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Response of summer maize growth, water use and yield to staged deficit irrigation in the seasonally arid regions of Southwest China

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ABSTRACT

Understanding drought response mechanisms is critical for high-efficiency maize production in the seasonally arid regions of Southwest China. A two-year field experiment (2022–2023) was conducted using a randomized block design with two deficit degrees (D25% and D50%) imposed at single or multi stages to investigate summer maize growth, yield and water use responses to stage-specific deficit irrigation (DI). The study site is located in a typical seasonally arid region with subtropical climate. Results indicated that DI during vegetative growth (VG) period significantly inhibited maize morpho-physiological traits ($p < 0.05$) but triggered compensatory recovery after reirrigation, and enhanced instantaneous water use efficiency and grain dry matter proportion (7.75%–12.52% higher than CK). Conversely, DI during reproductive growth (RG) period markedly decreased grain yield and protein content. DI at VG and early RG period also effectively increased starch content by 2.38%–15.78%. Moreover, deficit degree and stage generally significantly affected maize morpho-physiological traits, dry matter, yield and quality ($p < 0.05$). Entropy-TOPSIS evaluation identified the D25% treatment at seedling stage as the optimal strategy, as it maintained yield stability (4.52% reduction, $p > 0.05$) while enhancing water use efficiency (3.26%). We conclude that stage-specific DI serves as a practical, climate-adaptive tool for summer maize production in seasonally arid regions.

ARTICLE HISTORY

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KEYWORDS

Deficit irrigation; grain yield; maize growth; water productivity; irrigation strategies

Introduction

Maize is a cornerstone of global agriculture, vital for animal husbandry, industry, and food production (Erenstein et al. 2022). However, as a crop with high water requirements, its production is increasingly threatened by water scarcity (Wang et al. 2019; Allakonon et al. 2022). To balance yield stability with water conservation, deficit irrigation (DI) has emerged as a strategic management tool. By deliberately withholding water during non-critical growth stages, DI can enhance water productivity (WP) while maintaining or even increasing crop yields (Kang et al. 2000; Du et al. 2015; Comas et al. 2019). This approach is fundamentally based on the strategic allocation of limited water resources to crop growth stages that require them most (Yang et al. 2022; Gao et al. 2025), making its efficacy highly stage-dependent.

The impact of DI on grain yield, quality, and water productivity depends on the intensity, duration, and frequency of water stress, as well as stage-specific crop sensitivity (Farré and Faci 2009; Chai et al. 2016; Comas et al. 2019). Implementing DI during vegetative growth (VG) period allow plants to trigger morpho-physiological acclimation, enhancing resilience to subsequent moisture stress (Pieruschka and Schurr 2019). Such adaptive strategies include root system expansion to enhance water uptake (Pandey et al. 2000; Li et al. 2011), alongside physiological adjustments such as osmolytes accumulation and enhanced antioxidant enzyme activity to maintain cell turgor and mitigate metabolic functions damage (Pieruschka and Schurr 2019; Sun et al. 2025). Although DI-induced stomatal closure may restrict leaf area and photosynthetic capacity, it effectively conserves soil moisture and improves WP (Liao et al. 2022). While severe deficit can inhibit dry matter (DM) accumulation and cause yield loss (Ye et al. 2020), moderate stress during VG period often allows for complete physiological recovery after re-irrigation, minimizing negative effects on crop development and productivity (Abid et al. 2018). Notably, this recovery capacity also varies by deficit stage

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and severity; for instance, maize at the tillering stage exhibits higher resilience than those at the jointing stage (Cai et al. 2020).

Furthermore, DI during the late VG period may not significantly reduce grain yield (Peng et al. 2021; Wang et al. 2024). This may be attributed to efficient DM translocation toward reproductive organs (Cai et al. 2020; Sun et al. 2025). Concurrently, in accordance with the functional balance theory, DI shifts DM partitioning, prioritizing root growth over shoots to enhance water acquisition (Zhang et al. 2019; Cheng et al. 2021; Cai et al. 2023). In contrast, the reproductive growth (RG) period is significantly more vulnerable. DI during this period leads to pronounced grain abortion and reduced grains number (Gao et al. 2024). Grain quality also responds variably to deficit stage, with DI at the silking stage typically increasing protein content while lowering starch content (Wang et al. 2021). Ultimately, DI serves as a strategic trade-off, maximizing WP by non-significantly sacrificing yield. In semi-arid regions, DI has been shown to enhance WP by 22%–47% despite yield declines of 2%–33% (Stepanovic et al. 2021). Further research comparing DI treatments employed at different growth stages indicates that higher WP was observed under greater deficits during the VG period (Comas et al. 2019; Jiao et al. 2024).

Southwest China is a primary hub for maize, accounting for approximately 30% of the national cultivation area and yield (Liu et al. 2025). Despite its subtropical climate, the region suffers from remarkably uneven spatial and temporal precipitation, leading to seasonal droughts that threaten stable summer maize production. This necessitates the development of resilient irrigation management strategies. While DI has been widely implemented in traditionally arid regions (Wang et al. 2024) and proven to be a promising approach for enhancing crop WP while minimizing adverse effects on crop yield (Zheng et al. 2023; Wen et al. 2025). However, DI application in the unique, seasonally arid context of Southwest China remains insufficiently explored. Additionally, most existing literature categorizes DI treatments based on single or multiple growth stages or varying deficit levels throughout the entire growth period. There is a critical knowledge gap regarding high-resolution phenological responses of maize growth, grain yield and quality, and WP to single-stage versus multi-stage DI. Quantifying these phenological responses is essential for optimizing irrigation strategies amid local climatic fluctuations. In this study, we hypothesize that a scientifically optimized stage-based DI strategy can trigger compensatory growth mechanisms and favorable DM allocation, thereby enhancing WP without significantly reducing yield or compromising grain quality. The primary purposes are: (1) to characterize the morpho-physiological response variation of summer maize to DI during distinct growth stages; (2) to analyze how alterations in DM allocation under different DI regimes influence grain yield and quality formation; and (3) to identify an optimal DI schedule tailored for summer maize production in the seasonally arid regions of Southwest China. [Figure 1](#) presents a conceptual framework linking stage-specific DI regimes to maize morpho-physiological responses, DM allocation, and yield-quality-WP outcomes to optimize irrigation management.

Materials and methods

Study site introduction

The field experiments were conducted at the Dujiangyan Irrigation Experimental Station in Deyang City, Sichuan Province (104°26'E, 31°12'N) ([Figure 2](#)). This area is a typical seasonal arid region with an altitude of 490 m, an average annual rainfall of 1060 mm, evaporation of 1029 mm, and sunshine duration of 1361 h. The meteorological data during the maize growing season, as shown in [Figure 3](#), were collected using an automatic weather station (ET007, Insentek Co., Ltd., CN) located at the experimental site. The soil in the main root zone (0–100 cm) is purple soil, with an average soil bulk density of 1.55 g cm⁻³, field capacity of 31% (volumetric water content), pH of 7.87, available nitrogen content of 36.21 mg kg⁻¹, available phosphorus content of 6.57 mg kg⁻¹, active potassium content of 130 mg kg⁻¹ and organic matter content of 9.36 g kg⁻¹.

Experimental design

Deficit irrigation (DI) experiments were carried out during 2022–2023 in a dryland plot containing 36 test pits with bottoms and 2 large weighing lysimeters, all covered by an automatic movable rain shelter to prevent rainfall. The lysimeter weighing system has a resolution, measurement accuracy, and repeatability of ±0.01,

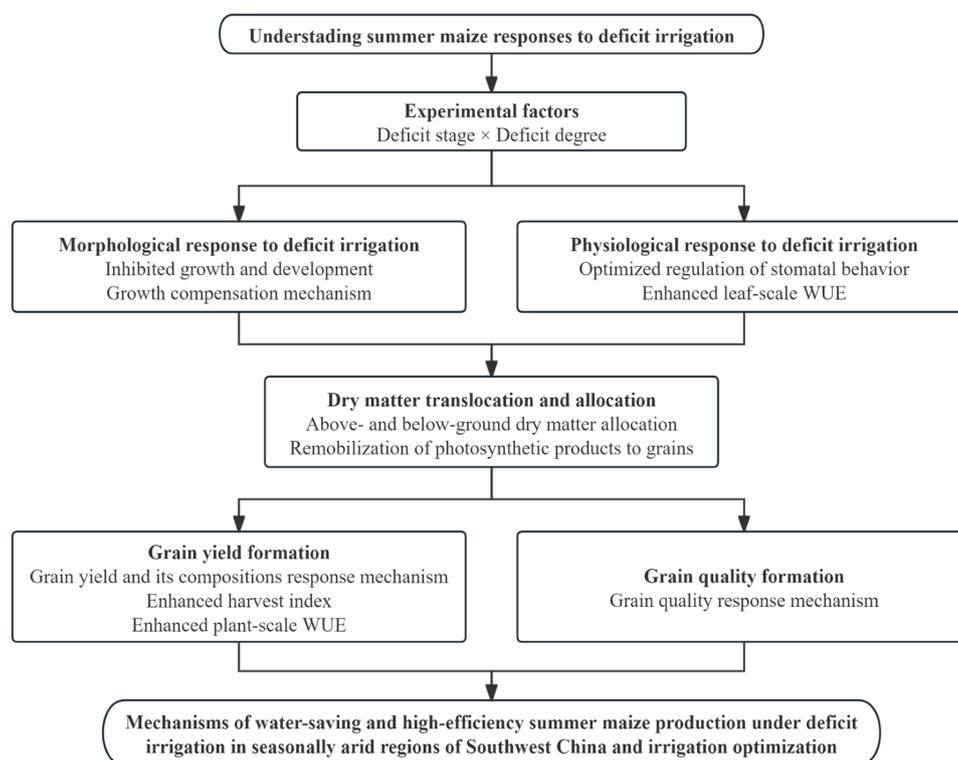


Figure 1. The conceptual framework for optimizing summer maize irrigation strategies based on stage-specific deficit irrigation.

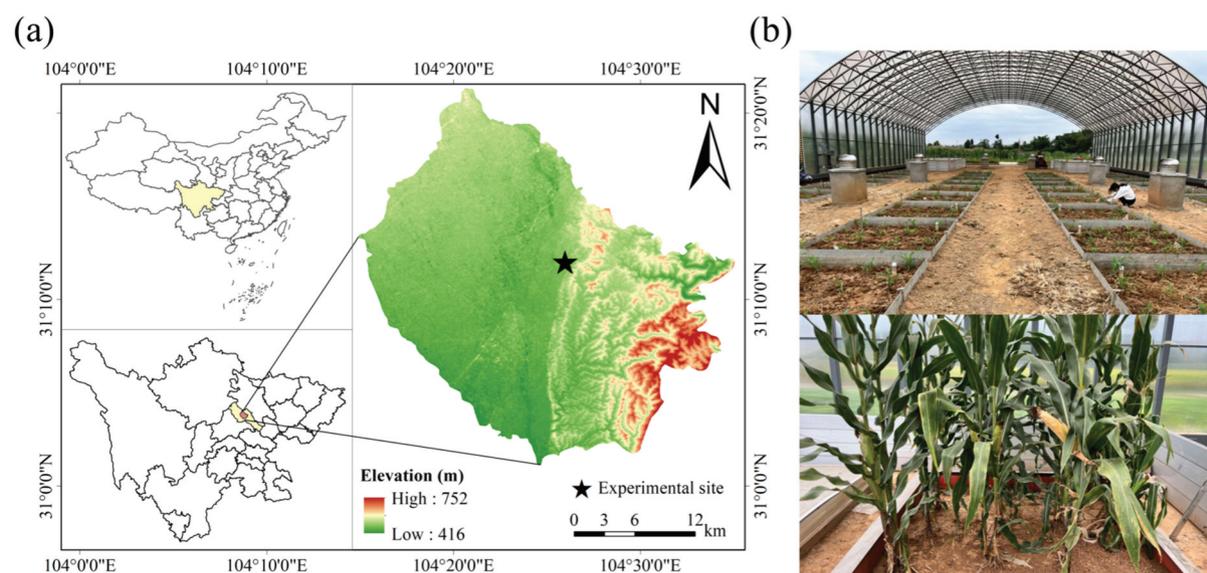


Figure 2. Experimental location and facilities. (A) the location of experimental site of Sichuan Province in China; (B) Overview of the study area.

± 0.05 , and ± 0.02 mm water depth, respectively, with no zero drift. Each lysimeter is equipped with 5TE sensors (Decagon Devices, Inc., U.S.A.) to measure soil moisture content at depths of 10, 40, 70, and 100 cm, respectively. The lysimeters measured 2.0 m \times 2.0 m \times 2.4 m (length \times width \times height), and the test pits with bottoms were arranged in 4 rows of 9 pits each, with dimensions of 2.0 m \times 2.0 m \times 2.3 m (length \times width \times height).

The experiment followed a randomized complete block design. 'Zhongyu 3' was selected as the experimental variety with a 50 cm \times 50 cm spacing. In 2022, maize was sown on June 22 and harvested on

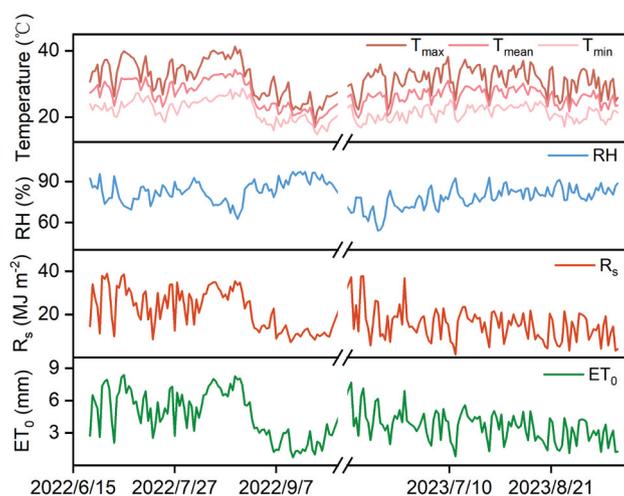


Figure 3. Meteorological factors during the growing season of summer maize from 2022–2023.

Table 1. Growth stages of summer maize in two growing seasons.

Growth stage	2022		2023	
	Date of beginning	Duration (d)	Date of beginning	Duration (d)
Seedling stage (I)	27 Jun	23	7 Jun	29
Jointing stage (II)	20 Jul	23	6 Jul	21
Tasseling stage (III)	12 Aug	17	27 Jul	17
Grain-filling stage (IV)	29 Aug	19	13 Aug	18
Maturity stage (V)	17 Sep	14	31 Aug	19

September 30; in 2023, it was sown on May 31 and harvested on September 18. The growth period was divided into five stages: seedling stage (I), jointing stage (II), tasseling stage (III), grain-filling stage (IV), and maturity stage (V) (Table 1). A control treatment (CK) was established and planted in large weighing lysimeters with two replicates. Two DI levels were applied at stages I–IV, with irrigation amounts set at 75% (D25%) and 50% (D50%) of CK, respectively. Additionally, these same DI levels were applied separately at the vegetative growth (VG) stages (stages I–II) and reproductive growth (RG) stages (stages III–IV). Each DI treatment was replicated three times, with plants grown in test pits. Irrigation was carried out whenever the soil water content of CK, monitored in real-time by sensors, approached or fell below the lower limit, until it reached the upper limit at each growth stage (Table 2). The irrigation frequency for the DI treatments was consistent with that of the CK, and the irrigation quotas for all treatments across different growth stages are shown in Table 3. Pest and disease control, along with other management practices, were identical across all treatments. Fertilization was uniform, consisting of a basal application of 750 kg ha⁻¹ of compound fertilizer (N: P₂O₅: K₂O = 15: 15: 15) and a top-dressing of 375 kg ha⁻¹ of urea at the tenth leaf stage. The large weighing lysimeters and test pits featured sidewalls elevated above the soil surface and sealed bottoms, effectively isolating the plots from surface runoff and groundwater recharge during the summer maize growing season.

Measurements index and methods

Plant growth

From the third leaf stage onward, three representative maize plants exhibiting uniform growth were randomly selected and labeled in each lysimeter and pit. The plant height, stem thick, and leaf area of the

Table 2. The upper and lower limits of soil water content for summer maize at each growth stage of the CK.

Growth stage	Seedling stage (I)	Jointing stage (II)	Tasseling stage (III)	Grain-filling stage (IV)	Maturity stage (V)
Lower limit	65% θ_f	75% θ_f	75% θ_f	70% θ_f	70% θ_f
Upper limit	75% θ_f	85% θ_f	85% θ_f	80% θ_f	80% θ_f

Note: θ_f represent field capacity.

Table 3. Irrigation quota at each growth stage of different treatments for summer maize (fraction of CK).

Stage	Treatment	Seedling stage (I)	Jointing stage (II)	Tasseling stage (III)	Grain-filling stage (IV)	Maturity stage (V)
Seedling stage (I)	I-D25%	75%	100%	100%	100%	100%
	I-D50%	50%	100%	100%	100%	100%
Jointing stage (II)	II-D25%	100%	75%	100%	100%	100%
	II-D50%	100%	50%	100%	100%	100%
Tasseling stage (III)	III-D25%	100%	100%	75%	100%	100%
	III-D50%	100%	100%	50%	100%	100%
Grain-filling stage (IV)	IV-D25%	100%	100%	100%	75%	100%
	IV-D50%	100%	100%	100%	50%	100%
Vegetative growth stages (VG)	I+II-D25%	75%	75%	100%	100%	100%
	I+II-D50%	50%	50%	100%	100%	100%
Reproductive growth stages (RG)	III+IV-D25%	100%	100%	75%	75%	100%
	III+IV-D50%	100%	100%	50%	50%	100%
	CK	100%	100%	100%	100%	100%

Notes: Deficit irrigation was applied at the seedling stage (I), jointing stage (II), tasseling stage (III), grain-filling stage (IV), vegetative growth stages (I-II), and reproductive growth stages (III-IV). Bold font for different treatments indicates the irrigation quota during the corresponding deficit period.

labeled maize plants were measured every 7–10 days. The length and maximum width of all leaves were manually recorded, and the leaf area index (LAI) was calculated following the method described by (Ma et al. 2025).

Photosynthetic parameters

Leaf photosynthetic parameters, including photosynthetic rate (P_n), transpiration rate (T_r), and stomatal conductance (G_s) were measured using an LCpro+ portable photosynthesis system (Analytical Development Co. Ltd., UK). Measurements were conducted on labeled maize plants in each plot before and 2–3 days after irrigation at different growth stages in 2023. Data were collected from the youngest fully expanded leaf during the VG period and from the ear leaf during the RG period. All measurements were performed on sunny days between 9:00 a.m. and 11:00 a.m. The instantaneous water use efficiency (WUE_i) was calculated as the ratio of P_n to T_r .

Dry matter

Three representative plants were randomly selected and cut off from the ground in each plot to determine final dry matter at maturity. The root was then obtained using the excavation method. Each plant was manually separated into leaf, stem, cob, and grain and root components. They were initially dried at 105°C for 30 min, then dried to a constant weight at 80°C before being weighed. The sum of the mean value of leaves, stems, cobs, and grains from three plants sampled per plots was considered as the above-ground dry matter (AGDM) for the corresponding treatment. Root dry matter (RDM) was determined using the same method, and the root-shoot ratio was calculated as the ratio of RDM to AGDM.

Grain yield, harvest index, and grain quality

At physiological maturity, ten representative maize plants were randomly harvested from each plot. The 100-grain weight (100-GW), grains number per ear (GN), and grain yield for each treatment were calculated as the mean values of three replicated plots. Grain yield was converted from the oven-dried grains weight to a standard water content of 14%. The harvest index (HI) was calculated as the ratio of grain yield to AGDM. The protein and starch contents of the dry maize grains were measured after harvest using the Kjeldahl nitrogen method and the acid hydrolysis method, respectively (Gao et al. 2024).

Water consumption and water use efficiency

Evapotranspiration (ET) of CK was determined using large weighing lysimeters throughout the entire growth stage, and ET for the DI treatments within the pits was calculated by the soil water balance equation:

$$ET = W_0 - W_t + I + P + U + R - D$$

where ET is water consumption (mm); W_0 and W_t are the soil water contents at the beginning and end of the calculation period (mm), respectively; I is irrigation amount (mm); P is effective rainfall (mm); U is ground-water recharge (mm); R is surface runoff (mm); and D is deep percolations (mm). In the present study, rainfall was prevented by a rain shelter, and R and D were neglected; therefore, $p = 0$, $U = 0$, $R = 0$, and $D = 0$. Additionally, plant-scale water use efficiency (WUE_y , kg m^{-3}) was determined as the ratio of grain yield to ET .

Comprehensive evaluation based on entropy-TOPSIS method

The entropy-TOPSIS (technique for order preference by similarity to an ideal solution) method was used to evaluate the comprehensive effects of DI regimes on maize production. This widely used analytical tool identifies the most feasible solution by defining positive and negative ideal solutions and selecting the one that is closest to the positive ideal with the highest rank and farthest from the negative ideal (Guo et al. 2024; Wang et al. 2023a). In this study, grain yield, 100-GW, GN, HI, WUE_y , and grain protein and starch contents were used as evaluation indices. The comprehensive evaluation index was calculated following the methods described by (Guo et al. 2024; Wang et al. 2023a).

Statistical analysis

Data were analyzed using SPSS version 22.0 (SPSS Inc., U.S.A.). One-way analysis of variance (ANOVA) was used for the different deficit irrigation treatments to assess the effects of the irrigation strategy on the measured variables. The Shapiro-Wilk and Levene's tests were conducted to confirm the data normality and homogeneity, respectively. The mean values of all treatments were compared for significant differences by Duncan's multiple range test at a significance level of $p < 0.05$. A three-way ANOVA was performed to test for the effects of deficit degree, deficit stage, year and their interaction on the measured variables. Principal component analysis (PCA) was conducted using OriginPro 2022 (OriginLab, North-Hampton, MA, U.S.A.) to examine relationships between growth, yield, quality and WP.

Results

Effects of deficit irrigation on plant growth of summer maize

DI during VG period significantly reduced plant height, stem thick, and LAI ($p < 0.05$) (Figures 4–6). During stages I and II, DI reduced plant height by 9.69%–20.40%, stem thick by 4.49%–12.57%, and LAI by 10.14%–63.78% during two experimental years compared to CK, respectively (Figures 4–6(a,b,f,g)). After re-irrigation, the two-year plant height, stem thick, and LAI of DI treatments remained significantly lower by 7.50%–14.95%, 2.40%–9.15%, and 10.47%–43.16% relative to CK, respectively ($p < 0.05$), whereas there was no significant difference in stem thick between DI treatments and CK ($p > 0.05$). In contrast, DI during RG period had a negligible impact on plant height ($p > 0.05$), which stabilized after stage III (Figure 4(c,d,h,i)). Compared with CK, variations in plant height under DI treatments at stages III–IV ranged between –0.39% and 3.13%. However, DI at stages III–IV significantly reduced stem thick by 3.88%–10.20% and LAI by 4.19%–31.71% compared to CK (Figures 5–6(c,d,h,i)). Multi-stage DI resulted in the most severe growth constraints ($p < 0.05$) (Figure 4-6(e, j)). Reductions in plant height (12.97%–19.79%), stem thick (7.07%–17.84%), and LAI (22.68%–51.08%) were observed when stress was maintained through VG and RG stages. These findings indicate that while re-irrigation accelerates growth rates, the structural deficits initiated during VG period persisted into subsequent growth period, whereas RG period are primarily characterized by accelerated senescence and LAI reduction rather than height loss. As shown in Table 4, both deficit degree (D) and deficit stage (S) had extremely significant effects on plant height, stem thick, and LAI in 2022 and 2023 ($p < 0.001$), whereas the interaction between these two factors (D×S) showed no significant effect only on stem thick in 2023 ($p > 0.05$). The S and year (Y) interaction (S×Y) was significant for all parameters ($p < 0.01$), while the D×S×Y interaction significantly affected only LAI ($p < 0.001$).

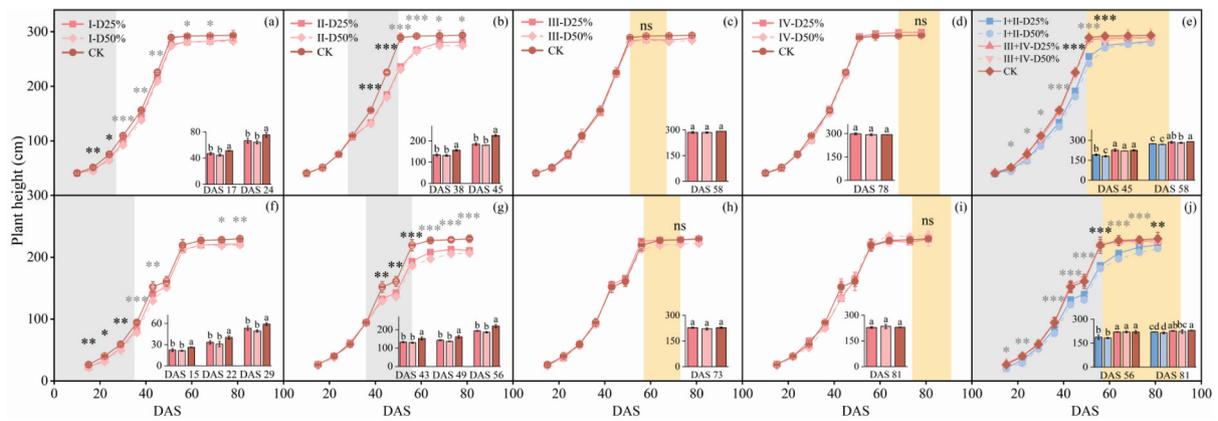


Figure 4. Variation of plant height under deficit irrigation of summer maize at the seedling (I) (a and f), jointing (II) (b and g), tasseling (III) (c and h), grain-filling (IV) (d and i), and multi-growth stages (d and j) in 2022 (a-e) and 2023 (f-j), respectively. CK is full irrigation, D25% and D50% were deficit irrigation levels where irrigated at 75% and 50% of CK, respectively. The grey and yellow areas indicate the duration of deficit irrigation under vegetative growth (I and II) and reproductive growth stages (III and IV), respectively. Values are the means of three replicates ($n = 3$) \pm standard deviation. Asterisks ** , *** , and **** indicate significant effect at the 0.05, 0.01 and 0.001 level among treatments, and 'ns' denotes non-significance. Bar graphs denote plant height of treatments at the corresponding dates marked in black font. Different letters indicate significant differences among the treatments ($p < 0.05$).

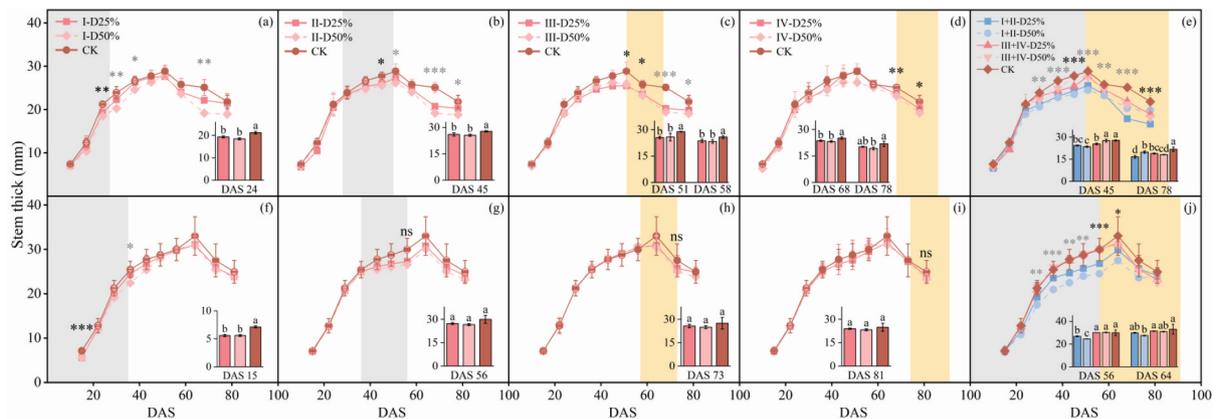


Figure 5. Variation of stem thick under deficit irrigation of summer maize at the seedling (I) (a and f), jointing (II) (b and g), tasseling (III) (c and h), grain-filling (IV) (d and i), and multi-growth stages (d and j) in 2022 (a-e) and 2023 (f-j), respectively. CK is full irrigation, D25% and D50% were deficit irrigation levels where irrigated at 75% and 50% of CK, respectively. The grey and yellow areas indicate the duration of deficit irrigation under vegetative growth (I and II) and reproductive growth stages (III and IV), respectively. Values are the means of three replicates ($n = 3$) \pm standard deviation. Asterisks ** , *** , and **** indicate significant effect at the 0.05, 0.01 and 0.001 level among treatments, and 'ns' denotes non-significance. Bar graphs denote stem thick of treatments at the corresponding dates marked in black font. Different letters indicate significant differences among the treatments ($p < 0.05$).

Effects of deficit irrigation on photosynthesis of summer maize

DI significantly affected P_n , T_r , G_s , and WUE_i of summer maize across various growth stages (Table 5). Statistical analysis showed that the D, S, and D \times S had significant effects on these photosynthetic traits ($p < 0.01$). Compared with CK, DI at stages I-IV significantly reduced P_n , T_r , and G_s ($p < 0.05$), with the magnitude of reduction generally intensifying as the growth stages progressed. Specifically, the reduction in P_n at stage I (8.26%–18.99%) peaked at stage IV (13.78%–28.16%). Similarly, the maximum reduction in T_r (17.75%–41.18%) and substantial declines in G_s (12.10%–19.57%) were both observed at stage IV. During the VG and RG stages, DI also significantly lowered these photosynthetic traits ($p < 0.05$), with the most pronounced declines in P_n (21.59%–37.89%) and T_r (28.89%–54.76%) occurring

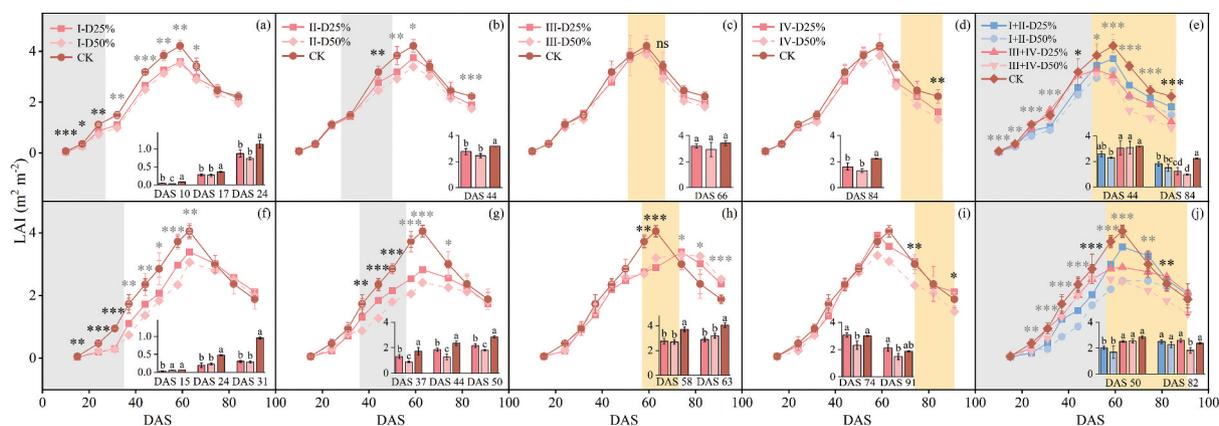


Figure 6. Variation of LAI under deficit irrigation of summer maize at the seedling (I) (a and f), jointing (II) (b and g), tasseling (III) (c and h), grain-filling (IV) (d and i), and multi-growth stages (d and j) in 2022 (a-e) and 2023 (f-j), respectively. CK is full irrigation, D25% and D50% were deficit irrigation levels where irrigated at 75% and 50% of CK, respectively. The grey and yellow areas indicate the duration of deficit irrigation under vegetative growth (I and II) and reproductive growth stages (III and IV), respectively. Values are the means of three replicates ($n=3$) \pm standard deviation. Asterisks * , ** , and *** indicate significant effect at the 0.05, 0.01 and 0.001 level among treatments, and 'ns' denotes non-significance. Bar graphs denote LAI of treatments at the corresponding dates marked in black font. Different letters indicate significant differences among the treatments ($p < 0.05$).

Table 4. Variance analysis (p value) of plant height, stem thick, and LAI of summer maize in 2022 and 2023.

Sources of variation	Plant height		Stem thick		LAI	
	2022	2023	2022	2023	2022	2023
Deficit degree (D)	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Deficit stage (S)	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
D×S	<0.001***	<0.001***	0.035*	0.877ns	0.003**	<0.001***
Year (Y)	<0.001***	<0.001***	<0.001***	<0.001***	0.144ns	<0.001***
D×Y	0.186ns		0.694ns		0.082ns	
S×Y	<0.001***		0.008**		<0.001***	
D×S×Y	0.386ns		0.98ns		<0.001***	

Notes: Asterisks * , ** , and *** indicate significant effect at the 0.05, 0.01 and 0.001 level, 'ns' indicates no significance.

during the RG stages. Notably, the D25% treatments across all stages resulted in less physiological inhibition than the D50% treatments.

After re-irrigation, a compensatory recovery was observed as P_n , T_r , and G_s increased relative to their deficit-period values. The P_n of DI treatments at stage I showed the greatest increase (14.35%–21.22%) compared to that during deficit period, while T_r and G_s also exhibited significant recovery (23.52–29.37% and 11.62%–15.99%). However, the maximum increases in T_r and G_s both occurred at stage III (29.14%–33.93% and 13.54%–14.69%). Early moderate water stress appears to triggers the plant's physiological defense mechanisms, potentially enhancing antioxidant enzyme activity and osmotic adjustment capacity. This physiological priming may contribute to a compensatory effect after re-irrigation, where the recovery capacity of photosynthetic traits at the VG period proves significantly superior to that at RG period. Notably, this recovery capacity was particularly marked in the D25% treatments.

Conversely, DI treatments generally improved WUE_i both during the deficit period and after re-irrigation, with significant improvements typically observed in the D50% treatments ($p < 0.05$). Specifically, WUE_i at stage II showed the highest increase (12.09%–33.43%) among all stages during deficit period. The highest WUE_i among all treatments was observed under the I+II-D50% treatment both during deficit period and after re-irrigation, reaching values of 5.52 and 4.85 $\mu\text{mol mmol}^{-1}$, respectively. Overall, while DI suppresses leaf gas exchange, it effectively enhances WUE_i , with the D25% treatments favoring physiological recovery and the D50% treatments maximizing WUE_i .

Table 5. Leaf photosynthesis of summer maize under deficit irrigation at different growth stages in 2023.

Deficit irrigation stage	Treatment	P _n (μmol m ⁻² s ⁻¹)		T _r (mmol m ⁻² s ⁻¹)		G _s (mol m ⁻² s ⁻¹)		WUE _i (μmol mmol ⁻¹)	
		Deficit irrigation	Re-irrigation	Deficit irrigation	Re-irrigation	Deficit irrigation	Re-irrigation	Deficit irrigation	Re-irrigation
Seedling stage	I-D25%	21.88 ± 2.41ab	25.02 ± 0.84b	4.55 ± 0.18b	5.62 ± 0.33b	0.210 ± 0.020a	0.280 ± 0.010b	4.80 ± 0.40a	4.46 ± 0.13ab
	I-D50%	19.32 ± 0.73b	23.42 ± 0.51c	3.95 ± 0.09c	5.11 ± 0.20c	0.183 ± 0.006b	0.247 ± 0.006c	4.89 ± 0.08a	4.59 ± 0.08a
	CK	23.85 ± 0.93a	26.78 ± 0.47a	5.14 ± 0.37a	6.26 ± 0.08a	0.233 ± 0.006a	0.300 ± 0.010a	4.65 ± 0.22a	4.28 ± 0.09b
	P	0.032*	0.002**	0.003**	0.002**	0.008**	<0.001***	0.576 ns	0.029*
Jointing stage	II-D25%	29.07 ± 1.26b	33.13 ± 0.66b	5.89 ± 0.24b	6.92 ± 0.05b	0.247 ± 0.006b	0.293 ± 0.006a	4.93 ± 0.02b	4.79 ± 0.08b
	II-D50%	23.87 ± 1.00c	27.94 ± 1.34c	4.46 ± 0.24c	5.50 ± 0.41c	0.193 ± 0.006c	0.233 ± 0.015b	5.36 ± 0.18a	5.08 ± 0.15a
	CK	32.58 ± 0.74a	35.98 ± 1.20a	6.70 ± 0.22a	7.57 ± 0.21a	0.287 ± 0.006a	0.313 ± 0.015a	4.86 ± 0.05b	4.75 ± 0.03b
	P	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	0.003**	0.012*
Tasseling stage	III-D25%	33.04 ± 0.90b	37.17 ± 0.76b	7.79 ± 0.12b	10.06 ± 0.47b	0.253 ± 0.006b	0.253 ± 0.006b	4.24 ± 0.05b	3.70 ± 0.12ab
	III-D50%	26.95 ± 0.38c	31.45 ± 1.21c	6.10 ± 0.13c	8.17 ± 0.20c	0.217 ± 0.006c	0.247 ± 0.015c	4.41 ± 0.03a	3.85 ± 0.05a
	CK	38.22 ± 1.83a	42.25 ± 1.72a	9.17 ± 0.53a	11.81 ± 0.40a	0.287 ± 0.015a	0.327 ± 0.015a	4.17 ± 0.06b	3.58 ± 0.02b
	P	<0.001***	<0.001***	0.001**	<0.001***	<0.001***	<0.001***	0.002**	0.013*
Grain-filling stage	IV-D25%	29.79 ± 1.81b	33.34 ± 1.14b	7.09 ± 0.13b	8.64 ± 0.35b	0.240 ± 0.010b	0.253 ± 0.006b	4.20 ± 0.18b	3.86 ± 0.07b
	IV-D50%	24.82 ± 1.03c	25.82 ± 0.83c	5.07 ± 0.58c	6.09 ± 0.49c	0.213 ± 0.006c	0.227 ± 0.012c	4.93 ± 0.38a	4.25 ± 0.21a
	CK	34.55 ± 0.57a	37.21 ± 1.52a	8.62 ± 0.60a	9.91 ± 0.48a	0.270 ± 0.010a	0.303 ± 0.012a	4.02 ± 0.21b	3.75 ± 0.04b
	P	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	0.014*	0.008**
Vegetative growth stage	I+II-D25%	26.52 ± 2.15b	30.38 ± 0.68b	5.01 ± 0.60b	6.42 ± 0.06b	0.230 ± 0.010b	0.260 ± 0.010b	5.31 ± 0.22a	4.73 ± 0.06b
	I+II-D50%	22.09 ± 1.03c	26.15 ± 0.62c	4.46 ± 0.23b	5.12 ± 0.14c	0.183 ± 0.006c	0.220 ± 0.010c	4.96 ± 0.21ab	5.10 ± 0.02a
	CK	32.58 ± 0.74a	35.98 ± 1.20a	6.70 ± 0.22a	7.57 ± 0.21a	0.287 ± 0.006a	0.313 ± 0.015a	4.86 ± 0.05b	4.75 ± 0.03b
	P	<0.001***	<0.001***	0.001**	<0.001***	<0.001***	<0.001***	0.048*	<0.001***
Reproductive growth stage	III+IV-D25%	27.09 ± 1.17b	28.50 ± 1.27b	6.13 ± 0.42b	7.16 ± 1.07a	0.213 ± 0.006b	0.243 ± 0.006b	4.42 ± 0.11b	4.02 ± 0.41b
	III+IV-D50%	21.46 ± 0.55c	21.98 ± 0.59c	3.90 ± 0.32c	4.54 ± 0.25b	0.167 ± 0.015c	0.183 ± 0.012c	5.52 ± 0.35a	4.85 ± 0.14a
	CK	34.55 ± 0.57a	37.21 ± 1.52a	8.62 ± 0.60a	9.91 ± 0.48a	0.270 ± 0.010a	0.303 ± 0.012a	4.02 ± 0.21b	3.75 ± 0.04b
	P	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	0.004**
Two-way ANOVA (p value)									
Deficit degree (D)		<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Deficit stage (S)		<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
D×S		<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	0.001**	<0.001***	<0.001***

Notes: P_n, T_r, G_s, and WUE_i represent net photosynthesis rate, transpiration rate, stomatal conductance, and instantaneous water use efficiency. CK is full irrigation, I, II, III, and IV represent the seedling, jointing, tasseling, and grain-filling stage, respectively; D25% and D50% were deficit irrigation levels where irrigated at 75% and 50% of CK, respectively. Values are the means of three replicates (n = 3) ± standard deviation. Different letters indicate significant differences among the treatments at the same stage within the same year (p < 0.05 by one-way ANOVA). 'P' is the significant analysis value by one-way ANOVA. Asterisks '*', '**', '***', and '****' indicate significant effect at the 0.05, 0.01 and 0.001 level, 'ns' indicates no significance.

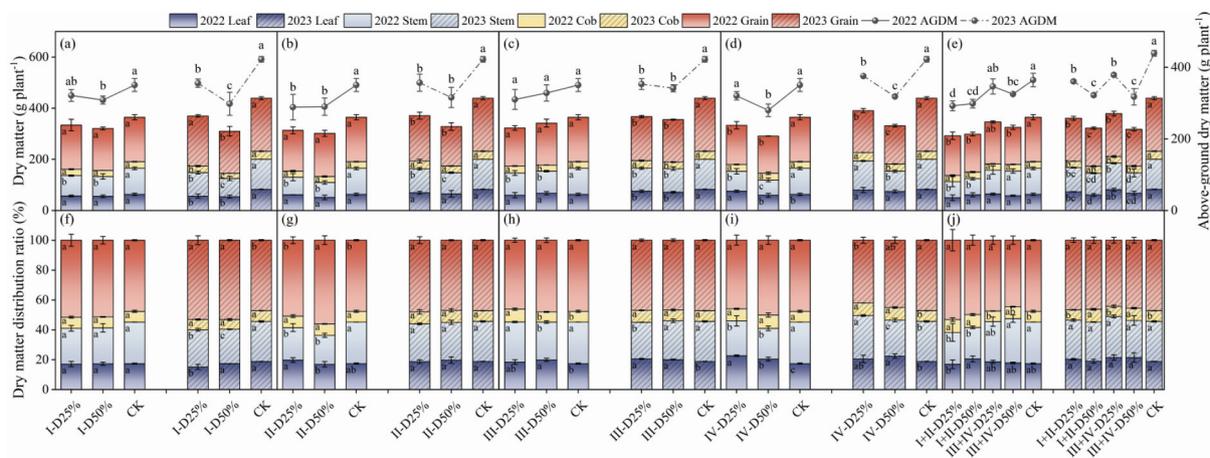


Figure 7. Above-ground dry matter and allocation, and proportion in various organs at maturity under deficit irrigation of summer maize at the seedling (I) (a and f), jointing (II) (b and g), tasseling (III) (c and h), grain-filling (IV) (d and i), and multi-growth stages (d and j) in 2022 (a-e) and 2023 (f-j), respectively. CK is full irrigation, D25% and D50% were deficit irrigation levels where irrigated at 75% and 50% of CK, respectively. Values are the means of three replicates ($n = 3$) \pm standard deviation. Different letters indicate significant differences among the treatments at the same stage within the same year ($p < 0.05$).

Effect of deficit irrigation on dry matter of summer maize

Above-ground dry matter and distribution

DI applied at different growth stages exerted distinct effects on summer maize above-ground dry matter (AGDM) and its components (Figure 7). Overall, AGDM followed a decreasing trend as deficit intensified across various stages. Grain DM consistently accounted for the largest proportion of AGDM accumulation, ranging between 41.99% and 56.05% over the two-year study, followed by stem DM (19.42%–29.72%), while cob DM remained the lowest (6.5%–8.95%).

At stage I, DI significantly inhibited DM accumulation across all organs (Figure 7(a)). Compared with CK, leaf, stem, cob, and grain DM decreased by 10.17%–34.66%, 21.49%–39.47%, 4.34%–36.42%, and 0.63%–20.54%, respectively, resulting in an 8.37%–29.41% reduction in AGDM. Notably, DI altered distribution proportions; leaf and stem DM proportions decreased by 0.23%–19.35% and 7.16%–14.35% compared with CK in two-year experiment, respectively, whereas grain DM proportion significantly increased by 7.75%–12.52% ($p < 0.05$) (Figure 7(f)). The shift in DM partitioning may reflect a survival strategy based on functional balance theory, potentially prioritizing reproductive success over vegetative biomass when resources are limited but later restored. DI at stage II showed similar inhibitory patterns but more severely affected stem and grain DM, with reductions of 20.27%–42.30% and 8.21%–25.55% compared with CK, respectively (Figure 7(b)). Although AGDM under DI treatments at stage II significantly decreased by 13.97%–25.24% compared to CK ($p < 0.05$), the proportion allocation to leaf, cob and grain generally exceeded that of CK (Figure 7(g)), demonstrating that stem growth was particularly sensitive to limited irrigation during this period.

DI applied at later growth stages (stages III-IV) generally had a minor impact on leaf DM compared to its effect on stem. In 2022, increases in leaf DM were observed under the IV-D25% and III-D50% treatments (19.24% and 7.12% higher than CK, respectively) (Figure 7(c,d)), while DI at stages III-IV decreased stem DM by 3.40%–40.91% in comparison with CK in both years. Additionally, the proportion of leaf DM under DI treatments (18.42%–22.65%) also exceeded that of CK (17.35%–21.44%) (Figure 7(h,i)). However, stage IV proved critical for grain development, with DI causing significant grain DM reductions of 11.76%–28.07% with respect to CK in 2022 and 2023 ($p < 0.05$).

Regarding multi-stage DI (Figure 7(e,j)), the I+II-D25% and III+IV-D50% treatments achieved the highest (49.89%) and lowest (45.04%) average grain DM proportions, respectively. The III+IV-D25% treatment was the most resilient, with AGDM declining by only 4.95%–13.75% in two years due to negligible differences in vegetative organ relative to CK. In contrast, the I+II-D50% treatment resulted in the lowest AGDM (18.06%–26.60% reduction, $p < 0.05$) due to pronounced suppression of stem growth.

Table 6. Variance analysis (p value) of above-ground dry matter and its allocation of summer maize in 2022 and 2023.

Sources of variation	Above-ground dry matter		Leaf dry matter		Stem dry matter		Cob dry matter		Grain dry matter	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
Deficit degree (D)	<0.001***	<0.001***	0.103ns	<0.001***	<0.001***	<0.001***	0.089ns	<0.001***	<0.001***	<0.001***
Deficit stage (S)	0.034*	0.213ns	0.042*	<0.001***	<0.001***	0.01*	0.415ns	0.003**	0.174ns	0.001**
D×S	0.141ns	0.151ns	0.007**	0.024*	0.019*	<0.001***	0.525ns	0.025*	0.262ns	0.062ns
Year (Y)	<0.001***		<0.001***		<0.001***		<0.001***		<0.001***	
D×Y	<0.001***		<0.001***		<0.004**		<0.001***		<0.001***	
S×Y	0.118ns		0.191ns		<0.001***		0.105ns		0.834ns	
D×S×Y	0.8ns		0.037*		0.009**		0.47ns		0.859ns	

Notes: Asterisks **, ***, and **** indicate significant effect at the 0.05, 0.01 and 0.001 level, 'ns' indicates no significance.

The stage-specific sensitivity of summer maize to water requirements dictates the final DM distribution. Across all stages except stage III, leaf, stem, grain DM, and AGDM increased with increasing irrigation volume, whereas cob DM followed this trend in single-stage DI but showed an inverse relationship in multi-stage treatments. As shown in Table 6, D significantly affected AGDM and its components in 2023 ($p < 0.001$); however, S only significantly affected individual components ($p < 0.05$). Both D and S had significant effects on stem DM and AGDM in 2022 ($p < 0.05$). Moreover, the D×S interaction significantly affected only leaf and stem DM in both years ($p < 0.05$). Y and D×Y interaction both significantly influenced AGDM and its components ($p < 0.01$).

Root dry matter and root-shoot ratio

The response of root dry matter (RDM) and root-shoot (R/S) ratio to DI at different growth stages is shown in Figure 8. In 2022, the IV-D25% treatment achieved the highest R/S ratio, which was 12.3% higher than that of CK ($p < 0.05$), while its RDM exceeded CK by 2.92% ($p > 0.05$). Two-year study identified that the IV-D25% treatment outperformed other DI treatments by maintaining an R/S ratio comparable to CK, despite an average 11.74% reduction in RDM. Notably, DI at stage IV exhibited the most positive effects on RDM and R/S ratio, followed by stage I. Conversely, multi-stage DI exerted depressive effects, with RDM and R/S ratio decreasing by 3.23%–42.77% and 6.32%–22.76% compared with CK in both years, respectively. Specifically, the III+IV-D25% treatment proved the most effective. RDM increased with irrigation volume during various growth stages, while R/S ratio primarily varied during the VG period. As shown in Table 7, D significantly affected RDM and R/S ratio ($p < 0.05$); however, the S effects were primarily limited to RDM in 2023 ($p < 0.05$). The D×S interaction significantly affected both parameters in 2022 ($p < 0.05$), while Y and the D×S×Y interaction had significant effects on both parameters ($p < 0.05$).

Effect of deficit irrigation on grain yield and quality of summer maize

Grain yield and its components

Overall, yield loss intensified as irrigation volume decreased (Table 8). Among all treatments, the I-D25% treatment recorded the lowest yield reduction (averaging 4.52%), which was not statistically significant

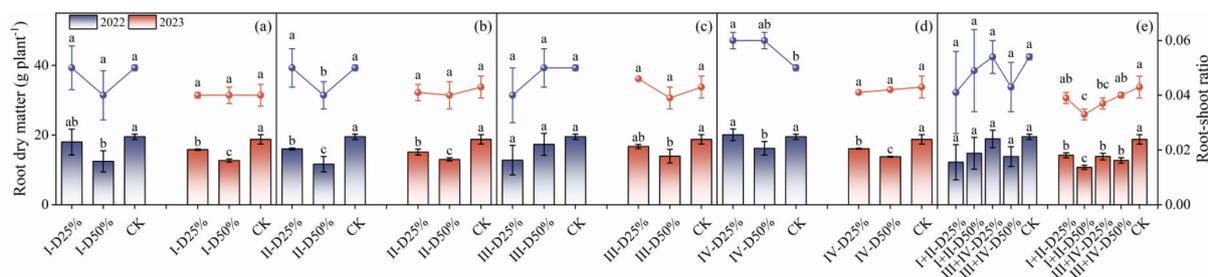


Figure 8. Root dry matter and root-shoot ratio under deficit irrigation of summer maize at the seedling (I) (a and f), jointing (II) (b and g), tasseling (III) (c and h), grain-filling (IV) (d and i), and multi-growth stages (d and j) in 2022 (a-e) and 2023 (f-j), respectively. CK is full irrigation, D25% and D50% were deficit irrigation levels where irrigated at 75% and 50% of CK, respectively. Values are the means of three replicates ($n = 3$) \pm standard deviation. Different letters indicate significant differences among the treatments at the same stage within the same year ($p < 0.05$).

Table 7. Variance analysis (p value) of root dry matter, root–shoot ratio, and yield compositions of summer maize in 2022 and 2023.

Sources of variation	Root dry matter		Root-shoot ratio		100-grain weight		Grains number per ear	
	2022	2023	2022	2023	2022	2023	2022	2023
Deficit degree (D)	<0.001***	<0.001***	0.011*	0.004**	<0.001***	0.015*	<0.001***	<0.001***
Deficit stage (S)	0.167ns	0.004**	0.138ns	0.053ns	0.123ns	0.415ns	0.094ns	0.084ns
D×S	0.025*	0.163ns	0.027*	0.093ns	0.411ns	0.972ns	0.096ns	0.538ns
Year (Y)	0.005**		<0.001***		<0.001***		0.457ns	
D×Y	0.703ns		0.28ns		0.384ns		0.214ns	
S×Y	0.329ns		0.163ns		0.306ns		0.435ns	
D×S×Y	0.014*		0.003**		0.934ns		0.86ns	

Notes: Asterisks ***, ****, and ***** indicate significant effect at the 0.05, 0.01 and 0.001 level, 'ns' indicates no significance.

compared to CK ($p > 0.05$). In contrast, DI during single-growth and multi-growth stages significantly reduced yield by 2.30%–22.84% and 15.74%–27.25% compared with CK in both years ($p < 0.05$), respectively. D significantly affected yield and its components in 2023 ($p < 0.05$), while the S effects were primarily limited to yield in 2022 ($p < 0.001$) (Tables 7, 8).

Across 2022 and 2023, the 100-grain weight (100-GW) and grains number per ear (GN) under different treatments ranged between 27.07–33.55 g and 609–724, respectively (Figure 9). Among single-stage DI treatments, the III-D25% treatment maintained a two-year average 100-GW comparable to CK, showing a non-significant 3.13% increase in 2022 and 1.67% decrease in 2023 ($p > 0.05$). However, it suffered the most significant GN reduction ($p < 0.05$), leading to yield loss. In contrast, the I-D25% treatment exhibited the highest resilience, showing minimal average reductions in both 100-GW (0.79%) and GN (5.30%) relative to CK. Regarding multi-stage DI treatments, the I+II-D25%, I+II-D50%, and III+IV-D25% treatments showed similar 100-GW declines (5.26%–5.96%), all performing better than the III+IV-D50% treatment. Notably, the I+II-D25% treatment exhibited the least non-significant GN reduction ($p > 0.05$).

In summary, grain yield was more sensitive to fluctuations in GN than in 100-GW, suggesting that DI during the RG stages may directly disrupt pollination and fertilization. This leads to grain abortion and indicates that the RG stages are the most critical for yield formation. In contrast, stage I was the most resilient period for yield components, resulting in minimal yield impact.

Harvest index

The response of HI to DI at different growth stages is shown in Table 8. Across both years, HI under DI treatments at stage I generally improved by 6.63%–20.65% compared to CK. Additionally, the III-D25%, IV-D50%, and I+II-D25% treatments raised HI by 6.23%, 7.56%, and 3.49% relative to CK in 2022, respectively. In 2023, most DI treatments sustained this upward trend (increase of 0.76%–20.65%), except for the IV-D25% and III+IV-D25% treatments, which exhibited minor reductions of 3.57% and 2.25% compared to CK, respectively. Moreover, D significantly affected HI in both years ($p < 0.01$), while the effects of S and the D×S interaction were significant in 2022 ($p < 0.001$). Y, and the D×Y and S×Y interactions also exerted significant influences on HI ($p < 0.01$).

Grain quality

As presented in Table 8, DI during single-growth and multi-growth stages significantly reduced grain protein content by 1.59%–15.21% and 4.20%–15.38% compared with CK across 2 years ($p < 0.05$), respectively. This reduction may be associated with impaired nitrogen uptake and transport. Among the DI treatments, the I-D25% treatment maintained the highest protein content. Single-stage DI basically promoted starch content accumulation. DI treatments at stages I–III effectively enhanced starch content by 2.38%–6.39%, 5.23%–15.78%, and 2.74%–11.55% in both years compared to CK, respectively. This increase may reflect the plant's resource reallocation strategy, where non-structural carbohydrates are efficiently transported to the grain under moderate stress. The greatest starch content was observed under the II-D25% treatment, with an average increase of 13.54% ($p < 0.05$). Notably, DI at stage II significantly affected starch content in 2023 ($p < 0.05$), whereas DI at stage IV marginally decreased it by 0.05%–2.90% compared to CK in both years ($p > 0.05$). D, S, and the D×S interaction significantly affected both protein and starch contents across 2 years ($p < 0.05$). Y and the D×Y interaction also significantly influenced grain quality ($p < 0.05$), while the S×Y interaction effect was limited to protein content ($p < 0.001$).

Table 8. Grain yield, harvest index (HI), grain protein and starch content, evapotranspiration (ET), and water use efficiency (WUE_y) of summer maize under deficit irrigation at different growth stages in 2022 and 2023.

Treatments	Grain yield (kg ha ⁻¹)		HI (%)		Protein content (%)		Starch content (%)		ET (mm)		WUE _y (kg m ⁻³)	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
I-D25%	7799.09 ± 426.89ab	7801.29 ± 183.17ab	58.37 ± 1.64a	52.79 ± 2.96a	8.08 ± 0.11b	9.85 ± 0.98a	68.50 ± 1.90ab	56.99 ± 2.46 cd	399.48 ± 7.13b	431.97 ± 4.26b	1.95 ± 0.08a	1.81 ± 0.05a
I-D50%	7018.99 ± 301.00c	7083.86 ± 370.35bc	54.66 ± 0.81ab	57.43 ± 4.90a	7.77 ± 0.03bc	9.55 ± 0.13b	66.10 ± 0.40b	52.26 ± 3.43efgh	379.55 ± 14.36cde	414.08 ± 4.89bcd	1.85 ± 0.06a	1.71 ± 0.08a
II-D25%	6979.91 ± 831.83c	7108.95 ± 375.61bc	58.15 ± 2.76a	47.96 ± 2.50a	7.85 ± 0.38bc	9.51 ± 0.14b	71.65 ± 3.05a	64.45 ± 1.20a	368.13 ± 10.31de	398.46 ± 7.72def	1.90 ± 0.26a	1.79 ± 0.11a
II-D50%	6192.66 ± 294.60de	6679.49 ± 218.36c	51.46 ± 3.16b	51.20 ± 5.79a	7.71 ± 0.11c	9.42 ± 0.04bc	67.75 ± 1.75ab	51.44 ± 1.00fgh	324.05 ± 12.58 g	379.97 ± 1.62f	1.91 ± 0.09a	1.76 ± 0.05a
III-D25%	6503.72 ± 378.40cde	7358.96 ± 953.99bc	50.48 ± 2.09b	50.14 ± 6.71a	7.54 ± 0.17c	9.13 ± 0.51d	66.15 ± 0.55b	62.09 ± 3.04ab	370.98 ± 2.13de	428.06 ± 12.90bc	1.75 ± 0.10a	1.72 ± 0.21a
III-D50%	6159.26 ± 584.01de	6981.86 ± 662.86bc	45.20 ± 4.99c	49.24 ± 6.07a	7.21 ± 0.05d	9.08 ± 1.15d	68.00 ± 0.70ab	59.07 ± 3.32bc	348.62 ± 12.12f	391.30 ± 24.88ef	1.77 ± 0.23a	1.80 ± 0.29a
IV-D25%	7256.62 ± 221.83bc	7173.34 ± 515.03bc	54.44 ± 0.42ab	45.90 ± 3.29a	7.84 ± 0.21bc	9.17 ± 0.97 cd	64.35 ± 0.25bc	54.69 ± 0.53defg	393.91 ± 24.50bcd	409.90 ± 12.41cde	1.85 ± 0.16a	1.75 ± 0.16a
IV-D50%	6841.04 ± 72.86 cd	6832.90 ± 442.23bc	58.88 ± 3.20a	51.59 ± 3.85a	7.75 ± 0.06c	8.74 ± 3.46e	64.70 ± 1.60b	54.05 ± 0.65deh	385.41 ± 2.50bcd	395.00 ± 9.48def	1.77 ± 0.02a	1.73 ± 0.08a
I+II-D25%	6612.68 ± 246.16 cd	6979.04 ± 323.44bc	56.65 ± 4.33a	48.40 ± 2.61a	7.54 ± 0.21c	9.47 ± 0.77b	67.30 ± 4.30b	50.68 ± 1.46gh	346.19 ± 5.72f	394.96 ± 8.07def	1.91 ± 0.10a	1.77 ± 0.11a
I+II-D50%	6094.35 ± 129.74de	6752.13 ± 1022.33c	51.06 ± 2.53b	52.44 ± 8.66a	7.71 ± 0.05c	9.52 ± 0.21b	65.10 ± 4.70b	55.32 ± 0.30cdef	296.83 ± 7.61 h	351.91 ± 4.21 g	2.06 ± 0.09a	1.92 ± 0.27a
III+IV-D25%	6078.90 ± 224.13de	7047.28 ± 485.14bc	43.90 ± 1.22c	46.53 ± 3.54a	7.81 ± 0.26bc	9.59 ± 2.58b	68.20 ± 0.60ab	50.69 ± 2.21gh	360.27 ± 7.03ef	390.03 ± 15.8ef	1.69 ± 0.09a	1.81 ± 0.15a
III+IV-D50%	5807.78 ± 514.53e	6336.46 ± 228.91c	44.64 ± 3.68c	50.09 ± 4.95a	7.19 ± 0.04d	9.14 ± 1.64d	60.50 ± 0.70c	50.20 ± 1.32 h	319.53 ± 8.13 g	347.58 ± 11.2 g	1.82 ± 0.17a	1.83 ± 0.11a
CK	7982.89 ± 409.82a	8363.84 ± 295.56a	54.74 ± 0.01ab	47.60 ± 0.82a	8.50 ± 0.12a	10.01 ± 0.14a	64.38 ± 2.38bc	55.67 ± 3.83cde	431.73 ± 0.51a	468.18 ± 6.03a	1.85 ± 0.09a	1.79 ± 0.04a
P	<0.001***	0.015*	<0.001***	0.307 ns	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	0.167 ns	0.956 ns
Three-way ANOVA (p value)	<0.001***	<0.001***	<0.001***	0.007**	<0.001***	<0.001***	<0.001***	0.012*	<0.001***	<0.001***	0.869ns	0.914ns
Deficit degree (D)	<0.001***	0.322ns	<0.001***	0.231ns	<0.001***	<0.001***	0.023*	<0.001***	<0.001***	<0.001***	0.071ns	0.873ns
Deficit stage (S)	0.073ns	0.918ns	<0.001***	0.811ns	0.001***	<0.001***	0.03*	<0.001***	<0.001***	<0.001***	0.42ns	0.92ns
D×S	<0.001***		<0.001***		<0.001***	<0.001***	<0.001***		<0.001***	<0.001***	0.007**	
Year (Y)	0.964ns		<0.001***		0.03*	0.041*	0.041*		0.913ns	0.913ns	0.481ns	
D×Y	0.253ns		0.006**		<0.001***	<0.001***	0.056ns		0.001**	0.001**	0.481ns	
S×Y	0.892ns		0.222ns		0.02*	0.02*	0.003**		0.052ns	0.052ns	0.974ns	

Notes: CK is full irrigation, I, II, III, and IV represent the seedling, jointing, tasseling, and grain-filling stage, respectively; D25% and D50% were deficit irrigation levels where irrigated at 75% and 50% of CK, respectively. Values are the means of three replicates (n = 3) ± standard deviation. Different letters indicate significant differences among the treatments at the same stage within the same year (p < 0.05 by one-way ANOVA). 'P' is the significant analysis value by one-way ANOVA. Asterisks **, ***, and **** indicate significant effect at the 0.05, 0.01 and 0.001 level, 'ns' indicates no significance.

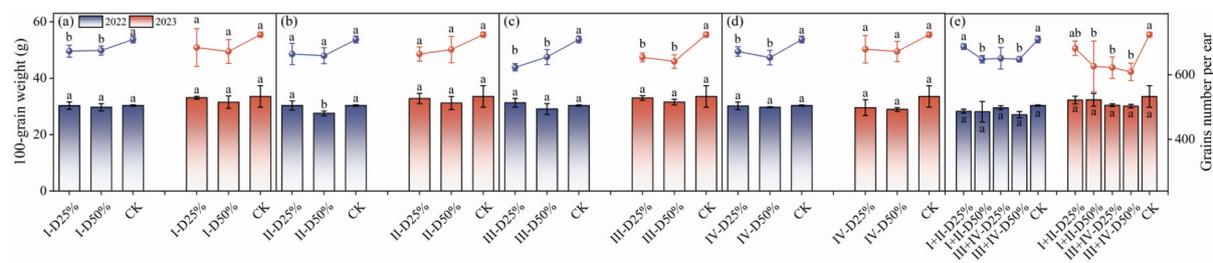


Figure 9. Yield compositions under deficit irrigation of summer maize at the seedling (I) (a and f), jointing (II) (b and g), tasseling (III) (c and h), grain-filling (IV) (d and i), and multi-growth stages (d and j) in 2022 (a-e) and 2023 (f-j), respectively. CK is full irrigation, D25% and D50% were deficit irrigation levels where irrigated at 75% and 50% of CK, respectively. Values are the means of three replicates ($n = 3$) \pm standard deviation. Different letters indicate significant differences among the treatments at the same stage within the same year ($p < 0.05$).

Effect of deficit irrigation on water consumption and use efficiency of summer maize

ET of summer maize increased with higher irrigation volumes (Table 8). Across 2022–2023, single-stage and multi-stage DI significantly reduced ET by 7.47%–24.94% and 15.64%–31.25% compared with CK ($p < 0.05$), respectively. The most substantial reductions occurred at stage II, identifying it as the most water-intensive stage for summer maize. WUE_y did not differ significantly among DI treatments at various growth stages ($p > 0.05$) (Table 8). The highest WUE_y was obtained under the I+II-D50% treatment, with increases of 11.35% and 7.26% compared with CK in 2 years, respectively. DI at stages I, II, and VG stages enhanced WUE_y by averages of 2.71%, 2.97%, and 7.30% relative to CK in 2022, respectively. In 2023, several treatments (I-D25%, III-D50%, III+IV-D25%, and III+IV-D50%) also showed minor WUE_y gains (0.56%–2.23%). Notably, the D50% treatments generally exerted a more positive effect on WUE_y but at the expense of yield. D, S, and the D \times S interaction significantly affected ET across both years ($p < 0.001$), while none significantly affected WUE_y ($p > 0.05$). Y also significantly influenced ET and WUE_y ($p < 0.01$), whereas the S \times Y interaction effect was limited to ET ($p < 0.01$).

Comprehensive evaluation based on entropy-TOPSIS and PCA analysis

The Entropy-TOPSIS method was employed to evaluate DI performance based on grain yield and quality, and WUE_y (Table 9). The comprehensive evaluation index (CEI) values for the I-D25% (0.758) and II-D25% (0.6000) treatments were the highest in 2022 and 2023, followed by CK (0.753) and the I-D25% treatment (0.583), respectively. The two-year average evaluation results presented that CK obtained the greatest CEI (0.699), followed by the I-D25% (0.649) and the II-D25% (0.584) treatments. Overall, the D25% treatments outperformed the D50% treatments. Notably, DI at VG period resulted in higher CEI values than at stages III-IV,

Table 9. The comprehensive evaluation index (CEI) of summer maize under different deficit irrigation treatments in 2022 and 2023.

Stage	Treatments	2022			2023			Two-year average		
		CEI	Rank1	Rank2	CEI	Rank1	Rank2	CEI	Rank1	Rank2
Single-growth stage	I-D25%	0.758	1	1	0.583	2	2	0.649	2	2
	I-D50%	0.568	4	4	0.400	7	6	0.421	6	4
	II-D25%	0.655	3	3	0.600	1	1	0.584	3	3
	II-D50%	0.387	10	8	0.306	10	8	0.341	9	7
	III-D25%	0.431	8	7	0.521	4	4	0.380	8	6
	III-D50%	0.287	12	9	0.446	6	5	0.265	12	9
	IV-D25%	0.562	5	5	0.333	9	7	0.390	7	5
Multi-growth stage	IV-D50%	0.501	7	6	0.303	11	9	0.290	11	8
	CK	0.753	2	2	0.544	3	3	0.699	1	1
	I+II-D25%	0.529	6	2	0.351	8	3	0.500	4	2
	I+II-D50%	0.431	9	3	0.511	5	2	0.484	5	3
	III+IV-D25%	0.332	11	4	0.288	12	4	0.312	10	4
	III+IV-D50%	0.202	13	5	0.279	13	5	0.221	13	5
	CK	0.753	2	1	0.544	3	1	0.699	1	1

Notes: CK is full irrigation, I, II, III, and IV represent the seedling, jointing, tasseling, and grain-filling stage, respectively; D25% and D50% were deficit irrigation levels where irrigated at 75% and 50% of CK, respectively. Rank1 represents the ranking of all treatments; Rank2 represents the ranking of treatments at the single-growth stage or multi-growth stage.

illustrating that the latter are critical water-demanding periods for summer maize grain yield and quality formation. Thus, the I-D25% (single-stage) and the I+II-D25% (multi-stage) treatments are recommended to enhance both quality and efficiency.

Principal component analysis (PCA) was conducted on measured indicators for single and multi-stage treatments in 2022 and 2023, respectively (Figure 10). Grain yield and its components, ET, and grain protein content showed significant positive correlations. In contrast, WUE_y/WUE_i were generally negatively correlated with plant growth indicators, AGDM, RDM, and R/S ratio. Analysis of loading variables revealed that ET, grain yield, protein content, and photosynthetic parameters were highly sensitive to water stress. Analysis also demonstrated that DI negatively affected grain yield, ET, and AGDM, as DI treatments located in opposite directions to variables.

Discussion

Stage-specific regulatory effects of deficit irrigation on maize growth and physiological traits

Vegetative growth period: growth inhibition and plasticity

The regulation of maize plant development under DI depends mainly on growth stages, as biological sensitivity to drought varies (Huang et al. 2023). DI applied at VG period significantly reduces plant height, stem thick, and LAI (Hazbawi et al. 2025; Wang et al. 2023b), representing the physiological response triggered by impaired cell expansion and restricted carbon supply. Because internodal and leaf primordia development relies on cell division and expansion, processes highly sensitive to leaf water potential, DI-

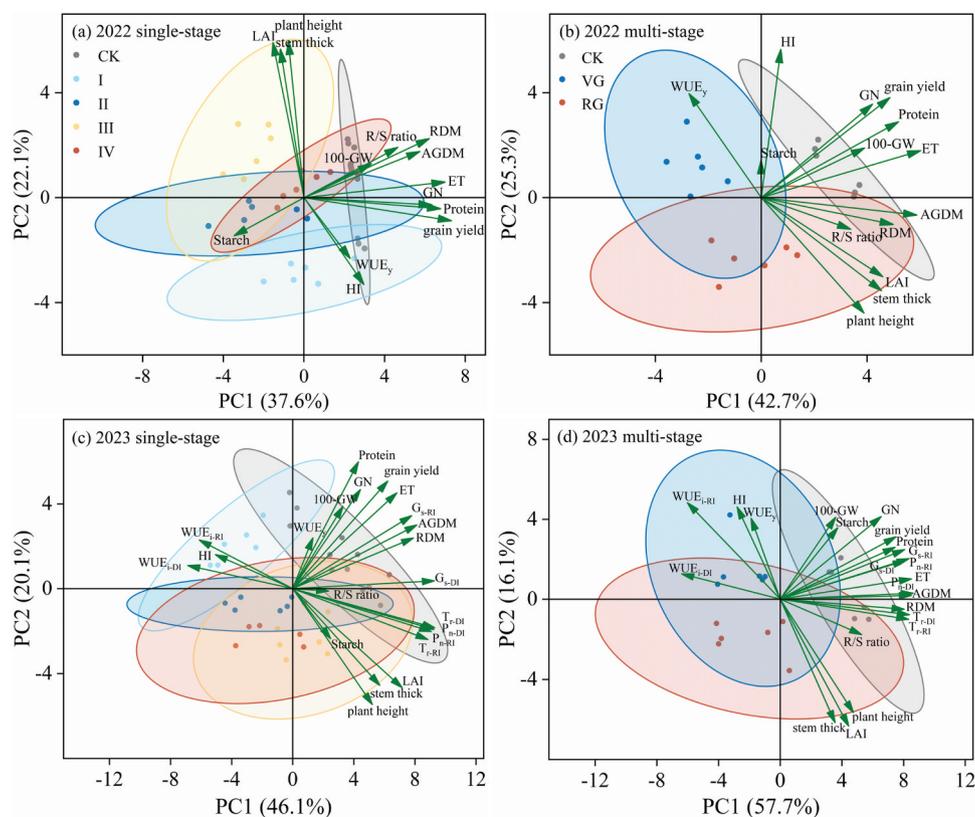


Figure 10. Principal component analysis biplot of deficit irrigation treatments at single-growth (a and c) and multi-growth (b and d) stages in 2022 (a and b) and 2023 (c and d). P_{n-DI} , P_{n-RI} , T_{n-DI} , T_{n-RI} , G_{s-DI} , G_{s-RI} , WUE_{i-DI} , WUE_{i-RI} , WUE_{r-DI} , WUE_{r-RI} represent net photosynthesis rate, transpiration rate, stomatal conductance, and instantaneous water use efficiency during deficit irrigation and after re-irrigation, respectively. 100-GW, 100-grain weight; GN, grains number per ear; LAI, leaf area index; AGDM, above-ground dry matter; RDM, root dry matter; R/S ratio, root to shoot ratio; HI, harvest index; ET, evapotranspiration; WUE_y , water use efficiency, respectively.

induced water deficits inhibit growth by downregulating expansions (cell wall-loosening proteins) and promoting abscisic acid (ABA) accumulation (Hazbawi et al. 2025).

Root-synthesized ABA is transported via the xylem to guard cells, triggering K^+ efflux (Kuromori et al. 2018) and leading to a reduction in turgor pressure and subsequent stomatal closure to prevent excessive transpiration (Kuromori et al. 2018, Li et al. 2018; Yang et al. 2023). While this maintains the plant's internal water status, it also restricts CO_2 diffusion into the mesophyll cells and lowers the P_n (Song et al. 2020). Additionally, reduced LAI further caused decreased P_n as the diminished canopy-scale photosynthetic capacity (Ye et al. 2020; Mu et al. 2022). Our study demonstrated that enhanced WUE_i because T_r is more sensitive to water scarcity than P_n , allowing the plant to maximize carbon gain per unit of water lost.

As demonstrated in previous studies, re-irrigation effectively restores water consumption intensity and photosynthetic capacity of plants subjected to water stress (Comas et al. 2019; Jiao et al. 2024), though this compensatory effect depends on the drought's severity and duration (Cai et al. 2020, 2023). In this study, maize plants exhibited significantly accelerated morpho-physiological development after re-irrigation. The narrower gaps in P_n , T_r , and G_s between DI treatments and CK suggest that increased stomatal aperture facilitates CO_2 diffusion to Rubisco carboxylation site (Abid et al. 2018). Notably, WUE_i was higher during the deficit than after re-irrigation, illustrating that P_n recovers more robustly than T_r when re-watered, which aligned with previous research (Wen et al. 2025). This reflects that water-deficient maize exhibits adaptive strategies to balance biomass accumulation and reproductive success by integrating inhibited vegetative growth with optimized gas exchange.

Reproductive growth period: developmental asynchrony and compensation limitation

Our studies observed that DI had a minimal impact on plant growth during the RG period, as the vegetative structure has now taken shape (Cai et al. 2020, 2023). However, DI significantly altered the timing and magnitude of the LAI peak. Water deficit at stage III, followed by re-irrigation, slightly increased the reduced LAI and delayed its peak compared to CK. This can be explained by the carry-over effect where water stress mitigates subsequent senescence. In contrast, maize under DI during stage IV reached an earlier LAI peak compared with CK, consistent with results proven by (Ma et al. 2025). This could specifically result from the chloroplast proteins degradation and nutrient remobilization (especially nitrogen) from aging leaves to developing grains (Ye et al. 2020). Such processes are potentially accelerated by a surge in senescence-associated hormones like ethylene and ABA (Sade et al. 2018), which likely contributes to the shortening functional period of the source leaves.

Photosynthesis was more severely inhibited at tasseling stage than jointing and milk stages under identical DI levels (Cai et al. 2020, 2023). Water deficit at tasseling stage induces both stomatal and non-stomatal limitations. This heightened drought sensitivity at this critical stage is potentially mediated by the rapid accumulation of reactive oxygen species, which damages the photosystem II reaction center (Choudhury et al. 2017). Therefore, sequential water stress during RG period not only drastically reduces LAI but also triggers premature peaking exacerbating leaf senescence and severely impairing photosynthetic capacity (Li et al. 2018).

The compensatory effect of re-irrigation on photosynthetic capacity during RG period varied by deficit degree. Re-irrigation slightly alleviated adverse impacts on P_n , T_r , G_s under the D25% treatments by promoting stomatal reopening and restoring metabolic homeostasis. However, no such improvement was observed under the D50% treatments. This lack of recovery is likely attributed to irreversible injury to cell membranes and intracellular enzymes, which imposes a physiological limit on the efficacy of rehydration (Mu et al. 2021; Seleiman et al. 2021).

Deficit irrigation modulates grain yield and quality by altering dry matter translocation and partitioning

DM accumulation and allocation are fundamental to yield formation and are influenced by abiotic factors such as nutrition, temperature, light, and soil moisture (Kumar et al. 2006). Crops adapt to water deficit by modifying leaf physiology to improve photosynthetic efficiency and biomass partitioning (Ramos-Fuentes et al. 2023). In this study, DI at stage I decreased leaf and stem DM but enhanced grain DM allocation by decreasing the proportion of vegetative organs. Specifically, mild deficit promoted early-stage DM accumulation. These results revealed that adequate re-irrigation facilitates the translocation of photosynthates from vegetative organs to 'sink' grains by reducing redundant above-ground growth, supported by improved re-irrigation photosynthetic

capacity (Cai et al. 2022). This recovery is likely driven by restored antioxidant enzyme activities and osmotic adjustment, allowing plants to maintain cellular integrity and resume carbon assimilation (Abid et al. 2018). Such adaptation reflects a shift in source-sink regulation, where the plant optimizes carbon-fixation capacity to prioritize grain filling following limited resource availability (Rodrigues et al. 2019). However, during RG period, not only does the decreased photosynthetic capacity reduce DM accumulation (Li et al. 2022), but the drought-induced ripening effects also inhibit DM redistribution (Cai et al. 2022).

Altered DM allocation also affected root growth (Djaman et al. 2013). DI during VG period increased R/S ratio, implying that water stress prioritizes dry matter allocation to roots (Cai et al. 2023). In this study, R/S ratio under the D25% treatments generally achieved higher values than CK. This may be attributed to roots prioritizing water absorption, diverting carbon and nutrients from shoot development to root maintenance (Lynch 2018). While successive DI during RG period also elevated the R/S ratio, this was primarily due to the cumulative negative effects on above-ground development being more severe than the impact on roots.

Grains number is the primary contributor to yield, and grain weight directly influences both yield and quality (Niu et al. 2024). Our results showed that DI across various growth stages reduced GN (3.1%–15.88%) and 100-GW (0.07%–13.71%), resulting in an overall yield reduction of 2.30%–27.25%. Consistent with (Allakonon et al. 2022), DI at VG period caused less yield loss than at RG period. Stage I had the least negative effect; specifically, the I-D25% treatment resulted in the lowest and insignificant yield reduction compared to CK. This confirms that low to moderate DI at early VG period can maintain maize yield (Du et al. 2015). Conversely, RG period is critical for grain setting and yield formation and is highly vulnerable to water stress, which disrupts in pollen development, silk elongation, and fertilization processes (Aslam et al. 2015; Chen et al. 2023). Previous studies have identified reductions in grain number and weight as the primary drivers of yield loss in maize under water deficit during RG period (Liu et al. 2021; Guo et al. 2023). Notably, water deficit at stage III most severely impacted GN, as stress-induced delays in silk growth led to pollination failure (Tardieu et al. 2018). In contrast, stress at stage IV more significantly affected 100-GW by limiting sucrose transport and starch synthesis (Aslam et al. 2015). The findings of (Huang et al. 2023) also support the present results.

Nutrients accumulated during VG period can be redistributed and used to synthesize additional grain quality in subsequent maize grain formation (Zhang et al. 2020), whereas reduced LAI and above-ground DM during RG period hinder grain quality accumulation (Sun et al. 2025). Our study found that DI at VG period resulted in better grain quality than at RG period, showing a consistency with the work of (Huang et al. 2023). DI at stages I-III effectively enhanced grain starch content by 2.38%–15.78%. This increase is likely driven by elevated ABA levels, which enhance enzymes activities that convert soluble sugars into starch (Zhang et al. 2012). This response reflects a carbon-water regulation strategy where plants optimize water use efficiency and prioritize the photoassimilates partitioning toward grain starch accumulation (Tardieu et al. 2018). Consequently, this mechanism supports substantial starch accumulation in grains during grain-filling stage, provided irrigation is managed effectively (Sun et al. 2025). In contrast, DI significantly reduced grain protein content (1.59%–15.38%). This may result from excessive green leaf retention during later stages, which hinders nitrogen transfer efficiency and causes nitrogen retention (Wang et al., 2023). Furthermore, drought during RG period disrupts nitrogen metabolism and amino acid synthesis, and limits the carbon skeletons required for protein synthesis, reducing protein accumulation (Aslam et al. 2015).

Synergistic enhancement of maize water productivity improvement through stage-specific deficit irrigation

Strategies for enhancing maize WP through optimized DI rely not only on reducing irrigation volumes but also on precise timing based on crop physiological sensitivity (Kresović et al. 2016; Wang et al. 2023). In this study, ET declined as deficit degree increased. This reduction, particularly during water-insensitive stages, is largely attributable to decreased soil evaporation and moderated transpiration through stomatal regulation (Kresović et al. 2016). As noted by (Rudnick et al. 2017), the impact of DI on ET is highly stage-dependent, where soil water depletion during the VG period has a less detrimental effect on ET than stress during the RG period. Therefore, under limited water resources, moisture should be preserved for critical phenological stages by coordinating the trade-off between biomass accumulation and transpiration loss (Tolimir et al. 2024).

WUE_y was primarily enhanced under DI by reducing water application during non-critical growth periods (Gao et al. 2025) and optimizing crop physiological responses to water deficiency (Pieruschka and Schurr

2019; Sun et al. 2025). Our studies show that WUE_y increased under mild DI compared to well-watered conditions, except during stage III, aligning with previous findings (Guo et al. 2021; Zhang et al. 2022). Moderate stress during VG period can restrict excessive leaf area development, thereby reducing 'luxury' water consumption without harming reproductive organ formation (Kresović et al. 2016). Furthermore, limited irrigation at this period may stimulate deeper root exploration, optimizing the use of stored soil water for later growth (Rudnick et al. 2017). Conversely, WUE_y decreased significantly with increasing water stress during stage IV (Djaman and Irmak 2012; Tolimir et al. 2024). This decline during the late RG period is often linked to accelerated leaf senescence and reduced chlorophyll content, which impairs the mobilization of pre-anthesis carbon reserves to the grains (Kresović et al. 2016). Notably, the I+II-D50% treatment achieved the highest WUE_y despite having the lowest average ET and a moderate yield reduction, representing a higher return per unit of water (Tolimir et al. 2024). By ensuring adequate water allocation during pivotal growth stages and implementing mild DI during less sensitive stages, producers can improve WP without significant yield loss (Attia et al. 2021). To address environmental uncertainties, integrated programming that balances water-saving goals with quality-guarantee constraints is essential to maintain crop quality under deficit conditions (Guo et al. 2018).

Limitations and future works

Although this study has successfully identified the stage-specific responses of summer maize to DI and established an optimized irrigation schedule for seasonally arid regions, certain limitations need further discussion. While this research primarily utilized morpho-physiological traits and DM partitioning to determine the regulatory pathways affecting yield and WP, the intricate water regulation mechanisms within the root-soil system remain insufficiently explored. Specifically, the interactions between root-derived signals, root architecture, and the spatio-temporal variation of soil moisture under varying DI regimes require deeper investigation. Furthermore, the field experiments were conducted over only 2 years, which may not fully reflect the long-term variability and extreme weather events characteristic of the subtropical monsoon climate.

In the future, we intend to conduct long-term, stage-specific DI experiments to further elucidate the underlying water regulation mechanisms within the root-soil system and evaluate the cumulative effects of repeated DI on soil properties and root development. Furthermore, crop models will be employed to simulate the impacts of diverse climate change scenarios on maize production in Southwest China. By identifying key climatic constraints and characterizing future weather patterns, irrigation regimes can be refined to enhance the climate resilience of local maize production. Ultimately, coupling field experiments with crop models and economic assessments will support the design of site-specific DI strategies to improve the risk-mitigation capacity and climate adaptability of maize production in Southwest China.

Conclusion

This study demonstrates that deficit degree and stage exert highly significant interactive effects ($p < 0.001$) on summer maize growth and yield formation in the seasonally arid regions of Southwest China. DI during the RG period leads to significant yield loss and quality degradation. In contrast, the VG period, particularly the seedling stage (stage I), exhibited remarkable resilience. Implementing a moderate deficit (D25%) during this period triggered morpho-physiological acclimation. The I-D25% treatment maintained grain yield stability (4.52% lower than CK, $p > 0.05$) through a significant compensatory photosynthetic effect ($p < 0.05$) and optimized DM reallocation, specifically increasing the grain DM proportion (7.75%–12.52%, $p < 0.05$), as well as enhancing WUE_y (3.26%). The Entropy-TOPSIS evaluation further confirmed that the I-D25% treatment provided the optimal balance between water conservation and crop productivity. For drought-prone regions in Southwest China, implementing the I-D25% (single-stage) or I+II-D25% (multi-stage) DI regimes can significantly alleviate seasonal water scarcity and enhance drought adaptive capacity. This study provides a technical foundation for sustainable intensified agriculture and ensures regional food security in a changing climate.

Disclosure statement

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Data availability statement

The authors do not have permission to share data.

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