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Improving yield by breaking the seed furrow and covering the soil after sowing in strip-tillage mode

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Abstract: Based on strip-tillage technology, this study explores the optimal seedbed environment for maize growth through a three-year field agronomic experiment. A comparative analysis of two planting modes, flat planting and ridge planting, was conducted, and a two-factor, three-level experimental design was implemented (furrow-breaking width: 8, 10 and 12 cm; furrow-breaking depth: 2, 3 and 4 cm), with manual soil covering without furrow breaking as the control group. Analysis of the averaged data over three years indicates that furrow-breaking treatment significantly increased maize yield under both flat and ridge planting modes, highlighting the importance of furrow breaking for maize growth. Ridge planting increased yield by an average of 7.58% compared to flat planting. The optimal yield was achieved at a furrow-breaking width of 10 cm and a depth of 4 cm, where ridge and flat planting yields were 10.37% and 10.43% higher than the average values at each level, respectively. Additionally, at the optimal yield level, the chlorophyll soil-plant analysis development (SPAD) values for ridge and flat planting were 15.36% and 17.06% higher than the average values. The emergence rates of ridge and flat planting maize were 5.43% and 4.93% higher than the average values, respectively. This not only enhanced crop stress resistance but also improved overall economic benefits.

Keywords: strip tillage; breaking width and depth; maize yield; flat tillage and ridge tillage; seedbed environment

With the rapid growth of the global population, food demand continues to rise. As one of the most important staple maize worldwide, maize faces increasing production pressure (Godfray et al. 2010). According to the United Nations, the global population is expected to reach 9.7 billion by 2050, making food security a critical global concern. As the world's second most populous country, China urgently needs to enhance maize yield, with Northeast China, known as the "granary of China," playing a vital role in maize production. This region, characterised by vast plains and fertile black soil, is well-suited for maize cultivation, contributing nearly one-third of the national production (Zhang et al. 2018b).

In recent years, excessive tillage and improper agricultural practices have led to severe land degradation in Northeast China (Wang et al. 2021, Zhang et al. 2023). China has been actively promoting conservation strip-tillage technology to address this challenge, which improves soil structure and ecological functions by reducing mechanical operations and increasing organic matter input. This approach has become an effective method for protecting black soil resources and developing sustainable agriculture (Zhang et al. 2007, 2012, Zuber et al. 2015).

Under conservation tillage, improving grain yield per unit area has become a key issue. Current research mainly focuses on increasing planting density (Luo

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et al. 2020, Mylonas et al. 2020, Wu et al. 2023), improving soil structure (Parihar et al. 2018, Huang et al. 2021, Wang et al. 2024), and optimising fertilisation strategies (Tian et al. 2024). However, studies on constructing high-quality seedbeds remain relatively limited (Wang 2019). Seedbed quality directly influences maize seed germination, root development, and final yield. An ideal seedbed should provide a growth environment characterised by "loose upper and firm lower" soil (Zheng 2017). Conventional furrow openers often lead to soil compaction on the sides of the seed furrow during sowing, reducing soil aeration and water permeability, thereby restricting maize root growth. Additionally, improper soil covering, whether too thin or too thick, can reduce seed germination rate and seedling quality, ultimately affecting yield (Guo et al. 2017, Lu et al. 2024). Therefore, optimising the seedbed environment by determining the optimal furrow-breaking width and depth is crucial for maize growth.

Based on the characteristics of black soil in Northeast China, this study explores the optimisation of seed furrows formed by conventional openers through secondary furrow breaking and soil covering techniques. To obtain comprehensive data, different planting modes and furrow-breaking methods were used. Key indicators such as maize chlorophyll content at the R1 silking stage, emergence rate, and grain yield were analysed through field experiments. The study provides the following insights for the sowing process: (1) Optimal furrow-breaking width and depth for flat planting maize seedbeds; (2) optimal furrow-breaking width and depth for ridge planting maize seedbeds, and (3) the significant impact of high-quality seedbed environments on maize yield.

MATERIAL AND METHODS

Meteorology and soil character. As shown in Figure 1, the study was conducted at the Xiangyang Experimental Base of Northeast Agricultural University in Harbin, Heilongjiang Province. The geographical coordinates of the experimental site are 45°76'N latitude and 126°93'E longitude, with an altitude of 184 m a.s.l. The soil type is classified as typical phaeozem (Staff 1998), locally known as "black soil." The region experiences a temperate continental monsoon climate, with an average annual precipitation of 500 to 600 mm and an average annual temperature of 4.25 °C. The groundwater depth generally ranges between 14.15 and 46.50 m. The data on precipitation and daily average temperature during the maize growing season from 2022 to 2024 are shown in Figure 2. The soil properties of the study area included an alkali-hydrolysed nitrogen content of 23.82 kg/ha, available phosphorus content of 2.72 kg/ha, available potassium content of 24.93 kg/ha, and an organic carbon content of 2.98%. The bulk density of the cultivated soil layer was 1.29 g/cm^3, with a soil pH of 5.98.

Experimental design. The experiment was conducted using a strip-till planting system, specifically divided into flat planting and ridge planting modes. The specific operational procedures were as follows: in April

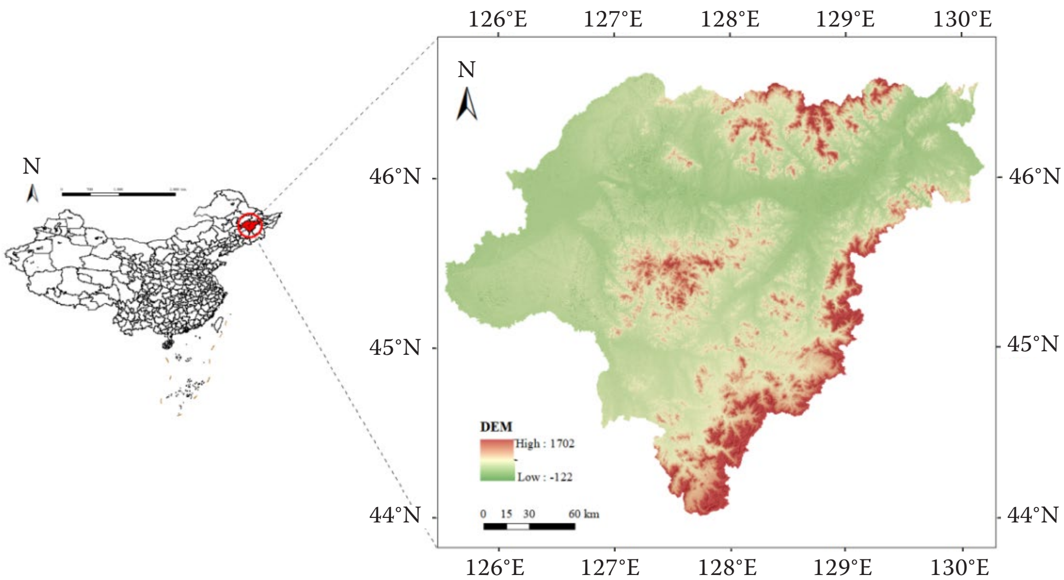

Figure 1. The location of the experimental site in China

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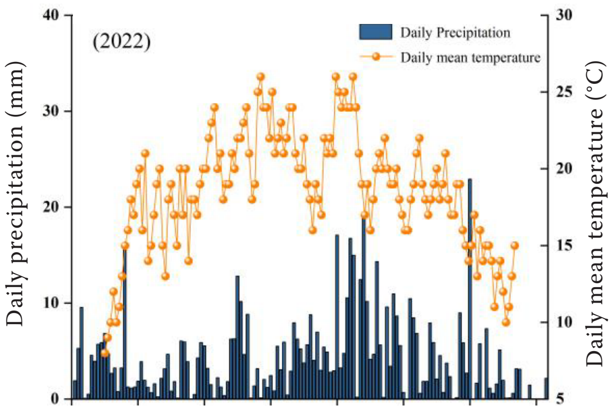
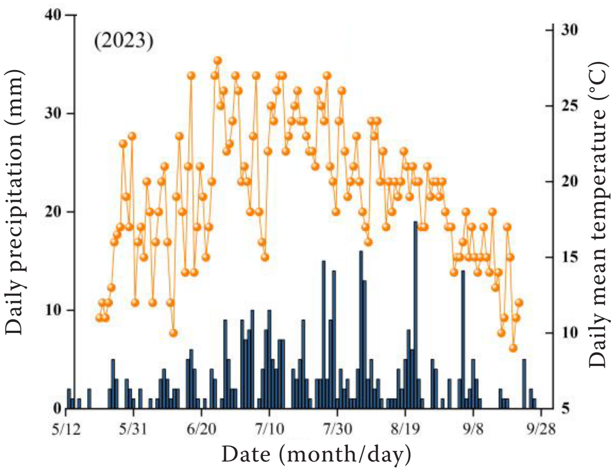




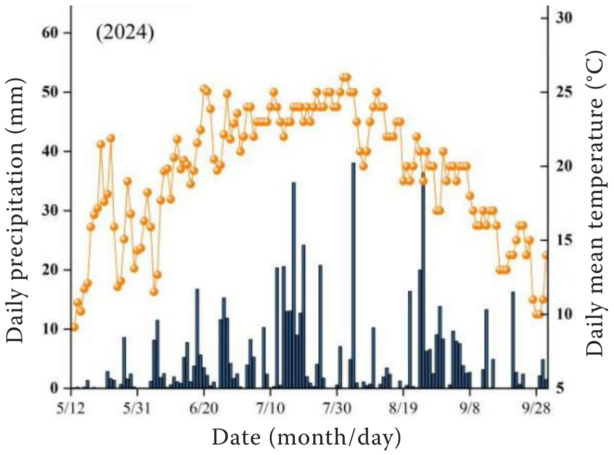
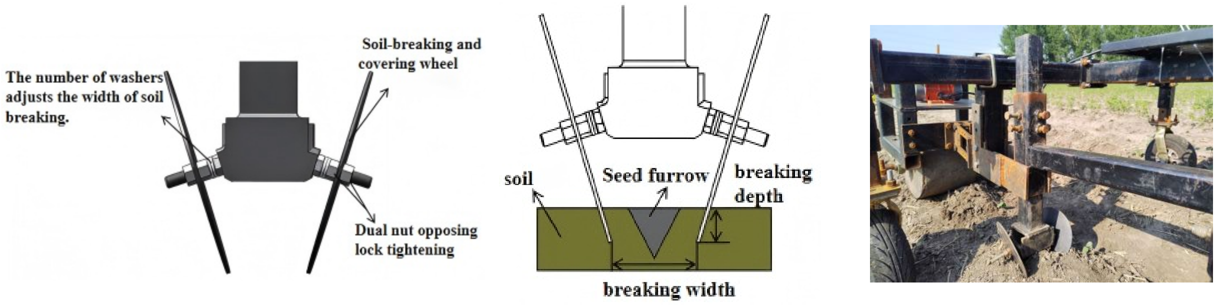


Figure 2. Precipitation and daily average temperature during the maize growing season in the northeast experimental region from 2022 to 2024

of the spring prior to the experiment, deep ploughing was conducted on the flat plots. Deep ploughing was first performed for the ridge plots, followed by ridge formation using mechanical equipment to create an alternating structure of ridges and furrows. The ridge width was 65 cm, and the ridge height was 20 ± 2 cm. In mid-May, after the soil at a depth of 5 cm stabilised at 10 °C, the research team used a strip-till machine equipped with a pre-planting roller and furrow opener, as well as a post-planting roller, while manually sowing seeds (sowing while moving) to complete the operation in a single pass. The breaking depth is manually adjusted using the friction force between the eight opposing bolts and the square steel connected to the breaking and soil-covering wheel. The breaking width is adjusted by increasing or decreasing the number of washers to regulate the width. The furrow depth is controlled at 5.5 ± 0.5 cm, the seed furrow width at 5.5 ± 0.5 cm, and the seeding depth at 5 ± 0.5 cm based on the seed furrow width. The specific experimental apparatus and operational diagram are shown in Figure 3.



(a) Three-dimensional diagram of the soil covering device
(b) Definition diagram of soil-breaking width and depth
(c) Close-up diagram of the soil-breaking device

Figure 3. Experimental apparatus and operational schematic diagram

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This experiment utilised "Fumin 985," one of the primary maize cultivars in the region, as the experimental material from 2022 to 2024. Sowing is conducted in mid-May each year, followed by harvesting in early October. During the growth period, compound fertiliser (N-P-K: 20%-9%-13%) was applied at an 850 kg/ha rate, with a single application within seven days after sowing. The experiment adopted a randomised complete block design. The inter-row spacing of maize plants was 25 cm, with 50 maize plants per group and three replicates. The planting density was approximately 61 500 plants per hectare. A 3-m equipment adjustment zone was set at both ends of each test plot to ensure smooth operations within the experimental plots. An 8-m-wide buffer zone was also arranged around the experimental area to minimise the edge effects on maize growth and development. The specific experimental plot layout is shown in Figure 4. The planting area was approximately 150 m long and 30 m wide, with 10 rows. The green area represents the experimental plots, the blue area is the equipment adjustment zone, and the yellow area is the buffer zone. The experiment included two planting modes: flat planting (FP) and ridge planting (RP). For each planting mode, different furrow-breaking widths (8 cm (L8), 10 cm (L10), 12 cm (L12)) and depths (2 cm (W2), 3 cm (W3), 4 cm (W4)) were tested in a 3 × 3 factorial design. Additionally, a control group without furrow breaking but with manual soil covering was included for both flat and ridge planting. A total of 20 experimental groups were established.

Sampling and measurement

Grain yield and its component factors. At the maize maturity stage, nine maize ears were randomly selected from the central area of each experimental plot (divided into three groups, each containing three ears). Before threshing, the number of grains per ear was measured. The specific method involved counting the number of kernel rows in a uniform section of the ear and randomly selecting a row to count the number of kernels. To determine the 100-kernel weight, three maize ears were randomly selected from each experimental group and manually threshed. Four complete rows were selected from each ear during the threshing process, removing damaged, diseased, and other abnormal kernels to ensure that more than 100 kernels remained. The total number of kernels was first counted, then a batch of over 100 kernels was wrapped in a newspaper as a sample. Each experimental group had three such seed samples. These samples were then placed in an oven at 105 °C and dried to a constant weight. The dried kernels were re-weighed to determine the 100-kernel weight. This process was repeated three times to ensure accuracy. Finally, maize yield was calculated according to the national grain storage standard (with a moisture content of approximately 14%) (Liu et al. 2022, Zhang et al. 2022).

$$Y_G = \delta \times \theta \times W_G \times 10^{-5} / (1 - 0.14) \quad (1)$$

Where: YG – grain yield (kg/ha); δ – number of ears harvested (ear/ha); θ – number of kernels per ear (kernels/ear); WG – hundred-grain weight (g).

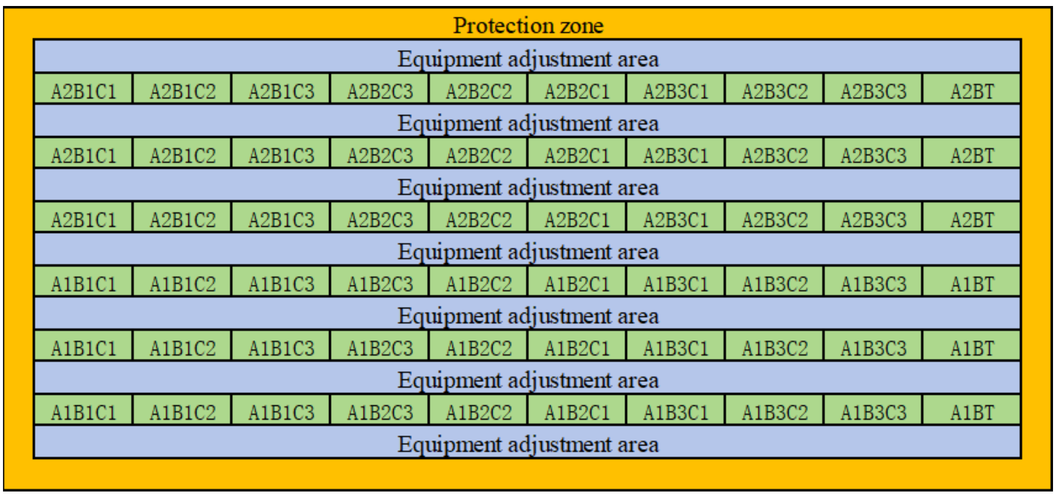

Figure 4. Division of experimental plots (A1 – flat planting; A2 – ridge planting; B1, B2, and B3 – breaking wall depths of 2, 3 and 4 cm, respectively; while C1, C2, and C3 – breaking wall widths of 8, 10 and 12 cm, respectively; A1BT – flat planting blank treatment; A2BT – ridge-planting blank treatment)

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Chlorophyll content. To determine the chlorophyll content, the SPAD values were measured using a chlorophyll meter (Minolta SPAD-502, Tokyo, Japan) during the R1 silking stage of maize. SPAD value is an indicator used to quickly and non-destructively measure the relative chlorophyll content in plant leaves using a portable chlorophyll meter. It does not directly represent the actual concentration of chlorophyll but is a dimensionless relative value used to reflect the relative abundance of chlorophyll in leaves, which is closely related to the plant's photosynthetic capacity, nitrogen nutrition status, and overall health.

During the R1 silking stage of maize, three representative plants were selected from each experimental group, and three leaves were randomly selected from each plant. Each leaf was measured three times using the SPDA method. These readings included one measurement near the centre of each randomly selected leaf and two measurements 3 cm from the centre on both sides. The average of these three readings was considered the representative SPAD value for that leaf (Peng et al. 1993, Jinwen et al. 2009). Each plant yields a total of nine statistical data points. Finally, the average SPAD value of the three maize plants is calculated as the average SPAD value for that experimental group.

Soil moisture content. During maize sowing and the R6 maturity stage, the soil bulk density and porosity were measured using the soil core method. Undisturbed soil core samples (diameter: 5 cm, height: 10 cm) were collected three times from each experimental group to determine the bulk density of the 0–10 cm soil layer. These soil core samples were dried in an oven at 105 °C for 48 h to measure soil bulk density and gravimetric moisture content (Bao 2000). The volumetric moisture content was then calculated by multiplying the gravimetric moisture content by the soil bulk density.

$$W_i(\%) = \frac{(G_w - G_d)}{G_d} \times 100\% \quad (2)$$

Where: W_i – soil moisture content; G_W – wet weight of the soil; G_d – dry weight of the soil.

Seedling emergence rate and mean emergence time. The emergence rate is a key indicator for assessing the initial soil moisture status after maize sowing. Specifically, emergence was recorded when maize plants reached a height of 2 cm above the soil surface. Daily emergence counts were recorded at a fixed time within the experimental area during the emergence period, which spanned from the first to the last. The average emergence time (MET) and emergence rate (PE) were calculated as follows (Celik et al. 2007):

$$MET = \frac{N_1T_1 + N_2T_2 + \cdots N_nT_n}{N_1 + N_2 + \cdots N_n} \quad (3)$$

$$PE = \frac{S_{te}}{m} \times 100\% \quad (4)$$

Where: $N_1,...,_n$ – number of seedlings emerged from the previous time point; $T_1,...,_n$ – number of days after sowing; S_{te} – total number of emerged seedlings; m – seeding rate.

Statistical analysis. Statistical analysis and calculation of the mean and standard deviation for three years of agronomic trial data on maize yield and its components, chlorophyll content, and soil moisture content were performed using Microsoft Excel 2019 (Microsoft Inc., Redmond, USA). The results of the multifactor analysis of variance for different factor levels in the figures and tables were obtained using SPSS 22.0 (IBM, Inc., Armonk, USA) to obtain the results of the multi-factor variance analysis for the significance of maize seed furrow wall-breaking depth, wall-breaking width, and their interaction effects on grain yield and its constituent factors, among other indicators. The least significant difference method (*LSD*) was used for multiple comparisons, with $P < 0.05$ as the significance level. The box plots and bar charts illustrating the three-year data's average values and significance results were created using Origin 2021 (Origin Lab, Northampton, USA).

RESULT

Yield characteristics

Maize yield. During the research years, the analysis was conducted based on the average values of maize yield over three years. From the analysis in Figure 5, it can be concluded that the yield of rigid maize is generally higher than that of flat-planted maize. Specifically, the average yield of ridge-planted maize was 7.58% higher than that of flat-planted maize. The yield in the ridge and flat planting control groups was 9.48% and 4.14% lower than the respective average yields of their planting modes. Under ridge planting, maize yield showed significant differences at different furrow-breaking depths, with the highest yield observed at a depth of 4 cm compared to 3 cm and 2 cm. Specifically, at a furrow-breaking depth of 4 cm, maize yield was 3.9% and 15.7% higher than at depths of 3 cm and 2 cm, respectively. However, yield was

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no significant difference at different furrow-breaking widths under the same depth condition. For flat planting, neither different furrow-breaking depths under the same width nor different furrow-breaking widths under the same depth showed significant differences in maize yield. The effects of furrow-breaking depth and width, as well as their interaction in both planting modes, are presented in Table 1 based on a linear mixed-effects model. The optimal levels were found at a furrow-breaking width of 10 cm and a depth of 4 cm, where ridge and flat planting yields were 10.37% and 10.43% higher than the average yield at all levels, respectively. Additionally, at this optimal level, ridge-planted maize yield was 6.8% higher than that of flat-planted maize.

Yield composition. Throughout the study year, the number of ears per hectare did not differ significantly between the two planting modes. Ridge planting primarily increased yield by enhancing the number of kernels per ear and the 100-kernel weight (Table 2). The table shows that, under the same furrow-breaking width, the number of kernels per ear and the 100-kernel weight were generally not significantly different at different furrow-breaking depths. However, the highest number of kernels per ear and the highest 100-kernel weight were observed at a furrow-breaking depth of 4 cm. Similarly, under the same furrow-breaking depth, differences in kernel count and 100-kernel weight were not significant at different furrow-breaking widths, but the highest values were observed at a furrow-breaking width of 10 cm.

Figure 5 shows the maize yield (average values from 2022 to 2024) under different breaking depths and breaking widths of planting furrows for the two planting modes. W8, W10, and W12 represent breaking widths of 8, 10 and 12 cm, respectively, while L2, L3, and L4 represent breaking depths of 2, 3 and 4 cm. (A) refers to the ridge planting mode, while (B) refers to the flat planting mode; the horizontal dashed lines in the figure represent the grain yield of the blank control group under the corresponding planting modes. The box's boundaries represent the mean ± standard deviation, while the whiskers indicate the 10th and 90th percentiles. The black solid line within the box represents the median, and the diamond symbol indicates the mean. n represents the number of data points obtained for each treatment across the research years, with each year's data being measured three times per group. According to the *LSD* analysis, different lowercase letters above the box plot indicate significant differences *(P* < 0.05) in maize yield among treatments at the same breakage width but varying breakage depths. Different uppercase letters indicate significant differences (P < 0.05) in maize yield among treatments at the same breakage depth but varying breakage widths.

Chlorophyll content

As shown in Figure 6A, chlorophyll values (SPAD) under ridge planting conditions exhibited significant differences at the R1 stage. Calculated based on the three-year average in the R1 stage, the effect of furrow-breaking width on chlorophyll content followed the order of 10 cm > 8 cm > 12 cm, indicating that the highest chlorophyll content was achieved at a furrow-breaking width of 10 cm. Under this condition, a furrow-breaking depth of 4 cm increased the average chlorophyll content by 17.44% and 1.7% compared to depths of 2 cm and 3 cm, respectively. Similarly, the effect of furrow-breaking depth followed the order of 4 cm > 3 cm > 2 cm, indicating that a depth of 4 cm resulted in the highest chlorophyll

Table 1. Significance analysis of variance for the effects of breakage depth, breakage width, and their interaction on maize grain yield under two planting modes

ANOVA		Freedom	Mean square	F-test	Maize yield
	breaking depth	2	2 575 658.7	2.262	***
Ridge planting	breaking width	2	12 219 566.0	10.733	ns
	breaking depth × breaking width	4	261 437.8	0.230	ns
	breaking depth	2	3 319 212.9	13.992	***
Flat planting	breaking width	2	7 867 823.7	33.166	***
	breaking depth × breaking width	4	522 611.4	2.203	ns

*P < 0.05; **P < 0.01; ***P < 0.001, indicating statistically significant differences; ns –no statistically significant difference at P < 0.05

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Table 2. Composition of maize yield under different planting furrow depths and widths for the two planting modes (average values from 2022 to 2024)

Breaking midth (cm)	Breaking depth (cm)	Number of ears (per hectare)	Number of grains per ear	Hundred-grain weight (g)
Ridge planting				
	2	55 733.4 ± 679.6^{Ac}	626.7 ± 26.6^{Aa}	35.0 ± 1.2^{Aa}
8	3	58 472.9 ± 578.1^{Bb}	646.0 ± 27.3^{Ba}	35.9 ± 1.1^{Ba}
	4	60 150.3 ± 314.7^{Ba}	660.3 ± 25.8^{Aa}	36.6 ± 1.0^{Aa}
	2	57 236.2 ± 997.1^{Ab}	630.7 ± 26.9^{Ab}	35.4 ± 1.1^{Ab}
10	3	59 901.9 ± 509.6^{Aa}	664.7 ± 26.3^{Aa}	36.8 ± 1.0^{Aa}
	4	60 864.9 ± 292.3^{Aa}	668.7 ± 25.3^{Aa}	37.0 ± 1.0^{Aa}
	2	56 607.0 ± 792.4^{Ab}	623.0 ± 26.8^{Ab}	34.8 ± 1.2^{Ab}
12	3	58 196.7 ± 858.9^{Ba}	642.0 ± 29.9^{Ba}	35.9 ± 1.0^{Ba}
	4	59 206.7 ± 497.1^{Ba}	650.7 ± 25.6^{Aa}	36.0 ± 1.2^{Aa}
Blank control group		56 672.3 ± 632.1	631.3 ± 25.6	34.0 ± 1.1
Flat planting				
	2	55 255.9 ± 292.0^{Bc}	598.0 ± 15.5^{Aa}	34.4 ± 1.5^{Aa}
8	3	58 283.2 ± 218.5^{Bb}	617.3 ± 11.1^{Ba}	35.0 ± 1.4^{Aa}
	4	59 342.5 ± 372.4^{Ba}	629.0 ± 12.3^{Ba}	35.4 ± 1.4^{Aa}
	2	56 510.8 ± 348.4^{Ab}	606.3 ± 14.0^{Aa}	34.6 ± 1.6^{Ab}
10	3	60 069.0 ± 260.3^{Aa}	636.0 ± 12.2^{Aa}	35.5 ± 1.4^{Aa}
	4	60 751.4 ± 622.9^{Aa}	640.0 ± 13.9^{Aa}	35.7 ± 1.4^{Aa}
	2	56 219.9 ± 285.5^{Ac}	602.3 ± 15.6^{Aa}	34.2 ± 1.4^{Aa}
12	3	57 325.7 ± 475.8^{Cb}	612.7 ± 14.1^{Ba}	34.8 ± 1.5^{Aa}
	4	58 817.1 ± 261.9^{Ca}	624.3 ± 11.0^{Ba}	35.2 ± 1.3^{Aa}
Blank control group		56 112.3 ± 302.3	615.4 ± 11.3	34.6 ± 1.3

Using the *LSD* method, values within a column that contain different lowercase letters indicate significant differences in maize yields among treatments at different breaking depths under the same breaking width ($P < 0.05$). Values within a column that contain different uppercase letters indicate significant differences in maize yield compositions among treatments at different breaking widths under the same breaking depth ($P < 0.05$)

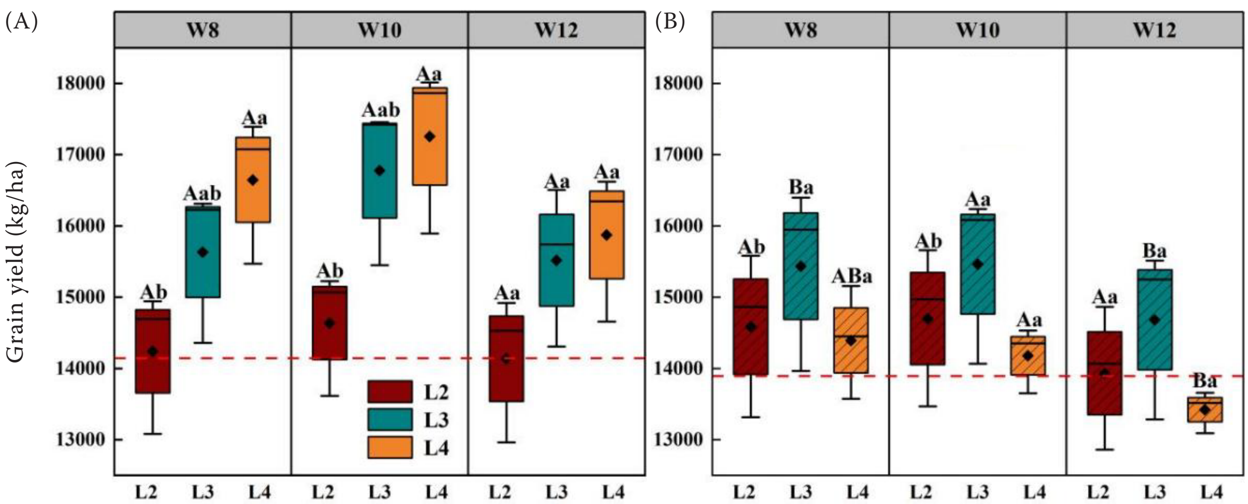

Figure 5. It shows the maize yield under different breaking depths and breaking widths of planting furrows for the two planting modes (average values from 2022 to 2024) (n = 9)

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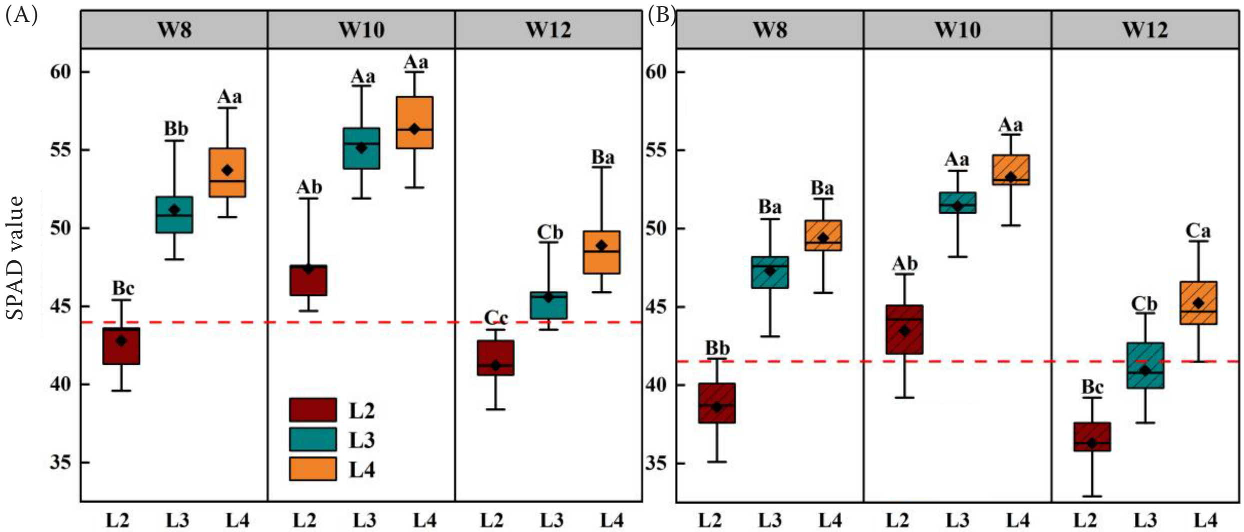

Figure 6. It shows the chlorophyll content (SPAD values) of summer maize during the R1 stage under different breaking depths and widths in the planting furrow for the two planting modes (average values from 2022 to 2024 (n = 9))

content. At this depth, the average chlorophyll content at a furrow-breaking width of 10 cm was 4.02% and 14.35% higher than at 8 cm and 12 cm, respectively.

As shown in Figure 6B, chlorophyll values (SPAD) under flat planting conditions also exhibited significant differences at the R1 stage. Calculated based on the three-year average in the R1 stage, the effect of furrow-breaking width on chlorophyll content followed the order of 10 cm > 8 cm > 12 cm, confirming that the highest chlorophyll content was obtained at a furrow-breaking width of 10 cm. Under this condition, a furrow-breaking depth of 4 cm increased the average chlorophyll content by 22.61% and 2.21% compared to depths of 2 cm and 3 cm, respectively. Similarly, the effect of furrow-breaking depth followed the order of 4 cm > 3 cm > 2 cm, indicating that the highest chlorophyll content was observed at a depth of 4 cm. At this depth, the average chlorophyll content at a furrow-breaking width of 10 cm was 6.39% and 15.94% higher than at 8 cm and 12 cm, respectively.

Comparing chlorophyll content (SPAD) between flat and ridge planting modes, ridge planting generally showed higher chlorophyll content than flat planting. Specifically, the chlorophyll content of the ridge planting control group was 5.92% higher than that of the flat planting control group, but this difference was not significant. The linear mixed-effects model analysis in Table 3 indicated that the individual effects of furrow-breaking width and depth, as well as their interaction, were significant under both planting modes. The optimal levels were found at a furrow-breaking width of 10 cm and a depth of 4 cm, where ridge and flat planting chlorophyll content values were 15.36% and 17.06% higher than the average values at each level, respectively.

Table 3. Significance variance analysis of the effects of two factors, breaking depth and breaking width, and their interaction on SPAD under two planting modes

ANOVA		Freedom	Mean square	F-test	SPAD
Ridge planting	breaking depth	2	614.4	122.474	***
	breaking width	2	405.4	80.809	***
	breaking depth × breaking width	4	12.6	2.513	ns
Flat planting	breaking depth	2	698.4	158.776	***
	breaking width	2	496.7	112.913	***
	breaking depth × breaking width	4	11.1	2.522	*

SPAD – chlorophyll content; *P < 0.05; **P < 0.01; ***P < 0.001, indicating statistically significant differences; ns – no statistically significant difference at P < 0.05

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Table 4. Analysis of variance for the significance of two factors, breaking depth and width of maize seed furrows, and their interaction on soil volumetric water content (%) under two planting modes

ANOVA		Freedom	Mean square	*F*-test	Water content
Ridge planting	breaking depth	2	58.3	36.639	***
	breaking width	2	3.8	2.392	ns
	breaking depth × breaking width	4	0.8	0.525	ns
Flat planting	breaking depth	2	58.7	20.184	**
	breaking width	2	0.191	0.066	ns
	breaking depth × breaking width	4	2.1	0.706	ns

**P* < 0.05; ***P* < 0.01; ****P* < 0.001, indicating statistically significant differences; ns – no statistically significant difference at *P* < 0.05

Soil moisture content

The effects of the two factors, breaking depth and breaking width, and their interaction on soil moisture content under ridge and flat cultivation patterns during the three experimental years are shown in Table 4. The analysis indicates that wall-breaking depth significantly impacts soil moisture content. Based on the data results after averaging over three years, as shown in Figure 7A, under ridge planting conditions, when the furrow-breaking width was constant, soil moisture content significantly decreased as furrow-breaking depth increased. Overall, the soil moisture content followed the order of 2 cm > 3 cm > 4 cm. The highest soil moisture content was observed at a furrow-breaking width of 10 cm and a depth of 2 cm, reaching 23.26%. Compared to the same furrow-breaking width at depths of 3 cm and 4 cm, soil moisture content increased by 1.99% and 2.96%, respectively. The lowest soil moisture content occurred at a furrow-breaking width of 12 cm and a depth of 4 cm, with a difference of 3.89% compared to the maximum moisture content.

Figure 7B shows that soil moisture content significantly decreased under flat planting conditions as furrow-breaking depth increased while maintaining a constant furrow-breaking width. Overall, the ranking of soil moisture content across the three furrow-breaking depths was 2 cm > 3 cm > 4 cm. The highest soil moisture content was observed at a furrow-breaking width of 8 cm and a depth of 2 cm, reaching 25.64%. Compared to the same furrow-breaking width at depths of 3 cm and 4 cm, soil moisture content increased by 2.12% and 2.83%, respectively. The lowest soil moisture content was recorded at a furrow-breaking width of 12 cm and a depth of 4 cm, with a difference of 3.57% compared to the maximum moisture content. Additionally, the soil moisture

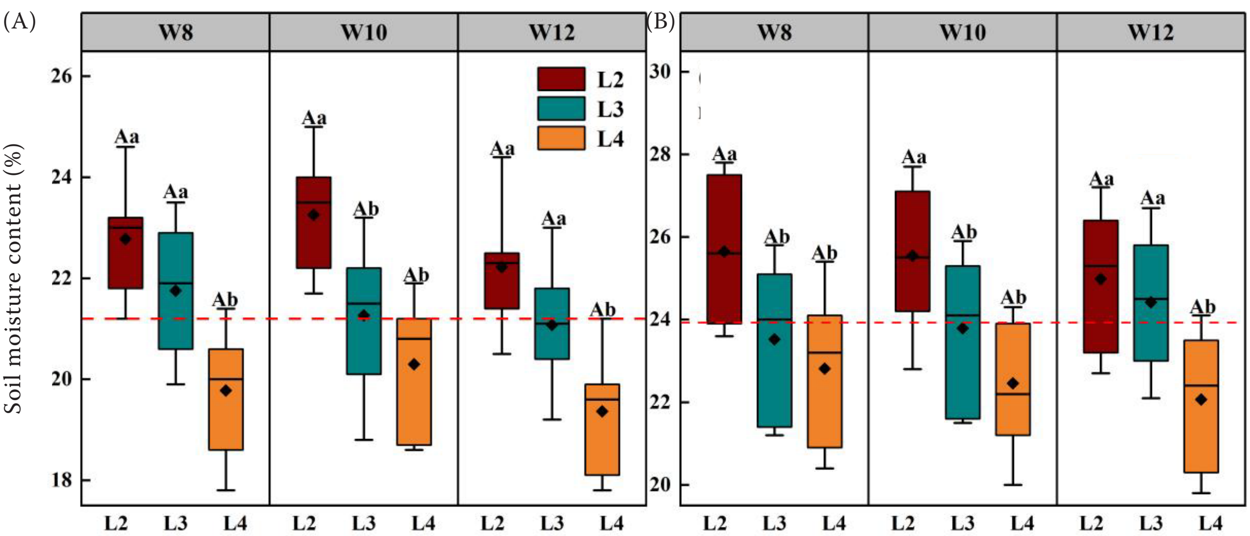

Figure 7. It shows the soil moisture content (volumetric) in maize fields under different rupture depths and widths of planting furrows in two planting systems (average values from 2022 to 2024) (*n* = 9)

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Table 5. Analysis of variance for the significance of the two factors, breaking depth and breaking width, and their interaction effects on maize emergence rate (%) under two cultivation modes

ANOVA		Freedom	Mean square	*F*-test	Emergence rate
Ridge planting	breaking depth	2	96.9	75.554	***
	breaking width	2	26.4	20.584	***
	breaking depth × breaking width	4	2.8	2.183	*
Flat planting	breaking depth	2	83.6	181.236	***
	breaking width	2	22.0	47.769	***
	breaking depth × breaking width	4	2.9	6.347	**

*P < 0.05; **P < 0.01; ***P < 0.001, indicating statistically significant differences; ns – no statistically significant difference at P < 0.05

content in the ridge and flat planting control groups was 1.96% and 1.72% higher than the average values of their respective planting modes. Moreover, overall soil moisture content was higher in the flat planting mode compared to the ridge planting mode.

Seedling characteristics

Seedling emergence rate. The effects of furrow-breaking width, furrow-breaking depth, and their interaction on maize emergence rate under ridge and flat planting modes are shown in Table 5. Analysis of the average values obtained from three years of agronomic trial data. As illustrated in Figure 8A, under ridge planting conditions, when the furrow-breaking width was 10 cm, the emergence rate significantly increased with increasing furrow-breaking depth. The highest emergence rate of 98.89% was observed at a furrow-breaking depth of 4 cm, which was 1.78% and 7.33% higher than at depths of 3 cm and 2 cm, respectively. Similarly, at a furrow-breaking depth of 4 cm, the emergence rate for a furrow-breaking width of 10 cm was 2.45% and 4.00% higher than for widths of 8 cm and 12 cm, respectively. The lowest emergence rate of 88.89% was recorded at a furrow-breaking width of 8 cm and a depth of 2 cm, with a difference of 10.00% compared to the highest emergence rate.

As shown in Figure 8B, similar trends were observed under flat planting conditions. The highest overall emergence rate was recorded at a furrow-breaking width of 10 cm, and the emergence rate increased with increasing furrow-breaking depth. At a depth of 4 cm, the emergence rate peaked at 99.78%, which was 1.56% and 7.11% higher than at depths of 3 cm and 2 cm, respectively. Similarly, at a furrow-breaking depth of 4 cm, the highest emergence rate of 98.89% was observed at a furrow-breaking width of 10 cm,

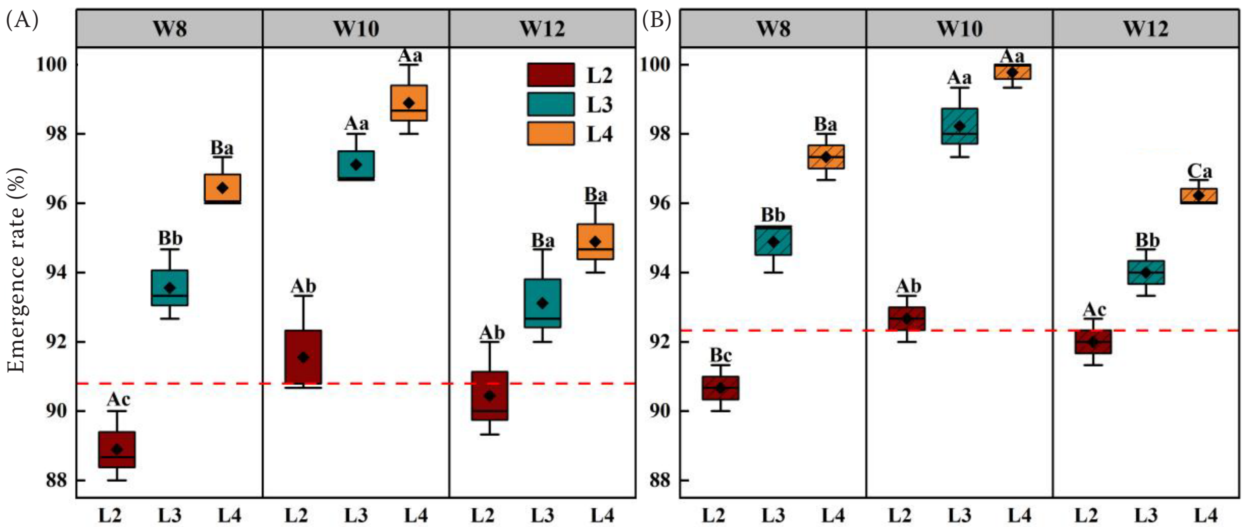

Figure 8. It shows the emergence rates of summer maize under different breaking depths and widths of seed furrows in two planting modes (average values from 2022 to 2024) (n = 9)

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Table 6. Analysis of variance for the significance of the two factors, breaking depth and breaking width, and their interaction effects on average emergence time (day) under two cultivation modes

ANOVA		Freedom	Mean square	*F*-test	Average emergence time
Ridge planting	breaking depth	2	1.3	15.408	***
	breaking width	2	0.4	4.370	ns
	breaking depth × breaking width	4	0.1	0.344	ns
Flat planting	breaking depth	2	0.8	2.351	ns
	breaking width	2	0.4	1.148	*
	breaking depth × breaking width	4	0.2	0.669	ns

*P < 0.05; **P < 0.01; ***P < 0.001, indicating statistically significant differences; ns –no statistically significant difference at P < 0.05

which was 2.45% and 3.56% higher than at widths of 8 cm and 12 cm, respectively. The lowest emergence rate of 90.67% occurred at a furrow-breaking width of 8 cm and a depth of 2 cm, with a difference of 9.11% compared to the highest emergence rate.

Overall, the optimal emergence rate in both planting modes was achieved at a furrow-breaking width of 10 cm and a depth of 4 cm, where emergence rates in ridge and flat planting were 5.43% and 4.93% higher than the average values across all levels, respectively. Additionally, the emergence rates for flat and ridge planting in the control groups were 3.39% and 2.99% lower than the average values across all levels.

Average emergence time. The effects of furrow-breaking width, furrow-breaking depth, and their interaction on the average emergence time of maize under ridge and flat planting modes are shown in Table 6. Analysis of the average values obtained from three years of agronomic trial data. As illustrated in Figure 9A, under ridge planting conditions, the average emergence time significantly decreased with increasing furrow-breaking depth at the same furrow-breaking width. The shortest average emergence time was observed at a furrow-breaking width of 10 cm, with the optimal level at a furrow-breaking depth of 4 cm and a width of 10 cm, resulting in an average emergence time of 14.27 days. This was 0.2 and 0.83 days shorter than at depths of 3 cm and 2 cm, respectively. Furrow-breaking depth had no significant effect on emergence time, so further analysis was not conducted. The longest average emergence time was recorded at a furrow-breaking width of 12 cm and a depth of 2 cm, reaching 15.40 days, which was 1.13 days longer than the shortest emergence time.

Similarly, as shown in Figure 9B, different furrow-breaking widths significantly affected the average emergence time at the same furrow-breaking depth

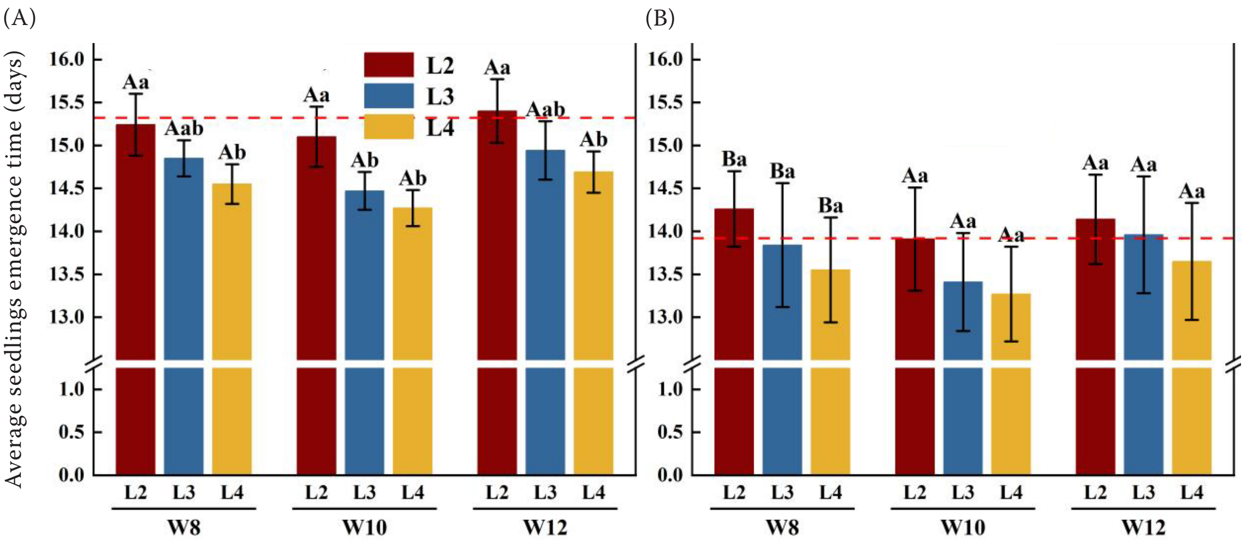

Figure 9. It shows the average emergence time of summer maize under different breaking depths and widths of seed furrows in two planting modes (average values from 2022 to 2024) (mean ± standard deviation, n = 9)

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under flat planting conditions. The longest average emergence time was recorded at a furrow-breaking width of 8 cm, whereas no significant differences were observed between 10 cm and 12 cm widths. The optimal level was observed at a furrow-breaking width of 10 cm and a depth of 4 cm, with an average emergence time of 13.27 days, which was 0.58 days and 0.2 days shorter than at furrow-breaking widths of 8 cm and 10 cm, respectively. Furrow-breaking width had no significant effect on emergence time, so further analysis was not conducted. The longest average emergence time was recorded at a furrow-breaking width of 8 cm and a depth of 2 cm, reaching 14.36 days, which was 1.09 days longer than the shortest emergence time.

Overall, the optimal emergence time in both ridge and flat planting modes was observed at a furrow-breaking width of 10 cm and a depth of 4 cm. Under these optimal conditions, the emergence time in ridge and flat planting was reduced by 3.92% and 3.84%, respectively, compared to the average values at each level. Additionally, the average emergence time in the control groups was 3.3% and 1.1% higher than the average values across all levels.

DISCUSSION

Maize yield. A deeper analysis and quantification of the relationship between furrow-breaking width, furrow-breaking depth, and maize yield are crucial to maximising maize yield potential without increasing tillage input (Huang et al. 2023). Studies have shown that seeding depth uniformity directly affects maize growth (Dongyan et al. 2015), and that the compaction of seed furrow sidewalls and seedbed soil properties significantly influence maize development (Wang et al. 2020). However, an optimal standard for furrow-breaking width and depth during secondary furrow breaking and soil covering has yet to be established. There is an urgent need to develop agronomic guidelines for furrow-breaking techniques. Recent research on conservation tillage has extensively analysed how to maximise the potential of topsoil (Feng et al. 2018, Ning et al. 2022), revealing that increasing topsoil thickness and enhancing soil aggregation effectively improve the number of ears per hectare, the number of kernels per ear, and the 100-kernel weight, thereby boosting maize yield (De La Rosa et al. 2000, Meena et al. 2020).

The experiment found that flat cultivation's germination rate was comparable to ridge cultivation overall, but the average germination time was shorter. The possible reasons for this are as follows: on one hand, the soil structure in flat cultivation is compact, enabling seeds to accumulate the necessary heat for germination quickly. While the "air insulation effect" of ridge cultivation is beneficial for stress resistance in the later stages, it delays heat accumulation in the early stages, thereby delaying germination time. On the other hand, the moisture content in flat cultivation is higher than in ridge cultivation in the early stages, prioritising the conditions required for seed germination.

Notably, although the number of ears per hectare did not differ significantly between ridge and flat planting, ridge planting achieved higher yields by increasing the number of kernels per ear and the 100-kernel weight, which aligns with previous research (Song et al. 2013). Compared to the untreated control groups, furrow-breaking treatment significantly increased maize yield, likely due to improved seedbed conditions. However, this study was based on a limited experimental area, which may restrict the generalisability of the conclusions. Further research is needed to optimise furrow-breaking parameters for different regions and soil conditions.

Leaf characteristics. The seedbed soil environment is a key factor affecting plant photosynthesis. An ideal seedbed should have loamy soil, providing good aeration and water retention. High-quality soil texture supports healthy root growth, enhances nutrient and water absorption efficiency, and promotes leaf photosynthesis. Photosynthesis is the foundation of maize yield formation and is positively correlated with chlorophyll content, which is an important indicator of a plant's photosynthetic capacity (Gaju et al. 2016, Zhang et al. 2018a). Existing research suggests that increased grain weight is closely associated with the accumulation of photosynthetic products during the reproductive stage, which is consistent with this study's findings on the correlation between 100-kernel weight and chlorophyll content (Shi et al. 2017).

Comparative analysis with the untreated control groups indicates that furrow-breaking treatment positively impacted maize chlorophyll content, suggesting that topsoil properties play a crucial role in plant growth. Investigating topsoil characteristics may provide practical strategies for enhancing maize yield, a conclusion consistent with existing domestic and international research (Sun et al. 2017).

Soil characteristics. The experimental results indicate that soil moisture content gradually de-

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creased with increasing furrow-breaking depth in both planting modes. This trend may be attributed to soil moisture distribution, structure, and evaporation rates. The untreated control groups exhibited higher soil moisture in the seed furrows, likely because furrow-breaking reduces soil compaction. As furrow-breaking depth increases, more soil is disturbed, increasing soil porosity and aeration, facilitating deeper water infiltration and reducing surface soil moisture (Feng et al. 2011, Zhang et al. 2018c). This moisture redistribution around the seed furrow allows plant roots to access deeper water and nutrients, contributing to higher yield at greater furrow-breaking depths. The consistency of these findings with previous research confirms the reliability of this experiment. Currently, the relationship between furrow-breaking width and soil moisture content remains unclear.

Seedling characteristics. The experimental results indicate that when the furrow-breaking width was between 8 and 12 cm, both flat and ridge planting achieved the highest emergence rates at a furrow-breaking width of 10 cm. Compared to the untreated control groups, appropriate furrow-breaking depth and width significantly improved emergence rates and shortened the average emergence time. A possible explanation is that a furrow-breaking width that is too narrow reduces soil aeration near the seed furrow, while an excessively wide furrow may lead to poor furrow closure, exposing seeds to environmental stress and pest damage (Weiguo and Wei 2023). Additionally, improper furrow width may affect fertiliser distribution; a narrow furrow can cause uneven nutrient distribution, increasing the risk of seedling burn, while a wide furrow may lead to fertiliser leaching, reducing nutrient availability and seedling growth.

Further analysis showed that deeper furrow-breaking depths also significantly improved emergence rates. This may be attributed to the increased soil cover thickness above the seed. Seeds placed at greater depths experience more stable soil temperatures, adequate moisture, and reduced exposure to pests, creating favourable conditions for rapid and uniform emergence (Molatudi and Mariga 2009, Kimmelshue et al. 2022).

Overall summary. The study findings indicate that compared to the untreated control groups, appropriate furrow-breaking treatment positively impacts maize growth. Precisely controlling secondary furrow-breaking depth and width is an effective method for increasing maize yield. The effects of furrow-breaking position on soil coverage and properties significantly influence maize seed development. The results demonstrate that furrow-breaking depth and width substantially affect maize growth and yield. The highest yield was achieved at a furrow-breaking depth of 4 cm and a width of 10 cm in both flat and ridge planting, whereas the lowest yield was recorded at a depth of 2 cm and a width of 8 cm. Additionally, appropriate furrow-breaking parameters were positively correlated with chlorophyll content, soil moisture content, emergence rate, and average emergence time, all of which contributed to increased yield. A comparative analysis of flat and ridge planting under the same conditions showed that soil moisture content and emergence rates were higher in flat planting. However, from an economic efficiency perspective, ridge planting remains more advantageous for conservation tillage in Northeast China.

Although deeper tillage depths can significantly improve soil aeration, break through the plow pan, promote oxygen diffusion in the soil, accelerate microbial decomposition of straw and other organic matter, and release more nitrogen, phosphorus, and other nutrients under most conditions, they can also disrupt soil aggregates, accelerate organic matter mineralisation, and lead to carbon loss. In practice, deeper tillage depths require higher energy consumption and mechanical specifications. They must be precisely matched with agronomic measures, which may result in high costs that offset the benefits. It is worth noting that in the Northeast's heavy black soil regions, soil pores are prone to compaction after deep ploughing, which may lead to reduced aeration and negative impacts on the soil environment.

Furthermore, the 3–5 cm soil layer is the region with the most stable soil moisture during the spring planting season in the Northeast. The primary purpose is to ensure seedling emergence efficiency and root development. Theoretically, deeper furrow depths can promote the activation of nutrients in deeper layers, accelerate biomass decomposition and mineralisation to release nitrogen, and facilitate water infiltration and salt leaching. However, this also increases the risk of seeds coming into contact with dry soil in deeper layers, leading to reduced moisture retention, lower temperatures delaying seedling emergence, weakened hypocotyl elongation, and increased plant lodging rates in later stages. Considering all factors, further practical testing of deeper tillage and furrow depths has not been conducted.

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During the three-year observation period, rainfall was relatively low in 2022 and 2023, while higher in 2024. Maize yield, chlorophyll content, and germination rate remained relatively stable over the three years, while moisture content was influenced by rainfall, with higher moisture content in 2024, resulting in an average germination time approximately 1.5 days shorter than in other years. However, during the ongoing monitoring of later growth, it was found that the shorter average germination time did not affect yield. The possible reason is that within a certain rainfall range (excluding extreme weather conditions), maize can maintain high yield stability through its physiological regulation and utilisation of soil water reserves. The findings of this study provide valuable insights for decision-makers, helping to optimise sowing practices and maximise maize yield in rain-fed regions of Northeast China.

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