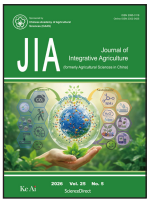
Journal of Integrative Agriculture 2026, 25(5): 1871–1886

Available online at ScienceDirect

Journal of Integrative Agriculture



RESEARCH ARTICLE

Productivity and economic benefits of winter wheat in Northwest China by optimizing irrigation and planting density

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Highlights

- Optimized irrigation at jointing enhanced grain yield and net economic benefits.
- Lower planting density enhanced dry matter accumulation (DMA), SPAD, and leaf area index (LAI), significantly improving yield.
- Reduction in irrigation at key growth stages enhanced water-use efficiency (WUE) by mitigating evapotranspiration.
- Integrated optimization of irrigation and planting density offers improved productivity and farm income in semi-arid Northwest China.

Abstract

Winter wheat is a key staple crop in Northwest China, yet optimizing its productivity and economic returns remains a challenge due to water constraints and suboptimal planting densities. This study evaluates the combined effects of irrigation strategies and planting density (PD) on winter wheat yield, resource-use efficiency, and net economic benefits (NEB). A two-year field experiment was conducted under four irrigation treatments (I1, no irrigation; I2, before winter and jointing; I3, jointing; I4, jointing and anthesis) and three PD treatments (PD1, 562.5×10^4 plants ha^{-1}; PD2, 375 ×10^4 plants ha^{-1}; PD3, 187.5×10^4 plants ha^{-1}). Through field trials, we identified optimal water-saving irrigation regimes and planting densities that maximize grain yield while enhancing water productivity. Our results demonstrated that lower PD (187.5×10^4 plants ha^{-1}) under reduced irrigation significantly improved dry matter accumulation (DMA), SPAD, and leaf area index (LAI), leading to higher grain yield. Moderate irrigation at the jointing stage (I3) enhanced grain yield in higher planting densities by up to 18.42% compared to other irrigation regimes, while the highest overall yield (6,310 kg ha^{-1}) was achieved in medium PD under the I3 irrigation. Water-use efficiency (WUE) was significantly improved by reducing irrigation at specific growth stages, mitigating excessive evapotranspiration. PD3–I3 achieved the highest NEB, exceeding I1, I2, and I4 by 11.9, 18.4, and 16.4%, respectively, in 2022–2023 and by 15.1, 14.0, and 8.4%, respectively, in 2023–2024. The findings provide practical insights for sustainable wheat production, ensuring higher profitability while conserving water resources. Implementing optimized irrigation and PD strategies offers a strategic pathway to improving food security and farm income in the semi-arid regions of Northwest China.

Keywords: grain yield, irrigation, net economic benefits, planting density, water use efficiency, winter wheat

1. Introduction

The escalating severity of droughts, driven by climate change, poses a significant threat to global food security (Hameed *et al.* 2020; Dai *et al.* 2023). Arid and semi-arid regions suffer from limited and uneven precipitation, leading to reduced crop productivity and inefficient water and nitrogen use (Yang *et al.* 2022; Dai *et al.* 2023). Although the sub-humid, drought-prone regions of Northwest China receive more annual precipitation than arid and semi-arid zones, their continental monsoon climate results in a highly seasonal rainfall pattern, with over 70% of precipitation occurring between June and

Received 31 March 2025; Received in revised form 11 June 2025; Accepted 20 June 2025; Available online 5 July 2025
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doi: 10.1016/j.jia.2025.07.005

September, creating challenges for sustainable winter wheat production (Bai *et al.* 2023). Winter wheat is one of the primary staple crops in this region (Geng *et al.* 2023; Wu *et al.* 2024); however, water scarcity and inefficient water use remain major constraints to its productivity (Li H R *et al.* 2023; Zhang T *et al.* 2023). Ensuring stable and high grain yields requires developing water-efficient agronomic strategies that optimize both crop productivity and irrigation efficiency. While supplemental irrigation is commonly used, inadequate scheduling and excessive water application often reduce water-use efficiency (WUE) and increase production costs. In current wheat production, precise optimization of planting density (PD) serves as a key cultivation strategy to enhance yield, alongside fertilizer and irrigation inputs (Gao *et al.* 2021). Planting density critically influences wheat growth, plant size, biomass allocation, and fertile tiller production (Yang *et al.* 2019). Thus, optimizing both PD and irrigation timing is essential for enhancing winter wheat yield and crop performance while ensuring sustainable water use.

Planting density is a key agronomic factor influencing crop biomass, yield potential, and resource utilization efficiency (Khan *et al.* 2017; Zhang Z *et al.* 2023). Optimized PD enhances light interception, canopy productivity, and dry matter accumulation (DMA), contributing to improved harvest index and grain yield (Gao *et al.* 2021; Liu *et al.* 2021; Dai *et al.* 2022). However, improper PD can negatively affect yield: low PD limits total biomass production, while excessive PD increases inter-plant competition, reducing individual plant productivity and increasing lodging risks (Bastos *et al.* 2020; Mylonas *et al.* 2020). At higher PD, increased vegetative competition for resources (light, water, and nutrients) can suppress grain yield (Friedman 2024). In contrast, lower PD prioritizes reproductive organ development but may not fully utilize available resources (Hecht *et al.* 2016; Wang *et al.* 2021). Therefore, optimizing PD is crucial for improving both yield formation and resource use efficiency, particularly in water-scarce environments.

Water availability is a primary limiting factor for winter wheat production in Northwest China. The region receives an average precipitation of 200 mm, far below the water requirement of approximately 450 mm (Nie *et al.* 2019). This deficit is most critical during jointing and anthesis stages, when rapid plant growth demands higher water availability (Cao *et al.* 2022; Wu *et al.* 2023). Strategic irrigation at these growth stages has been shown to improve yield and WUE by increasing tiller survival, photosynthesis rate, and spike number (Shang *et al.* 2020; Wang *et al.* 2023). However, excessive irrigation at anthesis may not always improve yield, especially when pre-sowing soil moisture and rainfall contribute significantly to water supply (Xu *et al.* 2018; Li H R *et al.* 2023). Studies indicate that winter wheat yield gains from anthesis irrigation become negligible when precipitation between jointing and anthesis exceeds 31.9 mm (Li H T *et al.* 2023). This highlights the potential for reducing irrigation at anthesis as a water-saving strategy without sacrificing productivity. Despite these findings, inefficient irrigation practices remain widespread in Northwest China, leading to water waste, lower WUE, and decreased economic returns (Zeng *et al.* 2023). Therefore, an irrigation strategy that balances water conservation with yield stability is urgently needed.

The interaction between irrigation and PD critically shapes winter wheat productivity by mediating source–sink relationships (Liu *et al.* 2024). Under water-limited conditions, high PD exacerbates competition, reducing photosynthetic capacity (source limitation) and grain filling (sink limitation) (Smith *et al.* 2018), whereas excessive irrigation with low PD promotes vegetative overgrowth at the expense of grain allocation (Si *et al.* 2023). Optimizing PD alongside growth-stage-specific irrigation enhances canopy efficiency, biomass remobilization, and sink–source balance, ultimately maximizing yield and economic returns through efficient resource use. While irrigation and PD are well-studied independently, their interactive effects on wheat yield, lodging risk, and economic returns remain poorly quantified. To address this gap, we hypothesized that adjusting PD and optimizing irrigation at key growth stages could enhance grain yield, WUE, and economic returns in winter wheat production. Specifically, the objectives of this study were to (1) evaluate the interactive effects of irrigation timing and PD on soil water content (SWC) and agronomic traits (plant height, LAI, and SPAD index), (2) assess how irrigation and PD influence dry matter accumulation dynamics, grain yield, and yield components, and (3) analyze the impact of different irrigation and PD treatments on water use efficiency and net economic benefits. By systematically investigating these factors, this study aimed to develop practical agronomic recommendations for winter wheat growers in drought-prone regions. The findings will provide a scientific basis for sustainable irrigation management and PD optimization, thereby improving food security while conserving water resources.

2. Materials and methods

2.1. Site description

The field experiments were conducted from 2022–2024 at Liangke Smart Agriculture Demonstration Base, an experimental research station of Northwest A&F University (NWAFU) located in an arid region of Northwest China (34°24′N, 107°59′E; 521 m a.s.l.). The experimental site is a typical dryland agriculture region in Yangling County, Shaanxi Province, China. The conventional cropping pattern includes a winter wheat–summer maize cropping system. The experimental area experiences a typical monsoon climate with an average annual air temperature of 13°C, precipitation of 590 mm, and pan evaporation of 1,500 mm. Daily maximum and minimum temperatures and precipitation during the cropping seasons are presented in Fig. 1. The soil nutrient content in the 0–20 cm layer before sowing is listed in Appendix A.

2.2. Experimental design

The experiment was arranged in a split-plot design, with PD as the main plot factor and irrigation treatment as the sub-plot factor. The winter wheat variety “Weilong 169” was used in the experiment. The PD treatments included PD1 (high PD; 562.5×10^4 plants ha^{-1}), PD2 (medium PD; 375×10^4 plants ha^{-1}), and PD3 (low PD; 187.5×10^4 plants

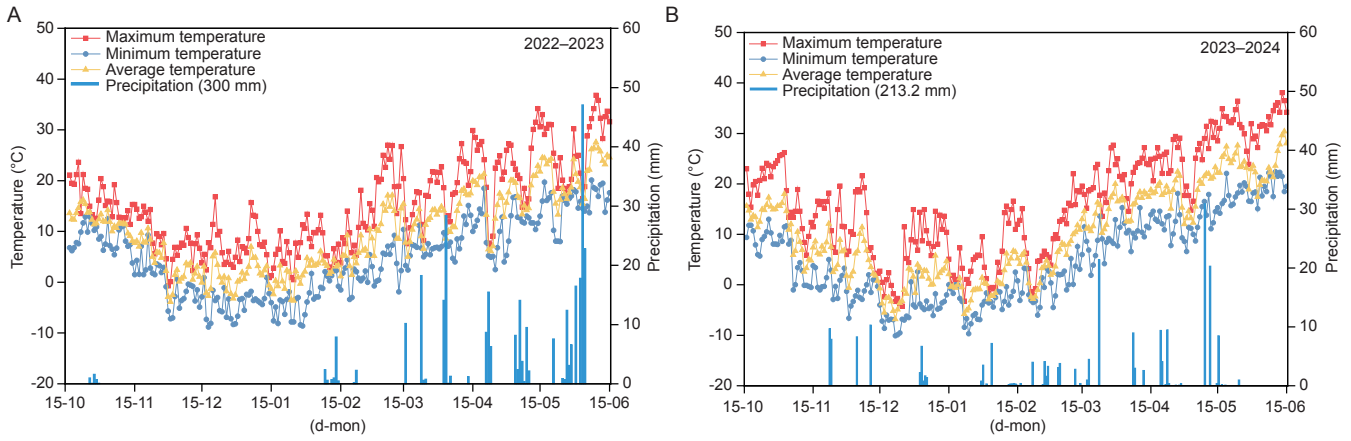


Fig. 1 Temperature and precipitation during the 2022–2023 (A) and 2023–2024 (B) winter wheat growing seasons.

ha^{-1}). The corresponding seed rates were 360, 240, and 120 kg ha^{-1}, respectively. The irrigation treatments included: I0 (no irrigation), I1 (before winter+jointing), I2 (jointing), and I3 (jointing+anthesis). These were 12 treatments with three replicates, and each subplot measured 21 m^2 (3 m wide×7 m long).

Irrigation at each stage was applied after soil sampling, based on available soil moisture content. The irrigation amount was determined using a previously established method (Wang 2017) and applied using a micro-spray belt (ZL2014104993757). The irrigation amount was calculated using the equation:

Irrigation amount=$0.1\times D_h\times\rho i\times(\theta_t-\theta_n)$

where D_h is the planned irrigation layer depth (cm), ρi is the soil bulk density (g cm^{-3}), θ_t is the targeted soil water content (SWC) (mg g^{-1}), and θ_n is the SWC before irrigation.

The ternary compound fertilizer (N:P_2O_5:K_2O=15:15:15) was applied as a basal application at 750 kg ha^{-1}, while at the jointing stage, urea (N, 46%) was applied as a topdressing at 240 kg ha^{-1}. Weeds, insects, and diseases were controlled as required, and all other production management practices were based on those used by local farmers.

2.3. Data collection and measurements

Agronomic traits Plant height was measured on 10 representative stems per plot at maturity. Chlorophyll content was assessed from flag leaves from jointing to maturity using a Minolta SPAD-502 chlorophyll meter. The measurement was carried out in the middle of the leaf, and the direct light was avoided. In each treatment, the average was taken from 30 flag leaves out of three plots. The LAI was measured using an LAI-2200 canopy analyzer (LI-COR, USA), ensuring avoidance of direct light. All the measurements were taken between 9:00 and 11:30 a.m. on sunny days above and below the canopy, and the average of 10 values was used in this experiment.

Soil water content (SWC) SWC was measured at key growth stages (sowing, before winter, returning green, jointing, anthesis, dough, and maturity) using the standard gravimetric method. Samples were taken every 10 cm depth in the 0–40 cm layer, while every 20 cm in the 40–200 cm layer with a hand-held soil auger. Three replicates were conducted per plot. After measuring wet weight (W1), the soil samples were dried at 105°C for 48 h until a constant weight (W2) was reached. Soil water content was calculated using the following equation (Gardner 1986):

$$\text{SWC}\ (\%)=\frac{(W1-W2)}{W2}\times 100 \quad (1)$$

Soil water storage (SWS) was calculated using the following equation:

$$\text{SWS}=\sum_{i}^{n}(hi\times\rho i\times SWC_i\times 10) \quad (2)$$

where hi is the soil thickness (cm), ρi (g cm^{-3}) is the soil bulk density of each sample layer; SWC_i is the soil water content of each sample layer; n is the number of sample layers, and i=10, 20, 30, 40,…, 200.

Dry matter accumulation and partitioning Plant samples (n=20) were collected randomly from each plot at key growth stages. At anthesis, plant samples were separated into leaves, stem and sheath, and spikes; at maturity, they were separated into leaves, stem and sheath, stalk and glume, and grains. The samples were then oven-dried at 75°C for 48 h after being heated at 105°C for 30 min, and weighed. DMA was analyzed using a logistic growth model (Ma *et al.* 2024):

$$D=\frac{Y_{\max}}{(1+ae^{-kt})} \quad (3)$$

where D is the aboveground dry matter accumulation (kg ha^{-1}), $Y_{\max}$ is the maximum dry matter (DM) (kg ha^{-1}), k is the growth rate, and t is the number of days after sowing (d).

Evapotranspiration and water use efficiency The evapotranspiration (ET) was calculated using the water balance equation:

$$ET=P+I+C+(SWS_{t1}-SWS_{t2})-D-R \quad (4)$$

where P is the precipitation in the winter wheat growing season, I is the irrigation amount, and C is the upward flow into the root zone; SWS is the soil water storage in the 0–200 cm soil layer; D represents the drainage below the measured root zone; R represents runoff.

Water use efficiency (WUE) and irrigation water use efficiency (IWUE) were calculated using the following equation (Huang *et al.* 2005):

$$WUE=\frac{\text{Grain yield}}{\text{Evapotranspiration}} \quad (5)$$

$$IWUE=\frac{\text{Grain yield}}{\text{Irrigation}} \quad (6)$$

where grain yield is in kg ha^{-1}, and evapotranspiration is in mm for the entire growing season.

Grain yield and components Grain yield was determined by harvesting two 1-m rows from each plot at physiological maturity. There were three independent replicates for each treatment. Grain yield was standardized to 14% moisture. The number of spikes, 1,000-grain weight, and grain number per spike were recorded.

Economic analysis The total cost of agricultural inputs, including seed, fertilizer, labor, pesticide, and machinery from sowing to maturity, was recorded. The prices of production inputs and grain were estimated based on local market prices. The cost of agricultural production, total output, and net economic benefits were calculated as follows:

Net economic benefits (CNY ha^{-1})=Grain income–Total cost

Total cost=Agricultural cost+Water cost+Labor expenses+Others

where agricultural costs included seeds, fertilizer costs, and other expenditures.

2.4. Statistical analysis

Data were processed using Excel 2016 (Microsoft Corp., NM, US), and statistical analyses were performed using Statistix 8.1 (Analytical Software, Tallahassee, FL, USA). A two-way ANOVA was used to evaluate treatment effects, with multiple comparisons made using the least significant difference (LSD) test at $P<0.05$. Error bars in the figures represent standard errors of the means from the three experimental replicates. Figures, including correlation analysis, were generated using Origin 2024b (OriginLab Corporation, Northampton, USA).

3. Results

3.1. SPAD value

PD and irrigation significantly influenced the SPAD value during both winter wheat growing seasons ($P<0.01$). The most significant interaction effect of PD and irrigation occurred at all growth stages except maturity (Table 1). The three-factor interaction among year (Y), PD, and irrigation (I) was highly significant at heading ($P<0.001$), significant at jointing and anthesis ($P<0.01$), and not significant at milking and maturity ($P>0.05$). SPAD values followed an increasing trend, peaking at anthesis, and then gradually declined through milking and maturity in both years (Fig. 2). SPAD increased with higher irrigation levels, with I4 significantly ($P<0.05$) increasing SPAD by 6.38, 3.42, and 1.22% in 2023 and by 5.71, 9.52, and 9.52% in I4, I3, and I2, respectively, under higher PD. PD significantly ($P<0.05$) affected SPAD at different stages, with SPAD increasing with higher PD at various growth stages. Medium PD exhibited significantly ($P<0.05$) higher SPAD than higher and lower PD at different growth stages under I2 and I4.

3.2. Leaf area index (LAI)

Irrigation and PD consistently influenced LAI across both growing seasons (Fig. 3). The interaction between irrigation and PD significantly impacted LAI ($P<0.001$) at all critical growth stages (Table 1), though the interaction among irrigation, PD, and year was not significant ($P>0.05$). LAI increased until anthesis and declined afterward until maturity. At anthesis, I3 had 15.33, 19.55, and 9.4% higher LAI than control (I1) for PD1, PD2, and PD3, respectively, while at maturity, these differences were reduced to 7.28, 1.89, and 4.77%. Among PDs, PD1 had the highest LAI (Fig. 3).

3.3. Soil water content (SWC)

Irrigation, PD, and rainfall significantly influenced SWC at various growth stages (Fig. 4-A and B). Before the jointing stage, SWC showed minor fluctuations but decreased significantly afterward, particularly as crop growth advanced, leading to increased water utilization from deeper soil layers (100–200 cm). Our results showed that higher PD led to faster depletion of SWC in the upper soil layers, especially under I1 (control). In contrast, lower PD exhibited better

Table 1 Analysis of variance for relative chlorophyll content and leaf area index (LAI) under various treatments of irrigation (I) and planting densities (PD) of winter wheat at various growth stages

Parameter	Source of variation	Jointing	Heading	Anthesis	Milking	Maturity
SPAD	I	3.20*	24.25***	3.92*	10.84***	1.38 ns
	PD	48.02***	9.04**	14.68***	73.86***	11.30**
	Year (Y)	0.26 ns	8.33**	18.25**	11.46**	95.56***
	I×PD	5.87***	9.03***	4.15**	4.15**	2.10 ns
	I×Y	2.68 ns	2.40 ns	0.28 ns	2.13 ns	3.90*
	PD×Y	0.46 ns	16.29***	2.39 ns	5.19**	4.71*
	I×PD×Y	4.60**	7.17***	3.38**	1.79 ns	1.06 ns
LAI	I	6.42***	25.49***	21.93***	16.99***	5.53**
	PD	7.72**	2.36 ns	7.09**	5.55**	32.14***
	Y	51.55***	6.95**	0.25 ns	0.04 ns	0.77 ns
	I×PD	3.00**	17.36***	3.75***	3.47**	2.70**
	I×Y	1.74 ns	3.52**	2.27*	1.39 ns	0.93 ns
	PD×Y	7.93***	1.30 ns	1.11 ns	0.11 ns	5.07**
	I×PD×Y	1.37 ns	4.95***	2.19*	1.29 ns	1.25 ns

***, **, and * indicate significances at 0.001, 0.01 and 0.05 probability levels, respectively; ns indicates no significance difference.

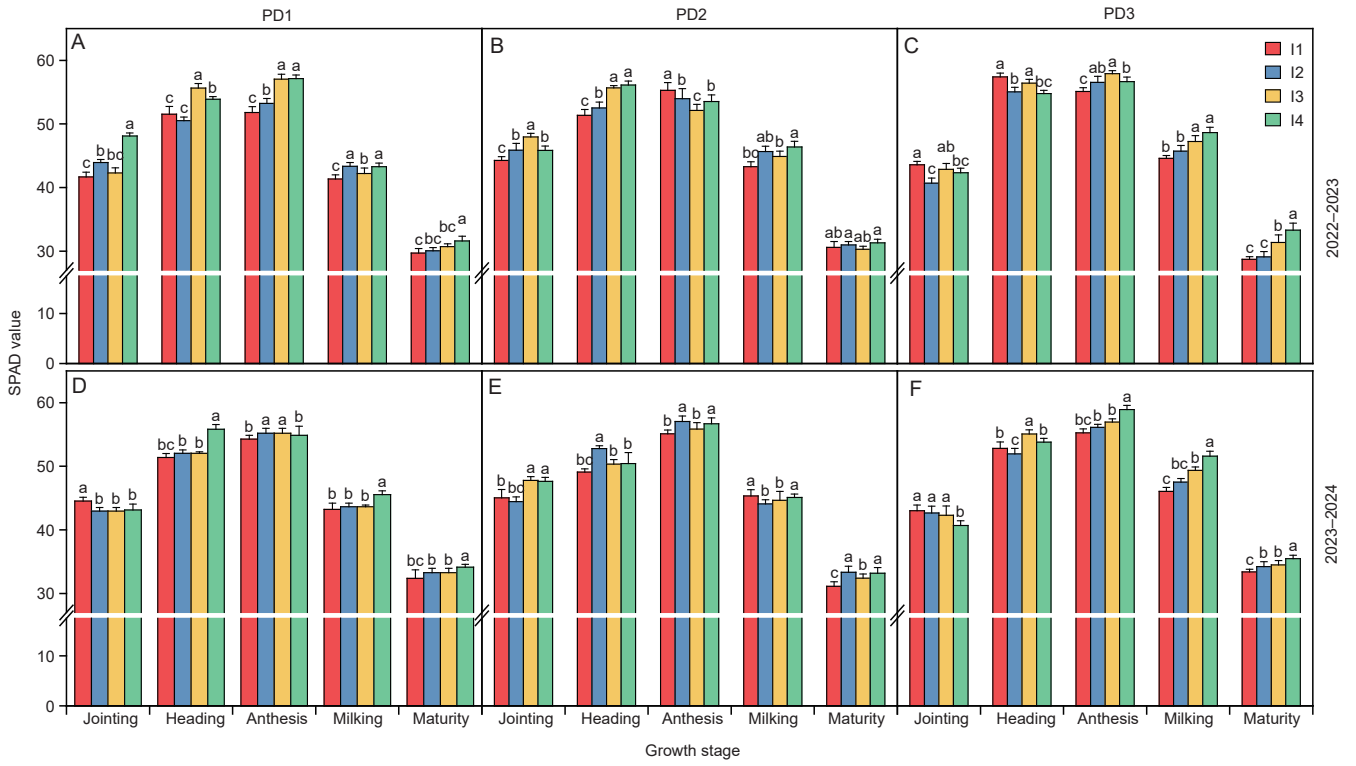


Fig. 2 Effect of different irrigation and planting densities on the chlorophyll contents (SPAD value) of winter wheat in 2023 and 2024. I1, no irrigation; I2, irrigation at before wintering and jointing stage; I3, irrigation at jointing; I4, irrigation at jointing and anthesis stage. PD1, PD2, and PD3, 562.5×10^4, 375×10^4, and 187.5×10^4 plants ha^{-1}, respectively. Bars are means±SD (n=30, from 3 independent plots). Different lowercase letters above bars indicate significant differences (P≤0.05) according to LSD.

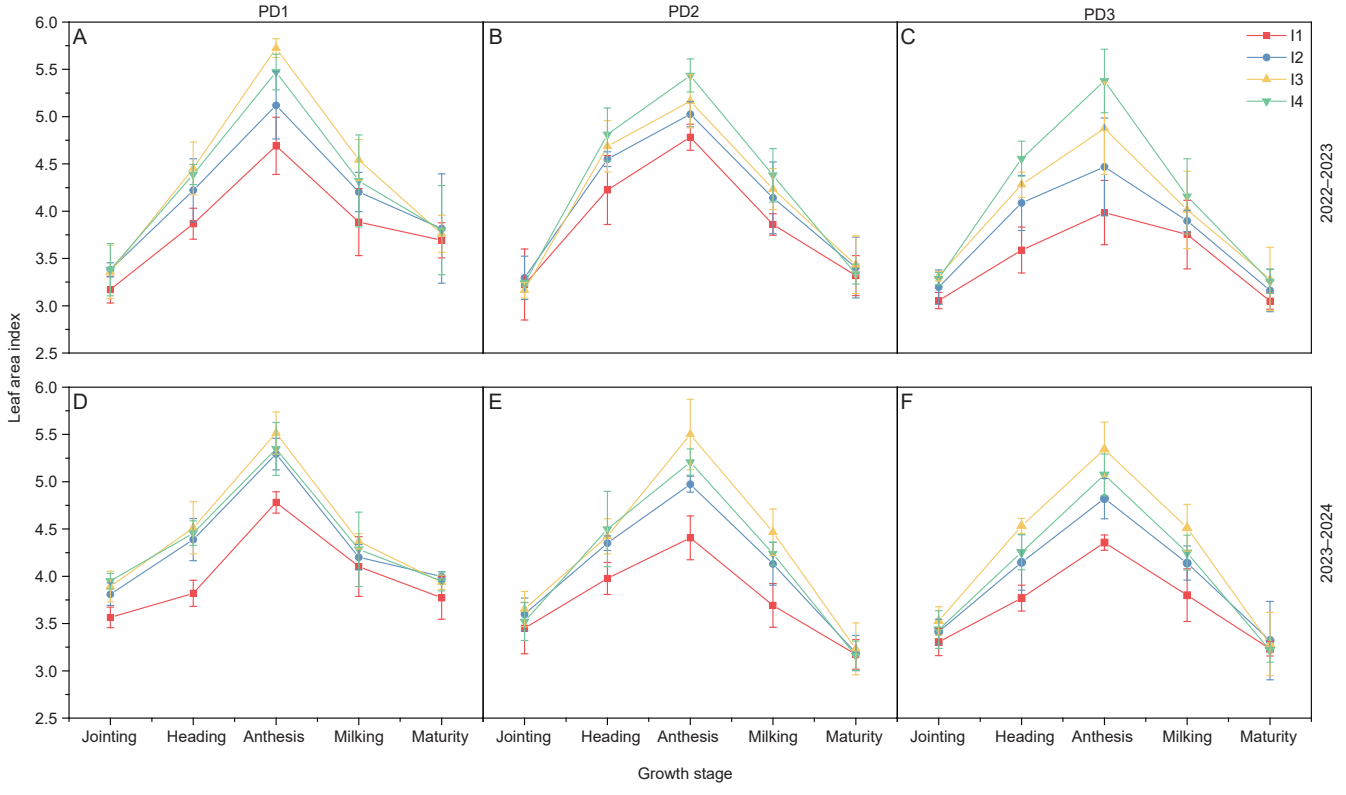


Fig. 3 Effect of different irrigation and planting densities on the leaf area index of winter wheat in 2023 and 2024. I1, no irrigation; I2, irrigation at before winter and jointing stage; I3, irrigation at jointing stage; I4, irrigation at jointing and anthesis stage. PD1, PD2, and PD3, 562.5×10^4, 375×10^4, and 187.5×10^4 plants ha^{-1}, respectively. Bars represent mean±SD (n=20, from 3 independent plots).

moisture distribution across all soil layers and growth stages, particularly with combined irrigation at jointing+anthesis (I4). Medium PD maintained relatively stable SWC in the 60–100 cm soil layers, especially during jointing and anthesis stages, while higher PD resulted in more distinct depletion at deeper layers.

In higher PD, SWC in the 0–100 cm layer decreased significantly (P<0.05) from the jointing to maturity stages. Compared to I1, the average SWC of the 100 cm soil layer at maturity decreased by 1.47, 3.67, and 2.60% in I4, I3, and I2, respectively, in 2023–2024; it increased by 8.12 and 7.73% in I4 and I3, respectively, while increased by 3.40% in I2 in 2022–2023. The increased SWC in 2023–2024 was likely due to improved precipitation distribution (Fig. 4-A and B), which resulted in better moisture retention at deeper soil layers. In contrast, 2022–2023 experienced rapid SWC depletion, especially at deeper depths under higher PD, highlighting the role of precipitation in water storage. During the winter wheat growing season, moderate drought stress was observed under I1 in both years, particularly during anthesis and dough stages. However, better rainfall distribution in 2023–2024 led to shorter drought periods compared to 2022–2023, especially under irrigation at jointing or jointing+anthesis stage.

3.4. DMA and dry matter partitioning

DMA The logistic function was used to model DMA of winter wheat for both growing seasons (Fig. 5). Aboveground DM of winter wheat was increased with the advancement of the growth period under irrigation and PD treatments (Fig. 5) and was divided into three accumulation periods; gradual increase (from seedling to jointing), rapid increase (from jointing to filling), and slow increase (from filling to maturity). The logistic fitting parameters of different treatments are shown in Table 2. The fitted model coefficients of determination ranged between 0.96 and 0.99, indicating that the logistic model showed excellent performance in simulating DMA. With increasing PD or irrigation level, the maximum DMA and accumulation rate were the highest in the PD1–I3 treatment, with average values of 23,700 kg ha^{-1} and 251.25 kg ha^{-1} d^{-1} over 2 years, which were 19.14 and 9.87% higher than those of the control (PD1–I1). The rapid accumulation start time of this treatment was 3 to 4 days earlier than in the I1 and I3 treatments at the same density, indicating that a reasonable irrigation and PD combination can promote the accumulation of aboveground DM in winter wheat. Higher PD is conducive to extending the rapid accumulation period of DM, as the average rapid accumulation period of medium and higher PD treatments increased by 9 to 13 days and 6 to 14 days, respectively, compared with lower PD.

Across both growing seasons, PD significantly influenced DMA (P<0.05) at all growth stages, with higher PD generally yielding more biomass (Table 3). Irrigation also significantly (P<0.05) affected DMA at jointing and anthesis, underscoring the critical role of water availability during these growth periods for optimal DM production. The DM at different growth stages gradually decreased with increasing irrigation and was notably higher under I3 compared to I4, I2, and I1. For irrigation, DM increased by 9.09, 4.16, and 5.10% in I3, I4, and I2 compared to I1 (in 2023). Contrary to 2023, DMA decreased by 3.02 and 11.48% in I3 and I4 while increased by 14.70% in I2 as compared to I1 (in 2024) at the maturity stage under higher PD (Fig. 6). While the maximum increase in DM was observed in PD2-I3 by 25.72% as compared to I1 (2023) while same for PD2-I3 have increased 15% DM as compared to I1 (2024). As the PD decreased, the DM gradually increased in the different growth stages under the same irrigation treatment. Compared to higher PD, the DM of medium and lower PD increased at maturity in I1 by 5.77 and 18.2% (2023), 0.64 and 6.68% (2024), respectively.

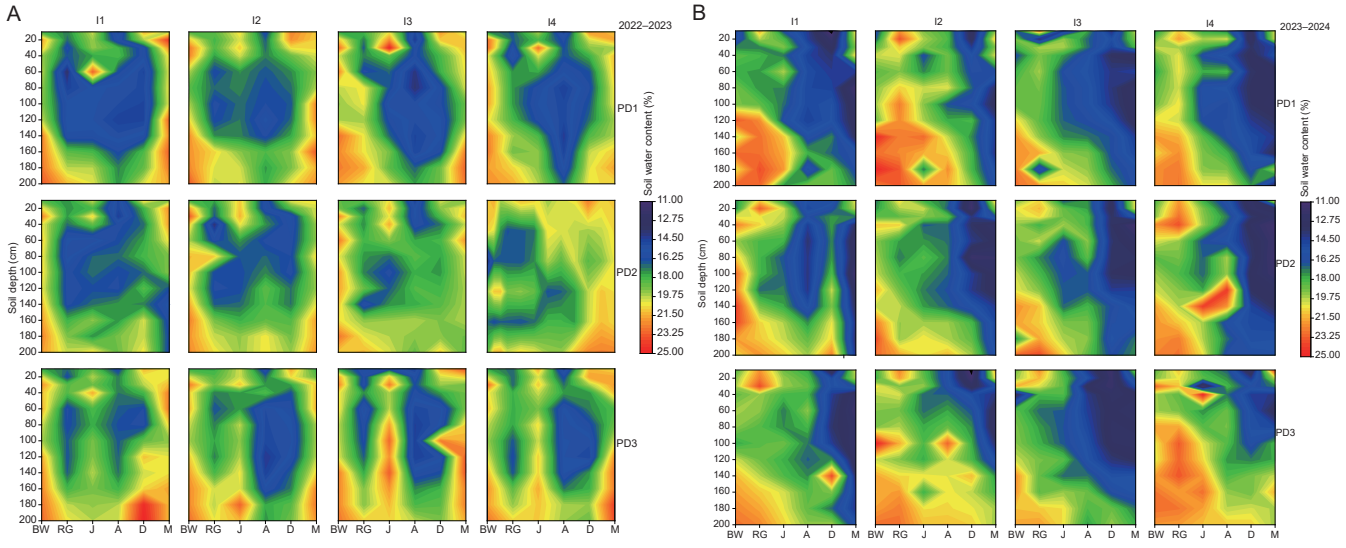


Fig. 4 Dynamics of the soil water content in the 0–200 cm soil layer in 2023 and 2024. BW is before wintering stage, 59 days after sowing (DAS); RG is the returning green stage, 139 DAS; J is the jointing stage, 163 DAS; A is the anthesis stage, 188 DAS; D is the dough stage, 215 DAS; M is the maturity stage, 229 DAS. I1, no irrigation; I2, irrigation at before winter and jointing stage; I3, irrigation at jointing stage; I4, irrigation at jointing and anthesis stage. PD1, PD2, and PD3, 562.5×10^4, 375×10^4, and 187.5×10^4 plants ha^{-1}, respectively.

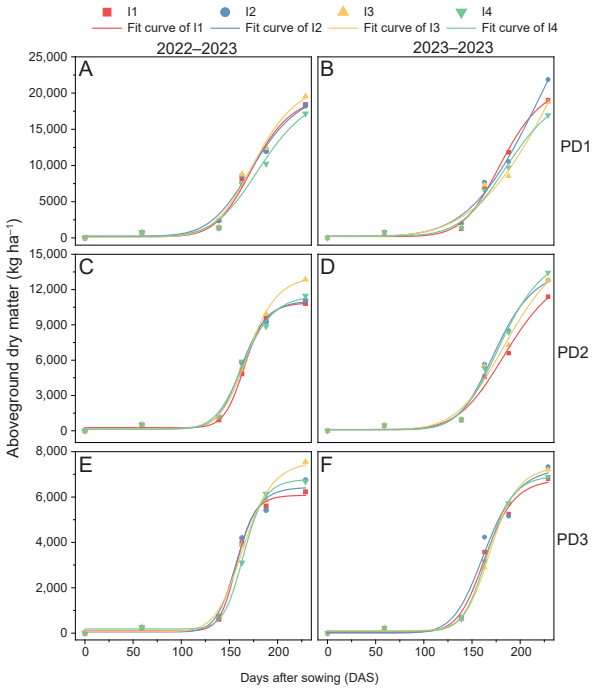


Fig. 5 Observed values (points) and the corresponding aboveground dry matter masses fitted by eq. (3) (curves) for winter wheat under different planting densities and irrigation conditions. I1, no irrigation; I2, irrigation at before winter and jointing stage; I3, irrigation at jointing stage; I4, irrigation at jointing and anthesis stage. PD1, PD2, and PD3, 562.5×10⁴, 375×10⁴, and 187.5×10⁴ plants ha⁻¹, respectively.

The medium PD has increased the DM by 17.75, 21.91, and 14.45% for I2, I3, and I4, respectively, compared to higher PD.

Dry matter partitioning The results showed significant differences in DMA at anthesis and maturity stages under varying PD and irrigation levels across two growing seasons (Fig. 7). At anthesis, stems and sheaths accounted for the largest proportion of DMA, ranging from 46–58%, depending on PD. Higher PD showed a relatively balanced distribution, with 46–49% of DMA in stems and sheaths, 29–32% in spikes, and 19–25% in leaves. Medium PD exhibited a slight increase in stem and sheath allocation, ranging 50–54%, and a stable spike proportion of 26–27%, while lower PD revealed the highest allocation to stems and sheaths (51–58%), with reduced contributions from spikes (23–30%) and leaves (17–21%). Moreover, the influence of irrigation on DMA was evident as reduced irrigation (I3) resulted in a slight reduction in DMA to stems and sheaths, particularly at lower PD, while spikes exhibited compensatory growth under reduced irrigation levels. Across two growing seasons, spikes generally accumulated more dry matter in 2023–2024 compared to 2022–2023, indicating improved reproductive growth in the second year, especially under medium and lower PD.

At the maturity stage, DM shifted predominantly towards grains, which became the primary sink. Grains accounted for 44–55% of DMA, depending on PD, irrigation, and year. Higher PD showed 44–47% of DMA allocated to grains in 2022–2023, which was further increased to 51–53% in

Table 2 Parameters of logistic model of dry matter (DM) of winter wheat under different treatments[1)]

Year	PD[2)]	Irrigation[3)]	Y_{max} (kg C^{-1} d^{-1})	R^2	$T1$ (d)	$T2$ (d)	$T3$ (d)	ΔT (d)	V_{max} (kg C^{-1} d^{-1})
2022–2023	PD1	I1	20,563	0.98544	147	175	201	54	205.63
		I2	25,403	0.97884	149	176	204	55	271.18
		I3	26,600	0.95394	164	178	203	39	250.34
		I4	19,676	0.97496	155	169	195	40	204.97
	PD2	I1	13,092	0.97305	162	173	206	44	137.17
		I2	13,365	0.97497	164	171	202	38	176.05
		I3	14,923	0.96103	170	188	205	35	149.11
		I4	14,526	0.98102	154	178	199	45	177.61
	PD3	I1	6,699	0.98115	161	189	203	42	115.59
		I2	7,202	0.94786	151	178	198	47	107.52
		I3	7,279	0.99722	155	181	199	44	130.82
		I4	6,891	0.99635	158	185	202	44	133.73
2023–2024	PD1	I1	19,228	0.97459	160	183	201	41	251.69
		I2	19,810	0.97794	160	180	204	44	215.48
		I3	20,800	0.96742	165	178	198	33	252.25
		I4	19,268	0.96543	167	187	208	41	206.40
	PD2	I1	10,844	0.99629	170	193	209	39	240.84
		I2	10,968	0.99160	163	190	201	38	213.35
		I3	12,995	0.99404	167	185	200	33	221.46
		I4	11,384	0.98343	165	190	204	39	190.62
	PD3	I1	6,039	0.99317	170	195	206	36	167.79
		I2	6,326	0.97338	164	187	208	44	151.12
		I3	7,477	0.98482	169	185	205	36	127.48
		I4	6,773	0.99623	165	184	206	41	150.69

[1)] Y_{max}, the maximum dry matter accumulation; $T1$, beginning time of rapid accumulation; $T2$, time corresponding to the maximum accumulation rate; $T3$, end time of rapid accumulation; ΔT, time corresponding to the maximum accumulation rate; V_{max}, the maximum dry matter accumulation rate.
[2)] PD1, PD2, and PD3, 562.5×10⁴, 375×10⁴, and 187.5×10⁴ plants ha⁻¹, respectively.
[3)] I1, no irrigation; I2, irrigation at before winter and jointing stage; I3, irrigation at jointing stage; I4, irrigation at jointing and anthesis stage.

Table 3 Analysis of variance for aboveground dry matter accumulation (DMA) under various treatments of irrigation and planting densities of winter wheat at various growth stages

Source of variation	Before winter	Regreening	Jointing	Anthesis	Heading	Maturity
Irrigation (I)	2.98 ns	13.77***	40.38***	66.80***	93.50***	77.73***
Planting density (PD)	1.38 ns	0.98 ns	6.84***	0.48 ns	0.78 ns	2.97*
Year (Y)	9.29**	5.73*	2.60 ns	2.43 ns	0.05 ns	23.25***
I×PD	1.20 ns	3.95**	4.51***	1.53 ns	0.48 ns	2.37*
I×Y	3.02*	0.92 ns	0.43 ns	0.23 ns	17.71***	2.86 ns
PD×Y	0.27 ns	0.01 ns	0.34 ns	0.28 ns	0.97 ns	1.17 ns
I×PD×Y	0.34 ns	0.62 ns	0.17 ns	0.31 ns	1.04 ns	2.05 ns

***, **, and * indicate significances at 0.001, 0.01, and 0.05 probability levels, respectively; ns indicates no significance difference.

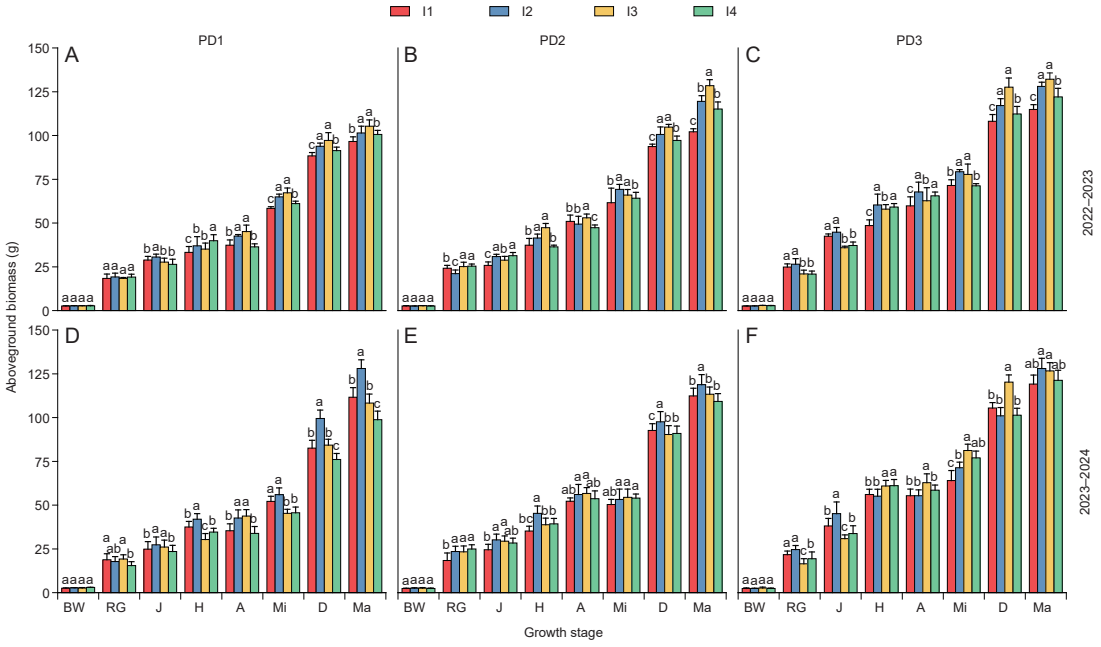


Fig. 6 Effect of different irrigation and planting densities on dry matter accumulation of winter wheat in 2023 and 2024 from before winter to maturity stages. BW is before winter stage, 59 days after sowing (DAS); RG is the returning green stage, 139 DAS; J is the jointing stage, 163 DAS; H is the heading stage, 181 DAS; A is the anthesis stage, 188 DAS; Mi is the milking stage, 198 DAS; D is the dough stage, 210 DAS; M is the maturity stage, 229 DAS. I1, no irrigation; I2, irrigation at before winter and jointing stage; I3, irrigation at jointing; I4, irrigation at jointing and anthesis stage. PD1, PD2, and PD3, 562.5×10^4, 375×10^4, and 187.5×10^4 plants ha^{-1}, respectively. Bars are mean±SD (n=20, from 3 independent plots). Different lowercase letters above bars indicate significant differences (P≤0.05) according to LSD.

2023–2024. Medium PD showed a similar increase in grain allocation, from 45–55%, with a corresponding decline in stems and sheaths by 42–46%. Lower PD exhibited the highest grain allocation, ranging from 43–52%, with stems and sheaths contributing 42–44%. Comparison between the two stages revealed that stems and sheaths dominated DMA at anthesis, while grains became the dominant sink at maturity. Leaves showed a consistent decline in their contribution from anthesis (19–27%) to maturity (7–15%), reflecting senescence and the translocation of assimilates to grains. Spikes contributed more DM at anthesis compared to glume and axis at maturity, highlighting their role as a major sink during the final growth stage. Yearly variations were notable, with better grain partitioning observed in the 2023–2024 season, likely due to improved environmental or management conditions. The optimal combination of medium PD-I2 and lower PD-I3 provided optimal conditions for DMA to grains, enhancing yield potential.

3.5. SWS, WUE, and evapotranspiration

Increasing PD and decreasing irrigation decreased the SWS significantly (P≤0.05) (Table 4). The SWS was significantly influenced by irrigation (P≤0.01) and PD (P≤0.05) of the 200 cm soil layer for both growing seasons. Compare with I1, in 2023, I2, I3, and I4 showed significant increases in SWS at higher PDs in the 200 cm layer by 8.97, 5.77, and 14.71%, respectively; in 2024, they increased by 6.31% but decreased by 11.09 and 13.32%, respectively. The maximum average increase in SWS occurred under the lowest PD, 44.26% (2023) and 49.51% (2024). The WUE increased significantly (P≤0.05) with reduced irrigation in both years. Increased irrigation at jointing (I2) and anthesis (I4) reduced the WUE by 8.34 and 7.79%, while improved by 5.41% only irrigation at jointing (I3) (2023) compared with I1, similarly reduced by 9.32 and 3.71% for I2 and I3 and improved by 8.66% for I3 (2024) in higher PD (Fig. 8). However, the IWUE

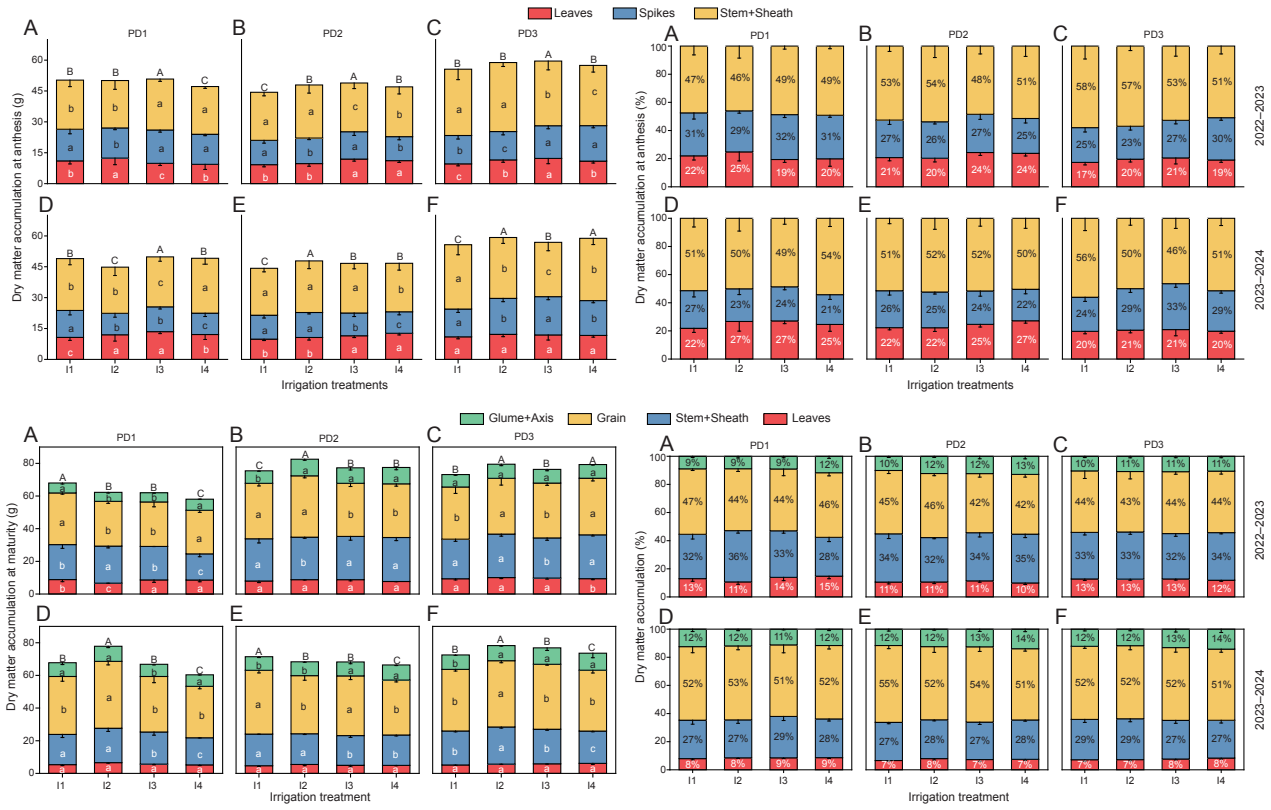


Fig. 7 Effect of different irrigation and planting densities on dry matter distribution of winter wheat at anthesis and maturity stage in 2023 and 2024. I1, no irrigation; I2, irrigation at before winter and jointing stage; I3, irrigation at jointing stage; I4, irrigation at jointing and anthesis stage. PD1, PD2, and PD3, 562.5×10^4, 375×10^4, and 187.5×10^4 plants ha^{-1}, respectively. Bars are mean±SD (n=20, from 3 independent plots). Different lowercase letters above bars indicate significant differences (P≤0.05) according to LSD.

of winter wheat generally decreased with the increase in PD and irrigation amount (Fig. 8). For 2023–2024, the IWUE of winter wheat was significantly higher under I1 than under the other treatments. The IWUE varied significantly among I2, I3, and I4 among all PD. The lower PD have higher IWUE as compared to medium and higher PD (Fig. 8).

Irrigation significantly (P≤0.05) affected total ET and ET in each growth stage (Appendix B). Compared with I1, average ET in I2, I3, and I4 increased by 14.55, 9.72, and 14.76% (2023), 7.23, 2.24, and 7.16% (2024). The ET of each stage increased with the increment in PD under the same irrigation. The precipitation during the crop growing season plays a significant role in determining the crop ET. ET from sowing to before winter was higher in 2024 than in 2023 due to greater precipitation in 2024, whereas ET from anthesis to maturity was higher in 2023 because of a heavy precipitation spell during that year. Compared with PD1, the average total ET of PD2 and PD3 decreased by 2.03 and 2.54%, respectively, in 2023 and by 5.72 and 8.77%, respectively, in 2024. The maximum and minimum ET values were recorded in PD2–I2 and PD3–I4 of all the treatments in both years.

3.6. Yield and components

Irrigation significantly (P≤0.05) affected grain yield, while PD and its interactions were insignificant. Compared to PD1–I1, the average yield of PD1–I2 and PD1–I4 decreased by 5.42 and 3.79%, respectively, in 2023 but increased by 0.96 and 6.17%, respectively, in 2024 (Table 5). Irrigation (I3) increased grain yield in PD1 by 11.99, 18.42, and 16.42% compared to I1, I2, and I4, respectively. Yield components such as 1,000-grain weight and grain numbers per spike significantly (P≤0.01) reduced in 2023 due to increased rainfall at the grain-filling stage. Irrigation and PD significantly influenced the 1,000-grain weight. In PD1, the average 1,000-grain weight decreased by 4.2% for I2 and 0.20% for I4, while it increased by 1.49% for I3 as compared to I1. For PD2, 1,000-grain weight decreased by 8.79, 3.84, and 6.29% for I2, I3, and I4, respectively, compared to I1. Irrigation didn't significantly affect 1,000-grain weight in PD3. However, the spike number was significantly increased by irrigation (P≤0.01) by 15, 33, and 29% for I2, I3, and I4, respectively, compared to I1. For PD2, the spike number increased by 14, 17, and 5% for I2, I3, and I4, respectively, compared to I1. For PD3, the spike number decreased by 2.7 and 7.9% for I2 and I4, respectively, but increased by 2.39% compared to I1. Grain number per spike was significantly (P≤0.01) influenced by irrigation and PD, as the average grain number per spike increased by 7.90, 3.29, and 2.73% in I3 compared to I1 for PD1, PD2, and PD3, respectively. As PD decreased, the plant height increased due to greater light interception and increased biomass. Specifically, plant height increased by 3.34 and 2.78% in PD2 and PD3, respectively, compared to PD1.

Table 4 Effect of different irrigation and planting densities on soil water storage (SWS) and water-use efficiency (WUE) of winter wheat in 2023 and 2024

Year	Planting density[1)]	Irrigation[2)]	Precipitation (mm)	Irrigation (mm)	SWS (mm)	ET (mm)	WUE (kg ha^{-1} mm^{-1})
2022–2023	PD1	I1	302.8	40.50	–62.87	403.57	12.42±0.29 cde
		I2	302.8	95.88	–57.23	453.31	11.38±0.30 e
		I3	302.8	71.88	–59.24	431.32	13.09±0.50 bcd
		I4	302.8	108.27	–53.62	462.52	11.45±0.42 e
	PD2	I1	302.8	40.50	–66.22	406.92	12.82±0.29 bcd
		I2	302.8	97.42	–51.33	470.67	11.62±0.22 e
		I3	302.8	72.42	–73.05	389.55	13.93±0.44 b
		I4	302.8	108.81	–39.73	448.20	12.34±0.44 de
	PD3	I1	302.8	40.50	–19.30	360.00	15.30±0.34 a
		I2	302.8	99.77	–16.42	416.38	13.54±0.36 bc
		I3	302.8	73.57	–48.78	455.61	12.77±0.18 cd
		I4	302.8	110.50	–21.37	430.38	12.92±0.44 bcd
2023–2024	PD1	I1	203.5	32.50	–142.08	377.58	13.96±0.52 bc
		I2	203.5	98.32	–133.11	439.43	13.02±0.34 bcd
		I3	203.5	66.10	–157.84	426.94	14.24±0.56 b
		I4	203.5	102.92	–161.01	466.93	12.75±0.63 cd
	PD2	I1	203.5	32.50	–187.17	427.67	13.21±0.30 bcd
		I2	203.5	94.16	–169.15	471.31	12.07±0.42 d
		I3	203.5	59.24	–144.69	411.93	14.06±1.09 bc
		I4	203.5	90.25	–195.57	488.82	12.91±0.48 bcd
	PD3	I1	203.5	32.50	–197.43	432.93	13.23±0.30 bcd
		I2	203.5	91.46	–113.58	411.83	13.97±0.25 bc
		I3	203.5	61.78	–156.27	421.45	12.93±0.23 bcd
		I4	203.5	98.38	–60.24	361.62	16.30±0.07 a
Source of variation							
Irrigation (I)			–	–			5.82**
Planting density (PD)			–	–			15.55**
Year (Y)			–	–			18.32**
I×PD			–	–			7.67**
Y×I			–	–			4.59*
Y×PD			–	–			3.47*
Y×I×PD			–	–			4.53**

[1)] PD1, PD2, and PD3, 562.5×10^4, 375×10^4, and 187.5×10^4 plants ha^{-1}, respectively.
[2)] I1, no irrigation; I2, irrigation at before winter and jointing stage; I3, irrigation at jointing stage; I4, irrigation at jointing and anthesis stage.
** and *, significances at 0.01 and 0.05 probability levels, respectively; ns indicates no significance difference.

3.7. Economic analysis

The total input costs were categorized into five key components: labor expenses, mechanical operations, seed costs, fertilizer and nutrient costs, and irrigation costs. Among these, irrigation had the most significant impact on total expenditures, particularly influencing water and electricity costs. A reduction in irrigation led to lower overall costs, whereas an increase in PD resulted in higher total expenses due to the rising cost of seeds (Fig. 9). For all treatments, fertilizer and nutrient costs remained constant at 3,750 CNY ha^{-1}, while labor expenses were 1,800 CNY ha^{-1}. However, the economic returns varied significantly depending on irrigation levels and planting densities. The highest net economic benefits (NEB) were observed at PD3–I3, where NEB increased by 11.9, 18.4, and 16.4% compared to I1, I2, and I4 in the 2022–2023 season (P<0.05). Similarly, in 2023–2024, PD3-I3 exhibited an increase of 15.1, 14.0, and 8.4% compared to I1, I2, and I4, respectively.

The response of PD2 varied across years. In 2022–2023, PD2 did not show a statistically significant difference in NEB. However, in 2023–2024, PD2–I4 achieved a NEB increase of 6.62% compared to I1, while PD2–I3 increased by 7.73% relative to I2. For PD3, I3 consistently delivered the highest NEB, with only a 2.26% increase compared to I1. Nonetheless, in 2022–2023, I3 achieved substantial increases of 7.96 and 11.76% in NEB compared to I2 and I4, respectively. Interestingly, in 2023–2024, PD3 did not show a significant difference, as the I1 yielded the maximum NEB of 15,299 CNY ha^{-1}.

A comparative cost-benefit analysis across both years highlights the economic advantage of I3 due to its reduced irrigation costs. The total cost, including water expenses, was significantly lower in I3 than in I2 and I4, reinforcing its economic feasibility. Specifically, in PD1–I3, total costs were

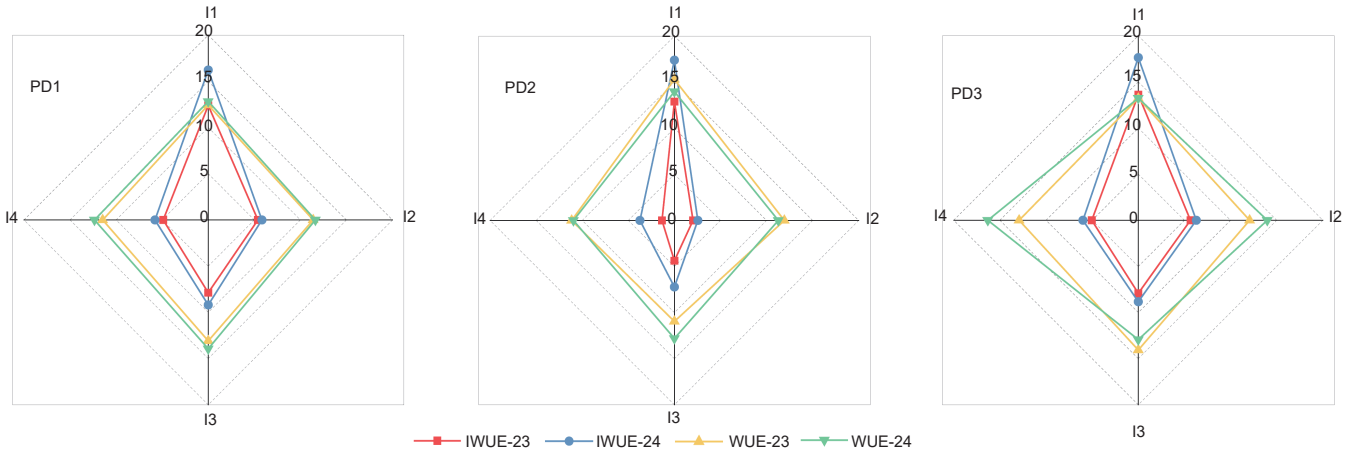


Fig. 8 Irrigation water-use efficiency (IWUE) and water-use efficiency (WUE) of different irrigation and planting density treatments in two growing seasons of 2023 and 2024. I1, no irrigation; I2, irrigation at before winter and jointing stage; I3, irrigation at jointing stage; I4, irrigation at jointing and anthesis stage. PD1, PD2, and PD3, 562.5×10⁴, 375×10⁴, and 187.5×10⁴ plants ha⁻¹, respectively.

Table 5 Impact of various planting densities and irrigation treatments on plant height, yield and its components of winter wheat in 2023 and 2024

Year	Planting density	Irrigation	Plant height (cm)	Grains per spike (no./spike)	1,000-grain weight (g)	Spike number (×10⁴ ha⁻¹)	Grain yield (kg ha⁻¹)
2022–2023	PD1	I1	76.73±1.11 abc	40.49±1.47 de	34.60±1.33 bc	306.06±10.07e	5,014.23±118.99 c
		I2	74.78±0.92 bcd	39.06±1.71 e	32.50±1.01 c	353.05±40.98 abcde	5,162.00±138.16 bc
		I3	75.92±3.61 abc	43.81±1.71 c	36.24±1.12 ab	407.5±27.22 a	5,649.35±217.94 ab
		I4	72.46±1.99 d	43.83±1.19 c	34.20±0.72 bc	397.5±46.60 ab	5,298.75±197.88 bc
	PD2	I1	77.38±0.19 abc	42.48±1.45 cd	36.22±1.05 ab	322.33±30.10 de	5,218.70±119.87 bc
		I2	78.48±0.73 ab	42.02±0.83 cd	34.12±1.01 bc	377.66±46.49 abcd	5,473.37±105.30 abc
		I3	76.66±1.33 abc	42.63±1.53 cd	35.36±1.32 ab	389.50±34.28 abc	5,428.70±173.50 abc
		I4	77.38±2.28 abc	43.56±2.06 c	34.12±1.53 bc	336.66±32.50 bcde	5,534.77±197.42 ab
	PD3	I1	78.68±1.18 a	51.62±0.95 b	38.42±0.77 a	355.16±32.19 abcde	5,509.75±123.54 ab
		I2	76.81±1.01 abc	54.60±0.51 a	35.90±1.13 ab	335.33±5.50 cde	5,641.18±151.63 ab
		I3	78.54±1.29 ab	55.73±1.57 a	36.82±1.52 ab	351.70±16.40 abcde	5,819.23±83.92 a
		I4	74.20±3.15 cd	54.84±2.46 a	36.91±0.65 ab	306.83±35.88 e	5,562.90±189.91bc
2023–2024	PD1	I1	73.53±1.14 b	50.73±1.36 g	39.88±0.37 ab	341.83±16.54 cd	5,273.88±197.37 c
		I2	74.09±1.47 b	54.43±1.35 f	38.91±0.59 bc	377.33±13.32 abcd	5,723.23±152.16 abc
		I3	77.67±2.09 a	54.60±1.45 ef	39.18±0.70 bc	425.66±34.28 a	6,081.77±239.51 ab
		I4	75.12±2.41 ab	54.36±1.12 f	40.18±0.44 ab	409.50±31.63 ab	5,957.93±297.31 ab
	PD2	I1	76.27±0.50 ab	57.67±2.21 d	41.36±1.25 ab	349.66±14.33 bcd	5,650.78±129.08 bc
		I2	75.27±1.52 ab	61.27±1.06 ab	36.49±0.75 c	391.00±22.11 abcd	5,689.50±201.07 bc
		I3	76.08±1.09 ab	62.60±0.93 ab	39.17±0.54 bc	395.83±54.70 abc	6,310.67±235.71 a
		I4	76.34±2.66 ab	57.20±1.44 de	38.56±0.47 bc	373.33±49.13 cd	5,793.62±453.05 abc
	PD3	I1	75.01±2.99 ab	56.73±0.87 def	40.73±0.20 ab	338.50±16.82 cd	5,451.20±97.11 bc
		I2	77.12±3.42 ab	60.36±1.77 bc	40.58±0.68 ab	339.07±9.98 cd	5,753.30±106.74 abc
		I3	74.48±2.18 ab	63.16±1.98 a	42.56±1.03 a	358.23±25.10 bcd	5,895.83±25.36 abc
		I4	76.29±1.52 ab	58.20±0.75 cd	42.48±2.18 a	331.14±42.39 d	5,731.02±132.40 abc
Sources of variation							
Irrigation (I)			1.40 ns	7.95**	5.79**	8.00**	4.51*
Planting density (PD)			5.19*	229.04**	15.13**	8.87**	1.47 ns
Year (Y)			3.87 ns	1,023.34**	138.01**	4.42*	19.55**
I×PD			1.16 ns	2.61*	0.92 ns	3.73**	1.78 ns
Y×I			3.12*	15.14**	0.54 ns	0.15ns	1.52 ns
Y×PD			1.28 ns	88.61**	1.26 ns	0.59ns	2.96 ns
Y×I×PD			1.95 ns	4.14**	2.10 ns	0.33ns	0.57 ns

Values followed by different lowercase letters indicate significances at $P<0.05$, ***, **, and *, significances at 0.001, 0.01, and 0.05 probability levels, respectively; ns indicates no significance difference.

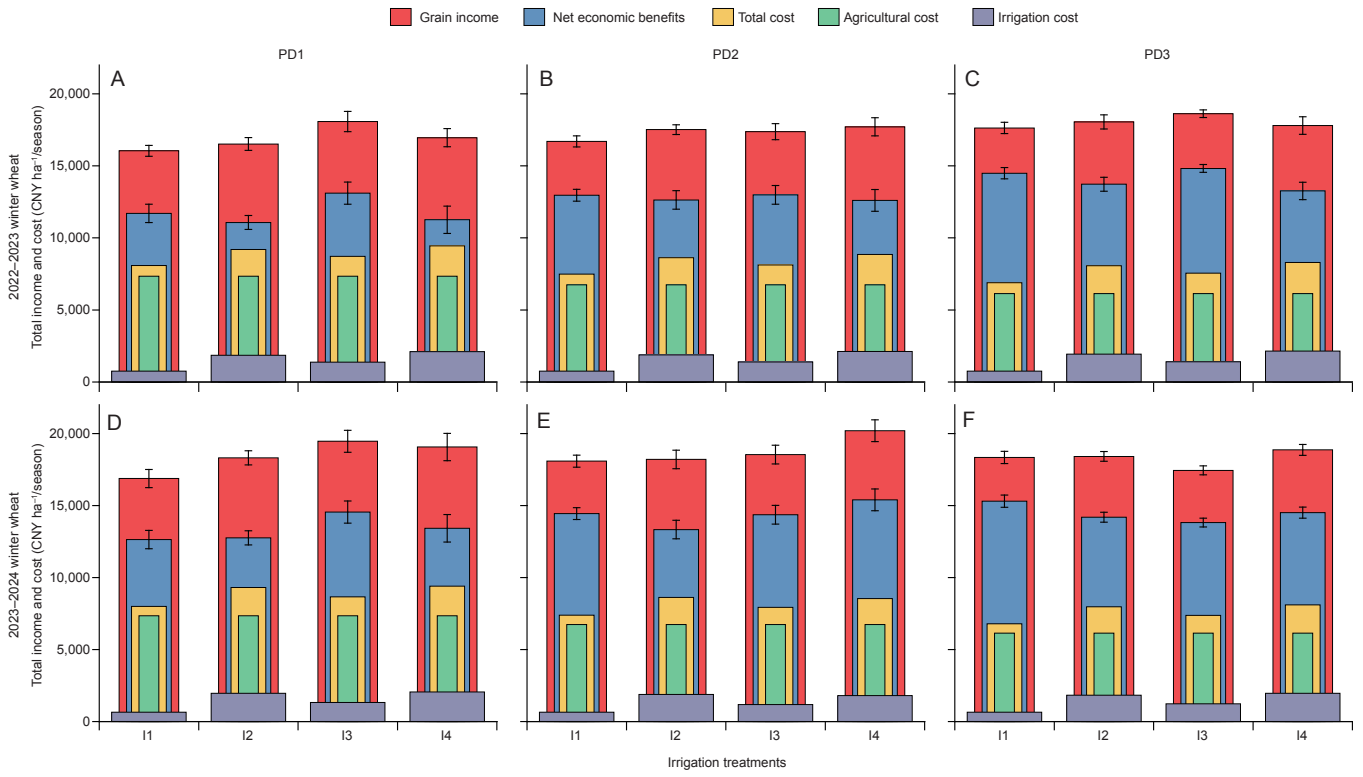


Fig. 9 Grain income, net economic benefits, total cost including agricultural cost and irrigation of winter wheat in 2023 and 2024 under various planting densities and irrigation treatments. I1, no irrigation; I2, irrigation at before winter and jointing stage; I3, irrigation at jointing stage; I4, irrigation at jointing and anthesis stage. PD1, PD2, and PD3, 562.5×10⁴, 375×10⁴, and 187.5×10⁴ plants ha⁻¹, respectively. Bars mean SD (n=3).

6.06 and 7.76% lower than in I2 and I4, respectively. Similarly, PD2–I3 had 6.94 and 7.73% lower costs, while PD3–I3 reduced total costs by 6.96 and 8.96% compared to I2 and I4 (Fig. 9; Appendices C and D). These findings emphasize the economic efficiency of I3 at PD3, balancing cost reductions with maximized NEB. This highlights an optimal strategy for achieving economic sustainability in wheat production.

3.8. Correlation analysis

For 2020–2023, grain yield strongly correlated with NEB (r=0.78), 1,000-grain weight (r=0.86), and grains per spike (r=0.79), highlighting the importance of grain size and number for productivity and profitability. LAI improved plant height but reduced ET, suggesting a trade-off between canopy growth and water loss (Appendix E). For 2023–2024, grain yield showed weaker ties to yield components (1,000-grain weight, grain per spike) and no significant link to NEB, suggesting environmental stress disrupted typical yield determinants. LAI had a stronger negative impact on ET (r=–0.70) but positively influenced spike number (r=0.78), indicating denser canopies supported spike formation under drought. The WUE–IWUE relationship was weakened (r=0.51), reflecting less predictable water efficiency under stress (Appendix E). This analysis underscores the need for adaptive management based on seasonal conditions to balance yield, WUE, and NEB.

4. Discussion

Numerous studies have explored optimizing resource use and improving grain yield formation through planting density (PD) and agronomic management practices, including irrigation (Fan *et al.* 2019; Yang *et al.* 2019; Khan *et al.* 2020; Gao *et al.* 2021; Dai *et al.* 2022, 2023; Zhang Z *et al.* 2023). However, these results often vary due to differences in genotype, environmental conditions, and agronomic practices. This variability underscores the complexity of agricultural systems and the need for site-specific recommendations. Optimizing PD is crucial for achieving high yield and economic benefits in winter wheat by ensuring robust crop establishment, improved resource utilization, and enhanced sustainability. The current study highlights key findings on irrigation practices across various PD levels in winter wheat.

4.1. Soil water storage, evapotranspiration, and water use efficiency

Irrigation and precipitation are the primary sources of soil water recharge, both playing vital roles in maintaining optimal soil moisture levels (Bai *et al.* 2020). Sowing winter wheat with adequate soil water storage (SWS) enhances grain yield; however, uneven precipitation during critical growth stages can result in drought stress, affecting water consumption and crop development. During the first year of the current experiment, excess rainfall increased the SWS from anthesis to maturity, which suppressed the growth of higher PD. This led to lodging, adversely affected the grain-filling process, and ultimately reduced grain yield. As PD decreased, there was a continuous increase in the SWC

of the 0–200 cm soil layer throughout the growth stages of winter wheat. Compared to lower PD, the SWS in the 200 cm soil layer under high and medium PD was reduced (Fig. 3). Previous studies also reported that increasing PD resulted in a substantial decline in SWC (Gao *et al.* 2021; Guo *et al.* 2021), likely due to greater transpiration demand at higher plant densities. Previous studies have shown that higher PD can improve SWS consumption in deep soil layers (Liu *et al.* 2018). In addition, a suitable PD can enhance crop water consumption by transforming precipitation and irrigation from soil transpiration to crop transpiration, thereby increasing crop water productivity (Dai *et al.* 2022; You *et al.* 2022).

Improving WUE is critical for maximizing crop productivity and optimizing resource utilization (Ullah *et al.* 2019; Mbava *et al.* 2020). In this study, compared with no irrigation, WUE increased with reduced irrigation at higher PD and lower PD, whereas at medium PD the opposite trends were observed, with WUE increasing in 2023 but decreasing in 2024 (Table 4). Our results for irrigation are in line with Wu *et al.* (2023), who reported that irrigation at sowing and jointing maximized the yield and WUE by using rainwater before anthesis in the Huang-Huai-Hai Plain. In the North China Plain (NCP), Xu *et al.* (2018) reported that irrigation applied at jointing and anthesis stages achieved the maximum grain yield and WUE, which is contrary to our findings. Increasing PD also results in lower WUE (Table 4), indicating that adjusting PD is an effective strategy to improve WUE across years with varying rainfall, depending on the specific irrigation conditions. Consistent results have been reported in earlier studies, indicating that PD should be decreased to avoid excessive vegetative growth before the winter period (Ren *et al.* 2019; Shah *et al.* 2020). In current research, higher PD under the no-irrigation treatment (I1) was still able to use irrigation water from the preceding maize crop during the grain-filling stage. The current findings, supported by previous research, indicates that grain yield was not maximized, and WUE was relatively low under the highest irrigation and PD treatment. Optimally reduced irrigation has the potential to enhance both grain yield and WUE on Northwest dryland region of China.

Under varying rainfall conditions, limited irrigation has proven an effective strategy for sustaining wheat production and conserving water resources. The coefficient of variation for ET across different growth stages exceeded, regardless of whether the crop was managed under low or higher PD. It was primarily due to the effects of precipitation and irrigation, although other factors may also play a role (Appendix B). Nevertheless, the proportions of ET from jointing to anthesis and from anthesis to maturity varied across irrigation and PD treatments due to increased precipitation, which impacted the yield formation in the current studies. The current findings are in accordance with Gao *et al.* (2021), who reported that with increasing PD, ET and water consumption decreased before jointing, whereas water consumption increased after jointing. This may be because the growth period from sowing to jointing lasts approximately 180 days. During this time, the plant grows slowly due to lower temperatures, and a significant portion of the soil remains exposed to the air, resulting in soil evaporation exceeding plant transpiration (Noor *et al.* 2020; Shah *et al.* 2020; Wang *et al.* 2023).

4.2. Winter wheat growth and yield

Optimizing PD and irrigation management is vital for enhancing winter wheat growth, maximizing yield, and improving resource efficiency (Bastos *et al.* 2020; Gao *et al.* 2021). Seasonal rainfall variability and frequent droughts significantly impact wheat productivity in semi-arid China (Ju *et al.* 2013; Han *et al.* 2023). Irrigation substantially influenced wheat biomass accumulation, which was closely linked to soil moisture availability. Dai *et al.* (2022) reported that reduced irrigation led to a considerable reduction in aboveground dry matter accumulation. In this research, the higher irrigation levels (I2 and I4) resulted in increased biomass production, but reduced irrigation (I3) achieved higher efficiency. This may be because increased irrigation (I2 and I4) boosted biomass by promoting vegetative growth, whereas reduced irrigation (I3) likely improved efficiency by optimizing water use and diverting more resources to grains rather than excessive foliage. This balance enhanced the harvest index while minimizing water waste. Moreover, the amount of irrigation applied has significantly affected winter wheat yield by influencing growth and development. The findings on grain yield align with previous research (Zhang *et al.* 2016; Yang *et al.* 2019), which show that a mild water deficit could promote dry matter in the vegetative organ to grain, increasing wheat grain yield and WUE. Seasonal rainfall patterns also influenced these results. In 2022–2023, rainfall during anthesis to maturity alleviated water stress under I1, whereas in 2023–2024, lower rainfall at the same stage resulted in greater yield reductions.

Higher PD increased total biomass but did not necessarily improve grain yield. Optimal moisture conditions promoted tillering and effective spike formation, while excessive PD resulted in yield declines due to competition for resources. This research reported that irrigation at jointing significantly improved plant height, leaf area index, effective spike number, and 1,000-grain weight. The observed increase was driven by suitable soil moisture levels, which stimulated winter wheat tillering and increased the effective spike count per unit area (Shang *et al.* 2020; Dai *et al.* 2022; Wang *et al.* 2023). Previous studies have shown that increasing PD can compensate for wheat yield losses under low SWS in dry years but has limited benefits under adequate initial moisture conditions (Xu *et al.* 2016). However, when the SWC at sowing was adequate, the yield-enhancing impact of increasing PD was limited. This may be because higher PD produced greater yet ineffective spikes per unit area, thus reducing grain yield. In some cases, lower PD can still achieve high yield when optimal conditions are provided, such as appropriate irrigation and cultivar selection (Fischer *et al.* 2019).

The interaction between PD and irrigation significantly influenced winter wheat growth and yield by altering resource availability, canopy structure, and physiological processes (Mao *et al.* 2017; Bastos *et al.* 2020). In this study, medium PD (PD2) under adequate irrigation (I3) improved yield due to enhanced light interception and higher LAI, which supported increased DMA. The highest yield in the PD2–I3 treatment resulted from an optimal balance between PD and irrigation,

which synergistically enhanced canopy photosynthesis, resource use efficiency, and sink strength. The results for PD2–I3 are in accordance with Li *et al.* (2020) and Tian *et al.* (2025), who reported that under the optimized PD, the canopy structure allowed efficient light distribution, minimizing mutual shading while maintaining sufficient photosynthetic leaf area. In our research, winter wheat under the no-irrigation treatment could still utilize irrigation water of preceding maize during the filling stage. Additionally, the optimum seeding density was not the highest density and it was related to microclimate, i.e., rainfall and temperature. In contrast, higher PD increased light competition, reducing photosynthetic efficiency, while lower PD underutilized available space and resources. Thus, PD2–I3 represents a physiological and ecological optimum, where source and sink capacities were balanced, microclimate stress was minimized, and resource competition was optimized for maximum yield. This aligns with the Law of Optimum, where intermediate levels of both density and irrigation produce the most favorable growth conditions (van Ittersum *et al.* 2003). The findings suggest a threshold beyond which increasing plant population under sub-optimal water supply becomes counterproductive. The synergistic or antagonistic effects of PD and irrigation indicate that optimal yield can be achieved by balancing population pressure with soil moisture availability, ensuring efficient water use without compromising productivity (Sun *et al.* 2018).

4.3. NEB of winter wheat production

Economic returns are a primary factor influencing farmers' decisions (Chou *et al.* 2021). In the current experiment, the evaluation of water prices considered the electricity cost for groundwater pumping. The maximum NEB was achieved at lower PD with irrigation at the jointing stage. These results support previous findings that rainfed wheat or single irrigation at jointing achieves higher NEB than multiple irrigations (Wu *et al.* 2023). Therefore, limiting water availability by taking pre-anthesis rainfall and irrigation into account has proven to be an effective strategy for ensuring sustainable high yield.

The NEB from irrigation often exceeds the value of crop yield alone. Reducing irrigation frequency compared to a well-irrigated strategy allows the available irrigation water to be distributed over a proportionally larger area. Although yield per hectare is lower under a deficit irrigation strategy compared to full irrigation, the economic gains from reduced water costs outweigh yield reductions, making it a viable strategy for resource-limited regions. For farmers, the economic efficiency of winter wheat relies on balancing both cost savings and yield benefits. The highest net income was recorded for PD3–I3, at 14,820 CNY ha^{-1} (2022–2023) and 13,818 CNY ha^{-1} (2023–2024). Over-investment in irrigation and planting was offset by yield improvements, reinforcing the importance of balanced input costs. These findings highlight that economic efficiency depends on optimizing both production and cost savings.

Beyond farm-level benefits, reducing irrigation frequency can minimize groundwater depletion and nutrient leaching, supporting environmental sustainability. Educating farmers on the economic and ecological advantages of optimal PD and irrigation strategies can enhance regional agricultural resilience. Encouraging the implementation of low PD and reduced irrigation will not only maximize profits but also promote sustainable farming practices in water-scarce regions.

5. Conclusion

This study underscores the pivotal role of planting density (PD) and irrigation strategies in optimizing winter wheat yield, water-use efficiency (WUE), and net economic benefits (NEB) in Northwest China. Our findings reveal that excessive PD and frequent irrigation (before winter+jointing or jointing+anthesis) reduced the number of effective spikes and negatively impacted key yield components, ultimately decreasing grain yield due to excessive vegetative growth and increased lodging risk, particularly when unexpected rainfall occurred during grain filling. Yield improvements were observed primarily when irrigation was applied at the jointing stage, while higher irrigation frequencies (before winter+jointing or jointing+anthesis) led to diminishing returns. Optimized irrigation at the jointing stage significantly enhanced post-anthesis biomass accumulation, leading to improved grain yield, WUE, and NEB. The highest yield was achieved at medium PD under jointing-stage irrigation, whereas lower PD was most effective in maintaining soil moisture, promoting dry matter accumulation, and maximizing NEB under water-limited conditions. Therefore, the optimal strategy for sustainable winter wheat production in this semi-humid yet drought-prone region is a lower PD combined with irrigation at the jointing stage. This approach not only conserves water but also enhances yield potential and farm profitability, offering a viable solution for wheat growers facing water constraints.

Acknowledgements

This work was supported by the Open Project of Shaanxi Laboratory for Agriculture in Arid Areas, China (2024ZY-JCYJ-02-30), the National Key Research and Development Program of China (2024YFD2300205), and the Key Research and Development Technology Projects in Shaanxi Province, China (2023-ZDLNY-01).

Declaration of competing interest

The authors declare that they have no conflict of interest.

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

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

Appendices associated with this paper are available at https://doi.org/10.1016/j.jia.2025.07.005

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