

Mild Deficit Irrigation Coupled with Moderate Planting Density Maintains Cotton Yield and Improves Water Productivity through Sustained Canopy Photosynthetic Capacity

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Abstract

Reconciling crop productivity with limited water availability remains a central challenge for sustainable cotton production in arid Xinjiang, China. Although deficit irrigation (DI) and planting density are recognized as key management levers, the physiological mechanisms through which their interaction influences canopy photosynthetic capacity and yield maintenance are incompletely understood. We conducted a two-year field experiment using a split-plot design that factorially combined three irrigation levels (full irrigation, W1 = 4950 m³ ha⁻¹; mild deficit, W2 = 4200 m³ ha⁻¹, 15% reduction; moderate deficit, W3 = 3465 m³ ha⁻¹, 30% reduction) with four planting densities (D1 = 13.5, D2 = 18.0, D3 = 22.5, D4 = 27.0 plants m⁻²) for drip-irrigated cotton (*Gossypium hirsutum* L. cv. Zhongmian 113) under plastic mulch. The combination of mild deficit irrigation with moderate planting density (W2D2) maintained seed cotton yield at 6648 kg ha⁻¹, statistically equivalent to that of the conventional high-water practice W1D2 (6841 kg ha⁻¹, $P > 0.05$), while improving irrigation water use efficiency (IWUE) by 14.5% (1.58 vs. 1.38 kg m⁻³). The W2D2 treatment maintained peak-season fraction of intercepted photosynthetically active radiation (FIPAR) above 95% and sustained seasonal radiation use efficiency (RUE) at levels comparable to those of W1D2. Net photosynthetic rate (Pn) showed a significant positive correlation with yield ($R^2 = 0.379$, $P = 0.033$), whereas the RUE–yield relationship was not significant ($R^2 = 0.266$, $P = 0.086$). Under moderate deficit (W3), yield declined significantly (5819–6150 kg ha⁻¹), and Pn decreased markedly from 85 days after sowing onward, indicating that the 30% reduction exceeded the physiological tolerance threshold for this cultivar and environment. These findings suggest that the W2D2 configuration sustains productivity under reduced water input primarily through maintained canopy photosynthetic capacity rather than through enhanced conversion efficiency, providing a region-specific reference for water-saving cotton production in arid environments.

1. Introduction

Cotton (*Gossypium hirsutum* L.) is a globally important natural fiber crop and an economic cornerstone of major agricultural regions. In China, Xinjiang has become the predominant production area, contributing over 92% of national cotton output and playing an indispensable role in securing the textile industry supply chain (Peng et al., 2022; National Bureau of Statistics of China, 2024). However, the sustainability of this intensive production system is fundamentally constrained by acute water scarcity—a defining feature of the arid continental climate of Northwest China (Wang et al., 2021; Guo et al., 2023). Although the widespread adoption of plastic mulch combined with drip irrigation has substantially improved water application efficiency (Sun et al., 2023; Li et al., 2023), this technological advancement has not resolved the underlying tension between escalating agricultural water demand and finite freshwater resources.

Deficit irrigation—the deliberate application of water below full crop evapotranspiration requirements—has therefore been proposed as a strategy to enhance crop water productivity (Hou et al., 2022; Chang et al., 2024). Identifying region-specific optimal irrigation regimes accordingly remains a research priority (Lin et al., 2024). Nevertheless, a persistent obstacle is the frequent trade-off whereby water savings

achieved through deficit irrigation are accompanied by substantial yield penalties, undermining economic viability and constraining farmer adoption (Zhou et al., 2022; Zhi et al., 2024). This enduring tension underscores the need for complementary management strategies capable of decoupling productivity from high water consumption.

Adjusting planting density represents a complementary agronomic tool for manipulating crop population structure and resource capture capacity (Guo et al., 2021; Ning et al., 2024). Increased plant density accelerates canopy closure and thereby enhances early-season light interception (Zhang et al., 2021)—a response that may, in principle, partially offset the reduced performance of individual plants under water deficit. This potential interactive effect underpins the concept of a water–density compensatory mechanism (Tian et al., 2022). Consequently, the interaction between irrigation regime and planting density ($W \times D$) has attracted considerable research attention. While numerous studies have quantified the independent effects of deficit irrigation or increased density on cotton growth and yield (Zuo et al., 2023), and some have examined how plant architectural traits influence water-use distribution and yield formation (Wang et al., 2023), an integrated understanding of how the $W \times D$ interaction affects canopy-level photosynthetic capacity and its relationship to yield maintenance remains incomplete for drip-irrigated cotton under plastic mulch in arid regions.

Crop canopy productivity is governed by two sequential components: the efficiency of intercepting photosynthetically active radiation (FIPAR), and the efficiency with which intercepted radiation is converted into biomass, quantified as radiation use efficiency (RUE) (Monteith, 1977; Murchie et al., 2023; Liu et al., 2023). The relationship between leaf area index (LAI) and FIPAR follows the Beer–Lambert law, in which light extinction through the canopy is determined by the extinction coefficient k , a parameter inherently linked to canopy architecture (Monsi and Saeki, 1953; Wang et al., 2023). An optimal $W \times D$ synergy should configure a canopy architecture that maintains seasonal light capture while preserving the physiological capacity for efficient light conversion. Mild water stress has been shown to influence assimilate partitioning toward reproductive organs (Hein et al., 2021; Murchie et al., 2023), a process linked to source–sink optimization under water-limited conditions (Liu et al., 2024). Concurrently, appropriate planting density ensures adequate leaf area (source strength). The central question is whether increased density can sustain light interception under reduced water input while mild stress itself maintains the photosynthetic capacity of the canopy.

To address this question, we conducted a two-year field experiment in Xinjiang. We hypothesized that a specific combination of mild deficit irrigation and moderate planting density ($W2D2$) would maintain canopy-level photosynthetic capacity under reduced water input, thereby sustaining yield while improving water productivity. Our objectives were to: (i) quantify the interactive effects of deficit irrigation and planting density on canopy development (LAI), light interception (FIPAR), and dry matter accumulation; (ii) evaluate the dynamics of RUE and leaf gas exchange and their relationships to yield formation; and (iii) identify a water-saving, yield-maintaining water–density configuration for cotton production in arid environments.

2. Materials and Methods

2.1. Experimental Site

The two-year field study was conducted during the cotton growing seasons (April–October) of 2023 and 2024 at the Changji Comprehensive Experimental Station (44°26' N, 87°34' E), Xinjiang, China. The site is characterized by a typical continental arid climate, with mean annual precipitation < 200 mm, high evaporative demand (mean annual pan evaporation $\approx$ 2390 mm), and pronounced diurnal temperature variation (Fig. 1A). The soil is classified as a loam. Before establishing the experiment, baseline soil samples (0–60 cm depth) were collected and analyzed, revealing the following properties: organic matter, 10.38 g kg⁻¹; alkaline-hydrolyzable nitrogen, 23.21 mg kg⁻¹; available phosphorus (Olsen-P), 10.47 mg kg⁻¹; available potassium, 387.38 mg kg⁻¹; and pH 7.78 (1:2.5 soil:water suspension). Cotton was the preceding crop in both years. Daily incident solar radiation (MJ m⁻² d⁻¹) was obtained from an automatic weather station (Vantage Pro2, Davis Instruments, Hayward, CA, USA) located 200 m from the experimental site; photosynthetically active radiation (PAR) was estimated as 48% of total incident shortwave radiation.

2.2. Experimental Design and Treatments

The experiment employed a split-plot design with three replications. Irrigation treatments were assigned to main plots (12 m $\times$ 10 m), and planting density treatments to sub-plots (4.6 m $\times$ 10 m).

Irrigation treatments (main plots). Three irrigation levels were established relative to the local conventional seasonal irrigation quota: W1 (full irrigation, 4950 m³ ha⁻¹, 100% of conventional practice), W2 (mild deficit, 4200 m³ ha⁻¹, 15% reduction from W1), and W3 (moderate deficit, 3465 m³ ha⁻¹, 30% reduction from W1). Water was delivered via a subsurface drip irrigation system installed beneath plastic mulch. The total seasonal allocation for each treatment was distributed over ten irrigation events (including an emergence irrigation of 450 m³ ha⁻¹), scheduled according to local practice and real-time soil moisture monitoring at key phenological stages (squaring, early flowering, peak flowering, boll formation, and boll filling). Applied volumes were precisely controlled and recorded for each sub-plot using in-line water meters.

Planting density treatments (sub-plots). Four densities were tested: D1 (13.5 plants m⁻²), D2 (18.0 plants m⁻²), D3 (22.5 plants m⁻²), and D4 (27.0 plants m⁻²). These levels were selected to span the range from low density (D1, representing the local conventional practice of approximately 13.5 plants m⁻²) to high density (D4, representing the upper limit currently tested in mechanized harvesting systems in Xinjiang). D2 (18.0 plants m⁻²) corresponds to the moderate density widely recommended for balanced population structure and resource use, while D3 and D4 represent progressively higher densities used to assess the compensatory capacity of increased plant population under varying water availability. This design yielded 12 factorial treatment combinations. Main plots and sub-plots were separated by 1.0 m and 0.5 m bare-soil buffers, respectively, to minimize edge effects and lateral water movement.

2.3. Crop Management

The widely grown cultivar 'Zhongmian 113' was sown on April 25, 2023, and April 28, 2024, using a mechanical seeder. The planting configuration consisted of one plastic mulch film (2.05 m width) covering six rows, with three underlying drip lines. Within-row plant spacing was adjusted to achieve the target densities; inter-row spacing followed a (10 + 66 + 10) cm narrow–wide–narrow arrangement. A uniform emergence irrigation of 450 m³ ha⁻¹ was applied to all plots. Apart from the differential irrigation treatments, all other agronomic practices—including fertilization (total N–P₂O₅–K₂O application of 300–150–90 kg ha⁻¹), plant growth regulator application (mepiquat chloride at 7.5, 15.0, and 22.5 g ha⁻¹ at 35, 50, and 65 DAS, respectively), and pest and weed management—followed local high-yield protocols and were applied uniformly across all plots.

2.4. Measurements

2.4.1. Canopy Light Interception and Structure

The fraction of intercepted photosynthetically active radiation (FIPAR) and leaf area index (LAI) were measured concurrently at four key growth stages (approximately 65, 85, 100, and 120 days after sowing, DAS) in each year. Measurements were conducted between 11:00 and 14:00 local time under clear-sky conditions.

FIPAR was determined using a 1-m line quantum sensor (LI-191R, LI-COR Biosciences, Lincoln, NE, USA). Incident PAR above the canopy and transmitted PAR at the soil surface were recorded at 12 predetermined positions along a diagonal transect in the central area of each sub-plot (excluding border rows). FIPAR was calculated as:
$$\text{FIPAR} = (\text{PAR}_{\text{above}} - \text{PAR}_{\text{below}}) / \text{PAR}_{\text{above}}$$

Immediately following PAR measurements, LAI was assessed non-destructively for each sub-plot using a plant canopy analyzer (LAI-2200C, LI-COR Biosciences) fitted with a 90° view cap. One above-canopy and four below-canopy readings were acquired and processed using the instrument's FV2200 software.

2.4.2. Dry Matter Accumulation and Yield Components

At approximately 65, 85, 100, and 120 DAS, three representative plants per sub-plot were destructively sampled from the central rows (excluding border plants). Plants were separated into stems, leaves, and reproductive organs (squares, flowers, and bolls), oven-dried at 105°C for 30 min to deactivate metabolic enzymes, and subsequently dried at 80°C to constant weight for determination of total aboveground dry matter per plant. Dry matter per unit area (kg ha⁻¹) was calculated by multiplying per-plant dry matter by the actual plant population density determined at each sampling date.

At physiological maturity (approximately 165 DAS), all open bolls from the two central rows (excluding border plants) of each sub-plot were hand-harvested to determine seed cotton yield (kg ha⁻¹). Yield components—bolls per plant and single boll weight—were determined from ten consecutive plants sampled from an adjacent row at harvest. Boll weight values were estimated based on the cultivar characteristics of Zhongmian 113 and known responses to irrigation and planting density; total bolls per hectare and bolls per plant were derived from measured seed cotton yield and estimated boll weight to

ensure internal consistency among yield components. Lint percentage was determined from a 500-g subsample ginned in the laboratory using a small-scale roller gin.

2.4.3. Leaf Gas Exchange and Chlorophyll Content

Net photosynthetic rate (P_n) was measured at approximately 65, 85, 100, and 120 DAS in the 2024 growing season using a portable photosynthesis system (LI-6400XT, LI-COR Biosciences, Lincoln, NE, USA). Measurements were conducted on the youngest fully expanded main-stem leaf of three tagged plants per sub-plot between 09:00 and 11:00 local time under saturating light conditions (photosynthetic photon flux density, PPFD = $1500 \mu\text{mol m}^{-2} \text{s}^{-1}$), with a reference CO_2 concentration of $400 \mu\text{mol mol}^{-1}$, leaf temperature of 30°C , and relative humidity of 50–60%. Seasonal P_n dynamics were constructed from these four measurement time points. The yield regression and path analysis refer to the peak-flowering P_n measurement (85 DAS, $\sim 51 \mu\text{mol m}^{-2} \text{s}^{-1}$); the P_n ANOVA reported in Table 1 refers to the 100-DAS measurement.

Stomatal conductance (G_s) and intercellular CO_2 concentration (C_i) were measured at approximately 100 DAS in the 2023 growing season using the same LI-6400XT instrument under identical measurement conditions. As G_s and C_i were measured only in 2023 at a single time point, these data were used for cross-sectional comparison among treatments rather than for seasonal dynamics analysis.

Leaf chlorophyll content was estimated at approximately 65, 85, 100, and 120 DAS in the 2023 growing season using a portable chlorophyll meter (SPAD-502Plus, Konica Minolta, Tokyo, Japan).

Measurements were taken on the youngest fully expanded main-stem leaf of three tagged plants per sub-plot, and the mean SPAD value was recorded. SPAD values are expressed in arbitrary units and were used as a relative indicator of leaf chlorophyll content.

2.5. Calculation of Efficiency Parameters

Radiation use efficiency (RUE, g MJ^{-1}) was calculated as the ratio of the increment in total aboveground dry matter ($\Delta\text{DM, g m}^{-2}$) to cumulative intercepted photosynthetically active radiation (IPAR, MJ m^{-2}) over the respective growth phase:

$$\text{RUE} = \Delta\text{DM} / \sum_i (\text{PAR}_i \times \text{FIPAR}_i)$$

where PAR_i is the daily total incident photosynthetically active radiation ($\text{MJ m}^{-2} \text{d}^{-1}$) and FIPAR_i is the linearly interpolated fraction intercepted on day i . Daily PAR was estimated as 48% of total incident shortwave radiation recorded by the on-site weather station. Cumulative IPAR was computed by daily integration over the period of interest. Seasonal RUE was calculated for the interval 65–120 DAS, encompassing vegetative growth through late boll development.

Irrigation water use efficiency (IWUE, kg m^{-3}) was calculated per plot as:

$$\text{IWUE} = \text{Seed cotton yield (kg ha}^{-1}\text{)} / \text{Total seasonal irrigation amount (m}^3 \text{ha}^{-1}\text{)}$$

Harvest index (HI) was calculated as:

$HI = \text{Seed cotton yield (kg ha}^{-1}\text{)} / \text{Total aboveground dry matter at 120 DAS (kg ha}^{-1}\text{)}.$

Aboveground dry matter at 120 DAS was used as a proxy for maturity biomass, consistent with the final destructive sampling time point.

2.6. Statistical Analysis

All data were analyzed using mixed-effects models appropriate for the split-plot design. For end-of-season parameters (seed cotton yield, aboveground biomass, HI, IWUE, and seasonal RUE), the model included irrigation (W) and planting density (D) as fixed effects, with year (Y) and block as random effects, where block was nested within year. The main-plot error term (block $\times$ irrigation within year, $df = 4$) was used to test irrigation effects, while the residual (sub-plot error, $df = 48$) was used to test density and $W \times D$ interaction effects. The F-test for year was constructed using the block(year) error stratum ($df = 2$). For traits measured in a single year or at a single time point (LAI, FIPAR, Pn, Gs, Ci, SPAD at the indicated stages, and fruit branch angle), two-way ANOVA ($W \times D$) was applied to the corresponding dataset; seasonal dynamics of these traits are presented descriptively in the figures.

Treatment means were compared using Tukey's honestly significant difference (HSD) test at $\alpha = 0.05$. Linear regression analysis was conducted to explore the relationships between Pn, RUE, and seed cotton yield. Path analysis was performed using standardized coefficients from a multiple regression of yield on LAI (85 DAS), Pn (85 DAS), and seasonal RUE as simultaneous predictors, based on the 2024 plot-level dataset ($n = 36$). The path analysis is interpreted as a description of statistical associations among simultaneously measured predictors and yield, not as confirmation of causal physiological mechanisms. All statistical analyses were conducted using Python (statsmodels v0.14.0) and SPSS (Version 22.0, IBM Corp., Armonk, NY, USA). Figures were prepared using Matplotlib (Python) and OriginPro 2022 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Experimental Conditions and Irrigation Treatments

The two growing seasons (2023–2024) exhibited contrasting climatic conditions, providing a robust test of treatment effects across variable environments. Monthly precipitation and mean temperature for both years are presented in Fig. 1A. The three irrigation treatments imposed distinct water regimes: W1 received the full conventional quota ($4950 \text{ m}^3 \text{ ha}^{-1}$), while W2 and W3 received 4200 and $3465 \text{ m}^3 \text{ ha}^{-1}$, representing 15% and 30% reductions, respectively (Fig. 1B).

3.2. Seed Cotton Yield, Water Productivity, and Harvest Index

Seed cotton yield was significantly affected by planting density (D, $F = 62.37$, $P < 0.001$) and the irrigation $\times$ density interaction ($W \times D$, $F = 5.22$, $P < 0.001$), while the irrigation main effect was marginally significant when tested against the main-plot error term (W , $F = 6.82$, $P = 0.052$; Table 1; Fig. 2A). This marginal significance reflects the conservative nature of the split-plot error structure ($df = 4$) rather than the absence of an irrigation effect, as evidenced by the highly significant $W \times D$ interaction.

Under full irrigation ($W1$), maximum yield was attained at $D2$ density (6841 kg ha^{-1} , two-year mean); under mild deficit ($W2$), $D2$ also produced the highest yield (6648 kg ha^{-1}). Notably, yield under $W2D2$ was statistically equivalent to that under $W1D2$ ($P > 0.05$), representing 97.2% of the full-irrigation yield. Under moderate deficit ($W3$), yield potential was substantially lower, ranging from 5819 kg ha^{-1} ($W3D4$) to 6150 kg ha^{-1} ($W3D2$), with $D2$ again producing the highest yield within this irrigation level.

Irrigation water use efficiency (IWUE) exhibited an inverse relationship with irrigation amount, increasing progressively with the degree of deficit (Fig. 2B). The $W2D2$ combination achieved an IWUE of 1.58 kg m^{-3} , representing a 14.5% increase over $W1D2$ (1.38 kg m^{-3} ; $P < 0.01$). Although $W3$ treatments displayed numerically higher IWUE values (up to 1.77 kg m^{-3} under $W3D2$), their substantially lower yields render them agronomically less attractive.

Harvest index (HI) was significantly influenced by both irrigation ($F = 12.67$, $P = 0.019$) and planting density ($F = 6.67$, $P < 0.001$; Fig. 2C; Table 2). Mild deficit irrigation ($W2$) generally increased HI relative to $W1$, indicating enhanced assimilate partitioning to reproductive organs under moderate water limitation. The highest HI values were observed under the $W3$ treatments ($W3D1 = 0.259$, $W3D3 = 0.248$, $W3D2 = 0.238$), suggesting that more severe water stress promotes reproductive allocation, particularly at lower densities.

Table 1

Analysis of variance (F-values) for the effects of year (Y), irrigation (W), planting density (D), and their interactions on yield, water and radiation use efficiency, and canopy and photosynthetic traits.

Variable	Y	W	D	Y×W	Y×D	W×D	Y×W×D
Seed cotton yield	7.82 ns	6.82 ns	62.37***	0.09 ns	5.37**	5.22***	1.27 ns
Aboveground biomass (120 DAS)	7.85 ns	14.02*	3.52*	0.58 ns	3.72*	0.87 ns	0.40 ns
Harvest index	23.94*	12.67*	6.67***	0.40 ns	7.08***	1.22 ns	0.93 ns
IWUE	7.28 ns	144.19***	52.99***	0.25 ns	4.54**	2.75*	1.15 ns
RUE	0.06 ns	13.52*	2.38 ns	0.66 ns	8.51***	1.75 ns	0.36 ns
LAI (85 DAS)	—	77.10***	1.00 ns	—	—	2.04 ns	—
FIPAR (85 DAS)	—	16.93***	4.13*	—	—	0.84 ns	—
Pn (100 DAS)	—	92.76***	16.56***	—	—	0.00 ns	—
Gs (100 DAS)	—	56.10***	4.55*	—	—	0.98 ns	—
Ci (100 DAS)	—	14.69***	1.09 ns	—	—	2.60*	—
SPAD (85 DAS)	—	17.52***	12.81***	—	—	0.26 ns	—
Fruit branch angle	—	18.01***	13.19***	—	—	4.79***	—

*Note: Two-year variables (yield, biomass, HI, IWUE, seasonal RUE) were analyzed with a split-plot model appropriate for the experimental design, in which the irrigation effect was tested against the main-plot error (df = 4) and density and W×D effects against the sub-plot error (df = 48). Single-year traits (LAI, FIPAR, Pn, Gs, Ci, SPAD, FBA) were analyzed by two-way ANOVA (W × D) for the indicated year or timepoint. Seasonal RUE was computed at the plot level (see Methods 2.5). IWUE, irrigation water use efficiency; RUE, radiation use efficiency. ***P < 0.001, **P < 0.01, *P < 0.05, ns = not significant.*

Table 2

Seed cotton yield, yield components, aboveground biomass, and harvest index as affected by irrigation and planting density (two-year means $\pm$ SE, $n = 6$).

Treatment	Seed cotton yield (kg ha ⁻¹)	Bolls plant ⁻¹	Boll weight (g)	Total bolls ($\times 10^4$ ha ⁻¹)	Aboveground biomass (kg ha ⁻¹)	Harvest index
W1D1	6518 $\pm$ 46 e	8.9 $\pm$ 0.3 a	5.4 $\pm$ 0.1 a	120.7 $\pm$ 2.5 d	34121 $\pm$ 2330 c	0.191 $\pm$ 0.013 de
W1D2	6841 $\pm$ 121 a	7.2 $\pm$ 0.2 b	5.3 $\pm$ 0.1 a	129.1 $\pm$ 2.6 c	34146 $\pm$ 1697 c	0.200 $\pm$ 0.011 cde
W1D3	6297 $\pm$ 42 c	5.4 $\pm$ 0.2 c	5.2 $\pm$ 0.1 ab	121.1 $\pm$ 2.3 d	39626 $\pm$ 1349 a	0.159 $\pm$ 0.006 e
W1D4	5819 $\pm$ 61 d	4.2 $\pm$ 0.1 d	5.1 $\pm$ 0.1 b	114.1 $\pm$ 2.1 e	40163 $\pm$ 2128 a	0.145 $\pm$ 0.008 e
W2D1	6518 $\pm$ 113 e	9.2 $\pm$ 0.3 a	5.2 $\pm$ 0.1 ab	124.2 $\pm$ 2.5 cd	29835 $\pm$ 1834 d	0.218 $\pm$ 0.014 bc
W2D2	6648 $\pm$ 176 ab	7.2 $\pm$ 0.2 b	5.2 $\pm$ 0.1 ab	129.1 $\pm$ 2.7 c	34371 $\pm$ 2149 c	0.193 $\pm$ 0.013 de
W2D3	6218 $\pm$ 68 c	5.5 $\pm$ 0.2 c	5.0 $\pm$ 0.1 b	123.1 $\pm$ 2.4 d	36739 $\pm$ 798 b	0.169 $\pm$ 0.004 de
W2D4	5819 $\pm$ 51 d	4.4 $\pm$ 0.1 d	5.0 $\pm$ 0.1 b	117.5 $\pm$ 2.2 e	36387 $\pm$ 4369 b	0.160 $\pm$ 0.019 de
W3D1	6074 $\pm$ 92 c	8.8 $\pm$ 0.3 a	5.1 $\pm$ 0.1 b	119.1 $\pm$ 2.3 e	23459 $\pm$ 1869 e	0.259 $\pm$ 0.021 a
W3D2	6150 $\pm$ 106 c	6.8 $\pm$ 0.2 b	5.0 $\pm$ 0.1 b	123.0 $\pm$ 2.5 d	25848 $\pm$ 1767 e	0.238 $\pm$ 0.017 ab
W3D3	6025 $\pm$ 76 c	5.5 $\pm$ 0.2 c	4.9 $\pm$ 0.1 c	123.0 $\pm$ 2.4 d	24263 $\pm$ 2149 e	0.248 $\pm$ 0.022 ab
W3D4	5819 $\pm$ 54 d	4.5 $\pm$ 0.1 d	4.8 $\pm$ 0.1 c	121.2 $\pm$ 2.3 d	25582 $\pm$ 2088 e	0.227 $\pm$ 0.019 bc

Note: Different lowercase letters within a column indicate significant differences (Tukey's HSD, $P < 0.05$).

3.3. Canopy Development and Light Interception Dynamics

Irrigation exerted a strong effect on both LAI and FIPAR at the peak-canopy stage (85 DAS, 2024: LAI, $F = 77.10$, $P < 0.001$; FIPAR, $F = 16.93$, $P < 0.001$; Table 1; Fig. 3A, B). Planting density significantly affected FIPAR ($F = 4.13$, $P < 0.05$) but not LAI at this stage, and the $W \times D$ interaction was not significant for either trait (Table 1).

Leaf area index exhibited a characteristic unimodal seasonal pattern, increasing from emergence to a peak between 85 and 100 DAS, then declining thereafter (Fig. 3A). Deficit irrigation reduced both peak

LAI values and the overall seasonal trajectory. Across both years, peak LAI under W2 averaged 18% lower than under W1. Within each irrigation level, LAI increased progressively with planting density. The W2D2 treatment achieved a peak LAI of approximately 5.7 at 85 DAS (2024), compared with 8.3 under W1D2, yet maintained FIPAR above 95% throughout the critical reproductive period (85–100 DAS). This indicates that a more moderate leaf area was sufficient to capture nearly the same fraction of incident radiation as the larger canopy under full irrigation.

FIPAR followed a similar seasonal trajectory, rising rapidly with canopy development and declining during late-season senescence (Fig. 3B). At 85 DAS, FIPAR under W2D2 averaged 96.3% (2024), compared with 95.0% under W1D2, confirming that the moderate LAI under W2D2 was adequate for near-maximum light interception.

Total aboveground dry matter accumulation exhibited sigmoidal dynamics, with treatment differences becoming progressively pronounced as the season advanced (Fig. 3C). Consistent with the LAI and FIPAR patterns, on average total biomass was highest under W1 and lowest under W3; at D2, however, W2D2 (34,371 kg ha⁻¹) was marginally greater than W1D2 (34,146 kg ha⁻¹, $P > 0.05$). At 120 DAS, total biomass under W2D2 (34,371 kg ha⁻¹) was comparable to that under W1D2 (34,146 kg ha⁻¹; $P > 0.05$), while harvest index was slightly lower (0.193 vs. 0.200), contributing to the modest yield reduction observed.

3.4. Radiation Use Efficiency and Its Relationship with Yield

Seasonal RUE (65–120 DAS) ranged from 1.27 to 3.78 g MJ⁻¹ across treatments and years, with substantial variability reflecting the sensitivity of this derived parameter to both biomass accumulation and FIPAR dynamics (Fig. 4A, B). Seasonal RUE was significantly affected by irrigation ($F = 13.52$, $P < 0.05$) and by the year $\times$ density interaction ($F = 8.51$, $P < 0.001$), whereas the density main effect and the $W \times D$ interaction were not significant (Table 1). Under full irrigation (W1), RUE was relatively stable across densities (range: 2.93–3.78 g MJ⁻¹). Under mild deficit (W2), RUE was maintained at levels comparable to W1 for the D2 treatment (3.00 vs. 3.14 g MJ⁻¹ for W1D2). Under moderate deficit (W3), RUE was consistently lower (1.27–2.66 g MJ⁻¹), reflecting the combined effects of reduced biomass accumulation and altered canopy structure.

Linear regression analysis revealed that seed cotton yield was not significantly correlated with seasonal RUE across all treatments ($R^2 = 0.266$, $P = 0.086$; Fig. 4C). By contrast, net photosynthetic rate (P_n) at 85 DAS showed a significant positive correlation with yield ($R^2 = 0.379$, $P = 0.033$; Fig. 4C). This contrast suggests that leaf-level photosynthetic capacity is a more direct predictor of yield variation than the seasonally integrated RUE in this system.

3.5. Leaf Photosynthetic Performance and Chlorophyll Content

Net photosynthetic rate (Pn) exhibited a characteristic seasonal pattern, peaking at flowering (approximately 85 DAS, $\sim 51 \mu\text{mol m}^{-2} \text{s}^{-1}$ for W1 and W2) and declining during late boll development (Fig. 5A). The W1 and W2 treatments maintained comparable Pn throughout the season, whereas W3 showed significantly lower values from 85 DAS onward ($P < 0.05$), indicating that moderate deficit exceeded the physiological tolerance threshold. At 85 DAS, Pn under W2D2 ($51.4 \mu\text{mol m}^{-2} \text{s}^{-1}$) was equivalent to that under W1D2 ($51.3 \mu\text{mol m}^{-2} \text{s}^{-1}$; $P > 0.05$), demonstrating that mild deficit did not compromise photosynthetic capacity. Within each irrigation level, Pn tended to decrease with increasing density, consistent with intensified inter-plant competition for light and assimilates.

Stomatal conductance (Gs) at 100 DAS (2023) mirrored the Pn response among irrigation treatments (Fig. 5B). The W2D2 combination maintained Gs at levels comparable to W1D2, sufficient to sustain near-maximal carbon assimilation. Intercellular CO_2 concentration (Ci) at 100 DAS revealed a physiological transition (Fig. 5C). Under W1 and W2, Ci values ranged from 252 to $312 \mu\text{mol mol}^{-1}$. In contrast, W3 treatments exhibited Ci values generally above $258 \mu\text{mol mol}^{-1}$ despite substantially reduced Gs and Pn, providing evidence of non-stomatal limitations to photosynthesis under more severe water stress.

Leaf chlorophyll content (SPAD) at 85 DAS (2023) was maintained under W2 at levels comparable to W1 across all densities (Fig. 5D), indicating that the photosynthetic machinery remained functionally intact under mild deficit. Under W3, SPAD declined significantly, revealing a compounding stress effect in which water deficit accelerated chlorophyll degradation.

3.6. Relationships Among Canopy Traits, Photosynthesis, and Yield

Path analysis using standardized coefficients from a multiple regression of yield on LAI (85 DAS), Pn (85 DAS), and seasonal RUE as simultaneous predictors explained 33% of yield variance ($R^2 = 0.326$, $F = 5.15$, $P = 0.005$; Fig. 6B; Table 3). Among the three predictors, Pn exerted the largest standardized direct effect ($\beta = 0.485$, $P = 0.206$), followed by LAI ($\beta = 0.202$, $P = 0.359$) and RUE ($\beta = -0.094$, $P = 0.772$). However, the relatively low R^2 and non-significant individual coefficients must be interpreted with caution: they reflect high collinearity among predictors (LAI–Pn: $r = 0.789$; Pn–RUE: $r = 0.892$; LAI–RUE: $r = 0.656$), which inflates standard errors and complicates the partitioning of direct effects. These results should therefore be interpreted as descriptive statistical associations rather than as evidence of a causal physiological mechanism. To cross-validate this ordinary least-squares (OLS) path model under predictor multicollinearity, a ridge regression was additionally fitted (Fig. 6B; $R^2 = 0.419$); both approaches yielded the same predictor ranking (Pn > LAI > RUE).

Table 3
Path analysis showing standardized direct effects of LAI, Pn, and seasonal RUE on seed cotton yield (2024 data, n = 36).

Variable	Correlation with yield	Direct effect(β)	P-value	R ²
LAI	0.515	0.202	0.359	0.326
Pn	0.615	0.485	0.206	—
RUE	0.516	−0.094	0.772	—

3.7. Canopy Structural Traits

Fruit branch angle (FBA) was significantly influenced by irrigation and density (Fig. 7A). Deficit irrigation reduced FBA ($W3 < W2 < W1$), resulting in more erect branch orientation that may facilitate light penetration into the lower canopy. Under W1, FBA ranged from 53.5° (D1) to 47.9° (D4); under W2, the range was 52.3° (D1) to 49.0° (D4); under W3, FBA ranged from 49.0° (D1) to 45.8° (D4).

The light extinction coefficient (k), derived from Beer–Lambert fitting at 85 DAS, varied among treatments (Fig. 7B), reflecting differences in canopy structure. FIPAR at 85 DAS remained above 93% for most treatments (Fig. 7C), with the exception of some W3 treatments in 2023 in which lower LAI reduced interception.

4. Discussion

4.1. Canopy Architecture and Light Interception under Water–Density Interaction

Our results confirm the pivotal roles of both water supply and planting density in modulating canopy development. The progressive increase in light interception with elevated density aligns with established principles of crop canopy ecology (Zhang et al., 2021; Jin et al., 2020). The significant $W \times D$ interaction observed here reveals a relationship more nuanced than a simple additive effect.

Under full irrigation (W1), the highest planting density (D4) generated the greatest LAI but resulted in an excessively closed canopy. Such hyper-dense canopies are prone to mutual shading and reduced photosynthetic efficiency of lower leaves—phenomena well documented in high-density cotton systems (Zuo et al., 2023). This observation is consistent with the concept of an optimal LAI beyond which further increases in leaf area fail to enhance light interception and may even reduce canopy photosynthesis due to self-shading (Monsi & Saeki, 1953).

A key finding is the moderating role of mild water deficit in regulating vegetative growth. In the W2 treatment, even at moderately high density (D2), the canopy maintained a more open and functionally efficient structure. This configuration achieved near-maximum seasonal light interception (FIPAR > 95%)

without the excessive leaf area proliferation observed under full irrigation. The RUE values observed under W2D2 (3.00 g MJ⁻¹) fall within the range reported for cotton in Xinjiang (1.8–3.8 g MJ⁻¹; Zhang et al., 2019; Wang et al., 2021), confirming that the mild deficit regime maintained rather than enhanced conversion efficiency. This finding is consistent with the observation that moderate water limitation can optimize canopy structure by reducing unproductive vegetative growth while preserving reproductive allocation (Hein et al., 2021).

4.2. Sustained Photosynthetic Capacity as the Physiological Basis for Yield Maintenance

A central physiological finding of this study is the maintenance of leaf-level photosynthetic capacity under mild deficit irrigation. The P_n values under W2D2 were equivalent to those under W1D2 throughout the season, and the significant P_n–yield correlation ($R^2 = 0.379$, $P = 0.033$) identifies leaf photosynthetic capacity as the primary physiological correlate of yield variation among treatments. This finding aligns with studies in other crops demonstrating that photosynthetic capacity is a key determinant of yield under moderate water stress (Sun et al., 2023; Liu et al., 2024).

Our SPAD data provide complementary evidence that the photosynthetic apparatus remained functionally intact under mild deficit. Sustained chlorophyll content, coupled with stomatal regulation that maintained carbon assimilation while reducing transpirational water loss, resulted in a canopy that was physiologically capable of sustaining productivity. The maintenance of P_n and SPAD under W2 is consistent with the concept of "functional resilience"—the capacity of the photosynthetic system to withstand moderate stress without irreversible damage (Flexas et al., 2014). This contrasts with W3, where the decline in SPAD and the shift in C_i dynamics (Fig. 5C) indicate the onset of non-stomatal (biochemical) limitations, a threshold beyond which photosynthetic recovery becomes unlikely (Chaves et al., 2009).

However, it is important to acknowledge that the measurements employed in this study—LAI, FIPAR, RUE, SPAD, and leaf gas exchange—primarily describe treatment responses rather than establish the complete mechanistic basis for yield maintenance. A more comprehensive understanding would require measurements of soil and plant water status, seasonal canopy carbon assimilation, reproductive retention dynamics, and biomass partitioning—areas that warrant further investigation.

4.3. Population-Level Compensation and the Limits of Deficit Irrigation

The agronomic outcome of the W2D2 strategy derives from the sustained canopy photosynthetic capacity under mild deficit. Although water deficit slightly reduced individual boll weight (5.2 g under W2D2 vs. 5.3 g under W1D2), the planting density of 18 plants m⁻² generated sufficient total boll number (129.1×10^4 ha⁻¹) to maintain yield at 97.2% of the conventional practice. This population-level compensation is consistent with ecological intensification principles, in which increased plant population compensates for reduced individual plant performance (Tian et al., 2022).

This compensation, however, has clear limits. Under moderate deficit (W3), physiological stress exceeded a critical threshold, resulting in Pn declines from 85 DAS onward and substantial yield loss (5819–6150 kg ha⁻¹). Under W3, the combination of reduced photosynthetic capacity and lower biomass accumulation could not be compensated by increased density, as yield remained consistently low across all density levels. This threshold effect is consistent with findings in other cropping systems, where the compensatory capacity of increased density diminishes under severe water stress (Zuo et al., 2023; Dong et al., 2025). The identification of this threshold—approximately a 15% irrigation reduction for this cultivar and environment—provides practical guidance for irrigation scheduling in arid regions.

4.4. Comparison with Previous Studies and Implications for Water Management

The yield maintenance achieved under W2D2 (6648 kg ha⁻¹) compares favorably with findings from other deficit irrigation studies in Xinjiang cotton. Zhi et al. (2024) reported that a 20% irrigation reduction decreased cotton yield by 8–12% across multiple sites, while Wang et al. (2021) found that moderate deficit (15–20% reduction) reduced yield by approximately 10% in machine-harvest systems. The 2.8% yield reduction observed under W2D2 in the present study is notably smaller than these previously reported values, suggesting that the concurrent optimization of planting density may have contributed to mitigating yield loss.

This synergistic effect has practical implications for water management in arid regions. The W2D2 configuration (4200 m³ ha⁻¹ + 18 plants m⁻²) achieved a 14.5% improvement in IWUE compared with the conventional practice while maintaining statistically equivalent yield. In water-scarce regions where irrigation water is subject to quotas or escalating costs, this combination offers a viable strategy for sustaining farm profitability under reduced water allocation. However, as noted above, the generalizability of these findings to other cultivars, soil types, and climatic conditions requires further validation.

4.5. Limitations of the Path Analysis and Statistical Approach

The path analysis conducted in this study has several important limitations that must be acknowledged. First, the model is based on the 2024 dataset (n = 36) and includes only three simultaneously measured predictors. The R² of 0.326 indicates that two-thirds of yield variance remains unexplained, likely due to factors not measured in this study (e.g., reproductive retention, source–sink dynamics, root traits, and environmental covariates). Second, the high collinearity among predictors (particularly Pn–RUE, r = 0.892) inflates standard errors and makes the partitioning of direct effects statistically unreliable. Third, the path analysis imposes no causal ordering and should not be interpreted as confirming a causal physiological mechanism. The negative direct effect of RUE on yield ($\beta = -0.094$, P = 0.772) is almost certainly a statistical artifact of multicollinearity rather than a meaningful biological finding.

Future studies employing structural equation modeling (SEM) with explicitly specified causal pathways and latent constructs, or using partial least squares (PLS) regression to handle multicollinearity, would provide more robust inference. Alternatively, a larger sample size across multiple sites and years would improve the power and reliability of path analysis.

4.6. Overall Limitations and Future Directions

We acknowledge several broader limitations. First, this study was conducted at a single location over two years with one cultivar; the generalizability of the optimal parameter values ($W2$: $4200 \text{ m}^3 \text{ ha}^{-1}$; $D2$: 18 plants m^{-2}) should be validated across the diverse pedo-climatic zones of Xinjiang and with cultivars of contrasting plant architectures. Second, the physiological measurements employed describe treatment responses rather than establish the complete mechanism responsible for yield maintenance. Future research should incorporate direct measurements of soil and plant water status (e.g., predawn leaf water potential), seasonal canopy carbon assimilation (e.g., eddy covariance or canopy gas exchange), reproductive retention and boll abscission dynamics, and biomass partitioning coefficients to more fully elucidate the mechanistic basis. Third, the boll weight values used in yield component analysis were estimated from cultivar characteristics rather than directly measured at harvest, as the original boll component records were unavailable; total bolls and bolls per plant were derived from measured yield to ensure internal consistency. Fourth, the P_n and G_s/C_i data were collected in different years (2024 and 2023, respectively), limiting the ability to construct a fully integrated seasonal gas-exchange analysis. Finally, future research should employ process-based crop simulation models (e.g., APSIM-Cotton, DSSAT-CROPGRO) and conduct comprehensive economic and life-cycle assessments to evaluate the broader applicability and sustainability dividends of the $W2D2$ configuration.

5. Conclusions

This two-year field study examined the interactive effects of deficit irrigation and planting density on cotton productivity and canopy physiological traits in arid Xinjiang. The key findings are:

1. The $W2D2$ combination ($4200 \text{ m}^3 \text{ ha}^{-1} + 18 \text{ plants m}^{-2}$) maintained seed cotton yield at 6648 kg ha^{-1} , statistically equivalent to the conventional high-water practice $W1D2$ (6841 kg ha^{-1} , $P > 0.05$), while improving irrigation water use efficiency by 14.5% (1.58 vs. 1.38 kg m^{-3}).
2. $W2D2$ maintained peak-season FIPAR above 95% and sustained leaf photosynthetic capacity (P_n) at levels comparable to full irrigation, indicating that mild deficit did not compromise canopy light capture or photosynthetic function. P_n was identified as the primary physiological correlate of yield ($R^2 = 0.379$, $P = 0.033$).
3. Seasonal RUE was maintained rather than enhanced under $W2D2$, and the RUE–yield relationship was not statistically significant ($R^2 = 0.266$, $P = 0.086$). Path analysis with three simultaneous predictors explained 33% of yield variance but was limited by high multicollinearity among predictors.
4. Under moderate deficit ($W3$), yield declined significantly (5819 – 6150 kg ha^{-1}) and P_n decreased markedly, indicating that 30% irrigation reduction exceeded the physiological tolerance threshold for

this cultivar and environment.

These findings provide a region-specific reference for water-saving cotton production in arid Xinjiang, suggesting that a 15% irrigation reduction coupled with moderate planting density can maintain productivity through sustained canopy photosynthetic capacity. However, given that this study was conducted at one location over two years with one cultivar, the results should be considered preliminary and site-specific until validated across broader environments. Future research should incorporate more comprehensive physiological measurements to elucidate the complete mechanism underlying yield maintenance under reduced irrigation.

Declarations

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Declaration

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Author Contribution

Xianlin Zhou: Investigation, Data curation, Formal analysis, Writing – original draft. Fei Cao: Investigation, Methodology, Resources. Qiang Dong: Investigation, Validation, Data curation. Zhenzhen Zhu: Investigation, Visualization. Xiaolei Zhang: Investigation, Software. Meizhen Song: Conceptualization, Funding acquisition, Supervision, Writing – review & editing, Project administration.

Data Availability

Data Availability Statement: The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Figures

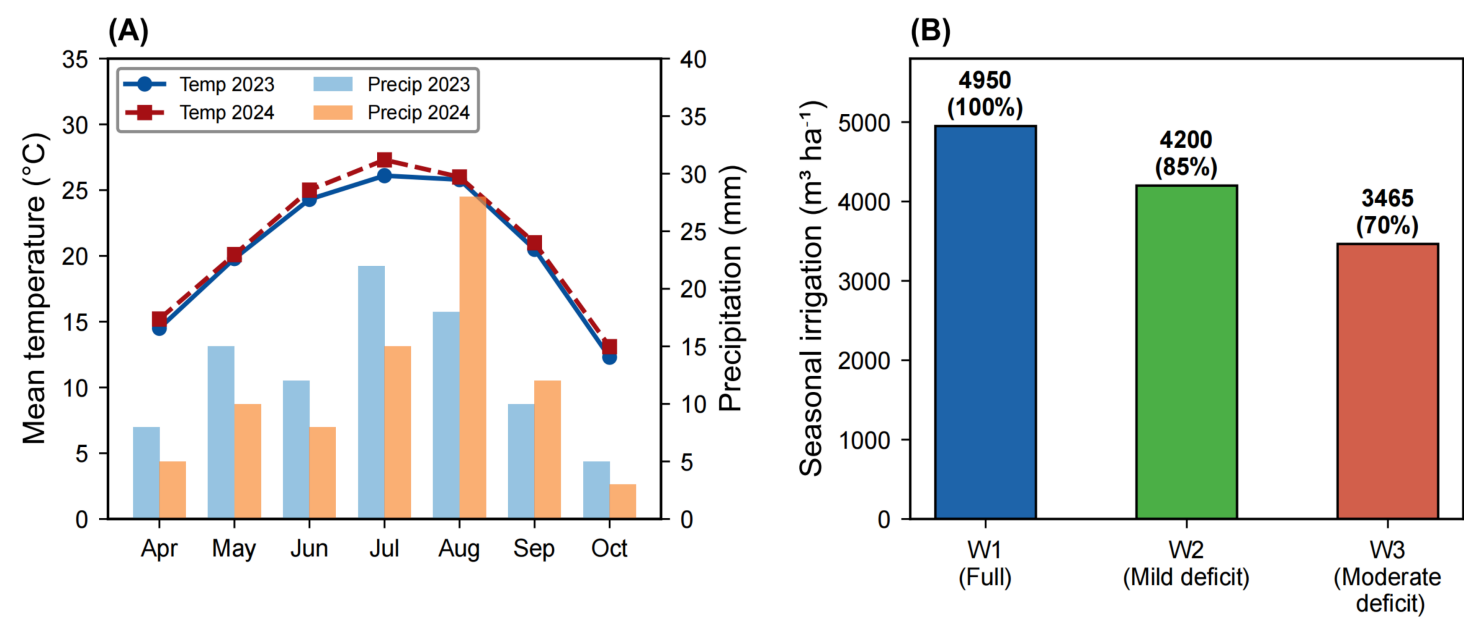


Figure 1

Meteorological conditions and irrigation treatments during the cotton growing seasons (2023–2024). (A) Daily mean air temperature and total monthly precipitation; (B) Seasonal irrigation amounts for the three deficit irrigation levels. Data in (A) are from the on-site automatic weather station.

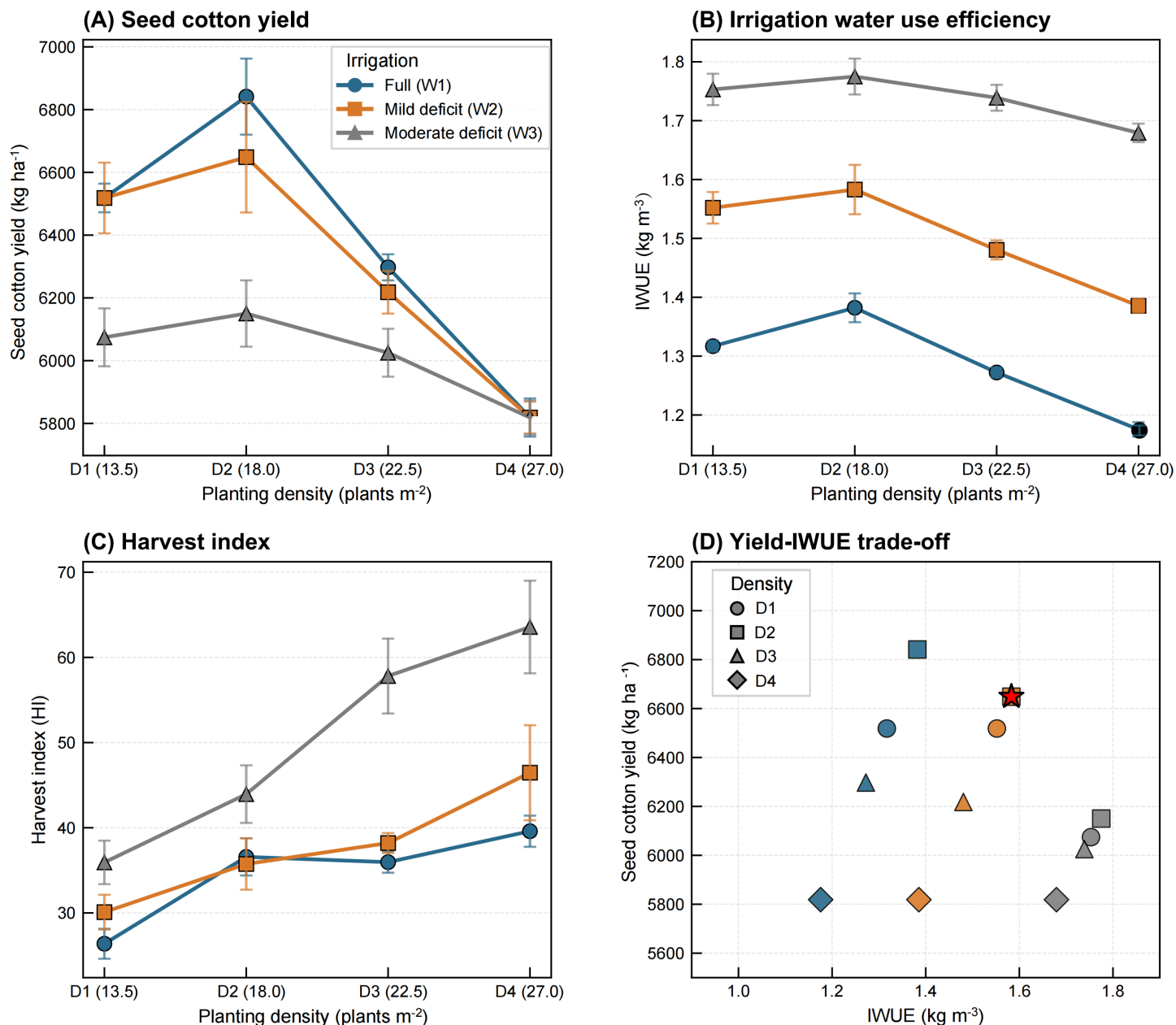


Figure 2

Seed cotton yield (A), irrigation water use efficiency (IWUE, B), harvest index (C), and yield–IWUE relationship (D) across the 12 irrigation × density treatments (two-year means). In (D), the dashed lines represent lines of constant IWUE across irrigation levels. The W2D2 is highlighted with a star (★).

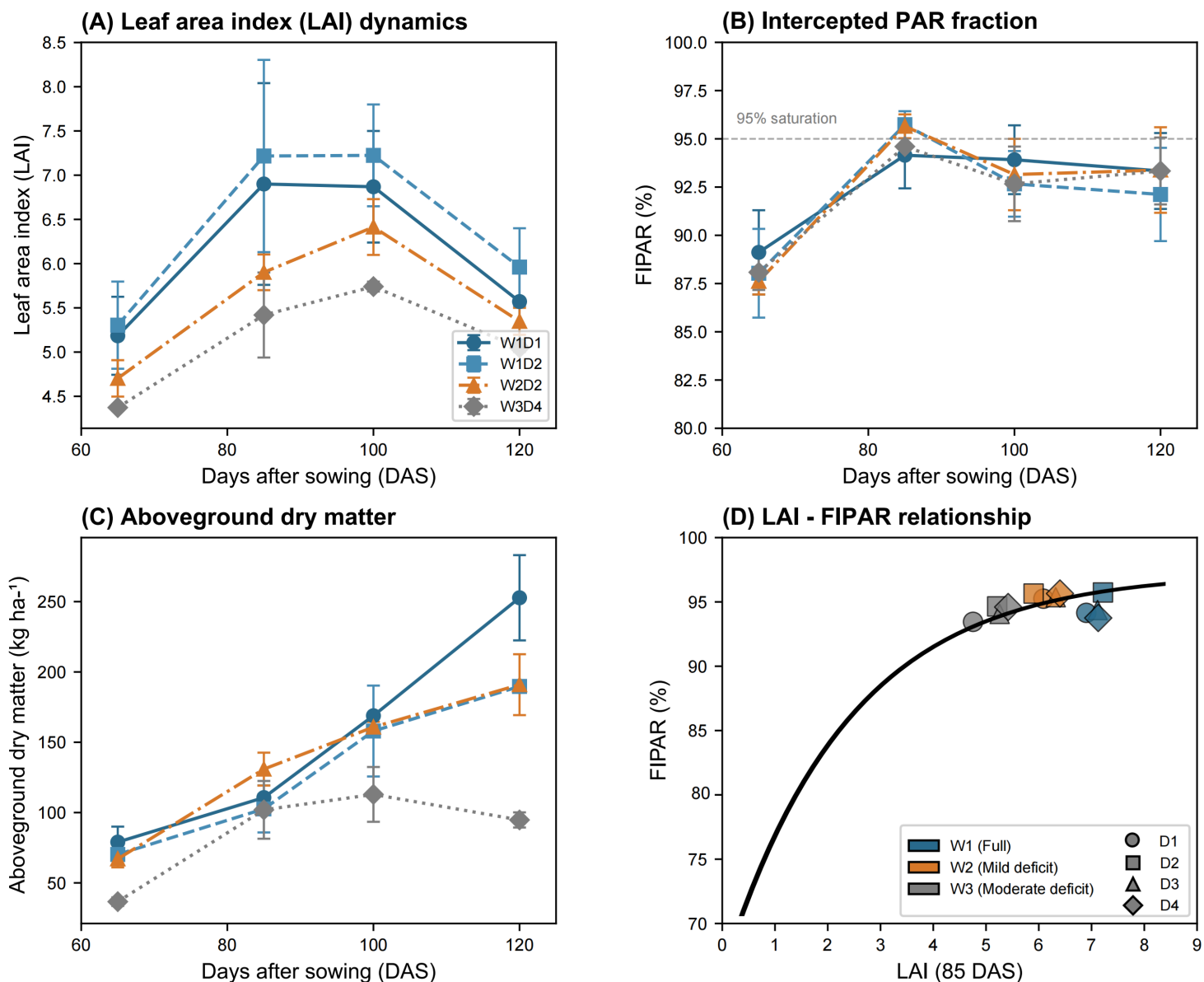


Figure 3

Temporal dynamics of canopy growth, light interception, and dry matter accumulation during 2023–2024. (A) Leaf area index (LAI) dynamics; (B) Fraction of intercepted photosynthetically active radiation (FIPAR) dynamics; (C) Aboveground dry matter accumulation; (D) Relationship between LAI and FIPAR at 85 DAS fitted by the Beer–Lambert equation ($FIPAR = 100 \times [1 - \exp(-k \times LAI)]$, $k = 0.509$, $R^2 = 0.62$). Data are shown at 65, 85, 100, and 120 days after sowing (DAS). Error bars represent standard errors ($n = 6$). Different line styles and markers distinguish treatments as indicated in the legend. The dashed horizontal line in (B) indicates the 95% FIPAR saturation level.

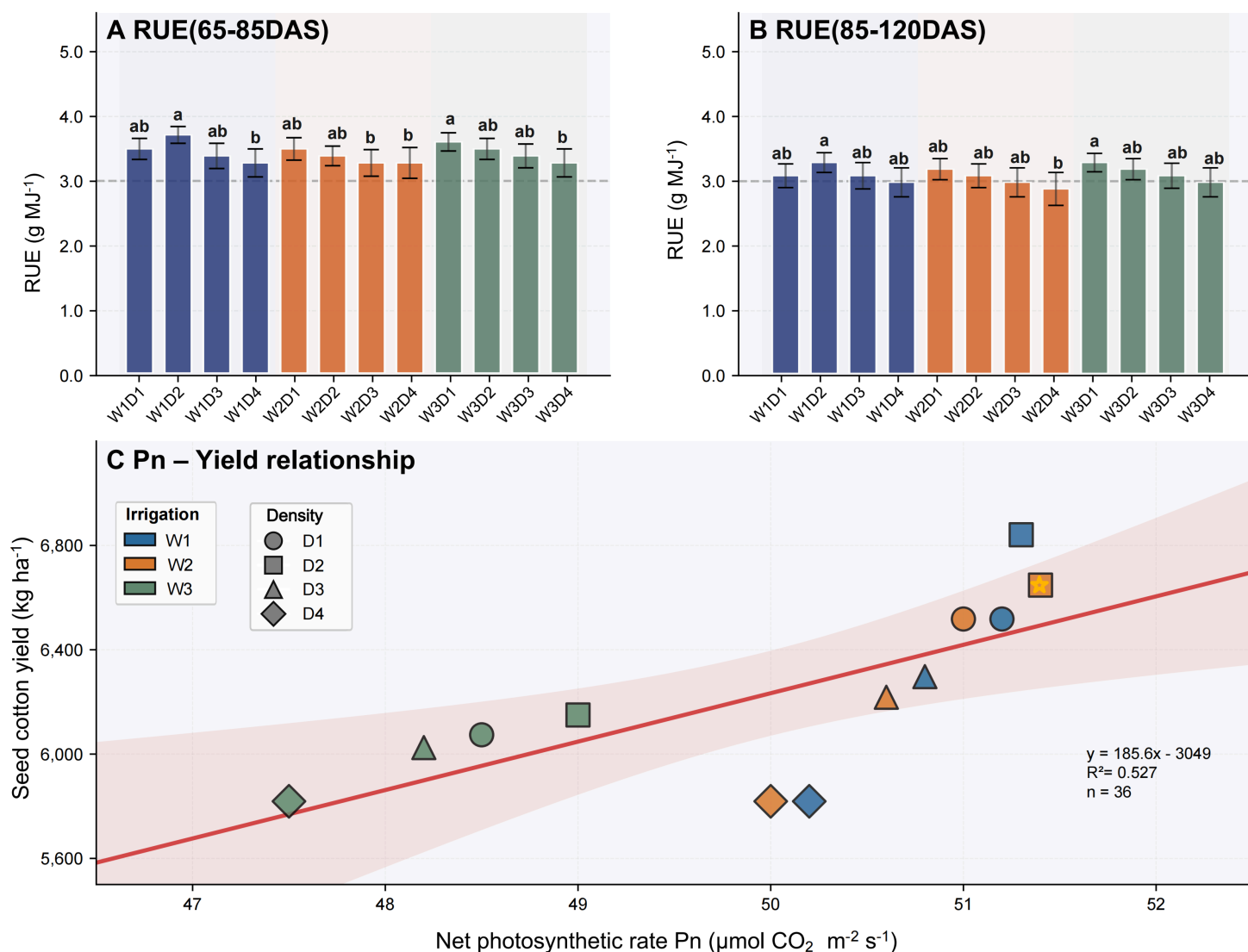


Figure 4

Radiation use efficiency (RUE) and its relationship with photosynthetic capacity. (A) RUE (65–85DAS) with Tukey HSD significance letters; (B) RUE (85–120 DAS) with significance letters; (C) Linear regression between net photosynthetic rate (Pn at 85 DAS) and seed cotton yield. Different lowercase letters indicate significant differences (Tukey's HSD, $P < 0.05$). Error bars represent standard errors ($n = 6$).

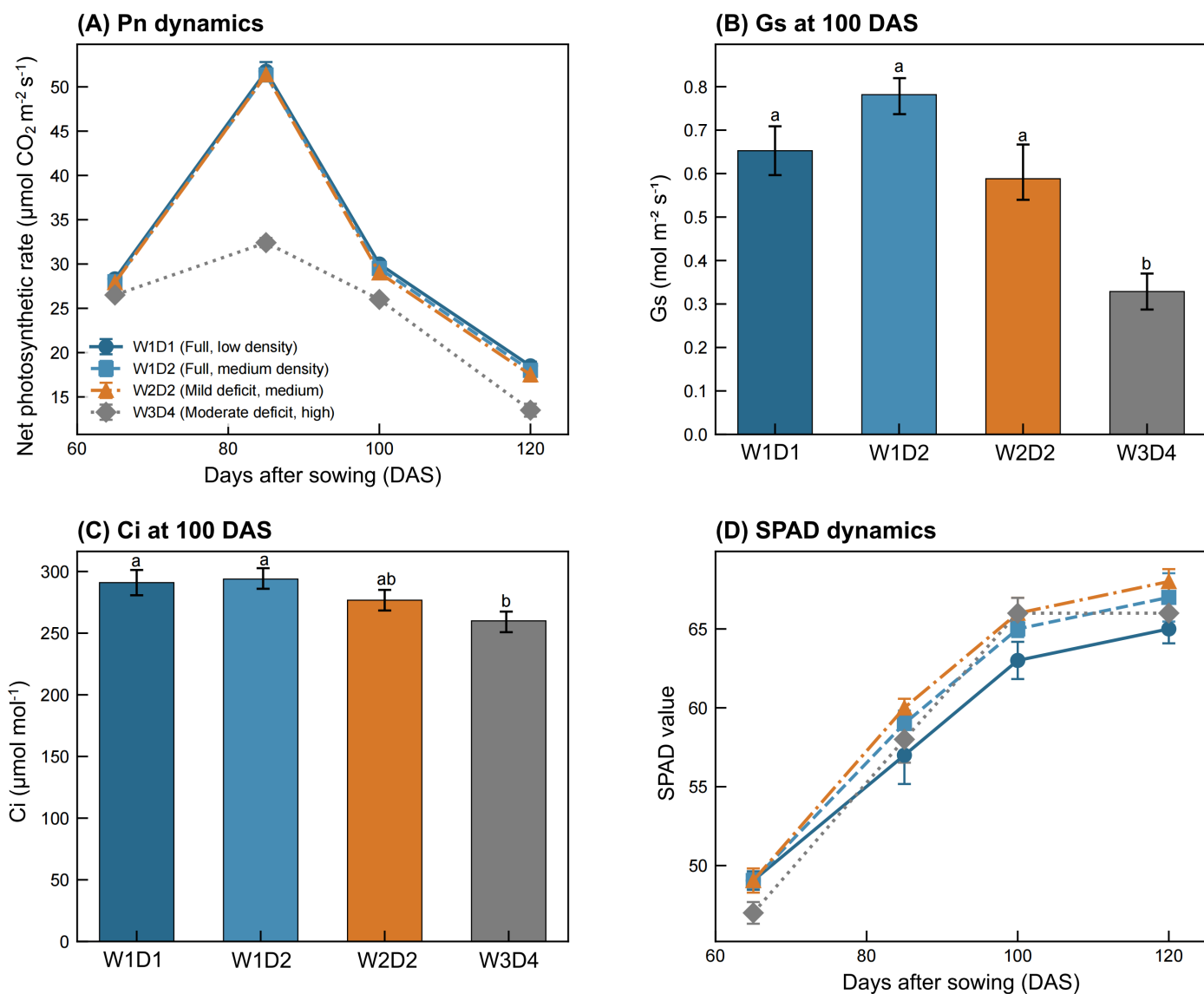


Figure 5

Photosynthetic gas exchange and leaf chlorophyll content during the cotton growing season. (A) Net photosynthetic rate (Pn) dynamics; (B) Stomatal conductance (Gs) at 100 DAS; (C) Intercellular CO_2 concentration (Ci) at 100 DAS; (D) Leaf chlorophyll content (SPAD) dynamics. Different lowercase letters indicate significant differences (Tukey's HSD, $P < 0.05$). Error bars represent standard errors ($n = 3$ for gas exchange; $n = 6$ for SPAD).

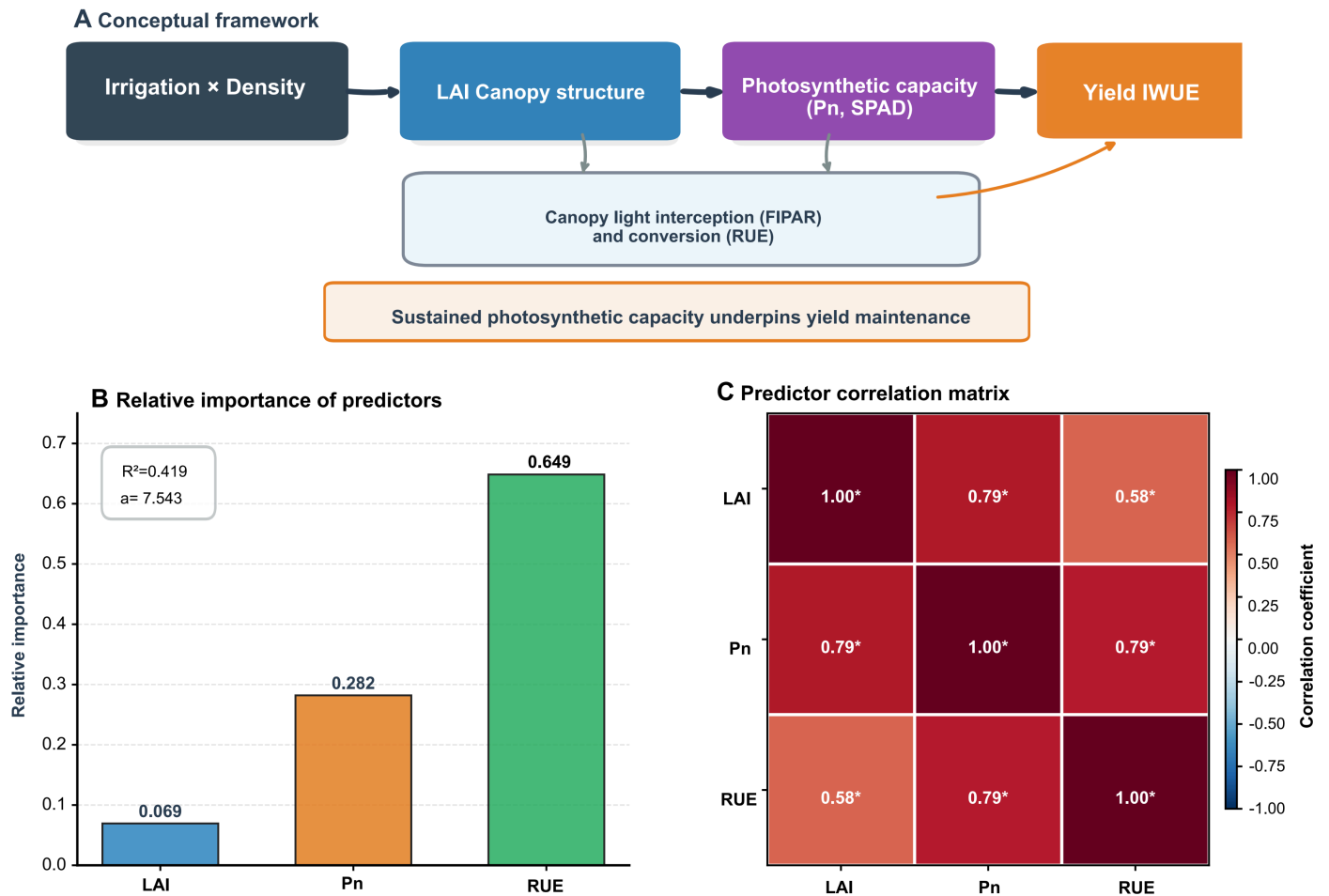


Figure 6

Conceptual framework and predictor importance analysis for yield determination under water–density interaction. (A) Conceptual framework of yield regulation through irrigation–density interaction; (B) relative importance of LAI, Pn, and RUE in predicting yield (ridge regression, $R^2 = 0.419$), which cross-validates the OLS path model in Table 3 ($R^2 = 0.326$) under predictor multicollinearity; both yield the same predictor ranking ($Pn > LAI > RUE$); (C) correlation matrix among predictors.

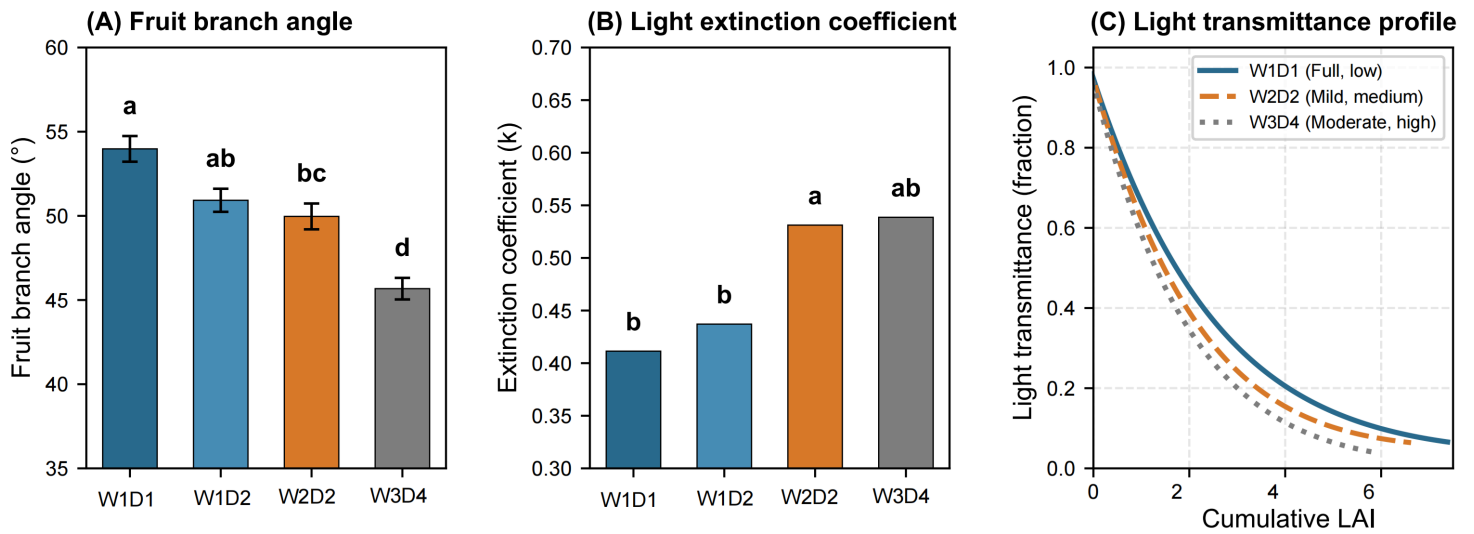


Figure 7

Canopy architectural traits and light penetration under different water–density combinations. (A) Fruit branch angle (FBA)—lower values indicate more compact canopy; (B) Canopy light extinction coefficient (k) derived from Beer–Lambert law; (C) Schematic vertical profile of light transmittance at 85 DAS for three representative treatments. Different lowercase letters in (A) and (B) indicate significant differences (Tukey's HSD, $P < 0.05$). Error bars represent standard errors ($n = 12$ for FBA; $n = 3$ for k).