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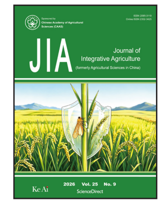

RESEARCH ARTICLE

Enhancing maize high-density population uniformity and yield through timely drip irrigation after sowing

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Highlights

- Timely application of drip irrigation for seedling emergence within 3 days after sowing in summer maize can significantly improve the emergence rate, increase the number of harvested ears and kernel weight per ear, while enhancing population uniformity, thereby boosting the final yield.
- The critical operation window for drip irrigation management is within 3 days after seeding, and the yield increase effect of drip irrigation cannot be fully realized if the window period is missed.
- Population uniformity is critically linked to yield; delayed irrigation disrupts uniformity through intensified resource competition, diminishing the yield potential of drip irrigation.

Abstract

Uneven crop stands arise from natural variations in emergence time, which are influenced by different irrigation measures applied post-sowing. In the pursuit of high-yielding maize populations, the emergence rate and uniformity of maize stands are critical factors. This study investigates the effects of different irrigation methods and drip irrigation at various days after sowing on the emergence uniformity and yield of summer maize. The experiment consisted of six treatments: drip irrigation on the 0th, 3rd, 6th, 9th, and 12th days after sowing (DAS0, DAS3, DAS6, DAS9, and DAS12), and sprinkling irrigation (SI) on the 0th day after sowing (SI0). Agronomic traits, ear characteristics, harvest yield, and indices of population uniformity were evaluated at critical growth stages. Results indicated that timely drip irrigation (DAS0–3) significantly increased the emergence rate and number of harvestable ears by 9.57% (8,621.61 plants ha^{-1}) and 10.54% (8,017.05 ears ha^{-1}) compared to the SI treatment. Treatment with DAS0–3 resulted in a significant increase of 13.50% in ear length and 24.85% in kernel weight per ear compared to the SI treatment. Maize populations subjected to delayed drip irrigation (DAS6–12) demonstrated a progressive decline in quality throughout the growth period. At the silk stage, the uniformity of plant height and ear height decreased by 47.19 and 44.85%, respectively, compared to the DAS0–3 treatment. Furthermore, at harvest, the uniformity of dry matter accumulation and leaf area index (LAI) was reduced by 28.24 and 41.83%, respectively, relative to the DAS0–3 treatments. Correlation analysis reveals that the uniformity of kernel weight per ear is most significantly associated with yield, as indicated by a correlation coefficient of 0.90^{**}. The yield in the DAS0–3 treatments was significantly higher than that in the SI treatment by 23.71%. The yields of the DAS6–12 treatments were notably lower than those of the DAS0–3 treatments, ranging from 13.18 to 23.97% lower, and were comparable to those observed in the SI treatment. The suboptimal implementation of drip irrigation technology has prevented it from realizing its full potential to increase crop yields. Each day's delay in initiating drip irrigation after the third day post-sowing reduces yield by an average of 0.32 Mg ha^{-1}. Timely drip irrigation following maize seeding significantly enhances emergence rate and population uniformity, increases the number of harvestable ears and kernel weight per ear, ultimately leading to higher final yields. Applying drip irrigation for seedling emergence within 3 days after sowing can better realize its yield-increasing potential.

Keywords: summer maize, irrigation methods, kernel weight, harvest ears, uniformity, yield

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1. Introduction

Maize is a globally significant food and feed crop and is the primary grain crop in China (Neumann *et al.* 2010; Cui *et al.* 2018). Increasing planting density has been proven to effectively increase maize yield and is applied in various regions (Ren *et al.* 2017; Li *et al.* 2020; Shao *et al.* 2024; Yan *et al.* 2024). This approach can allow optimal use of available sunlight, promoting efficient conversion of carbon dioxide and water into maize grains (Simkin *et al.* 2019; Ma *et al.* 2020; Hu *et al.* 2022). However, dense planting can lead to intraspecific competition for available resources, namely light (in the aerial tissues) and nutrients and water (in the roots) (Deng *et al.* 2012; Duan *et al.* 2023). Under high-density planting conditions, the uniformity of emergence and plant population uniformity significantly influence final yield.

Maize seed germination is highly sensitive to soil moisture and soil temperature (Li *et al.* 2011). Although summer maize is grown during the rainy season with high temperatures, unevenly rainfall distribution often causes short-term droughts, so supplemental irrigation is required during the critical growth stages of summer maize (Yan *et al.* 2017). Studies have demonstrated that maize emergence is rapid when soil moisture is between 21 and 25%, normal when it is between 18 and 21%, slow when it is between 16 and 18%, and markedly delayed when soil moisture falls below 16% (Ma *et al.* 2012). Thus, the traditional method of supply irrigation after sowing is commonly employed in field production to enhance the emergence rate of maize seeds (Zhou and Zhao 2019; Yi *et al.* 2022). Conventional flood irrigation and pipeline irrigation methods often lead to spatial variability in soil moisture and temperature. The variability in crop emergence, usually associated with spatial variability in soil moisture and temperature, is a major cause of heterogeneous plant sizes within a stand (Zhao *et al.* 2019).

Uniformity is often used to measure the degree of variation between individuals, indicating the production stability of a group. The degree of difference between plants in production is field uniformity, which is expressed by the reciprocal coefficient of variation (Tollenaar and Wu 1999; Liu *et al.* 2004; Boomsma *et al.* 2009). Early-emerging plants gain a competitive advantage in resource acquisition, becoming taller and developing a better root system earlier in the growing season (Liu *et al.* 2004), leading to higher yields. Studies have shown that grain yield decreases in unevenly emerged stands with increased planting density, where early-emerging plants produce more grain per plant than late-emerging ones (Ford and Hicks 1992). For example, studies have shown that grain yield can be reduced by 10 to 22% in plants with a 21-day delay in emergence compared to those that emerged initially (Carter *et al.* 1990), and individual plant yield can be reduced by 5.25% for each day of emergence delay (Nemergut *et al.* 2021). Studies evaluating plant-to-plant variability have shown that dominant plants outyield dominated plants, but the higher yield of the dominant plants does not compensate for the lower yield of dominated plants, such that the overall yield in a heterogeneous crop stand is reduced when compared to a homogeneous stand (Novak and Ransom 2018; Parra *et al.* 2022). Light is one of the most critical environmental factors influencing crop growth, development, and productivity, as 90–95% of total dry matter originates from the photosynthetic fixation of atmospheric carbon dioxide (Xie *et al.* 2019). Maximizing light interception ensures adequate energy supply for photosynthesis (Sarlikioti *et al.* 2011). However, with the increasing adoption of high-density planting for higher yields, leaf-to-leaf shading has become progressively more severe. Enhancing population uniformity and ensuring optimal light distribution within the maize canopy are essential strategies to achieve high yields (Li R F *et al.* 2021).

Drip irrigation is one of the most widely adopted irrigation methods globally. In recent years, due to the rapid advancement of agricultural modernization in China, drip irrigation has become increasingly prevalent in agricultural practices (Fan *et al.* 2017; Hu 2021). Compared to sprinkling, pipe, and furrow irrigation, drip irrigation offers several advantages, including maintaining optimal root zone moisture, high water use efficiency, short irrigation cycles, and distinct wet and dry interfaces, all of which promote uniform crop emergence (Yang *et al.* 2020; Jia *et al.* 2021; Wang and Wang 2024). Several studies have found that different crops and soil types respond positively to drip irrigation, significantly improving crop yield compared to sprinkling irrigation (Liu *et al.* 2022; Yan *et al.* 2022; Irmak 2024). Drip irrigation facilitates water conservation, enhances crop photosynthesis, promotes dry matter accumulation, grain filling, and yield formation (Madani *et al.* 2010; Cao *et al.* 2021; Li J P *et al.* 2021).

Currently, due to the gradual depletion of groundwater resources in the Huang-Huai-Hai region (Kong *et al.* 2016; Qi *et al.* 2022), local governments have strengthened groundwater management and promoted water-saving irrigation technologies. The traditional flood irrigation method after sowing has been largely abandoned by farmers due to its severe water waste, high labor costs, and time consumption. Currently, farmers predominantly adopt sprinkler irrigation systems for supplemental irrigation (Ren *et al.* 2023; Zhang *et al.* 2024). There is a lack of research on the effects of drip irrigation and sprinkling irrigation on the growth, development, and population uniformity of maize, with few systematic comparative studies conducted over multiple years. This study aims to (1) investigate the impact of drip irrigation at different days after sowing and sprinkling irrigation on the emergence rate and yield of summer maize; (2) determine the optimal window period for drip irrigation that maximizes yield potential; and (3) explore the relationship between varying levels of population uniformity and yield. By comparing the characteristics of different populations, this study provides a foundation for developing high-yielding maize cultivation techniques.

2. Materials and methods

2.1. Site description

Field experiments were conducted during the 2022–2024 maize growing seasons at the Luohe Experiment Station in Henan Province, China (113°76´15´´N, 33°60´27´´E), both affiliated with the Chinese Academy of Agricultural Sciences. Meteorological data, including air temperature and rainfall, for the study period are presented in Fig. 1. The physical and

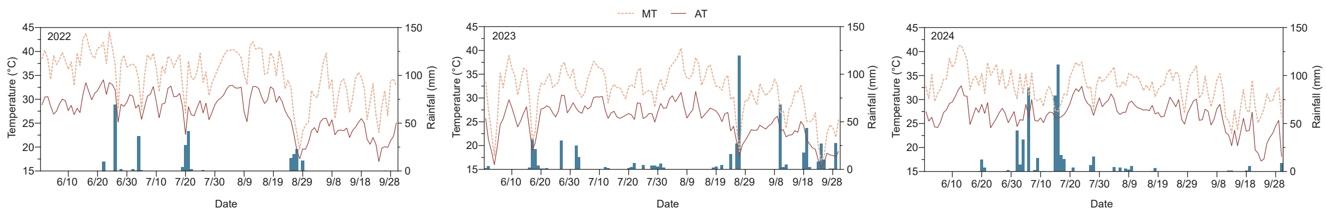

Fig. 1 Variability in average daily temperature (AT), maximum daily temperature (MT), and rainfall during the maize growth period in the field.

chemical characteristics of the soil are presented in Table 1. Soil samples were collected from the 0–30 cm depth layer prior to sowing.

2.2. Experimental design and field management

The maize varieties Jingnongke 728 (JNK728), widely cultivated in the Huang-Huai-Hai region, were selected for this study. From 2022 to 2024, the sowing date was consistently set on 5 to 6 June, while the harvesting period ranged from 1 to 5 October. The planting density across three years was 90,095 plants ha^{-1}. Randomly arranged plots measured 70 m×21.6 m, adhering to local field practices. A split-plot design was used, with seeds planted in alternating wide (80 cm) and narrow (40 cm) rows. Drip tape with a patch-type design, dripper spacing of 0.2 m, and a flow rate of 2.0 L h^{-1} (0.1 MPa) was installed. Each plot included a high-precision water meter (LXS-25, Ningbo, China), a pressure gauge, and a control valve to ensure consistent discharge and pressure stability. Before sowing, 30 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1}, and 105 kg K_2O ha^{-1} were applied. A total of 270 kg N ha^{-1} was applied through drip irrigation at the jointing, 12-leaf, silking, and filling stages of maize, with each application being uniform. Weeds, pests, and diseases were well controlled throughout the crop growing season.

The trial was divided into different irrigation methods after sowing and different days post-sowing for drip irrigation treatments. The specific experimental treatments and irrigation amounts are shown in Table 2. The sprinkler irrigation system operates by continuously moving in a parallel manner, evenly distributing water to the ground through a set of nozzles suspended from the equipment. The sprinkler irrigation plots are spaced sufficiently apart from the drip irrigation plots to prevent interference. Due to the influence of rainfall, the drip irrigation on the 12th day after sowing (DAS12) treatment was not conducted during 2023–2024.

Table 1 Soil properties at Luohe Experiment Station, Henan Province, China, before sowing, including soil organic matter (SOM), total nitrogen (TN), bulk density (BD), total porosity (TP), and field water content (FWC)[1)]

Year	SOM (g kg^{-1})	TN (g kg^{-1})	BD (g cm^{-3})	TP (%)	FWC (%)
2022	8.14	1.23	1.26	45.25	23.47
2023	9.30	1.18	1.01	43.11	22.14
2024	8.55	1.31	1.18	42.35	24.35

[1)] The soil texture is Fluvisols.

2.3. Measurement items and methods

Emergence rate In each plot, three 10 m sections were randomly selected from different rows, and the number of maize seedlings on both sides was counted at the third leaf collar (V3) stage. The plant density of maize at the V3 stage was calculated. Subsequently, the emergence rate was calculated using the following formula: Emergence rate (%)=(Emergence density/Sowing density)×100.

Leaf area index (LAI) During the jointing stage (V6), milk stage (R1), and harvest stage of maize, five uniformly growing plants previously marked in each plot were selected, leaf area was measured, and leaf area was calculated using the length–width coefficient method (0.75), and converted to LAI. The calculation formula is: Leaf area index (LAI)=Total leaf area on the land area/Land area.

Dry matter accumulation During V6, R1, and harvest of maize, representative plants in each plot were selected, three plants with consistent growth were chosen, the green was killed at 105°C for 30 min, dried at 80°C until constant weight, and the dry matter weight of the plants was weighed and measured.

Plant height and ear height During the silking stage of maize, 20 representative plants from each treatment were selected, and plant height and ear height were measured with a meter ruler, and their uniformity was calculated. Plant height uniformity=Plant height mean value/Plant height standard deviation, Ear height uniformity=Ear height mean value/Ear height standard deviation.

Ear length and kernel weight of per ear During the harvest stage of maize, 20 consecutive maize ears in each plot were randomly selected, the length of the ear was measured with a tape measure, the ears were manually threshed, dried at 80°C until constant weight, and the kernel weight per ear was weighed and measured. The mean, standard deviation, and uniformity of each parameter were calculated. The calculation formula is: Uniformity=Mean value/Standard deviation.

Yield During the maturity stage, 10 m of double rows in each plot were taken, repeated five times, the number of ears per hectare was calculated, the ears were threshed, and after determining the grain moisture content, the yield was converted to 14% moisture content (Chen *et al.* 2024).

Data statistics and analysis The data were processed using Excel 2021, and the Pearson correlation analysis and variance analysis of the measurement indicators were conducted using SPSS 26 software (IBM, Chicago, IL, USA). Regression models and graphs were generated in Graph Pad Prism 8.

Table 2 Sowing and irrigation dates for different treatments

Year	Treatment[1)]	Sowing data	Irrigation data	Interval between sowing and irrigation (d)	Irrigation method	Irrigation amounts (m^3)
2022	DAS0	6/5	6/5	0	Drip irrigation	30
	DAS3	6/5	6/8	3	Drip irrigation	30
	DAS6	6/5	6/11	6	Drip irrigation	30
	DAS9	6/5	6/14	9	Drip irrigation	30
	DAS12	6/5	6/17	12	Drip irrigation	30
	SI	6/5	6/5	0	Sprinkling irrigation	30
2023	DAS0	6/6	6/6	0	Drip irrigation	30
	DAS3	6/6	6/9	3	Drip irrigation	30
	DAS6	6/6	6/12	6	Drip irrigation	30
	DAS9	6/6	6/15	9	Drip irrigation	30
	SI	6/6	6/6	0	Sprinkling irrigation	30
2024	DAS0	6/5	6/5	0	Drip irrigation	30
	DAS3	6/5	6/8	3	Drip irrigation	30
	DAS6	6/5	6/11	6	Drip irrigation	30
	DAS9	6/5	6/14	9	Drip irrigation	30
	SI	6/5	6/5	0	Sprinkling irrigation	30

[1)] DAS0–12, drip irrigation on the 0th, 3rd, 6th, 9th, and 12th days after sowing; SI, sprinkling irrigation.

3. Results

3.1. Changes in maize yield under different irrigation methods and application timing

As illustrated in Fig. 2, the maize yield under drip irrigation after sowing was higher than that under sprinkling irrigation, except for the DAS12 treatment. With each day's delay in initiating drip irrigation for seedling emergence, the maize yield exhibited a gradual decline. Specifically, the yield of the DAS12 treatment was lower than that of the SI treatment. The yields of the DAS0 and DAS3 treatments were not significantly different, showing average increases of 25.21 and 22.21%, respectively, compared to the SI treatment. In contrast, the yields of the DAS6 and DAS9 treatments increased by an average of 7.57 and 0.80%, respectively, relative to the SI treatment, but these increases were not statistically significant. According to the fitted equation, each day's delay in initiating drip irrigation for seedling emergence resulted in an average yield reduction of 0.32 Mg ha^{-1}.

Comparing across different years, there were no significant differences in yield between the DAS0 (uniformity (UF)=27.33) and DAS3 (UF=27.55) treatments, both of which demonstrated high population uniformity (Fig. 2). Conversely, the DAS6 (UF=15.74) and DAS9 (UF=11.20) treatments exhibited significant interannual yield variability and low population uniformity.

3.2. Changes in emergence rate and harvest ears under different irrigation methods and application timing

As shown in Fig. 3, the emergence rate of maize seeds treated with drip irrigation for seedling emergence after sowing is consistently higher than that of the sprinkling irrigation method post-sowing. With each day's delay in initiating drip irrigation for seedling emergence, the emergence rate of maize exhibits a gradual decline. Specifically, the emergence rate of the DAS12 treatment is lower than that of the SI treatment. The emergence rates for the DAS0 and DAS3 treatments are predominantly above 90%, with the highest reaching 97.90%. Compared to the SI treatment, the emergence rates for the DAS0 and DAS3 treatments are significantly higher by 9.57%, while those for the DAS6–9 treatments show an increase of 3.33%. After sowing, for each additional day of delay in initiating drip irrigation for seedling emergence, the emergence rate decreases by an average of 0.97% (Fig. 3-A–C). The emergence rate of the DAS12 treatment was significantly lower than that of the DAS0–3 treatments by 15.05%. Timely application of supplementary drip irrigation after sowing can effectively improve the emergence rate of maize.

The trend in the number of harvest ears mirrors that of the emergence rate. There were no significant differences in the number of harvest ears between the DAS0 and DAS3 treatments, which on average increased by 11.65 and 9.42%, respectively, compared to the SI treatment. The DAS6 and DAS9 treatments increased the number of harvest ears by 0.83 and 0.21%, respectively, compared to the SI treatment, but these increases were not statistically significant. The harvest ears under the DAS0–3 treatments were significantly higher by 10.81% compared to the DAS6–9 treatments and by 20.79% compared to the DAS12 treatment. For each additional day of delay in initiating drip irrigation, the number of ears per ha decreased by an average of 83.34 ears (Fig. 3-D–F). Timely drip irrigation after sowing effectively increased the number of harvest ears, thereby laying a foundation for achieving high yield.

Comparing across different years, there are no significant differences between the DAS0 and DAS3 treatments. However, the emergence rates for the DAS6–12 treatments in different years are significantly lower than those for the DAS3 treatment, with an average reduction of 4.87%. The trend in the number

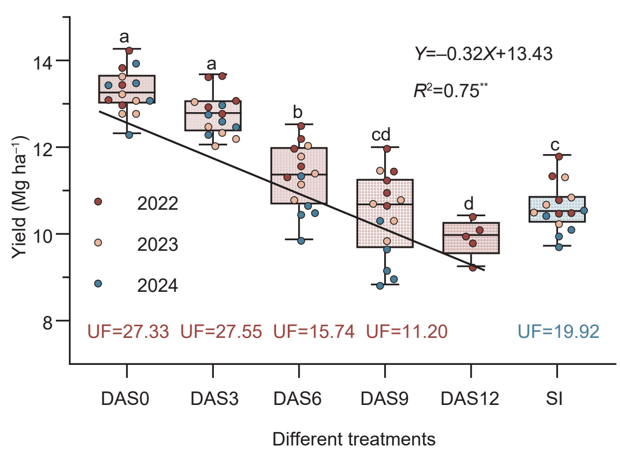

Fig. 2 Effects of different irrigation methods on maize yield. UF, uniformity. DAS0–12, drip irrigation on the 0th, 3rd, 6th, 9th, and 12th days after sowing; SI, sprinkling irrigation. Boxplots display the 25th percentile, means, and 75th percentile (horizontal line from top to bottom), and bars show the maximum (top edge) and minimum (lower edge) percentiles. The scattered points represent the data distribution. Different lowercase letters indicate significant differences among treatments (P<0.05).

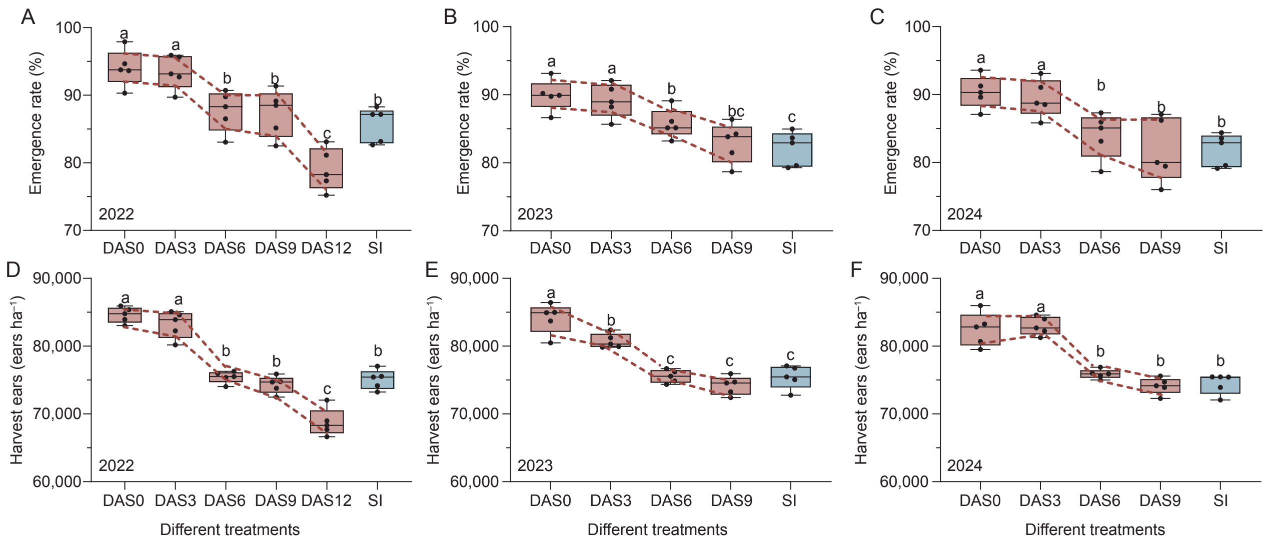

Fig. 3 Effects of different irrigation methods on emergence rate and harvest ears. DAS0–12, drip irrigation on the 0th, 3rd, 6th, 9th, and 12th days after sowing; SI, sprinkling irrigation. Boxplots display the 25th percentile, means, and 75th percentile (horizontal line from top to bottom), and bars show the maximum (top edge) and minimum (lower edge) percentiles. The scattered points represent the data distribution. Different lowercase letters indicate significant differences among treatments ($P<0.05$).

of harvested ears follows that of the emergence rate.

3.3. Impact of different irrigation methods and application timing on maize ear traits

Over the course of 3 years, there was a significant trend of decreasing ear length with the delay of drip irrigation after sowing. The ear lengths in the DAS0, DAS3, DAS6, and DAS9 treatments were increased by 18.85, 8.16, 6.34, and 2.57%, respectively, compared to the SI treatment. Among the treatments, only the difference between the DAS12 and SI treatments was significant, with no significant inter-annual differences (Fig. 4-A–C). The treatments of DAS 0–3 (UF=13.59–17.69) exhibited high uniformity. However, as irrigation was delayed after sowing, the uniformity of ear length gradually decreased (UF=8.76–15.01).

As shown in Fig. 4-D–F, the kernel weight per ear of maize treated with drip irrigation after sowing was generally higher than that of the sprinkling irrigation method post-sowing. The DAS0 treatment significantly increased the kernel weight per ear by 29.62% on average compared to the SI treatment, while the DAS3 treatment increased it by 20.08%, the DAS6 treatment by 17.21%, and the DAS9 treatment by 7.01%. For each additional day of delay in drip irrigation, the kernel weight per ear decreased by an average of 4.20 g. There was no significant difference in kernel weight per ear between the DAS12 treatment and the SI treatment. The treatments of DAS0–3 (UF=9.31–12.52) exhibited high uniformity. However, as irrigation was delayed after sowing, the uniformity of kernel weight gradually decreased (UF=3.29–9.37).

The results indicate that the timely initiation of drip irrigation after sowing significantly enhances maize ear length and kernel weight per ear, with the most substantial improvements observed in the DAS0–3 treatments. Conversely, delays in drip irrigation lead to a progressive decline in both ear length and kernel weight uniformity, highlighting the critical importance of prompt irrigation for optimizing maize yield.

3.4. Impact of different irrigation methods and application timing on plant height and ear height

As shown in Fig. 5, from DAS0 to DAS12 treatments and then to the SI treatment, there were no significant differences in plant height and ear height at silking stages among the various treatments. However, the degree of variation increased, and the uniformity decreased, with the DAS12 treatment reaching the lowest level. The range of plant height in the DAS0–3 treatments was 252.48–304.38 cm, in the DAS6–12 treatments it was 234.22–306.69 cm, and in the SI treatment it was 198.09–311.50 cm (Fig. 5-A–C). The variation range of ear height for the DAS 0–3 treatments was 85.77–116.34 cm, for the DAS6–12 treatments it was 66.86–131.96 cm, and for the SI treatment it was 87.80–120.60 cm, with similar trends observed across years (Fig. 5-D–F). The plant height and ear height of DAS0–3 (UF=14.06–55.76) exhibited high uniformity. However, as irrigation was delayed after sowing, the uniformity gradually decreased (UF=7.04–24.42).

The effects of different irrigation methods and delayed drip irrigation after sowing on plant height and ear height were primarily reflected in the uniformity, while the specific values of plant height and ear height across different treatments did not show a clear pattern.

3.5. Impact of different irrigation methods and application timing on dry matter accumulation and LAI

The differences in dry matter accumulation under various treatments increased as the growth period progressed. Maize populations that experience delayed drip irrigation (DAS6–12) exhibited a progressive deterioration in quality throughout the growth (Fig. 6-A). At the V6 stage, there were no significant differences among the treatments. At the R1 stage, the dry matter accumulation of the DAS0–3 treatments was significantly higher by 23.00% compared to the SI treatment and by 30.15% compared to the DAS6–12 treatments. At the harvest stage, the dry matter accumulation in the DAS0 and DAS3 treatments was significantly higher than in the SI treatment by 18.89 and 14.37%, respectively. On average, for each additional day of delay in drip irrigation for seedling emergence, the dry matter weight decreased by 1.57%. The dry matter weight of the SI treatment was comparable to that of the DAS6 treatment.

As shown in Fig. 6, the LAI of maize was significantly influenced by different irrigate ion methods and the timing of drip irrigation after sowing. During the R1 stage, the DAS0 treatment exhibited the highest LAI, which was 11.37% higher than that of the DAS12 treatment (Fig. 6-B).

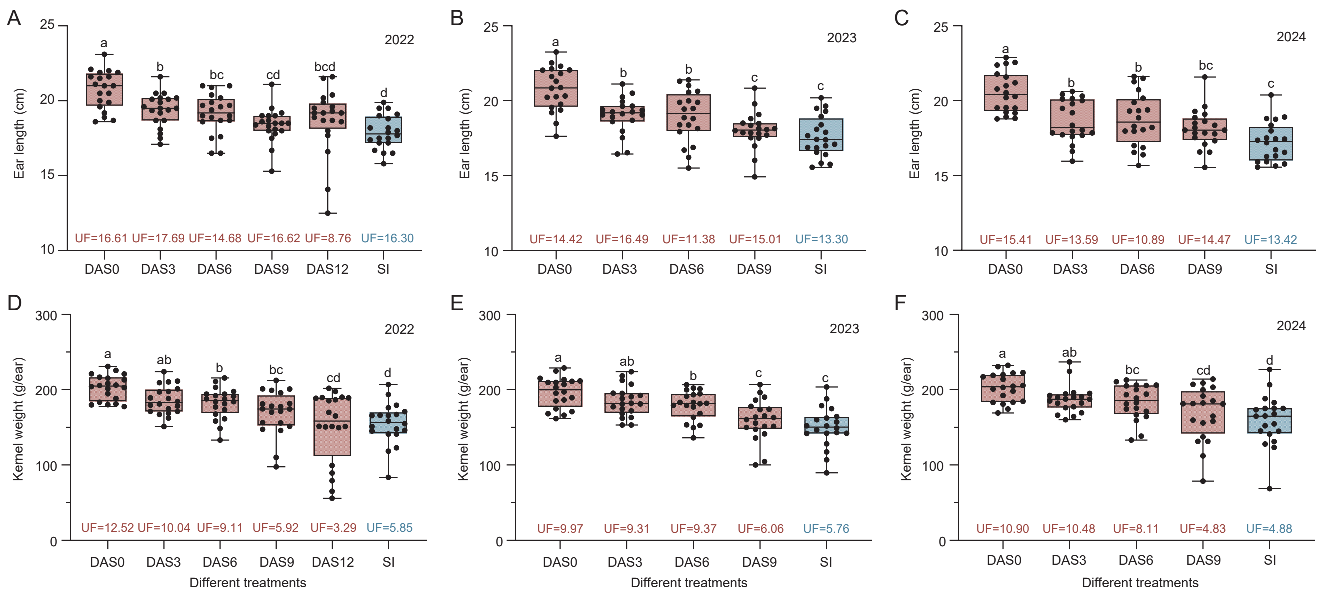

Fig. 4 Effects of different irrigation methods on ear traits. DAS0–12, drip irrigation on the 0th, 3rd, 6th, 9th, and 12th days after sowing; SI, sprinkling irrigation. UF, uniformity. Boxplots display the 25th percentile, means, and 75th percentile (horizontal line from top to bottom), and bars show the maximum (top edge) and minimum (lower edge) percentiles. The scattered points represent the data distribution. Different lowercase letters indicate significant differences among treatments (P<0.05).

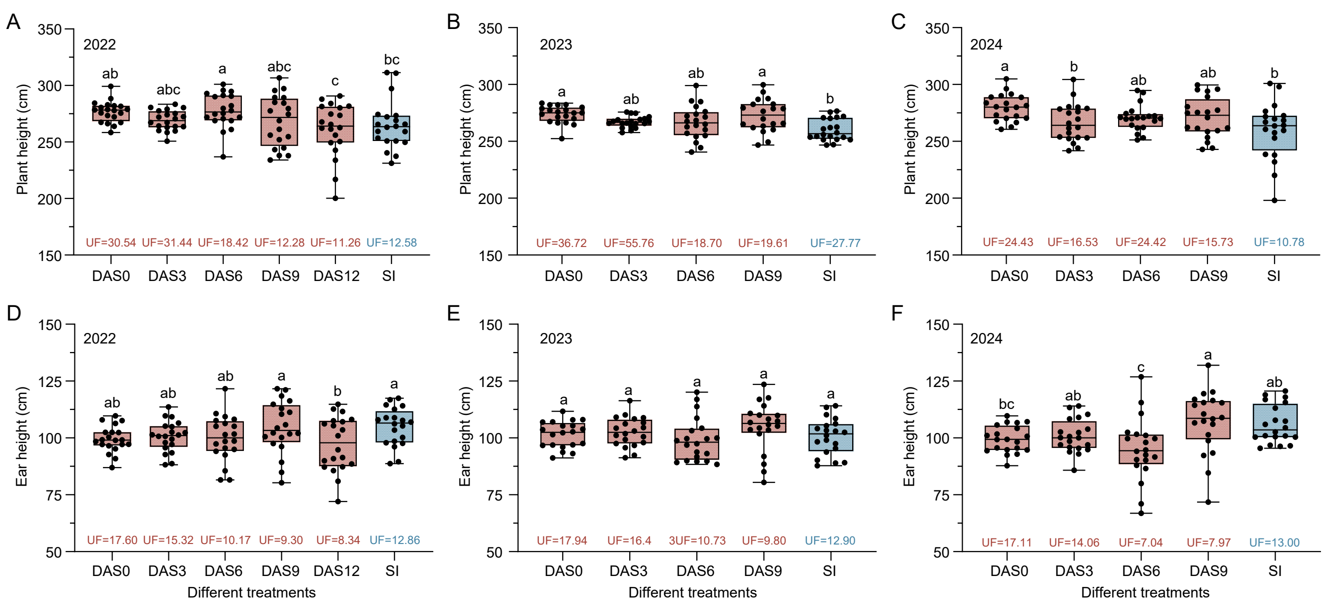

Fig. 5 Effects of different irrigation methods on plant height and ear height. DAS0–12, drip irrigation on the 0th, 3rd, 6th, 9th, and 12th days after sowing; SI, sprinkling irrigation. UF, uniformity. Boxplots display the 25th percentile, means, and 75th percentile (horizontal line from top to bottom), and bars show the maximum (top edge) and minimum (lower edge) percentiles. The scattered points represent the data distribution. Different lowercase letters indicate significant differences among treatments (P<0.05).

At the V6 stage, the above-ground dry matter accumulation exhibited high uniformity (UF=10.85–14.12). At the R1 stage, the uniformity of dry matter accumulation decreased progressively with delay drip irrigation after sowing, declining from an average of 13.58 (DAS0) to 9.67 (DAS9). At the harvest stage, the uniformity of dry matter accumulation decreased with delay drip irrigation, from 14.73 (DAS0) to 8.19 (DAS9), and further to 6.41 in the DAS12 treatment.

However, as irrigation was delayed after sowing, the uniformity gradually decreased (UF=5.24–11.48). The trend in the LAI is similar to that of the above-ground dry matter accumulation. At the R1 stage, with the delay of drip irrigation after sowing, the uniformity of LAI decreased from 17.63 (DAS0) to 13.41 (DAS9). At the harvest stage, with the delay of irrigation after sowing, LAI showed a gradually increasing trend; however, the uniformity decreased from 16.74 (DAS0) to 10.81 (DAS12) and further declined to 6.24 under the DAS12 treatment.

3.6. Correlation analysis of various indicators and their uniformity

The correlation analysis revealed that yield has the highest correlation with emergence rate, reaching a highly significant level (0.97**). It is also highly significantly correlated with dry matter, LAI, ear length, kernel weight per ear, and harvest ears, significantly correlated with plant height. There is no significant correlation with ear height, but a highly significant correlation with the uniformity of ear height. Additionally, yield is highly significantly correlated with the uniformity of dry matter, LAI, kernel weight per ear, and harvest ears (Fig. 7).

Path analysis indicates that compared to the DAS12 treatment (Fig. 8), the DAS0–3 treatments have a higher direct path coefficient for HE (0.78), while the DAS6–12 treatments have a higher direct path coefficient for KWE (0.51).

4. Discussion

4.1. Timely drip irrigation after sowing can effectively increase the emergence rate and harvest ears

The emergence rate is a critical factor influencing the number of harvest ears, with higher emergence rates ultimately leading to greater ear counts (Albarenque *et al.* 2023). Given that maize is highly sensitive to drought stress, prolonged burial of seeds in the soil can reduce their viability. Previous studies have found that the uneven distribution of soil moisture or soil temperature caused by straw returning to the field or cultivation methods is the key factor affecting the emergence rate of maize (Zhao *et al.* 2019). This study demonstrates that altering the irrigation method for maize seedling emergence and applying drip irrigation at different days after sowing can influence the emergence rate. Maize seeds under drip irrigation exhibit a significant emergence advantage compared to those under sprinkling irrigation, utilizing water and nutrients more efficiently. As the period of delayed drip irrigation after sowing increases, seed activity diminishes, leading to a decline in the emergence rate. Drip irrigation on the day of sowing achieves the highest maize emergence rate, averaging up to 94.05%, which is 8.36% higher than the average emergence rate under sprinkling irrigation. The number of harvest ears in treatments with timely drip irrigation after sowing (DAS0–3) was significantly higher by 10.54% compared to the sprinkling irrigation treatment. For each additional day of delay in drip irrigation after sowing, the number of harvest ears per ha decreases by an average of 83.34 ears.

4.2. Irrigation methods and application timing affect the uniformity of the population by influencing dry matter accumulation and LAI

Sprinkling irrigation can lead to uneven soil moisture

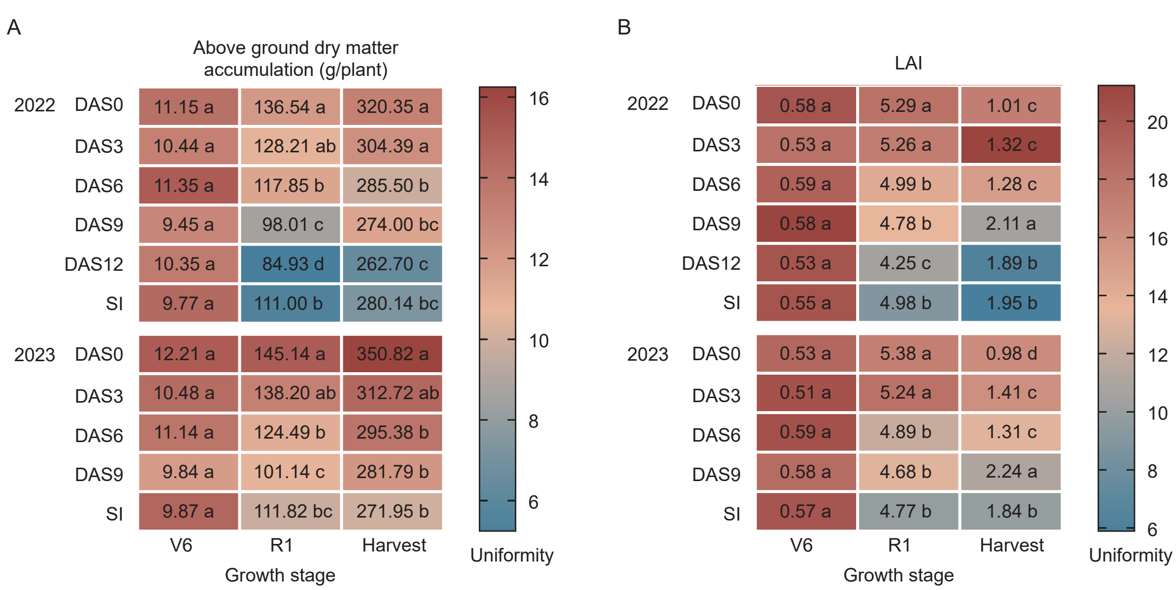

Fig. 6 Effects of different irrigation methods on dry matter accumulation and leaf area index (LAI). DAS0–12, drip irrigation on the 0th, 3rd, 6th, 9th, and 12th days after sowing; SI, sprinkling irrigation. Different lowercase letters indicate signiffcant differences among treatments (P<0.05).

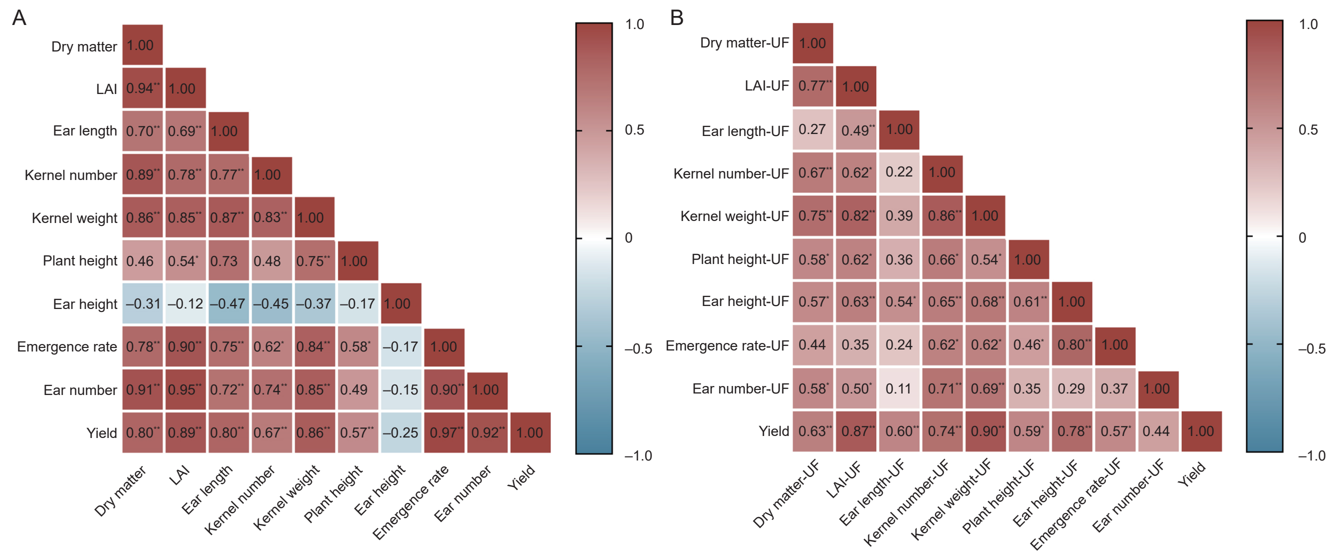

Fig. 7 Correlation analysis of various indicators and their uniformity. LAI, leaf area index; UF, uniformity. * and ** indicate significances at the 0.05 and 0.01 probability levels, respectively.

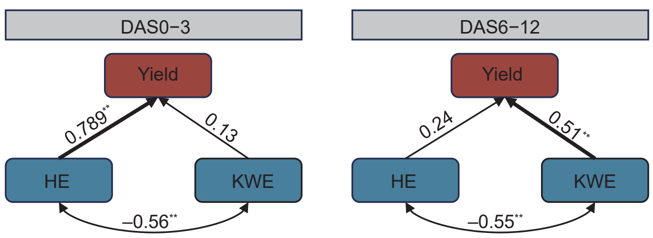

Fig. 8 Path analysis of the relationship between harvest ears (HE), kernel weight per ear (KWE), and yield. DAS0–12, drip irrigation on the 0th, 3rd, 6th, and 12th days after sowing. ** indicates signiffcance at the 0.01 probability level.

distribution, while delayed drip irrigation can cause a decline in seed vigor. Both factors contribute to reduced population uniformity. Uniform crop stands outperform non-uniform stands when growing conditions and management are favorable (Andrade and Abbate 2005; Rutto *et al.* 2014). Early-emerging plants have a competitive advantage in resource acquisition compared to later-emerging plants. They tend to grow taller and develop a more robust root system earlier in the growing season, leading to healthier plants (Liu *et al.* 2004). Material accumulation is the physical foundation for the formation of maize kernel yield, and within a certain range, the dry matter production capacity and the amount of dry matter accumulation are directly proportional to kernel yield (Liu *et al.* 2023). In this study, at the harvest stage, the dry matter accumulation in the timely drip irrigation after sowing (DAS0–3) treatments was 16.63% higher than under the SI treatment. During the R1 stage, the timely drip irrigation after sowing (DAS0–3) treatments exhibited a 12.12% higher accumulation than the DAS6–12 treatments. The treatment without timely irrigation after sowing exhibited delayed emergence compared to the timely drip irrigation treatment, ultimately failing to achieve full physiological maturity at harvest while demonstrating a 51.52% higher average LAI than the irrigated control. Although the maturity of maize at harvest is inconsistent due to non-uniform emergence times, it is traditionally harvested at the same time. This inconsistency in maturity is a significant contributor to yield loss.

4.3. Timely drip irrigation after sowing can increase the uniformity of the maize population and thereby enhance yield

Previous studies have demonstrated that single-seed precision sowing and precision fertilization can achieve uniform plant distribution, reduce inter-plant competition, and fully realize the production potential of individual plants (Zhang *et al.* 2020). In our study, the uniformity of plant height and ear height in the treatment with timely drip irrigation after sowing was significantly higher than that in the sprinkling irrigation treatment. Similar trends were observed in LAI at the R1 stage and dry matter accumulation at harvest. There were no significant differences in population uniformity (including plant height and ear height) between the DAS0 and DAS3 treatments. Delayed sowing and irrigation led to a reduction in the uniformity of plant height from an average of 32.57 (DAS0–3) to 17.20 (DAS6–12), and the uniformity of ear height decreased from 16.41 (DAS0–3) to 9.08 (DAS6–12). The specific values of plant height and ear height are less affected by different irrigation methods and drip irrigation at various days after sowing, with the primary impact being on the uniformity of plant height and ear height. This is primarily attributed to the inequitable competition for nutrients and spatial resources. The quality of each treated maize population exhibited a progressive deterioration throughout the growth period, with the extent of decline varying among groups. From the V6 to R1 stage, the uniformity of dry matter accumulation under the DAS0–3 treatments decreased from an average of 13.67 to 11.45, while under the DAS6–12 treatments, it dropped from an average of 13.87 to 8.39. Before the V6 stage, the competition among plants under the DAS0–3 treatments was relatively weak, resulting in a higher uniformity of the population. However, as the plants grew larger from the R1 stage and beyond, the competition for space and nutrients intensified, causing the uniformity of the population to decline to some extent as the growth period progressed. Nevertheless, the decline was much less significant compared to the DAS6–12 treatments. This decrease in uniformity may be related to reduced seed germination capacity caused by delayed irrigation, which affects plant growth consistency and final yield performance.

The literature is consistent in reporting the negative effect of delayed emergence on crop yield (Nafziger *et al.* 1991; Tollenaar and Wu 1999; Liu *et al.* 2004; Andrade and Abbate 2005). Some studies planted maize at several dates to simulate delayed emergence and reported yield reduction in plants with delayed emergence, noting that late emerged plants could not compete with early emerged plants for resources (Nafziger *et al.* 1991). A study reported per-plant yield reductions of 5.25% per day of delay in emergence when the plants emerged nearly 7 days after planting (Nemergut *et al.* 2021). The yield of timely drip irrigation after sowing (DAS0–3) treatments was significantly higher than in the SI treatment by 23.67%. The yield of the treatment without timely drip irrigation was significantly lower than that of the timely drip irrigation treatment by 13.18–23.97%, comparable to the yield of the SI treatment. The ineffective implementation of drip irrigation technology fails to leverage its yield-increasing effects. According to the fitted equation, after sowing, for every day the drip irrigation timing is delayed beyond the third day, the yield per hectare decreases by an average of 0.32 Mg. The correlation analysis revealed that yield has the highest correlation with emergence rate, reaching a highly significant level (0.97^{**}). Path analysis indicates that, compared to the DAS6–12 treatments, the DAS0–3 treatments have a higher direct path coefficient for HE (0.78), while the DAS6–12 treatments have a higher direct path coefficient for KWE (0.51) (Fig. 8). The reason for this difference may be due to the lower harvest ears of DAS6–12, which leads to the greater impact of individual plant productivity on population yield. Timely drip irrigation after sowing (DAS0–3) effectively maximizes the yield-enhancing effects of high-density planting, with the increased harvest ears contributing significantly to yield formation. Previous studies reported that delayed emergence decreased maize total yield and yield components, and the reduction in total crop yield could be explained by the reduction in the grain number per plant (Albarenque *et al.* 2023). However, this study has found that although the maize population could partially compensate for the yield loss through increased kernel weight per ear, the significant intra-population variation in kernel weight means that the elevated kernel weight in some plants was insufficient to offset the overall yield reduction at the population level.

5. Conclusion

Timely application of drip irrigation for seedling emergence within 3 days after sowing in summer maize can significantly improve emergence rate, increase the number of harvested ears and kernel weight per ear, and enhance population uniformity, thereby boosting the final yield. According to our findings, for every day the drip irrigation timing is delayed beyond the third day after sowing, the yield per hectare decreases by an average of 0.32 Mg. This highlights the critical operation window for drip irrigation management within 3 days after seeding, and the yield increase effect of drip irrigation cannot be fully realized if the window period is missed.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

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