Compatibility between rapeseed bare-root seedling morphological characteristics and the transplanter parameters

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Abstract: The compatibility between the morphological characteristics (MCs) of rapeseed bare-root seedlings and transplanters directly affects planting quality. To improve the adaptability of transplanters to the MCs of different rapeseed cultivars, this study focused on six winter rapeseed cultivars (A1: Huyou 17, A2: Huayouza 9, A3: Fengyou 520, A4: Zhongyou 108, A5: Zheyou 50, and A6: Huayouza 62). Five MCs—root length (RL), seedling height (SH), root diameter (RD), stem thickness (ST), and seedling width (SW)—were measured during the seedling ages (25-40 d). Multiple comparisons were conducted to identify cultivars with no significant differences (NSD, α=0.05) in MCs, while skewness and kurtosis were analyzed to assess temporal variations in MC distributions. Quadratic polynomial regression was employed to model the growth trends of MCs for each cultivar. The results showed that the skewness and kurtosis ranges of MCs were –0.65 to 1.16 and 1.62 to 6.28, respectively, indicating significant variability in growth symmetry and concentration both within and among cultivars. As seedling age increased, the number of cultivars with NSD in MCs progressively decreased (25 d: 5; 30 d: 4; 35 d: 3; 40 d: 2), but A3, A5, and A6 maintained consistent stability before 35 d. Based on MC statistical analysis, the key design parameters for the transplanter were determined as follows: flat belt width was 180 mm, positioning bar spacing was 70 mm, flexible belt width was 150 mm, clamping distance was 8 mm, seedling drop height was 180 mm, and planting depth was 40 mm. Field tests demonstrated that the transplanter exhibited superior compatibility with cultivars A3, A5, and A6, achieving seedling delivery success rates of 93.75% (A3), 93.23% (A5), and 92.71% (A6), along with significantly higher planting success rates compared to the control group (A1, A2, A4). This study provides a theoretical basis for optimizing the compatibility between transplanters and rapeseed bare-root seedlings, as well as guiding the structural design of transplanting machinery.

Keywords: rapeseed bare-root seedling, transplanter, morphological compatibility, cultivar selection, growth uniformity, seedling delivery device, design optimization
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1 Introduction

Rapeseed is an important economic and oil crop globally[1-3]. Transplanting rapeseed seedlings can alleviate crop rotation conflicts, increase yield per unit area, and improve the land multiple cropping index[4,5]. Compared to blanket seedlings and substrate block seedlings, bare-root seedling transplanting is simpler, more cost-effective, and highly practical, as it does not require specialized nursery techniques[6,7]. This makes bare-root seedling transplanting the main method for rapeseed cultivation in China[8]. However, it is predominantly done manually, which involves high labor intensity, low production efficiency, and high costs, thereby hindering the development of full mechanization in rapeseed cultivation[9,10].

To reduce labor costs and improve planting efficiency, major rapeseed-producing countries such as Canada, Germany, and Australia mainly adopt mechanical direct planting methods, with little research and reporting on mechanical transplanting of rapeseed seedlings. Research on mechanized rapeseed seedlings transplanting in China focuses primarily on blanket seedlings and substrate block seedlings[11,12]. Jiang et al.[13], drawing on the principles of rice transplanter block cutting and seedling insertion, designed a high-efficiency, fully automatic rapeseed blanket seedling transplanter by measuring and analyzing the three-dimensional parameters of the substrate blocks and the mechanical properties such as adhesion and friction coefficients when the seedling needles clamp the substrate. Jin et al.[14] developed a series of technologies and equipment for rapeseed blanket seedling cultivation, transplanting, and detection. Wu et al.[15] developed the 2ZY-6 rapeseed blanket seedling transplanter for seedlings grown in standard trays with specific density, height, and leaf age. Hu et al.[16] measured the side length, mass, seedling height, water content, and related friction coefficients and compression characteristics of rapeseed seedling substrate blocks, subsequently designing a bidirectional progressive

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seedling delivery device, a roller-type seedling picking device, and an integrated seedbed preparation device for furrowing, covering, and compacting, leading to the development of a fully automatic substrate block seedling transplanter. Cui et al.[17] designed an intermittent seedling delivery and automatic seedling separation mechanism based on the measured mechanical properties of substrate block compressive strength and friction angle, achieving the required success rate for seedling separation and substrate integrity. Based on comprehensive measurements of seedling height, width, and substrate block dimensions, Liao et al.[18,19] first developed an inclined seedling separation mechanism, followed by a reciprocating-type seedling picking device. Due to the protective and supportive role of the substrate in carrying the seedlings, the transplanting process for blanket and substrate block seedlings primarily involves the interaction between the substrate and the transplanting mechanism. Therefore, the design of these transplanters mainly considers the shape, size, and mechanical properties of the substrate[20]. Alternatively, improvements in nursery techniques can produce uniformly sized seedlings, enhancing their compatibility with the transplanter.

Unlike blanket seedlings and substrate block seedlings, bare-root seedling transplanting involves direct contact and interaction between the roots, stems, and leaves of the seedlings with the transplanter mechanisms. The morphological characteristics and their variations significantly influence the planting quality of the transplanter. Therefore, when designing and optimizing the key structural and operational parameters of rapeseed bare-root seedling transplanters, it is crucial to fully consider the morphological characteristics of the seedlings[9]. Zhu[21] found that the diameter of sweet potato seedlings gradually decreases with increased placement time, and this characteristic was used to optimize the design of the seedling clamping claw. Based on the specific main stem length, main root diameter, the average value of the cut length and cut diameter of Sanqi seedlings, Lai et al.[22,23] completed the structural design of the separation and directional planting devices, achieving low-damage and orderly separation and planting of the seedlings. Xu et al.[24] optimized the design of a duckbill-type film transplanting mechanism for Salvia miltiorrhiza based on the morphological characteristics of seedlings at a specific age and agronomic transplanting practices, improving the upright seedling and planting depth qualification rates. Liu et al.[8] analyzed the growth distribution of morphological characteristics such as the root length and plant cone angle of rapeseed bare-root seedlings from 28 to 40 d after sowing to determine the structural and operational parameter ranges for a duckbill-type rapeseed transplanter. In summary, researchers have conducted extensive studies on the compatibility of transplanters to bare-root seedlings like sweet potato, Salvia miltiorrhiza, and Sanqi, but these studies mainly focus on specific seedling age and single cultivar, which limits the general applicability of the corresponding machinery. The morphological characteristics of rapeseed bare-root seedlings vary across different cultivars and seedling ages, resulting in low seedling-transplanter compatibility. Further research is needed on the morphological characteristics of rapeseed bare-root seedlings from different cultivars for mechanical transplanting.

Statistics and analysis of the morphological characteristics' differences and growth trends among rapeseed seedlings of various stages and different cultivars can furnish foundational data for the design and optimization of transplanter structural and operational parameters. Concurrently, it provides guiding suggestions for selecting the best period and suitable cultivars for mechanical transplanting of rapeseed, thereby enhancing the compatibility of the transplanter to the morphological traits of rapeseed bare-root seedlings. This study selected six winter rapeseed cultivars suitable for cultivation in the mid-lower Yangtze River. From 25 to 40 d after sowing, the root length (RL), seedling height (SH), root diameter (RD), stem thickness (ST), and seedling width (SW) were measured. Multiple comparisons were conducted to identify cultivars with small statistical differences in morphological characteristics. The changes in the symmetry and concentration of the growth distribution of these characteristics were analyzed, and their trends over the seedling period were explored. Based on the research of the morphological characteristics in this paper, the structure and operational parameters of the seedling delivery device for a rapeseed bare-root seedling transplanter were designed. Field experiments were conducted to verify the transplanting effectiveness. This study provides theoretical data for the design of seedling-contact components in mechanized rapeseed bare-root seedling transplanting systems, while offering guidance for selecting optimal transplanting periods and suitable cultivars. These findings contribute to enhanced compatibility between transplanters and rapeseed bare-root seedlings.

2 Rapeseed seedling cultivation and measurement of morphological characteristic parameters

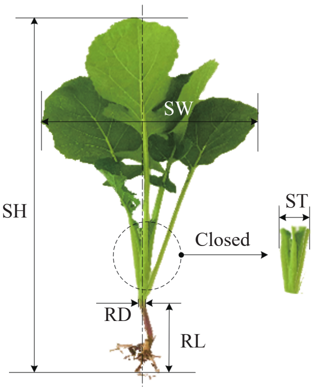
2.1 Experimental design for rapeseed seedling cultivation

Six commercial winter rapeseed cultivars suitable for cultivation in the mid-lower Yangtze River were selected for the study. The cultivars are Huyou 17 (A1), Huayouza 9 (A2), Fengyou 520 (A3), Zhongyou 108 (A4), Zheyou 50 (A5), and Huayouza 62 (A6). To closely simulate actual production conditions and in accordance with local rapeseed cultivation practices, the seedling cultivation experiment was conducted in an open environment. The experiment was carried out on September 20, 2022, at the rapeseed experimental base of Huazhong Agricultural University (30°47'N, 114°34'E). During the cultivation process, we used a 1GQN-200H rotary tiller (Haofeng Company, China) with consistent working parameters to prepare a block. The tillage depth was 100-150 mm and the moisture content was 31%. The block was then divided into six contiguous plots, each measuring 2 m×6 m, and numbered sequentially. The sowing plots for each variety were randomly assigned using the random number generation function in Excel[25]. For each plot, 7,800 seeds were prepared using an SLY-C microcomputer automatic seed counter (Top Instrument Company, Zhejiang, China), corresponding to a sowing density of 650 seeds/m^2. Finally, the seeds were manually and evenly scattered on the block surface, followed by a thin, fine layer of soil covering the seeds (just enough to cover the seeds, i.e., a sowing depth approximately equal to the seed diameter).

2.2 Measurement items and methods for morphological characteristic parameters of rapeseed bare-root seedlings

Starting 25 d after sowing, samples were taken every 5 days, totaling four sampling events. In each test plot, 300 rapeseed seedlings were randomly selected using the five-point sampling method for morphological characteristic (MCs) measurements, as detailed in Figure 1. To minimize random errors, each parameter was measured three times, and the average value was taken[26].

Root length (RL), seedling height (SH), and seedling width (SW): Photographs of bare-root seedlings were taken using a Nikon Z5 digital camera and a light calibration board. The images were then imported into the LA-S Series Plant Image Analysis System (Wanshen Inc., China) for measurement using the ruler tool. RL was measured as the vertical distance from the tip of the main root to the root-stem junction. SH was the vertical distance from the tip of the main root to the top of the bare-root seedling. SW was the distance between the two widest points of the bare-root seedling.



Note: RL is the root length; SH is the seedling height; RD is the root diameter; ST is the stem thickness; SW is the seedling width.

Figure 1 Morphological characteristics (MCs) of the rapeseed bare-root seedling

Root diameter (RD) and stem thickness (ST): The maximum diameter of the root-stem junction was measured as RD, and the maximum diameter of the stem after closing was measured as ST. These measurements were taken using an MNT951221 digital caliper (with a measurement error of 0.02 mm).

3 Statistical analysis of morphological characteristic parameters of rapeseed bare-root seedlings

3.1 Cultivars with no significant differences in morphological characteristics

The root length (RL), seedling height (SH), root diameter (RD), stem thickness (ST), and seedling width (SW) data of the rapeseed bare-root seedlings were subjected to multiple comparisons among the cultivars using IBM SPSS Statistics 25.0 (IBM, USA). If the same MCs of the rapeseed seedlings across different cultivars followed a normal distribution, one-way analysis of variance (ANOVA), Bonferroni multiple comparisons (for homogeneity of variance), or Tamhane's T2 multiple comparisons (for heterogeneity of variance) were employed. If the MCs did not completely follow a normal distribution, the Kruskal-Wallis H non-parametric test and Dunn's multiple comparisons were used[27].

The multiple comparisons of RL, SH, RD, ST, and SW among the six rapeseed cultivars from 25 to 40 d after sowing are listed in Table 1. The results indicated significant differences in these MCs among the six cultivars (α=0.05), with a coefficient of variation range of 8.79% to 28.10%. The cultivars with no significant differences (NSD, α=0.05) in each morphological characteristic are summarized in Table 2:

Table 1 Multiple comparisons of morphological characteristics (MCs) among rapeseed cultivars from 25 to 40 d of seedling ages (α=0.05)

MCs		25 d		30 d		35 d		40 d	
		Median/mm	COV/%	Median/mm	COV/%	Median/mm	COV/%	Median/mm	COV/%
RL	A1	43.7a	18.73	52.0a	17.99	53.3a	18.50	62.0ab	11.67
	A2	35.0b	23.99	44.3a	20.42	51.9a	20.81	52.7c	17.81
	A3	35.8ab	28.10	48.4a	21.31	58.8a	18.64	59.3abc	18.21
	A4	41.0ab	19.91	47.6a	24.89	52.7a	18.04	60.4abc	16.57
	A5	45.4a	19.12	49.7a	18.93	49.9a	19.98	55.6c	14.42
	A6	42.8ab	20.18	48.7a	19.66	53.4a	19.35	63.6a	11.72
SH	A1	215.3a	12.23	292.1a	10.97	308.8a	10.64	322.4abc	10.25
	A2	188.9b	15.10	279.2a	14.33	270.8b	13.33	297.0c	11.52
	A3	206.9ab	12.88	243.3bc	13.21	279.7b	11.74	314.3bc	11.07
	A4	213.0a	12.26	240.4bc	13.05	281.8b	11.42	315.8abc	10.73
	A5	213.6a	12.25	247.2b	13.11	293.3ab	12.09	326.7ab	9.96
	A6	205.3ab	12.81	267.6ab	12.28	290.8ab	10.80	338.4a	9.78
RD	A1	4.28ab	17.50	4.99a	15.54	5.10ab	17.12	5.32ab	13.27
	A2	4.64a	18.80	5.02a	16.75	5.47a	12.81	5.78a	13.56
	A3	4.16ab	23.87	4.33a	21.87	5.14ab	16.15	5.36ab	23.03
	A4	3.79b	21.60	4.69a	26.07	4.79b	16.39	5.14b	13.64
	A5	4.03ab	18.28	4.59a	17.95	4.59b	17.63	5.09b	18.28
	A6	4.21ab	24.31	4.57a	20.64	5.16ab	20.85	5.66a	15.46
ST	A1	9.4a	20.29	11.0ab	19.18	12.9c	11.48	15.4cd	9.84
	A2	8.4b	21.61	10.6b	19.63	11.5c	14.33	14.6d	10.63
	A3	8.5ab	21.78	12.5a	17.88	15.6ab	11.02	16.5bc	9.15
	A4	10.2a	18.54	13.6a	18.22	16.6a	9.79	18.2a	8.79
	A5	9.7a	18.80	11.3a	20.46	15.0b	11.19	15.3d	9.96
	A6	9.5a	20.30	11.1ab	21.67	14.8b	12.01	16.9ab	9.33
SW	A1	127.9a	24.52	173.0a	22.69	183.7a	22.22	195.0a	19.70
	A2	136.9a	24.50	185.4a	21.22	191.2a	21.74	200.0a	18.86
	A3	138.5a	24.14	170.9ab	20.40	183.1a	21.12	210.3a	18.49
	A4	126.2a	23.10	163.2b	24.23	181.5a	21.70	198.5a	20.05
	A5	135.0a	22.38	169.1b	23.49	189.0a	22.23	208.3a	18.57
	A6	125.0a	25.04	158.3b	26.25	167.3a	25.90	187.1a	20.33

Note: COV is the coefficient of variation; RL is the root length; SH is the seedling height; RD is the root diameter; ST is the stem thickness; SW is the seedling width; A1 is the Huyou 17; A2 is the Huayouza 9; A3 is the Fengyou 520; A4 is the Zhongyou 108; A5 is the Zheyou 50; A6 is the Huayouza 62. Different lowercase letters (a, b, and c) following the medians indicate significant differences at the 0.05 level.

Table 2 Summary of cultivars with no significant differences (NSD) in morphological characteristics (MCs)

Seedling ages	MCs	Cultivars with NSD (α=0.05)	Cultivars with NSD among all MCs
25 d	RL	(A1 A3 A4 A5 A6), (A2 A3 A4 A6)	(A1 A3 A4 A5 A6), (A2 A3)
	SH	(A1 A3 A4 A5 A6), (A2 A3 A6)	
	RD	(A1 A2 A3 A5 A6), (A1 A3 A4 A5 A6)	
	ST	(A1 A3 A4 A5 A6), (A2 A3)	
	SW	(A1 A2 A3 A4 A5 A6)	
30 d	RL	(A1 A2 A3 A4 A5 A6)	(A3 A4 A5 A6), (A1 A2)
	SH	(A1 A2 A6), (A3 A4 A5 A6)	
	RD	(A1 A2 A3 A4 A5 A6)	
	ST	(A1 A3 A4 A5 A6), (A1 A2 A6)	
	SW	(A1 A2 A3), (A3 A4 A5 A6)	
35 d	RL	(A1 A2 A3 A4 A5 A6)	(A3 A5 A6), (A3 A4)
	SH	(A1 A5 A6), (A2 A3 A4 A5 A6)	
	RD	(A1 A2 A3 A6), (A1 A3 A4 A5 A6)	
	ST	(A1 A2), (A3 A4), (A3 A5 A6)	
	SW	(A1 A2 A3 A4 A5 A6)	
40 d	RL	(A1 A3 A4 A6), (A2 A3 A4 A5)	(A1 A3)
	SH	(A1 A2 A3 A4), (A1 A3 A4 A5)、(A1 A4 A5 A6)	
	RD	(A1 A2 A3 A6), (A1 A3 A4 A5)	
	ST	(A1 A2 A5), (A1 A3), (A3 A6),(A4 A6)	
	SW	(A1 A2 A3 A4 A5 A6)	

Note: RL is the root length; SH is the seedling height; RD is the root diameter; ST is the stem thickness; SW is the seedling width; A1 is the Huyou 17; A2 is the Huayouza 9; A3 is the Fengyou 520; A4 is the Zhongyou 108; A5 is the Zheyou 50; A6 is the Huayouza 62.

a) At 25-d seedling age, the MCs (RL, SH, RD, ST, SW) showed NSD:

·Between cultivars A2 and A3

·Among cultivars A1, A3, A4, A5 and A6

b) At 30-d seedling age, all MCs showed NSD:

·Between A1 and A2

·Among A3, A4, A5 and A6

c) At 35-d seedling age, all MCs showed NSD:

·Between A3 and A4

·Among A3, A5 and A6

d) At 40-d seedling age, all MCs showed NSD exclusively between A1 and A3

Before 35-d seedling age (inclusive), the MCs of rapeseed seedlings showed high consistency and stability·among A3, A5 and A6. Differences in MCs can lead to poor compatibility of bare-root rapeseed seedlings to mechanical transplanting, resulting in high seedling damage and low transplanting efficiency. Therefore, in designing transplanter components and conducting mechanical transplanting, cultivars A3, A5, and A6 can be prioritized. Additionally, as the seedling age progressed, the maximum number of cultivars showing NSD in all MCs gradually decreased:

·At 25 d: 5 cultivars (A1, A3, A4, A5, A6)

·At 30 d: 4 cultivars (A3, A4, A5, A6)

·At 35 d: 3 cultivars (A3, A5, A6)

·At 40 d: only between A1 and A3

This progression clearly demonstrates that to ensure the transplanter's simultaneous compatibility with multiple cultivars, mechanical transplanting operations should be completed before the 35-d seedling age, thereby maximizing equipment universality.

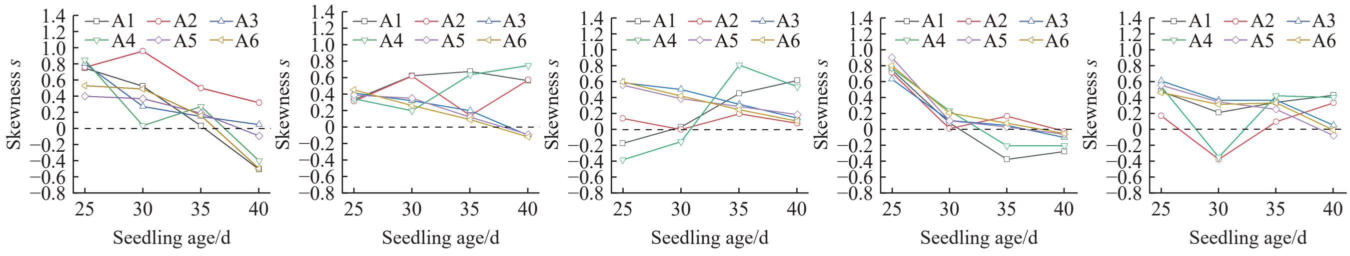
3.2 Growth distribution of morphological characteristics

The skewness and kurtosis of different morphological characteristics (MCs) at various seedling ages were calculated for all rapeseed cultivars. Skewness (s) is the third standardized central moment of a random variable, and kurtosis (k) is the fourth central moment of a random variable divided by the fourth power of the standard deviation[28]. For a sample of n rapeseed bare-root seedlings' morphological characteristic (denoted as the random variable X), the skewness and kurtosis are calculated as follows[29]:

$$\begin{cases} s = \dfrac{\hat{m}_3}{\hat{\sigma}^3} = \dfrac{\dfrac{1}{n}\sum\limits_{i=1}^{n}(x_i-\bar{x})^3}{\left[\dfrac{1}{n}\sum\limits_{i=1}^{n}(x_i-\bar{x})^2\right]^{\frac{3}{2}}} \\ k = \dfrac{\hat{m}_4}{\hat{\sigma}^4} = \dfrac{\dfrac{1}{n}\sum\limits_{i=1}^{n}(x_i-\bar{x})^4}{\left[\dfrac{1}{n}\sum\limits_{i=1}^{n}(x_i-\bar{x})^2\right]^{2}} \end{cases} \tag{1}$$

where, $\hat{m}_3$ and $\hat{m}_4$ are the third and fourth central moments of the random variable X, respectively.

The trends in skewness and kurtosis of root length (RL), seedling height (SH), root diameter (RD), stem thickness (ST), and seedling width (SW) for the six rapeseed cultivars from 25 to 40 d of seedling ages are shown in Figures 2 and 3, respectively. The range of changes in skewness and kurtosis for each morphological characteristic is summarized in Table 3. As seen in Figures 2, 3, and Table 3, during the 25 to 40 d of seedling ages, there were differences in the symmetry and concentration of the growth distribution of each morphological characteristic for both the same variety at different ages and different cultivars at the same age. Regarding skewness, there are left-skewed (s<0) and right-skewed (s>0) distributions; as for kurtosis, there are flat (k<3) and peaked (k>3) distributions. The overall skewness range was from –0.51 to 0.96, and the overall kurtosis range was from 1.50 to 5.87.

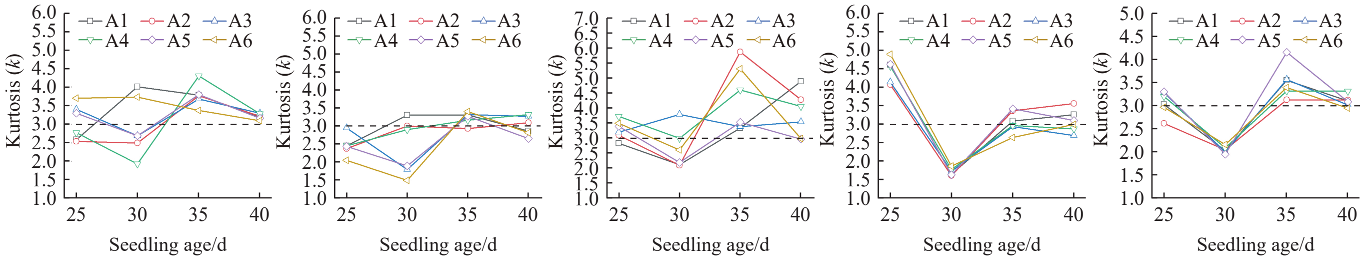


a. Root length (RL) b. Seedling height (SH) c. Root diameter (RD) d. Stem thickness (ST) e. Seedling width (SW)

Note: A1 is the Huyou 17; A2 is the Huayouza 9; A3 is the Fengyou 520; A4 is the Zhongyou 108; A5 is the Zheyou 50; A6 is the Huayouza 62.

Figure 2 Trends in skewness of morphological characteristics (MCs) from 25 to 40 d of seedling ages

Currently, the compatibility of transplanter seedling-contact components to the MCs of rapeseed bare-root seedlings needs further improvement. For example: (a) Flexible disc transplanter: This transplanter typically includes a furrow opener, flexible disc, and press wheel. During operation, the flexible disc rotates to hold the seedlings, guiding their roots vertically downward into the furrow, after which the soil is backfilled and compacted by the press wheel to complete the planting[30]. When the root length (RL) of rapeseed bare-root seedlings is too long, it is difficult to ensure effective soil coverage of the roots, which can lead to the seedlings bending over or being exposed. Conversely, when the RL is too short, soil can easily cover the leaves and stem, resulting in buried seedlings and reduced transplanting survival rates[31]. (b) Duckbill-type transplanter: This type comprises a duckbill planting device, rotary seedling drum, transmission mechanism, and press wheel. During operation, the rotary seedling drum positions the bare-root seedling into the duckbill planting device, which lowers it into the soil. Once the duckbill planting device retracts, the soil covers the roots, and the press wheel compacts the soil[32]. However, if the seedling height (SH) or the seedling width (SW) is too large, the seedlings can get stuck in the duckbill mechanism, causing issues such as seedling dragging or hanging, which leads to missed transplants[33]. (c) Chain clamp transplanter: This transplanter consists of a furrow opener, a chain-clamp rotating planting mechanism, and a press wheel. In operation, seedlings are manually placed into the clamp, which rotates and secures the seedlings, moving downward to the seedbed surface, positioning the seedlings into the furrow. The soil then immediately flows back to cover the roots, and finally, the press wheel compacts the soil to complete the transplanting process. However, when seedlings are either too short or too wide, the clamp mechanism may fail to grip them effectively, resulting in a lower success rate of transplanting[34]. The greater the kurtosis of the MCs of rapeseed bare-root seedlings, the more concentrated their distribution, which is highly beneficial for mechanical transplanting and can improve seedling utilization rate. To maximize the compatibility of transplanters to rapeseed bare-root seedlings, transplanting should be prioritized during seedling ages with higher kurtosis of MCs. Figure 4 presents the growth trend of skewness and kurtosis for the mean values of RL, SH, RD, ST, and SW for cultivars A3, A5, and A6. It can be observed that the skewness of each morphological characteristic of these three cultivars gradually decreases with the increase of the seedling age and tends towards 0; whereas kurtosis shows a trend of first decreasing and then increasing, eventually tending towards 3. This indicates that there are more vigorous seedlings in the early stage of this variety group, but the growth is more uniform in the later stage. Moreover, for these five MCs, except for stem thickness (ST), the seedling age corresponding to the maximum kurtosis is the 35 d. Therefore, for these three cultivars, it should be considered a priority to carry out mechanical transplanting at the seedling age of 35 d.



a. Root length (RL) b. Seedling height (SH) c. Root diameter (RD) d. Stem thickness (ST) e. Seedling width Note: A1 is the

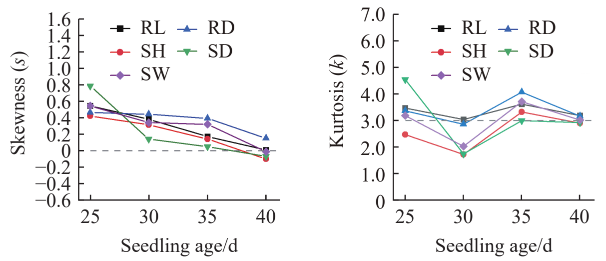
Note: A1 is the Huyou 17; A2 is the Huayouza 9; A3 is the Fengyou 520; A4 is the Zhongyou 108; A5 is the Zheyou 50; A6 is the Huayouza 62.

Figure 3 Trends in kurtosis of morphological characteristics (MCs) from 25 to 40 d of seedling ages

Table 3 Range of skewness and kurtosis for morphological characteristics (MCs) of rapeseed bare-root seedling

MCs	Skewness	Kurtosis	Coefficient of Variation
RL	–0.51 – 0.96	1.93 – 4.30	11.67% - 28.10%
SH	–0.12 – 0.75	1.50 – 3.40	9.78% - 15.10%
RD	–0.37 – 0.81	2.11 – 5.87	12.81% - 26.07%
ST	–0.37 – 0.90	1.62 – 4.88	8.79% - 21.78%
SW	–0.38 – 0.61	1.96 – 4.16	18.49% - 26.25%
All above	–0.51 – 0.96	1.50 – 5.87	8.79% - 28.10%

Note: RL is the root length; SH is the seedling height; RD is the root diameter; ST is the stem thickness; SW is the seedling width.



a. Mean skewness b. Mean kurtosis

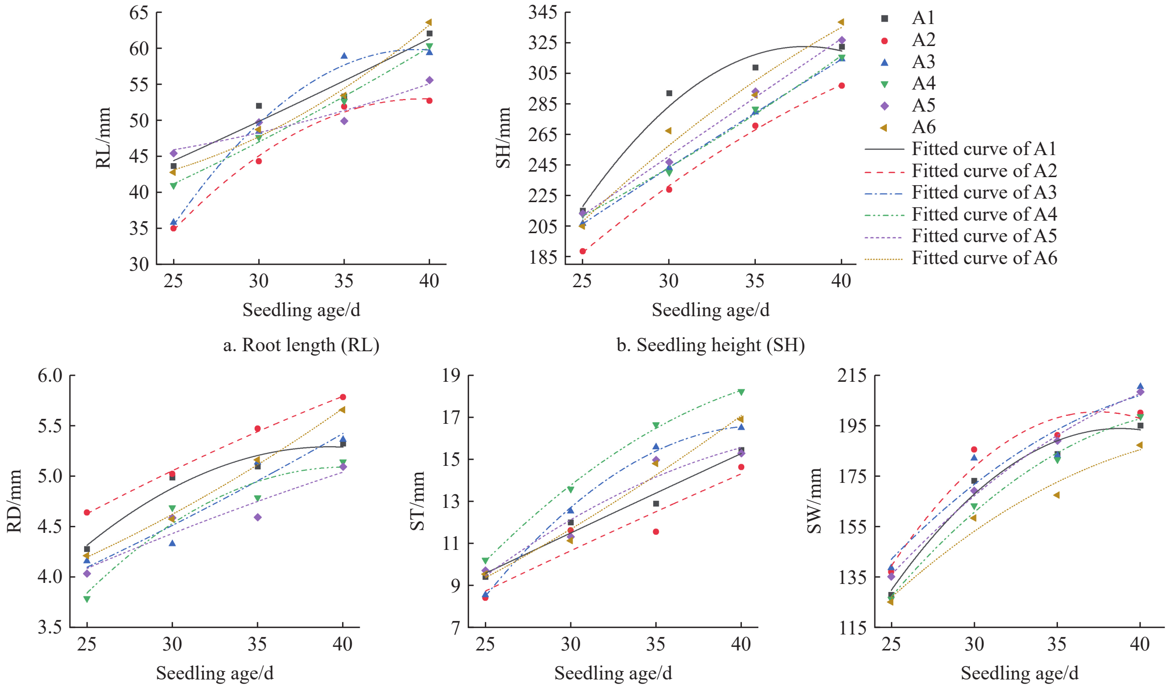
Note: RL is the root length; SH is the seedling height; RD is the root diameter; ST is the stem thickness; SW is the seedling width.

Figure 4 Trends in the mean skewness and mean kurtosis for rapeseed cultivars A3, A5, and A6

3.3 Growth trends of morphological characteristics

The arithmetic mean and median both represent measures of central tendency for a distribution. When the population follows a normal distribution, the arithmetic mean and median are equal, both reflecting the population's average level. However, when the population is skewed, the median better represents the average level[35]. Preliminary tests indicated that the morphological characteristics (MCs) of rapeseed bare-root seedlings exhibited skewed distributions, so the median was used to represent the average level of the seedlings at each seedling age. The median values of root length (RL), seedling height (SH), root diameter (RD), stem thickness (ST), and seedling width (SW) from the four measurements were subjected to quadratic polynomial regression analysis using the least squares method to examine the growth trends over time[36].

The results of the quadratic polynomial regression analysis for the MCs of rapeseed bare-root seedlings from the six cultivars are shown in Figure 5. The fitted curves for the MCs over the seedling ages (25-40 d) were obtained, and the parameters of the fitted curves along with the determination coefficients (R^2) are listed in Table 4. All R^2 values were greater than 0.893 60, with an average R^2 of 0.969 19, and the coefficients of the linear terms (a_1) were all non-zero. Based on the fitted curves in Figure 5 and the parameters in Table 4, it can be concluded that RL, SH, RD, ST, and SW of the different rapeseed cultivars exhibited near-linear or quadratic increases over the seedling ages from 25 to 40 d. The growth rates of the same morphological characteristic differed among cultivars, showing three patterns: constant rate increase, rapid increase, and slow increase. For example, considering stem thickness (ST) (Figure 5d), ST of cultivars A1 and A2 showed a near-linear increase over time, cultivars A3, A4, and A5 showed a slow increase, and variety A6 exhibited a rapid increase.



a. Root length (RL) b. Seedling height (SH)

c. Root diameter (RD) d. Stem thickness (ST) e. Seedling width (SW)

Note: A1 is the Huyou 17; A2 is the Huayouza 9; A3 is the Fengyou 520; A4 is the Zhongyou 108; A5 is the Zheyou 50; A6 is the Huayouza 62.

Figure 5 Quadratic polynomial fitted curves of morphological characteristics (MCs) of rapeseed bare-root seedlings

Table 4 Parameters and determination coefficients of quadratic polynomial fitted curves for morphological characteristics (MCs) of rapeseed bare-root seedlings from 25 to 40 d

MCs	Curve parameters and R^2	A1	A2	A3	A4	A5	A6
RL	a_0	19.96	−80.74	−125.85	19.83	44.11	51.63
	a_1	0.88	6.75	9.47	0.60	−0.27	−1.39
	a_2	0.00	−0.09	−0.12	0.01	0.01	0.04
	R^2	0.938 52	0.993 64	0.991 72	0.995 39	0.912 85	0.990 47
SH	a_0	−582.60	−136.32	10.14	102.70	18.58	−149.93
	a_1	47.82	16.51	8.30	2.73	7.78	18.01
	a_2	−0.63	−0.14	−0.02	0.07	0.00	−0.15
	R^2	0.976 37	0.997 90	0.999 98	0.996 26	0.995 75	0.978 18
RD	a_0	−2.16	1.93	2.43	−3.69	1.94	3.08
	a_1	0.38	0.13	0.05	0.44	0.10	0.01
	a_2	0.00	0.00	0.00	−0.01	0.00	0.00
	R^2	0.958 16	0.997 23	0.928 87	0.944 20	0.902 94	0.995 68
ST	a_0	−0.29	−1.73	−35.61	−21.51	−13.50	1.63
	a_1	0.40	0.45	2.53	1.72	1.24	0.18
	a_2	0.00	0.00	−0.03	−0.02	−0.01	0.01
	R^2	0.970 44	0.893 66	0.998 15	0.998 18	0.935 60	0.980 04
SW	a_0	−314.65	−355.23	−128.04	−189.63	−131.47	−105.66
	a_1	26.23	29.70	14.83	17.65	14.37	12.66
	a_2	−0.34	−0.40	−0.16	−0.20	−0.15	−0.13
	R^2	0.976 14	0.956 34	0.911 74	0.994 73	0.996 81	0.969 71

Note: A1 is the Huyou 17; A2 is the Huayouza 9; A3 is the Fengyou 520; A4 is the Zhongyou 108; A5 is the Zheyou 50; A6 is the Huayouza 62; RL is the root length; SH is the seedling height; RD is the root diameter; ST is the stem thickness; SW is the seedling width; a_0 is the constant term; a_1 is the linear term coefficient; a_2 is the quadratic term coefficient; R^2 is the determination coefficients.

At present, standardized mechanized transplanting protocols for rapeseed are lacking across different cultivating regions in China, and the cultivars of rapeseed planted vary by region. Therefore, the mechanical transplanting period should be selected based on the growth trends of the MCs of bare-root seedlings for each variety. For example, according to the seedling height (SH) trends in Figure 5b, cultivars A1, A5, and A6 grew faster from 25 to 40 d compared to cultivars A3 and A4, so the transplanting period should be appropriately earlier for A1, A5, and A6. Conversely, variety A2 grew more slowly and should have its transplanting period delayed. Table 5 summarizes the median ranges of RL, SH, RD, ST, and SW for the six cultivars of rapeseed bare- root seedlings from 25 to 40 d. For cultivars A3, A5, and A6, the ranges of these MCs are as follows: RL 35.8-63.6 mm, SH 205.3-338.4 mm, RD 4.03-5.66 mm, ST 8.5-16.9 mm, and SW 125.0-210.3 mm.

Table 5 Median ranges for morphological characteristics (MCs) of rapeseed bare-root seedlings with age of 25-40 d

Cultivars	RL		SH		RD		ST		SW	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
A1	43.7	62.0	215.3	322.4	4.28	5.32	9.4	15.4	127.9	195.0
A2	35.0	52.7	188.9	297.0	4.64	5.78	8.4	14.6	136.9	200.0
A3	35.8	59.3	206.9	314.3	4.16	5.36	8.5	16.5	138.5	210.3
A4	41.0	60.4	213.0	315.8	3.79	5.14	10.2	18.2	126.2	198.5
A5	45.4	55.6	213.6	326.7	4.03	5.09	9.7	15.3	135.0	208.3
A6	42.8	63.6	205.3	338.4	4.21	5.66	9.5	16.9	125.0	187.1
All above	35.0	63.6	188.9	338.4	3.79	5.78	8.4	18.2	125.0	210.3

Note: RL is the root length; SH is the seedling height; RD is the root diameter; ST is the stem thickness; SW is the seedling width; A1 is the Huyou 17; A2 is the Huayouza 9; A3 is the Fengyou 520; A4 is the Zhongyou 108; A5 is the Zheyou 50; A6 is the Huayouza 62.

4 Seedling delivery device of the transplanter for rapeseed bare-root seedlings and its parameter matching

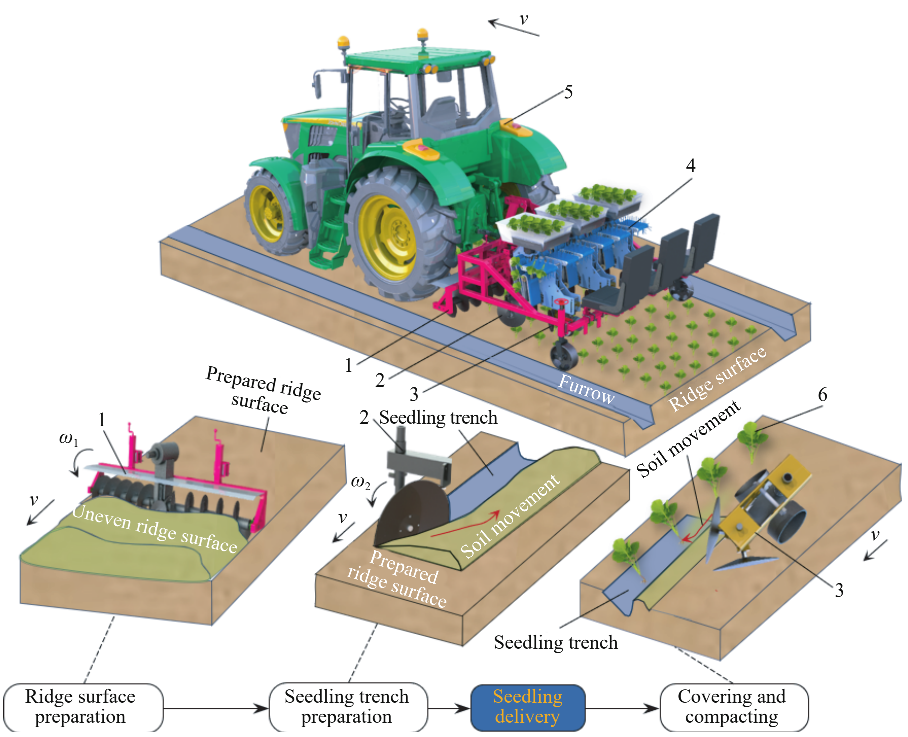
Based on the statistical analysis of morphological characteristic parameters of rapeseed bare-root seedlings, our team designed and developed a transplanter for rapeseed bare-root seedlings. The matching degree of key structural and operational parameters of the rapeseed bare-root seedling transplanter with the morphological characteristics (MCs) of rapeseed bare-root seedlings is a crucial factor affecting the transplanting performance[37].

4.1 Working principle of the transplanter and seedling feeding device

The main technical parameters of the transplanter are listed in Table 6, and a working schematic is provided in Figure 6. During transplanting, the transplanter was pulled by a tractor, and the seedbed preparation device leveled the seedbed surface. The furrowing device moved forward with the machine, turning the soil to one side to form a V-shaped furrow. The seedling delivery device sequentially placed the rapeseed bare-root seedlings into the furrow with leaves upward and roots downward, positioning them on one side of the furrow. After the seedlings fell into the furrow, the soil covering and pressing device turned the soil from the other side of the furrow to cover the roots of the seedlings, ensuring good soil contact and completing the transplanting process.

Table 6 Main technical parameters of the transplanter for rapeseed bare-root seedling

Parameters	Values
Working object	Rapeseed bare-root seedlings
Supporting power (electric motor)/kW	>60
Working speed/km·h^{-1}	0.72-1.20
Working width/mm	2000
Planting row distance/mm	Broad distance: 500 Narrow distance: 200
Plant distance/mm	200-300
Planting frequency/Plants·(row·min)$^{-1}$	40-60
Number of rows	6

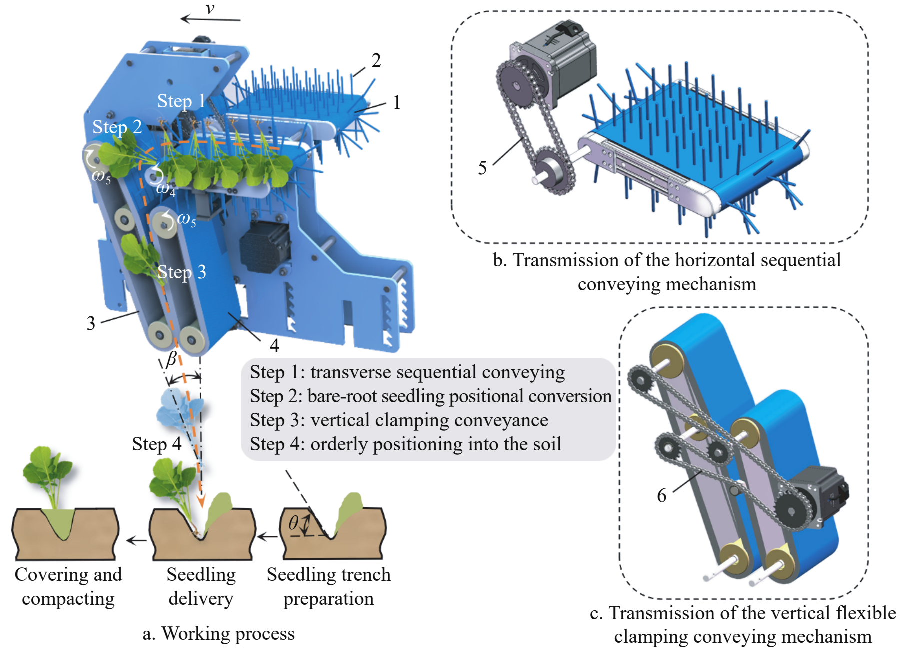


Note: v is the forward speed of the transplanter, km/h; ω_1 is the angular velocity of the seedbed preparation device, rad/s; ω_2 is the angular velocity of the seedling trench preparation device, rad/s.

1. Seedbed preparation device 2. Furrowing device 3. Soil covering and pressing device 4. Seedling delivery device 5. Tractor 6. Rapeseed bare-root seedling

Figure 6 Working schematic of the rapeseed bare-root seedling transplanter

The seedling delivery device is a key component of the transplanter, consisting of two main parts: the horizontal sequential conveying mechanism and the vertical positioning conveying mechanism. The horizontal sequential conveying mechanism is primarily composed of a transverse conveyor belt with positioned flexible bars attached to it, driven by chain Ⅰ. The vertical flexible clamping conveying mechanism mainly consists of two flexible belts operating at a constant speed in opposite directions driven by chain Ⅱ. The working process of the seedling delivery device is divided into four stages (shown in Figure 7): (a) Horizontal sequential conveying: The rapeseed bare-root seedlings are constrained between the positioned flexible bars of the horizontal sequential conveying mechanism, separated from other seedlings, and sequentially conveyed to the junction of the horizontal and vertical mechanisms; (b) Seedling position conversion: The positioned flexible bars guide the bare-root seedlings with their roots downward into the vertical flexible clamping conveying mechanism. The clamping area formed by flexible belt Ⅰ and flexible belt Ⅱ completes the position conversion; (c) Vertical clamping conveying: After entering the clamping area, the seedlings are steadily clamped and conveyed downward as flexible belt Ⅰ and flexible belt Ⅱ gradually move closer together; (d) Orderly positioning into soil: The seedlings are released from the clamping area and, under the influence of inertia, are directionally placed into the furrow below with roots first. The subsequent seedbed preparation device then promptly completes soil covering and pressing.



Note: v is the forward speed of the transplanter, m/s; ω_4 is the angular velocity of the transverse conveyor belt, rad/s; ω_5 is the angular velocity of the flex belt Ⅰ and Ⅱ, rad/s; β is the inclination angle of the clamped seedling, (°); θ is the inclination angle of the furrow slope, (°).

1. Flat belt 2. Positioned flexible bar 3. Flexible belt Ⅰ 4. Flexible belt Ⅱ 5. Chain Ⅰ 6. Chain Ⅱ

Figure 7 Working principle and transmission of the seedling delivery device

4.2 Matching of seedling delivery device parameters with morphological characteristics of rapeseed bare-root seedlings

During the process of delivering seedlings to the furrow, the seedling delivery device directly interacts with the bare-root seedlings. The design of the key structural and operational parameters of the delivery device must consider the relevant morphological characteristics (MCs) of the seedlings. The interaction between the seedling delivery device and the rapeseed bare-root seedlings is shown in Figure 8. The following key parameters are discussed:

(a) Flat belt width (B_1) and positioned flexible bar spacing (S_1): Bench tests indicated that when 3/5 of the entire seedling is on the horizontal conveyor belt, it ensures that the seedlings do not fall off during horizontal sequential conveying. To prevent seedlings from moving due to machine vibration during field operations, the positioned flexible bars should constrain the seedlings. The spacing (S_1) of the limiting soft strips should be greater than the stem thickness (ST) but less than the seedling width (SW), which can be expressed as:

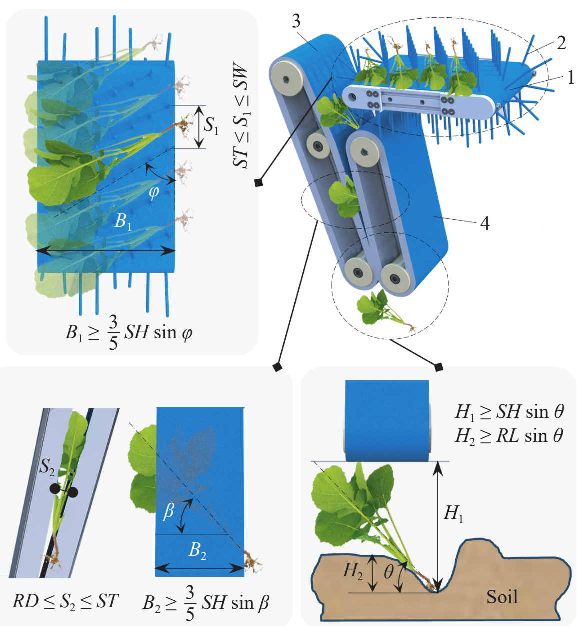
$$\begin{cases} B_1 \geq \frac{3}{5} SH \sin\varphi \\ ST \leq S_1 \leq SW \end{cases} \tag{2}$$

where, φ is the inclination angle of the positioned flexible bars, taken as 60°.

(b) Flexible belt width (B_2) and clamping distance (S_2): The flexible belts clamp the rapeseed bare-root seedlings and convey them downward while maintaining a fixed orientation with an inclination angle of β. To ensure stable clamping of the seedlings and minimize damage, at least 3/5 of the entire seedling should be clamped, and the clamping distance (S_2) should be smaller than the stem thickness (ST) but larger than the root diameter (RD), which can be expressed as:

$$\begin{cases} B_2 \geq \frac{3}{5} SH \sin\beta \\ RD \leq S_2 \leq ST \end{cases} \tag{3}$$

where, β is the inclination angle of the seedling in the clamped state, taken as 30°.



Note: Φ is the inclination angle of the positioned flexible bars, (°); β is the inclination angle of the clamped seedling, (°); θ is the inclination angle of the furrow slope, (°); B_1 is the width of the flat belt, mm; S_1 is the row distance of the positioned flexible bar, mm; B_2 is the width of the flexible belt, mm; S_2 is the clamping spacing, mm; H_1 is the height of seedling drop, mm; H_2 is the planting depth, mm.

1. Transverse conveyor belt 2. Positioned flexible bar 3. Flexible belt Ⅰ 4. Flexible belt Ⅱ

Figure 8 Key parameter analysis of the interaction between the seedling delivery device and rapeseed bare-root seedlings

(c) Seedling dropping height (H_1) and planting depth (H_2): After detaching from the seedling delivery device, the rapeseed bare-root seedlings rely on inertia to fall into the furrow. If the seedlings are too short, the large dropping space can cause random orientation changes, affecting the accuracy of placement in the furrow. Conversely, if the seedlings are too long, they may not completely detach from the delivery device before encountering soil interference, leading to issues such as dragging, burying, or exposing the seedlings, which impacts the planting success rate. To ensure the root system of the seedlings is adequately covered with soil, the following condition should be met when the seedlings drop into the furrow, as illustrated in Figure 8:

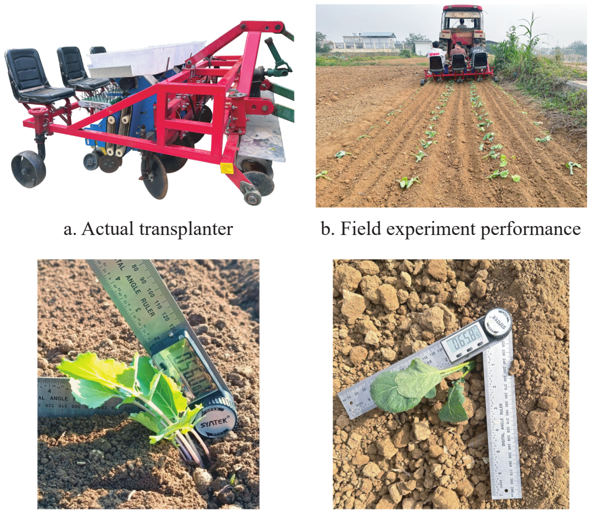
$$\begin{cases} H_1 \geq SH\sin\theta \\ H_2 \geq RL\sin\theta \end{cases} \tag{4}$$

where, θ is the inclination angle of the furrow slope. This angle is crucial for determining the uprightness of the seedlings after transplanting. According to the national standard "NY/T 1924-2010 Technical specifications of quality evaluation for rapeseed transplanters", the required uprightness of transplanted rapeseed seedlings is considered with θ set at 30°.

The MCs of rapeseed bare-root seedlings showed significant differences among all six cultivars (α=0.05). According to the statistical results in Table 2, there were no significant differences (NSD) in the MCs among cultivars A3, A5, and A6 during the 25-35 d of seedling ages. To enhance the compatibility of rapeseed bare-root seedlings with the developed transplanter, priority can be given to breeding cultivars A3, A5, and A6 among the six studied cultivars. Based on the morphological characteristic ranges for these three cultivars in Table 5 and Equations (2), (3), and (4), the following parameters can be determined: The width of the flat belt for the horizontal sequential conveying mechanism (B_1) should be >175.8 mm; the spacing of the positioned flexible bars (S_1) should be 16.9-125.0 mm; the width of the flexible belt (B_2) should be >101.5 mm; the clamping distance (S_2) should be 5.66-8.50 mm; the seedling dropping height (H_1) should be >169.2 mm; and the planting depth (H_2) should be >31.8 mm. For the design of this transplanter, the following values were selected: B_1 = 180 mm, S_1 = 70 mm, B_2 = 150 mm, S_2 = 8 mm, H_1 = 180 mm, and H_2 = 40 mm.

4.3 Field transplanting performance verification experiment

To validate the compatibility of the self-developed rapeseed bare-root seedling transplanter (Figure 9a) with selected cultivars, field experiments were conducted using six 35-day rapeseed cultivars at Huazhong Agricultural University's Modern Agricultural Demonstration Base on October 20, 2023 (Figure 9b). The experimental group comprised Fengyou 520 (A3), Zheyou 50 (A5), and Huayouza 62 (A6), while Huyou 17 (A1), Huayouza 9 (A2), and Zhongyou 108 (A4) served as controls. The experiment was conducted on rotary-tilled soil with an initial moisture content of 15.05% and soil fragmentation rate of 85.34%. A Dongfanghong 954 tractor was operated at speeds ranging from 0.80 to 1.20 km/h. Following DG/T103-2021 standard and referenced methods[16], a stable working section was randomly selected, with 64 consecutive seedlings sampled from each of the left, middle, and right rows (192 seedlings total). The seedling delivery success rate was calculated as the percentage of successfully delivered seedlings relative to the total sampled seedlings, with successful delivery defined by two criteria: complete insertion of the seedling into the furrow by the delivery device, and a placement angle (the acute angle between the main stem and the forward direction of the implement) of ≥45°. The planting qualification rate was determined as the percentage of qualified seedlings among the total sampled seedlings, where qualification required both effective soil coverage of the roots and a planting uprightness angle (the angle between the main stem and the ridge surface) of ≥30°. These angular parameters - the placement angle reflecting the seedling's orientation in the furrow and the uprightness angle indicating post-planting vertical stability - served as critical indicators of transplanting quality. All data were analyzed using χ^2 test with Bonferroni correction as presented in Tables 7 and 8.



a. Actual transplanter b. Field experiment performance

c. Planting uprightness d. Seedling placement angle

Figure 9 Rapeseed bare-root seedling transplanter and its field experiment performance

Table 7 Results of multiple comparisons for seedling delivery success rate (α=0.05)

Cultivars	Successful	Failed	Seedling delivery success rate/%
A1	156	36	81.25b
A2	151	41	78.65b
A3	180	12	93.75a
A4	103	89	53.65c
A5	179	13	93.23a
A6	178	14	92.71a

Note: A1 is the Huyou 17; A2 is the Huayouza 9; A3 is the Fengyou 520; A4 is the Zhongyou 108; A5 is the Zheyou 50; A6 is the Huayouza 62. Different lowercase letters (a, b and c) following the seedling delivery success rate indicate significant differences at the 0.05 level.

Table 8 Results of multiple comparisons for planting qualification rate

Cultivars	Qualified	Unqualified	Qualification rate/%
A1	79	113	41.15b
A2	74	118	38.54b
A3	135	57	70.31a
A4	50	142	26.04c
A5	139	53	72.40a
A6	136	56	70.83a

Note: A1 is the Huyou 17; A2 is the Huayouza 9; A3 is the Fengyou 520; A4 is the Zhongyou 108; A5 is the Zheyou 50; A6 is the Huayouza 62. Different lowercase letters (a, b and c) following the seedling delivery success rate indicate significant differences at the 0.05 level.

Seedling delivery performance analysis: As listed in Table 7, significant differences existed in seedling delivery success rates among cultivars (χ^2=181.32, p<0.001). Notably, cultivars A3, A5, and A6 demonstrated outstanding performance with success rates of 93.75%, 93.23%, and 92.71% respectively, all exceeding the operational standard requirement of 90%. These three cultivars showed significantly better delivery performance than controls (A1: 81.25%; A2: 78.65%; A4: 53.65%) (p<0.05), indicating superior mechanical adaptability.

Planting performance evaluation: As indicated in Table 8, the multiple comparison results of planting success rates further verified performance differences among cultivars. A3, A5, and A6 maintained significantly higher planting success rates than controls (p<0.05). However, it should be noted that none of the cultivars achieved the standard qualification rate of 85%. This suggests that planting quality depends not only on the compatibility between delivery device and seedlings, but also on other operational factors including furrow preparation quality and soil covering/compacting effects. To improve overall transplanting quality, further optimization of other key transplanter components will be conducted.

5 Conclusions

This study selected six winter rapeseed cultivars suitable for cultivation in the mid-lower Yangtze River: Huyou 17(A1), Huayouza 9 (A2), Fengyou 520 (A3), Zhongyou 108 (A4), Zheyou 50 (A5), and Huayouza 62 (A6). The root length (RL), seedling height (SH), root diameter (RD), stem thickness (ST), and seedling width (SW) of the bare-root seedlings were measured and analyzed from 25 to 40 d after sowing. Based on the analysis of the compatibility between the transplanter and the morphological characteristics (MCs) of rapeseed bare-root seedlings, the structural and operational parameters of the seedling delivery device were optimized. Field trials were conducted to verify the transplanting effectiveness.

(a) MCs of the six rapeseed cultivars were subjected to multiple comparisons, and the growth distribution changes in skewness and kurtosis were statistically analyzed. Significant differences were found in the MCs among the six cultivars (α=0.05), with coefficients of variation ranging from 8.79% to 28.10%. Differences were also observed in the symmetry and concentration of MCs both within the same variety and among different cultivars, with skewness ranging from –0.51 to 0.96 and kurtosis ranging from 1.50 to 5.87. As the seedling age progressed, the number of cultivars with no significant differences (NSD) in MCs gradually decreased. However, the same three cultivars consistently showed stable uniformity before 35 d of seedling ages. To improve the compatibility between the transplanter and rapeseed bare-root seedlings, it is advisable to select combinations of cultivars with minimal differences and high stability within the optimal planting period, or to conduct mechanical transplanting before 35 d of seedling age.

(b) Using the least squares method, growth trend curves of the MCs of rapeseed bare-root seedlings were fitted, and the growth ranges of these characteristics were statistically analyzed. This provided data support for the design of the structural and operational parameters of the transplanter. From 25 to 40 d after sowing, RL, SH, RD, ST, and SW exhibited linear or quadratic increases, with an average determination coefficient (R^2) of 0.970 90. Based on the differences in growth trends of the MCs related to mechanical transplanting among the cultivars, the transplanting period for each variety can be relatively advanced or delayed to enable the transplanter to accommodate more cultivars of rapeseed bare-root seedlings. In this study, compared to cultivars A3 and A4, the transplanting period for cultivars A1, A5, and A6 should be appropriately advanced, while the period for variety A2 should be slightly delayed.

(c) The compatibility between the key parameters of the seedling delivery device and the MCs of the seedlings was analyzed. For cultivars A3, A5, and A6, the following parameters were finally determined: the width of the flat belt for the horizontal sequential conveying mechanism (B_1) was 180 mm; the spacing of the positioned flexible bars (S_1) was 70 mm; the width of the flexible belt (B_2) was 150 mm; the clamping distance (S_2) was 8 mm; the seedling dropping height (H_1) was 180 mm; and the planting depth (H_2) was 40 mm. Field trials demonstrated that cultivars A3, A5, and A6 all achieved seedling delivery success rates exceeding 90%, meeting the operational requirements for rapeseed transplanters. These rates were significantly higher than those of control cultivars A1, A2, and A4 (p<0.05), indicating superior compatibility between the transplanter and the selected cultivars (A3, A5, and A6).

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[References]

[1] He A B, Yuan B, Jin Z Q, Man J G, Peng S B, Zhang L, et al. Comparative study on annual yield, water consumption, irrigation water use efficiency and economic benefits of different rice-oilseed rape rotation systems in Central China. Agricultural Water Management, 2021; 247: 106741.

[2] Quan W, Wu M L, Luo H F, Chen C P, Xie W. Soil hole opening methods and parameters optimization of pot seedling transplanting machine for rapeseed. Transactions of the CSAE, 2020; 36(11): 13–21, 327.

[3] Yuan J C, Wan X Y, Liao Q X, Gao D X, Xiao W L, Yang J. Mechanical compression characteristics of rapeseed based on continuous damage theory. Biosystems Engineering, 2022; 224: 301–312.

[4] Jin X, Yuan Y W, Ji J T, Zhao K X, Li M Y, Chen K K. Design and implementation of anti-leakage planting system for transplanting machine based on fuzzy information. Computers and Electronics in Agriculture, 2020; 169: 105204.

[5] Xu G W, Liu H X, Jian S C, Shi S, He T F. Design and test of transplanting mechanism on mulch-film of salvia miltiorrhiza based on five-bar mechanism. Transactions of the CSAM, 2018; 49(9): 55–65.

[6] Hu Q L, Liao Q, Wang Y. Mechanical and biological characteristics analysis of mechanically transplanted rapeseed substrate block seedlings. Transactions of the CSAE, 2019; 35(24): 58–65.

[7] Wu J, Tang Q, Yuan W S, Wang S F, Wu C Y. Design and parameter optimization of ditching and compacting parts of rapeseed carpet seedling transplanter. Transactions of the CSAE, 2016; 32(21): 46–53.

[8] Liu M F, Hu X P, Liao Y T, Liao Q X, Wan X Y, Ji M Y. Morphological parameters characteristics of mechanically transplanted plant in suitable transplanting period for different rape varieties. Transactions of the CSAE, 2015; 31(z1): 79–88.

[9] Yu G H, Wang L, Sun L, Zhao X, Ye B L. Advancement of mechanized transplanting technology and equipment for field crops. Transactions of the CSAM, 2022; 53(9): 1–20.

[10] Zhang H C, Wang L, Jin X L, Bian L M, Ge Y F. High-throughput phenotyping of plant leaf morphological, physiological, and biochemical traits on multiple scales using optical sensing. The Crop Journal, 2023; 11(5): 1303–1318.

[11] Tang Q, Wu J, Jiang L, Wu C Y, Xiao T Q, Jiang T. Design and test of hydraulic profiling system for rape seedling combined transplanter. Transactions of the CSAM, 2021; 23(11): 95–102.

[12] Hu Q L, Wang L, Li X Z, Yuan H, Yuan J C, Liao Q X. Design and experiment of the counter roll seedling taking equipment for rapeseed substrate block seedlings transplanter. Transactions of the CSAE, 2022; 38(9): 12–23.

[13] Jiang L, Wu C Y, Tang Q, Zhang M, Wang G. Kinematics model and parameter optimization of planting process of rape carpet seedling transplanter. Transactions of the CSAE, 2018; 34(21): 37–46.

[14] Jin X, Li R S, Tang Q, Wu J, Jiang L, Wu C Y. Low-damage transplanting method for leafy vegetable seedlings based on machine vision. Biosystems

Engineering, 2022; 220: 159–171.

[15] Wu J, Yu W, Zhang M, Wu C, Jiang L, Tang Q. Design and test of 2ZY-6 rapeseed carpet seedling transplanter. Transactions of the CSAM, 2020; 51(12): 95–102, 275.

[16] Hu Q L, Zhang Q, Li X, Wan X, Wang L, Liao Q X. Design and parameter analysis of seedling collection device of rapeseed substrate block seedlings transplanter machine. Transactions of the CSAE, 2021; 37(10): 18–27.

[17] Cui Z C, Guan C S, Xu T, Li J C, Chen Y Y, Song J L. Design and experiment of the automatic conveying and separating device for substrate block seedling transplanting machine. Transactions of the CSAE, 2023; 39(13): 68–79.

[18] Liao Q X, Wang Y, Hu Q L, Zhang Q S, He K, Xiao W L. Design and experiment on pick-up device for rapeseed substrate seedling transplanter. Transactions of the CSAM, 2020; 51(11): 93–102.

[19] Liao Q X, Zhang Z, Hu Q L, Xu B, et al. Design and trajectory analysis of pneumatic picking-up mechanism for rape paper pot seedling. Transactions of the CSAM, 2017; 48(11): 70–78.

[20] Cui Z C, Guan C S, Xu T, Fu J J, Chen Y S, Zheng S H. Design and experiment of double-row chain planting device for cabbage substrate block seedlings. Transactions of the CSAM, 2023; 54(6): 46–54.

[21] Zhu B B. Design and simulation of the seedling transplanting machine with sandwich type sweet potato. Shandong Agricultural University, 2017. https://doi.org/10.7666/d.D01211812

[22] Lai Q H, Yuan H K, Hu Z W, Su W. Design and experiment on seedling separation device of panax notoginseng seedlings based on roller zigzag mechanism. Transactions of the CSAM, 2018; 49(4): 121–129.

[23] Lai Q H, Zhao J W, Su W, Jia G X, Li J H, Lv Q. Design and test of air suction directional transplanting device for panax notoginseng seedlings based on DEM-CFD coupling. Transactions of the CSAM, 2021; 52(7): 60–70.

[24] Xu G W, Liu H X, Farman A C, Fang H M, Jian S C, He T F. Design and test of tilted transplanting mechanism on mulch-film of salvia miltiorrhiza. Transactions of the CSAM, 2019; 50(2): 78–89, 101.

[25] Forthofer R N, Lee E S, Hernandez M. Study Designs. Biostatistics. 2nd ed. 2006; pp.135–167. https://doi.org/10.1016/B978-0-12-369492-8.50011-X

[26] Guan J Y, Fan W G. Relationship between growth and root morphological characteristics of Rosa roxbunghii seedlings and endogenous hormone content under different phosphorus levels. Scientia Silvae Sinicae, 2019; 55(4): 51–61.

[27] Maxwell S E, Delaney H D, Kelley K. Designing experiments and analyzing data: A model comparison perspective. 3rd ed. New York: Routledge, 2017. (Chapter 5). https://doi.org/10.4324/9781315642956

[28] Han M, Lin K R, Zhang J L. Probability theory and mathematical statistics. 4th ed. Shanghai: Tongji University Press, 2019. (Chapter 6).

[29] Gai J Y. Experimental statistical method. 4th ed. Beijing: China Agriculture Press, 2018. (Chapter 13).

[30] Zhang J, Niu Z, Li T, Wu Y, Xi R, et al. Design and optimization of planting process parameters for 2ZYX-2 type green onion ditching and transplanting machine. Phyton-International Journal of Experimental Botany, 2020; 89(1): 147–166.

[31] Wu G W, An X F, Yan B X, Li L W, He Y F, Meng Z J. Design and experiment of automatic transplanter for sweet potato naked seedlings based on pretreatment seedling belt. Transactions of the CSAM, 2022; 53(s1): 99–109.

[32] Jin X, Ji J T, Liu W X, He Y K, Du X W. Structural optimization of duckbilled transplanter based on dynamic model of pot seedling movement. Transactions of the CSAE (Transactions of the CSAE), 2018; 34(9): 58–67.

[33] Sharma A, Khar S. Design and development of a vegetable plug seedling transplanting mechanism for a semi-automatic transplanter. Scientia Horticulturae, 2024; 326: 112773.

[34] Mu G Z, Wang Q Y, Zheng D H, Li D S, Zhang T T, Zhang G C. Design and experiment of the seedling planting device for a sweet potato horizontal multiple transplanter. Transactions of the CSAE, 2023; 39(24): 1–10.

[35] Nelsen T C. Means, medians, modes, and quartiles. Probability and Statistics for Cereals and Grains. 2022; pp.49–58. https://doi.org/10.1016/B978–0-323-91724-7.00010-1

[36] Li Y Y, Hu C R. Experiment design and data processing. 3rd ed. Beijing: Chemical Industry Press, 2017. (Chapter 4).

[37] Sun L, Shen J H, Zhou Y Z, Ye Z Z, Yu G H, Wu C Y. Design of non-circular gear linkage combination driving type vegetable pot seedling transplanting mechanism. Transactions of the CSAE, 2019; 35(10): 26–33.