwald, M.; Brunotte, J.; Duttmann, R. Wheel Load and Wheel Pass Frequency as Indicators for Soil Compaction Risk: A Four-Year Analysis of Traffic Intensity at Field Scale. *Geosciences* **2020**, *10*, 292. [CrossRef]
32. Colombi, T.; Keller, T. Developing Strategies to Recover Crop Productivity after Soil Compaction—A Plant Eco-physiological Perspective. *Soil Tillage Res.* **2019**, *191*, 156–161. [CrossRef]