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Regulated Deficit Irrigation Improves Yield Formation and Water and Nitrogen Use Efficiency of Winter Wheat at Different Soil Fertility Levels

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Abstract

Water scarcity and spatial variability in soil fertility are key constraints to stable grain production in the Huang-Huai-Hai Plain. However, the interaction mechanisms between regulated deficit irrigation and soil fertility influencing yield formation and water-nitrogen use efficiency in winter wheat remain unclear. In this study, a two-year field experiment (2022–2024) was conducted to investigate the effects of two irrigation regimes—regulated deficit irrigation during the heading to grain filling stage (D) and full irrigation (W)—under four soil fertility levels: F1 (N: P: K = 201.84: 97.65: 199.05 kg ha^{−1}), F2 (278.52: 135: 275.4 kg ha^{−1}), F3 (348.15: 168.75: 344.25 kg ha^{−1}), and CK (no fertilization). The results show that aboveground dry matter accumulation, total nitrogen content, pre-anthesis dry matter and nitrogen translocation, and post-anthesis accumulation significantly increased with fertility level ($p < 0.05$). Regulated deficit irrigation promoted the contribution of post-anthesis dry matter to grain yield under the CK and F1 treatments, but suppressed it under the F2 and F3 treatments. However, it consistently enhanced the contribution of post-anthesis nitrogen to grain yield ($p < 0.05$) across all fertility levels. Higher fertility levels prolonged the grain filling duration by 18.04% but reduced the mean grain filling rate by 15.05%, whereas regulated deficit irrigation shortened the grain filling duration by 3.28% and increased the mean grain filling rate by 12.83% ($p < 0.05$). Grain yield significantly increased with improved fertility level ($p < 0.05$), reaching a maximum of 9361.98 kg·ha^{−1} under the F3 treatment. Regulated deficit irrigation increased yield under the CK and F1 treatments but reduced it under the F2 and F3 treatments. Additionally, water use efficiency exhibited a parabolic response to fertility level and was significantly enhanced by regulated deficit irrigation. Nitrogen partial factor productivity (NPFP) declined with increasing fertility level ($p < 0.05$); Regulated deficit irrigation improved NPFP under the F1 treatment but reduced it under the F2 and F3 treatments. The highest NPFP (41.63 kg·kg^{−1}) was achieved under the DF1 treatment, which was 54.81% higher than that under the F3 treatment. TOPSIS analysis showed that regulated deficit irrigation combined with the F1 fertility level provided the optimal balance among yield, WUE, and NPFP. Therefore, implementing regulated deficit irrigation during the heading–grain filling stage under moderate fertility (F1) is recommended as the most effective strategy for achieving high yield and efficient resource utilization in winter wheat production in this region.



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Keywords: soil fertility level; regulated deficit irrigation; wheat yield; grain filling; resource use efficiency

1. Introduction

The Huang-Huai-Hai Plain (HHHP) is one of China's major grain-producing regions, contributing more than 60% of the national wheat output and playing a vital role in ensuring national food security [1]. However, precipitation in this region is highly unevenly distributed, with the majority occurring between July and September. During the winter wheat growing season, rainfall makes up only 20–30% of the annual total, which is insufficient to meet the crop's water demands [2,3]. In pursuit of high yields, farmers often resort to excessive irrigation [4], leading to low irrigation water use efficiency, the over-exploitation of groundwater, the formation of underground funnel areas, and ultimately posing a serious threat to regional water resources security. Therefore, improving irrigation efficiency while maintaining stable wheat yields has become a pressing challenge for agriculture in the HHHP.

With growing water scarcity, the development of water-saving irrigation technologies and the efficient utilization of limited water resources have become increasingly critical. Regulated deficit irrigation (RDI), which strategically applies water shortages during specific crop growth stages, is a promising technique to optimize water allocation and maintain or even enhance yield by leveraging crop physiological responses to moderate drought stress [5]. Studies have indicated that moderate water deficits can trigger a crop's "stress memory," enhancing its resilience to subsequent drought and promoting compensatory growth without significant yield loss [6,7]. For instance, Jiang et al. [8] observed that an appropriate water deficit induced wheat to undergo drought training, which led to compensatory growth upon rewatering without significant yield loss or even yield improvement; Lu et al. [9] demonstrated that deficit irrigation at 75% of crop evapotranspiration combined with nitrogen application at 170 kg·ha^{−1} achieved the highest yield and water use efficiency in a two-wheat-season experiment; similarly, Yan et al. [10] confirmed that a moderate water deficit coupled with proper fertilization improved grain filling and yield in winter wheat.

Crop responses to water deficit are not solely determined by irrigation management but are also significantly influenced by soil nutrient availability—particularly that of nitrogen. As two primary limiting factors in crop production, water and nitrogen interactively regulate dry matter accumulation, nutrient translocation, and yield formation [10]. Therefore, when designing RDI strategies, it is indispensable to consider the regulatory role of nitrogen supply capacity. Soil fertility across the HHHP varies considerably, with medium- and low-yielding fields accounting for more than 75% of the cultivated area [11]. This spatial heterogeneity has become a primary bottleneck restricting the balanced improvement of regional grain production.

Existing studies on RDI and fertilization mainly focus on the impact of isolated irrigation or of the fertilization application level on yield and resource use efficiency [12–14]. However, the interactive mechanisms between soil nutrient supply characteristics and crop physiological response to RDI under different soil fertility levels remain poorly understood. Nitrogen ranks second only to water in influencing wheat development, yield formation, and grain quality [15,16]. Although some research has explored water–nitrogen interactions in relation to dry matter accumulation and translocation, systematic studies addressing nitrogen uptake dynamics, translocation efficiency, and yield formation under RDI across different soil fertility levels are still lacking.

To address this gap, the present study conducted a two-year field experiment to investigate the effects of RDI on dry matter and nitrogen accumulation, translocation dynamics, grain filling characteristics, yield formation, and resource use efficiency in winter wheat under varying soil fertility levels. Specifically, the objectives were to (1) evaluate the effects of soil fertility levels and regulated deficit irrigation on the key growth indicators of winter wheat, including dry matter accumulation, total nitrogen content, and grain yield; and (2) identify optimal RDI patterns suitable for different soil fertility levels in the region. The results aim to provide theoretical support and practical guidance to improve RDI strategies and water–fertilizer management models in water-limited wheat production systems.

2. Materials and Methods

2.1. Study Area

Field studies were conducted during the 2022–2024 winter wheat growing seasons at the Xinxiang Comprehensive Experimental Station of the Chinese Academy of Agricultural Sciences (35.15° N, 113.80° E) in Xinxiang County, Henan Province, China. The site has a multi-year mean temperature of 14.1 °C, a 210-day frost-free period, and a 2398.9 h annual sunshine duration. Average annual precipitation is 589 mm, while evapotranspiration reaches 2000 mm. The soil is classified as sandy loam, with a mean bulk density of 1.51 g cm^{−3} (0–100 cm depth), a field capacity (FC) of 20.5% (by mass), and the groundwater depth exceeds 5 m. Agricultural practice follows an annual winter wheat–summer maize rotation system. The soil chemical properties (0–20 cm depth) before sowing are given in Table 1, and the precipitation and temperature over the wheat growing periods are shown in Figure 1.

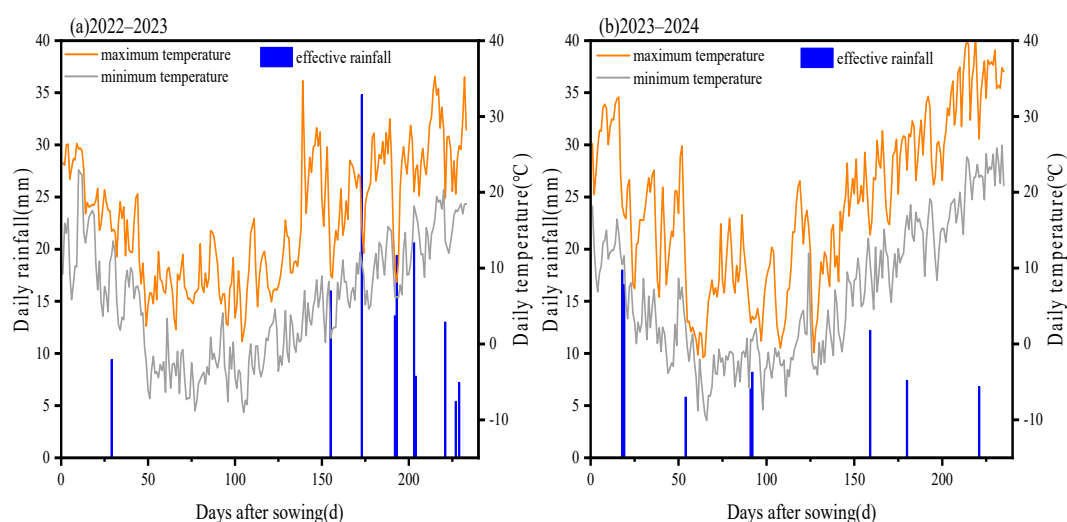


Figure 1. Daily rainfall and maximum and minimum temperature throughout winter wheat growing seasons in 2022–2024.

Table 1. Chemical properties of the 0–20 cm soil layer in 2022–2024.

Year	Treatment	pH	Organic Matter (g kg ^{−1})	Total Nitrogen (g kg ^{−1})	Alkali-Hydrolyzable Nitrogen (mg kg ^{−1})	Available Phosphorus (mg kg ^{−1})	Available Potassium (mg kg ^{−1})
2022–2023	F1	8.54 b	17.97 b	1.09 c	151.81 c	19.38 c	367.63 c
	F2	8.51 b	18.50 b	1.13 b	172.81 b	31.26 b	424.28 b
	F3	8.47 b	19.80 a	1.28 a	199.94 a	51.53 a	504.27 a
	CK	8.64 a	14.86 c	0.86 d	115.35 d	8.60 d	260.31 d

Table 1. Cont.

Year	Treatment	pH	Organic Matter (g kg ^{−1})	Total Nitrogen (g kg ^{−1})	Alkali-Hydrolyzable Nitrogen (mg kg ^{−1})	Available Phosphorus (mg kg ^{−1})	Available Potassium (mg kg ^{−1})
2023–2024	F1	8.61 b	17.02 b	1.08 c	145.64 c	18.54 c	390.29 c
	F2	8.53 c	17.95 ab	1.14 b	165.80 b	24.91 b	492.94 b
	F3	8.55 c	19.09 a	1.23 a	187.94 a	43.99 a	566.26 a
	CK	8.68 a	14.31 c	0.88 d	112.58 d	10.19 d	220.98 d

Different lowercase letters indicate significant differences among treatments at $p < 0.05$.

2.2. Experimental Design

This experiment utilized Zhoumai 22, a predominant winter wheat cultivar in the HHHP, with a sowing rate of 195 kg ha^{−1} and row spacing of 20 cm in both growing seasons. The winter wheat was sown on 17 October 2022 and 23 October 2023, and harvested on 2 June 2023 and 7 June 2024. A two randomized block design was employed with four soil fertility levels—F1, F2, F3, and unfertilized (CK); two irrigation levels—regulated deficit irrigation (D):60–65% FC and full irrigation (W):75–80% FC were applied throughout the heading–grain filling period; Each treatment was replicated three times, resulting in 24 experimental plots (40 m × 4 m = 160 m²). Protective buffers were established between the plots.

The irrigation method was drip irrigation, with a drip head flow rate of 2.2 L h^{−1}, a drip head spacing of 30 cm, and a capillary spacing of 60 cm. During the non-deficit period, 30 mm irrigation was applied to all treatments when the relative soil water content drops to 75%FC. During the heading to grain filling period, 20 mm irrigation was applied to the deficit adjustment treatment (D) when the relative soil water content dropped to 60%FC, and to the full irrigation treatment (W) when the soil water content dropped to 75%FC. Irrigation volumes were metered using dedicated water meters, and the accumulated irrigation amount is given in Figure 2. The fertilizer application rates for wheat seasons across fertility treatment were as follows: F1 (N: P: K = 201.84: 97.65: 199.05 kg ha^{−1}), F2 (N: P: K = 278.52: 135: 275.4 kg ha^{−1}), F3 (N: P: K = 348.15: 168.75: 344.25 kg ha^{−1}), and CK (no fertilization). In total, 50% urea, 100% compound fertilizer, and potassium sulfate were utilized as base fertilizers, and the remaining 50% urea was topdressed using a differential pressure fertilizer tank during the jointing stage. Table 1 indicates that soil chemical properties varied significantly with soil fertility level. Increasing soil fertility level led to significant increases in the contents of soil organic matter, total nitrogen, alkali-hydrolyzable nitrogen, available phosphorus, and available potassium, but a significant decrease in soil pH; the CK treatment exhibited a significantly higher pH compared to the other treatment. All other agronomic practices followed local high-yield field requirements.

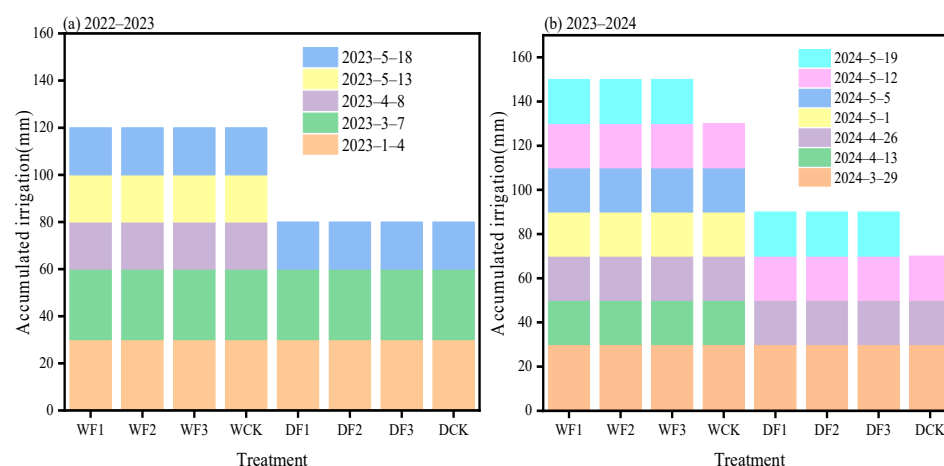


Figure 2. Accumulated irrigation amount during winter wheat growing seasons in 2022–2024.

2.3. Dry Matter Mass

During sampling, 30 representative plants per treatment were randomly selected and partitioned by growth stage. The plants of the jointing stage were separated into stem + leaf sheath and leaf; the plants of the flowering stage were separated into stem + leaf sheath, leaf, and spike. The plants of mature stage were separated into stem + leaf sheath, leaf, spike cob + glumes and grain. The samples were oven-dried at 105 °C for 30 min, then at 75 °C until a constant weight was achieved. Dry matter weight was recorded, and aboveground biomass per unit area was calculated using plant population density. Relevant calculations of the indicators related to dry matter allocation and translocation are as follows (according to the methods in [17,18]):

$$DM_T \text{ (kg ha}^{-1}\text{)} = DM_{\text{anthesis}} - DM_{\text{maturity, veg}} \quad (1)$$

$$DM_A \text{ (kg ha}^{-1}\text{)} = GDM_{\text{maturity}} - DM_T \quad (2)$$

$$\text{Contribution rate of pre-anthesis DM to grain (\%)} = DM_T / GDM_{\text{maturity}} \times 100\% \quad (3)$$

$$\text{Contribution rate of post-anthesis DM to grain (\%)} = DM_A / GDM_{\text{maturity}} \times 100\% \quad (4)$$

where DM_T is the pre-anthesis dry matter translocation (kg ha^{-1}); DM_{anthesis} is the dry matter at anthesis (kg ha^{-1}); $DM_{\text{maturity, veg}}$ is the dry matter of the vegetative organs at maturity (kg ha^{-1}); DM_A is the post-anthesis dry matter accumulation (kg ha^{-1}); and GDM_{maturity} is the grain dry matter at maturity (kg ha^{-1}).

2.4. Plant Total Nitrogen Content

Plant dry matter samples were weighed and bagged separately for total nitrogen analysis. The determination method was as follows: each plant component was ground, crushed, and sieved by a 0.5 mm sieve, then digested with $\text{H}_2\text{SO}_4\text{-H}_2\text{O}_2$, and the total nitrogen content of the samples was measured via AA3 continuous flow analyzer (SEAL AA3, Ludwigshafen, Germany). The nitrogen uptake of each organ was calculated by multiplying the dry matter weight with the total nitrogen content of the organ, whole-plant nitrogen accumulation was derived by summing all organ values, and the population-scale nitrogen accumulation was derived by multiplying the average nitrogen uptake of a single plant by the population density at each stage. The nitrogen allocation- and translocation-related calculation formulas [19] are as follows:

$$NA_T \text{ (kg ha}^{-1}\text{)} = NA_{\text{anthesis}} - NA_{\text{maturity, veg}} \quad (5)$$

$$NA_A \text{ (kg ha}^{-1}\text{)} = GNA_{\text{maturity}} - NA_T \quad (6)$$

$$\text{Contribution rate of pre-anthesis N to grain (\%)} = NA_T / GNA_{\text{maturity}} \times 100\% \quad (7)$$

$$\text{Contribution rate of post-anthesis N to grain (\%)} = NA_A / GNA_{\text{maturity}} \times 100\% \quad (8)$$

where NA_T is pre-anthesis nitrogen translocation (kg ha^{-1}); NA_{anthesis} is nitrogen accumulation at anthesis (kg ha^{-1}); $NA_{\text{maturity, veg}}$ is the nitrogen accumulation of the vegetative organs at maturity (kg ha^{-1}); NA_A is the post-anthesis nitrogen accumulation (kg ha^{-1}); and GNA_{maturity} is the grain nitrogen accumulation at maturity (kg ha^{-1}).

2.5. Grain Filling Characteristics

In each plot, 150 synchronously flowering spikes were tagged. Ten labeled spikes per treatment were sampled at six-day intervals from flowering to maturity. The sampled spikes underwent enzyme deactivation at 105 °C for 30 min (the early grains are too small to thresh, so they were first sterilized and then threshed), then at 80 °C until a constant

weight was recorded. Thousand-kernel weights (TKW) at 7, 14, 21, 28, and 35 days after anthesis were nonlinearly fitted using the logistic equation $y = a/(1 + be^{-cx})$. The grain filling characteristics were calculated using Equations (9)–(15) [20].

$$T_1 = (\ln b - 1.371)/c \quad (9)$$

$$T_{\max} = (\ln b)/c \quad (10)$$

$$T_2 = (\ln b + 1.371)/c \quad (11)$$

$$\Delta T = T_2 - T_1 \quad (12)$$

$$T_{\text{grain}} = (\ln b + 4.595)/c \quad (13)$$

$$G_{\text{mean}} = a/T_{\text{grain}} \quad (14)$$

$$G_{\max} = (a/10) \times [1 + (2T_{\text{grain}} - T_{\max})/(T_{\text{grain}}(T_{\text{grain}} - T_{\max}))] \times (T_{\max}/T_{\text{grain}})^{T_{\max}/(T_{\text{grain}} - T_{\max})} \quad (15)$$

where T_1 is the start time of rapid grain filling (d); $T_{\max}$ is the time of maximum grain filling rate (d); T_2 is the end time of rapid grain filling (d); ΔT is the duration of rapid grain filling (d); T_{grain} is the duration of grain filling (d); G_{mean} is the mean grain filling rate (mg grain⁻¹ d⁻¹); $G_{\max}$ is the maximum grain filling rate (mg grain⁻¹ d⁻¹).

2.6. Wheat Yield and Its Components

At maturity, 50 representative plants per plot were sampled for analysis to quantify spike number, grains per spike, and other indicators. Meanwhile, three representative 1 m² areas per plot were harvested [21]. Plot-harvested wheats were threshed individually, and kernels were placed in nylon mesh bags. After natural air-drying, they were recorded and converted to yield per unit area. Then thousand-kernel weights were determined by weighing three independent 1000-kernel samples from each mesh bag.

2.7. Resource Use Efficiencies

The total evapotranspiration was calculated via the soil water balance method. The formula is

$$ET_a = P + I + U - R - D - \Delta W \quad (16)$$

In the equation, ET_a represents actual evapotranspiration (total water consumption); P represents precipitation (mm); I represent irrigation amount (mm); U represents the water contribution from the crop rising through groundwater capillaries (mm); R represents surface runoff (mm); and D represents soil drainage (mm); ΔW is the difference between the soil water storage from post-harvesting to pre-sowing (mm). Due to the small irrigation quota of drip irrigation, R and D were 0. The groundwater depth is below 5 m, so U was 0.

Water use efficiency (WUE) was calculated by:

$$WUE \text{ (kg m}^{-3}\text{)} = 0.1 \text{ GY}/ET_a \quad (17)$$

where GY is the grain yield (kg ha⁻¹)

The nitrogen partial factor productivity (NPFP) can be calculated by:

$$NPFP \text{ (kg kg}^{-1}\text{)} = GY/N \quad (18)$$

where N is the nitrogen application rate (kg ha⁻¹).

2.8. Comprehensive Evaluation

The TOPSIS model evaluated multiple parameters throughout two winter wheat growing seasons using Equations (19)–(27). These included nitrogen, potassium, and phosphorus application rates; yield; total water consumption (0–100 depth) during crop whole growth; WUE; and NPFP.

The matrix of the evaluation indices (including the nitrogen, potassium, and phosphorus application rate; grain yield at maturity; the total water requirement throughout the growth stage of the crop; WUE; and NPFP) can be established with Equation (19).

$$X = (X_{ij})_{m \times n} \quad (19)$$

where m is the number of treatments, n is the number of the evaluation objectives, and X_{ij} is the j th indicator of the i th treatment.

To calculate the normalized matrix use the original data in Equation (20)

$$Z_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^m (X_{ij})^2}} \quad (i = 1, 2, 3, \dots, m); (j = 1, 2, 3, \dots, n) \quad (20)$$

Calculate the gap between each evaluation index and the optimal and worst vector using Equations (21) and (22)

$$D_i^+ = \sqrt{\sum_{j=1}^n w_j (Z_j^+ - Z_{ij})^2} \quad (21)$$

$$D_i^- = \sqrt{\sum_{j=1}^n w_j (Z_j^- - Z_{ij})^2} \quad (22)$$

where D_i^+ is the positive ideal solution distance of the i th treatment, D_i^- is the negative ideal solution distance of the i th treatment, and w_j is the weight of the j th index (the weight of each index is calculated by the entropy weight method, Equations (23)–(26), where Z_j^+ is the maximum value of the j th index, and Z_j^- is the minimum value of the j th index).

Calculate the weight of each index by the entropy weight method:

$$P_{ij} = \frac{Z_{ij}}{\sum_{i=1}^m Z_{ij}} \quad (23)$$

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m P_{ij} \ln P_{ij} \quad (24)$$

$$d_j = 1 - e_j \quad (25)$$

$$w_j = \frac{d_j}{\sum_{j=1}^n d_j} \quad (26)$$

where P_{ij} is the proportion of the j th index of the i th treatment, e_j is the entropy of the j th index, and d_j is the variation index of the j th index.

Calculate the comprehensive score of the treatments using Equation (27)

$$RC_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (27)$$

2.9. Statistical Analysis

Data processing and statistical analyses were performed using Excel 2016 (Microsoft Corporation, Albuquerque, NM, USA) and SPSS 25.0 software (IBM Corp., Armonk, NY, USA). All datasets underwent assessment for variance homogeneity and normality prior to analysis. Furthermore, ANOVA was conducted at the 0.05 significance level, followed by multiple comparisons using the least significant difference method. Moreover, linear fitting, logistic equation fitting, and other data visualizations were performed using Origin 2021 (Origin Lab Corporation, Northampton, MA, USA).

3. Results

3.1. Effect of Regulated Deficit Irrigation on Aboveground Dry Matter Mass of Winter Wheat at Different Soil Fertility Levels

As shown in Figure 3, the aboveground dry matter mass (DMM) of winter wheat exhibited a continuous increase from anthesis to the maturity stage during both the 2022–2023 and 2023–2024 growing seasons. On average, DMM increased by 29.48% from anthesis to the grain filling stage and by 21.85% from grain filling to maturity. Soil fertility had a significant effect on DMM ($p < 0.01$). Taking the maturity period as an example, compared to the CK treatment, the DMM of the F1, F2, and F3 treatments increased by 217.20%, 264.45%, and 302.62%, respectively. Although regulated deficit irrigation alone had no significant effect on DMM, its interaction with soil fertility was significant ($p < 0.01$). Specifically, compared to the WCK and WF1 treatments, the aboveground DMM of the DCK and DF1 treatments enhanced by 20.67% and 7.80%, respectively. Conversely, the aboveground DMM of the DF2 and DF3 treatments showed a 7.95% and 8.55% reduction compared to the WF2 and WF3 treatments, respectively. The highest DMM was observed under the WF3 treatment, reaching 22,810.11 kg ha⁻¹ and 22,441.97 kg ha⁻¹ in the 2022–2023 and 2023–2024 seasons, respectively. Meanwhile, the lowest DMM was recorded under the WCK treatment, at 5215.85 kg ha⁻¹ and 4356.76 kg ha⁻¹, respectively.

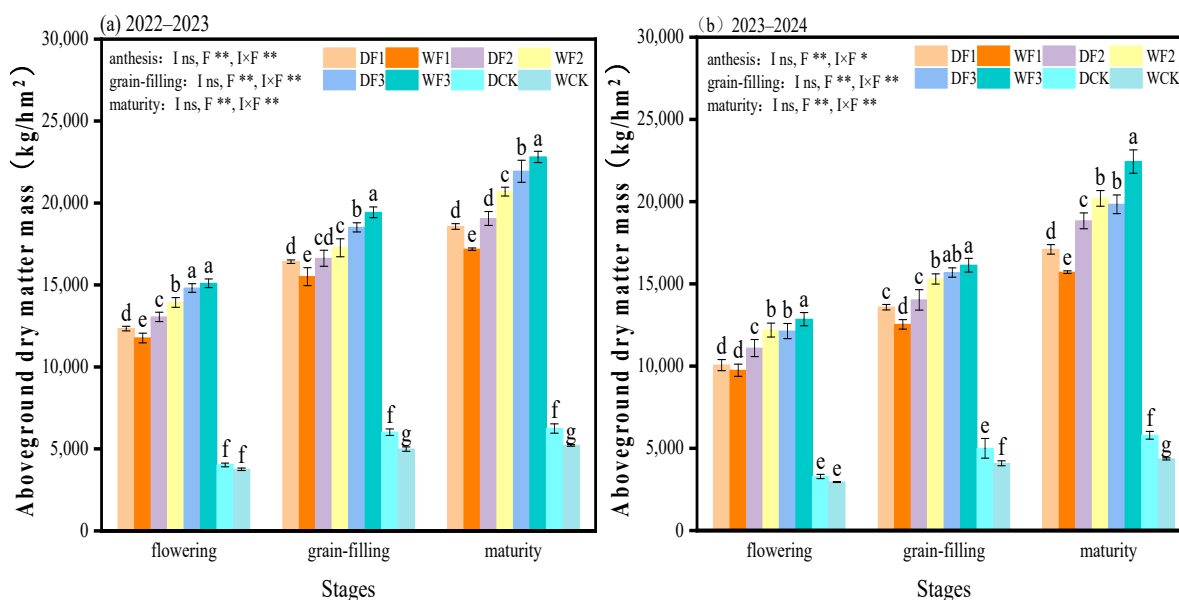


Figure 3. Effects of different treatments on aboveground dry matter mass of winter wheat at different growth stages in 2022–2024. “I” denotes the irrigation amount, “F” denotes fertilizer application. Different lowercase letters mean significant differences among treatments at $p < 0.05$; **, $p < 0.01$; *, $p < 0.05$; ns, $p > 0.05$. The same notation applies to the figures below.

3.2. Effect of Regulated Deficit Irrigation on Dry Matter Translocation and Distribution of Winter Wheat at Different Soil Fertility Levels

As shown in Figure S1, soil fertility had a marked impact on the allocation of dry matter among plant organs ($p < 0.05$). The stem proportion under the CK treatment was significantly larger than that under the F1, F2, and F3 treatments ($p < 0.05$), whereas the leaf proportion under the CK treatment was significantly lower than the others ($p < 0.05$), exhibiting a pattern of $CK < F1 < F2 < F3$ at maturity ($p < 0.05$). During the anthesis and grain filling periods, the spike proportion in the CK treatment was significantly larger compared to the other treatments; however, at maturity, the spike proportion in the CK treatment had decreased to the minimum. During the anthesis stage, water deficit had no marked impact on the proportion of stem, leaf, and spike. In contrast, water deficit significantly increased the proportions of leaf and grain at maturity ($p < 0.05$). Compared to the W treatment, the leaf and grain proportions under the D treatment enhanced by an average of 10.54% and 3.19%, respectively. Conversely, water deficit significantly reduced the stem proportion, with the D treatment showing an average decrease of 5.71% compared to the W treatment.

As shown in Table 2, the soil fertility significantly affected both DM_T and DM_A ($p < 0.05$). Compared to the CK treatment, the DM_T of the F1, F2, and F3 treatments enhanced by 238.16%, 266.96%, and 303.53%, respectively, while DM_A increased by 224.14%, 274.95%, and 322.66%, respectively. Water deficit increased DM_T and DM_A , but the effect was not significant. The interaction between water deficit and soil fertility had a marked influence on DM_A ($p < 0.05$). Specifically, compared to the WCK and WF1 treatments, DM_A increased by 65.20% under the DCK treatment and 16.60% under the DF1 treatment, respectively. However, DM_A decreased by 7.05% under the DF2 treatment and 14.22% under the DF3 treatment relative to the WF2 and WF3 treatments, respectively.

Table 2. Pre-anthesis dry matter translocation (DM_T), post-anthesis dry matter accumulation (DM_A), and their contribution rate to grain yield of winter wheat.

Year	Treatment	DM_T (kg ha ⁻¹)	DM_A (kg ha ⁻¹)	$DM_T/GDM_{maturity}$ (%)	$DM_A/GDM_{maturity}$ (%)
2022–2023	DF1	4438.42 bc	6225.59 cd	41.62 ab	58.38 ab
	DF2	4476.83 bc	5999.40 d	42.75 ab	57.25 ab
	DF3	5209.94 a	7129.17 b	42.25 ab	57.75 ab
	DCK	1321.88 d	2227.87 f	37.42 b	62.58 a
	WF1	4308.81 c	5415.91 e	44.33 a	55.67 b
	WF2	4847.57 ab	6763.28 bc	41.74 ab	58.26 ab
	WF3	4878.84 ab	7707.79 a	38.71 b	61.29 a
	WCK	1204.85 d	1461.28 g	44.94 a	55.06 b
	I	ns	ns	ns	ns
	F	**	**	ns	ns
	I × F	ns	**	*	**
2023–2024	DF1	2433.47 b	7039.97 c	25.69 bc	74.31 a
	DF2	3003.10 ab	7732.32 bc	27.96 bc	72.04 ab
	DF3	3495.85 a	7707.51 bc	31.31 b	68.69 b
	DCK	735.06 c	2507.90 e	22.66 c	77.34 ab
	WF1	2770.75 b	5960.86 d	31.71 ab	68.29 bc
	WF2	2812.21 b	8010.20 b	25.98 bc	74.02 ab
	WF3	3063.86 ab	9588.43 a	24.25 c	75.75 a
	WCK	863.90 c	1405.42 f	38.07 a	61.93 c
	I	ns	ns	ns	ns
	F	**	**	ns	ns
	I × F	ns	**	**	**

“I” denotes the irrigation amount, “F” denotes fertilizer application. Different lowercase letters mean significant differences among treatments at $p < 0.05$; **, $p < 0.01$; *, $p < 0.05$; ns, $p > 0.05$. The same notation applies to the tables below.

Neither water deficit nor soil fertility significantly affected $DM_T/GDM_{maturity}$ or $DM_A/GDM_{maturity}$; however, their interaction had a marked influence on both parameters ($p < 0.05$). Compared to the WCK and WF1 treatments, $DM_T/GDM_{maturity}$ decreased by 27.63% under the DCK treatment and by 11.48% under the DF1 treatment, respectively, while $DM_A/GDM_{maturity}$ increased by 19.61% and 7.07%, respectively. In contrast, the $DM_T/GDM_{maturity}$ of the DF2 and DF3 treatments increased by 4.41% and 16.85% relative to the WF2 and WF3 treatments, whereas $DM_A/GDM_{maturity}$ decreased by 2.26% and 8.90%, respectively, compared with the WF2 and WF3 treatments.

The results in Table S1 indicated that year had a significant effect on DM_T , DM_A , $DM_T/GDM_{maturity}$, and $DM_A/GDM_{maturity}$ ($p < 0.01$), and the effects of soil fertility, irrigation, and their interaction on these parameters were generally consistent with the findings in Table 2. However, irrigation had a significant effect on $DM_T/GDM_{maturity}$ and $DM_A/GDM_{maturity}$ ($p < 0.05$), which slightly differed from the results in Table 2. A significant interaction between year and soil fertility was observed for both DM_T and DM_A ($p < 0.05$). Notably, the three-way interaction among year, soil fertility, and irrigation had no significant effect on DM_T , $DM_T/GDM_{maturity}$, and $DM_A/GDM_{maturity}$, except for DM_A .

3.3. Effect of Regulated Deficit Irrigation on Total Nitrogen Content of Winter Wheat Plants at Different Soil Fertility Levels

As shown in Figure 4, the aboveground total nitrogen (N) content of winter wheat exhibited a continuous increasing trend from anthesis to maturity in both the 2022–2023 and 2023–2024 growing seasons. The average growth rate of total N content was 11.47% from anthesis to grain filling and 17.22% from grain filling to maturity.

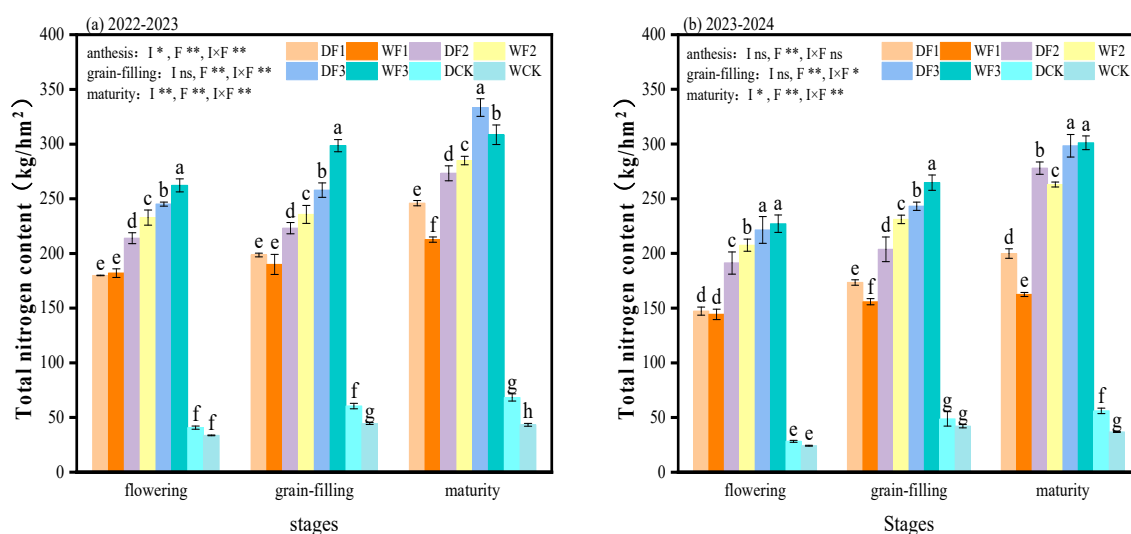


Figure 4. Effects of different treatments on total nitrogen in different growth stages of winter wheat in two growing seasons from 2022–2024.

Soil fertility significantly affected plant total N content ($p < 0.05$), except at the anthesis stage in 2023–2024. Water deficit and its interaction with soil fertility had a significant effect on the plant total N content ($p < 0.05$). Taking the maturity period as an example, compared to the CK treatment, plant total N content under the F1, F2, and F3 treatments increased by 301.38%, 437.26%, and 506.89%, respectively. Water deficit significantly increased plant total N content ($p < 0.05$), with an average increase of 8.72% under the D treatment compared to the W treatment. The highest plant total N content ($315.94 \text{ kg ha}^{-1}$) was recorded under the DF3 treatment, while the lowest (40.06 kg ha^{-1}) occurred under the WCK treatment.

3.4. Effect of Regulated Deficit Irrigation on the Proportion of Total Nitrogen Allocation in Various Organs of Winter Wheat at Different Soil Fertility Levels

As shown in Figure S2, the effect of soil fertility had a marked influence on the allocation of total nitrogen (N) among plant organs ($p < 0.05$), and the proportion of total N allocated to the spike reduced significantly with the increase in soil fertility level ($p < 0.05$), with the F1, F2, and F3 treatments decreasing by 13.20%, 19.41%, and 21.37%, respectively, compared to the CK treatment. Conversely, the proportions of total N in the stem and leaf significantly increased with the increase in soil fertility level ($p < 0.05$). Specifically, compared to the CK treatment, the stem total N proportion increased by 8.14%, 23.19%, and 27.42%, while the leaf total N proportion increased by 66.72%, 80.75%, and 85.97% under the F1, F2, and F3 treatments, respectively. Water deficit significantly affected the total N proportions in the stem and spike ($p < 0.05$), but not in the leaf. Compared to the W treatment, the D treatment exhibited an average increase of 3.82% in the spike total N proportion but a 10.69% decrease in the stem total N proportion.

As shown in Table 3, soil fertility significantly affected both NA_T and NA_A ($p < 0.05$). Compared to the CK treatment, the NA_T enhanced by 423.09%, 543.32%, and 617.93% under the F1, F2, and F3 treatments, respectively, while the NA_A enhanced by 115.45%, 225.69%, and 266.89%, respectively. Water deficit and its interaction with soil fertility also significantly affected both NA_T and NA_A ($p < 0.05$), except for NA_T in the 2023–2024 season. Compared to the W treatment, the D treatment exhibited a 3.47% decrease in NA_T and a 38.43% increase in NA_A .

Table 3. Pre-anthesis nitrogen translocation (NA_T), post-anthesis nitrogen accumulation (NA_A), and their contribution rate to grain nitrogen accumulation of winter wheat.

Year	Treatment	NA_T (kg ha ⁻¹)	NA_A (kg ha ⁻¹)	$NA_T/GNA_{maturity}$ (%)	$NA_A/GNA_{maturity}$ (%)
2022–2023	DF1	142.76 d	66.10 b	68.36 c	31.64 b
	DF2	170.83 c	59.30 bc	74.25 b	25.75 c
	DF3	185.46 b	88.35 a	67.75 c	32.25 b
	DCK	33.02 e	27.67 e	54.61 d	45.39 a
	WF1	144.51 d	30.71 e	82.50 a	17.50 d
	WF2	181.24 b	52.07 cd	77.67 ab	22.33 cd
	WF3	199.94 a	46.25 d	81.23 a	18.77 d
	WCK	27.39 e	9.7 f	73.94 b	26.06 c
	I	*	**	**	**
	F	**	**	**	**
	I × F	**	**	**	**
2023–2024	DF1	117.38 d	52.69 b	69.03 b	30.97 c
	DF2	138.98 c	86.69 a	61.56 c	38.44 b
	DF3	164.31 a	77.05 a	68.25 b	31.75 c
	DCK	21.02 e	27.84 c	43.06 d	56.94 a
	WF1	117.96 d	18.22 c	86.22 a	13.38 d
	WF2	151.70 b	55.48 b	73.23 b	26.77 c
	WF3	167.56 a	73.98 a	69.40 b	30.60 c
	WCK	18.48 e	12.65 c	59.39 c	40.61 b
	I	ns	**	**	**
	F	**	**	**	**
	I × F	ns	*	**	**

Soil fertility, water deficit, and their interaction significantly influenced both $NA_T/GNA_{maturity}$ and $NA_A/GNA_{maturity}$ ($p < 0.05$). Compared to the CK treatment, $NA_T/GNA_{maturity}$ enhanced by 32.69%, 24.12%, and 24.08% under the F1, F2, and F3 treatments, while $NA_A/GNA_{maturity}$ decreased by 44.68%, 32.97%, and 32.92%, respectively. Compared to the W treatment, the D treatment exhibited a 16.08% decrease in $NA_T/GNA_{maturity}$ but a 49.54% increase in $NA_A/GNA_{maturity}$.

The results presented in Table S2 showed that year had a significant effect on NA_T , $NA_T/GNA_{maturity}$, and $NA_A/GNA_{maturity}$ ($p < 0.01$), but not on NA_A . The effects on these parameters of soil fertility, irrigation, and their interaction were basically consistent with those reported in Table 3. The year $\times$ irrigation interaction had no significant effect on any of these indicators. However, both the year $\times$ soil fertility interaction and the three-way interaction among year, soil fertility, and irrigation significantly affected NA_T , NA_A , $NA_T/GNA_{maturity}$, and $NA_A/GNA_{maturity}$ ($p < 0.01$), except that the three-way interaction had no significant effect on NA_T .

3.5. Effect of Regulated Deficit Irrigation on the Grain Filling Characteristics of Winter Wheat at Different Soil Fertility Levels

As shown in Figure 5 and Table 4, the logistic equation was applied to model the dynamic changes in thousand-grain weight during the grain filling stage of winter wheat, and it was found that the fitted curve showed an “S” shape with R^2 value ranging from 0.986 to 0.999 ($p < 0.01$). Grain weight increased gradually during the initial phase, and then accelerated rapidly, and finally plateaued as maturity approached. Soil fertility significantly influenced the grain filling parameters ($p < 0.05$); the value of T_1 , T_{max} , T_2 , ΔT , and T_{grain} initially increased significantly with the enhancement of soil fertility levels, and then subsequently stabilized or slightly decreased. Compared to the CK treatment, the F1, F2, and F3 treatments showed increases of 15.87%, 19.76%, and 17.51% for T_1 ; 15.65%, 19.43%, and 18.84% for T_{max} ; 15.54%, 19.27%, and 19.49% for T_2 ; 15.22%, 18.80%, and 21.37% for ΔT ; and 14.82%, 19.09%, and 20.22% for T_{grain} . Water deficit suppressed T_1 , T_{max} , T_2 , ΔT , and T_{grain} , and particularly significantly affected T_{max} , T_2 , and T_{grain} in the 2023–2024 season ($p < 0.05$). While G_{mean} and G_{max} significantly reduced with the increase in soil fertility levels ($p < 0.05$), compared to the CK treatment, G_{mean} decreased by 11.59%, 15.82%, and 17.74% under the F1, F2, and F3 treatments, while G_{max} decreased by 11.06%, 15.19%, and 18.17%, respectively. Water deficit significantly enhanced G_{mean} and G_{max} ($p < 0.05$), compared to the W treatment; the D treatment showed an increase of 12.83% in G_{mean} and 4.78% in G_{max} .

Table 4. Estimation of grain filling parameters of winter wheat under different treatments.

Year	Treatment	T_1 (d)	T_{max} (d)	G_{mean} (g 1000 Grain ⁻¹ d ⁻¹)	T_2 (d)	G_{max} (g 1000 Grain ⁻¹ d ⁻¹)	ΔT (d)	R^2	T_{grain} (d)
2022–2023	DF1	13.02 c	19.57 d	11.36 b	26.13 cd	24.22 b	13.11 ab	0.99929 **	42.45 bc
	DF2	13.66 b	20.37 bc	10.97 c	27.07 bc	23.57 bc	13.41 a	0.99907 **	43.77 ab
	DF3	13.81 b	20.73 b	10.38 e	27.66 b	22.17 de	13.85 a	0.99712 **	44.90 ab
	DCK	13.72 b	19.77 cd	12.09 a	25.83 d	26.87 a	12.11 b	0.99941 **	40.90 cd
	WF1	15.06 a	22.05 a	10.78 cd	29.03 a	23.58 bc	13.97 a	0.99406 **	46.42 a
	WF2	14.08 b	20.88 b	10.58 de	27.68 b	22.85 cd	13.59 a	0.99781 **	44.59 ab
	WF3	13.87 b	20.59 b	9.85 f	27.31 bc	21.26 e	13.44 a	0.99820 **	44.04 ab
	WCK	12.12 d	18.19 e	12.35 a	24.26 e	26.37 a	12.14 b	0.99701 **	39.36 d
2023–2024	DF1	11.16 bc	17.10 c	13.32 b	23.04 c	27.93 ab	11.88 bc	0.99517 **	37.83 b
	DF2	11.29 bc	17.75 bc	12.51 bc	24.21 bc	25.70 bc	12.92 ab	0.99598 **	40.29 ab
	DF3	11.52 b	18.18 bc	12.02 cd	24.84 abc	24.62 c	13.32 ab	0.99713 **	41.42 ab
	DCK	8.21 d	13.32 d	14.91 a	18.43 d	29.92 a	10.22 c	0.99220 **	31.15 c
	WF1	10.63 c	17.13 c	12.17 c	23.62 c	24.54 c	12.99 ab	0.99606 **	39.79 ab
	WF2	12.51 a	19.34 a	11.28 d	26.16 a	23.49 c	13.64 ab	0.99811 **	43.14 a
	WF3	11.39 bc	18.44 ab	12.05 cd	25.50 ab	24.21 c	14.11 a	0.98826 **	43.06 a
	WCK	8.99 d	14.30 d	14.52 a	19.62 d	29.57 a	10.62 c	0.98602 **	32.83 c

Note: T_1 means the start time of rapid grain filling, T_{max} means the time of maximum grain filling rate, G_{mean} means the mean grain filling rate, T_2 means the end time of rapid grain filling, G_{max} means the maximum grain filling rate, ΔT means the duration of rapid grain filling, and T_{grain} means the duration of grain filling. Different lowercase letters indicate significant differences among treatments at $p < 0.05$.

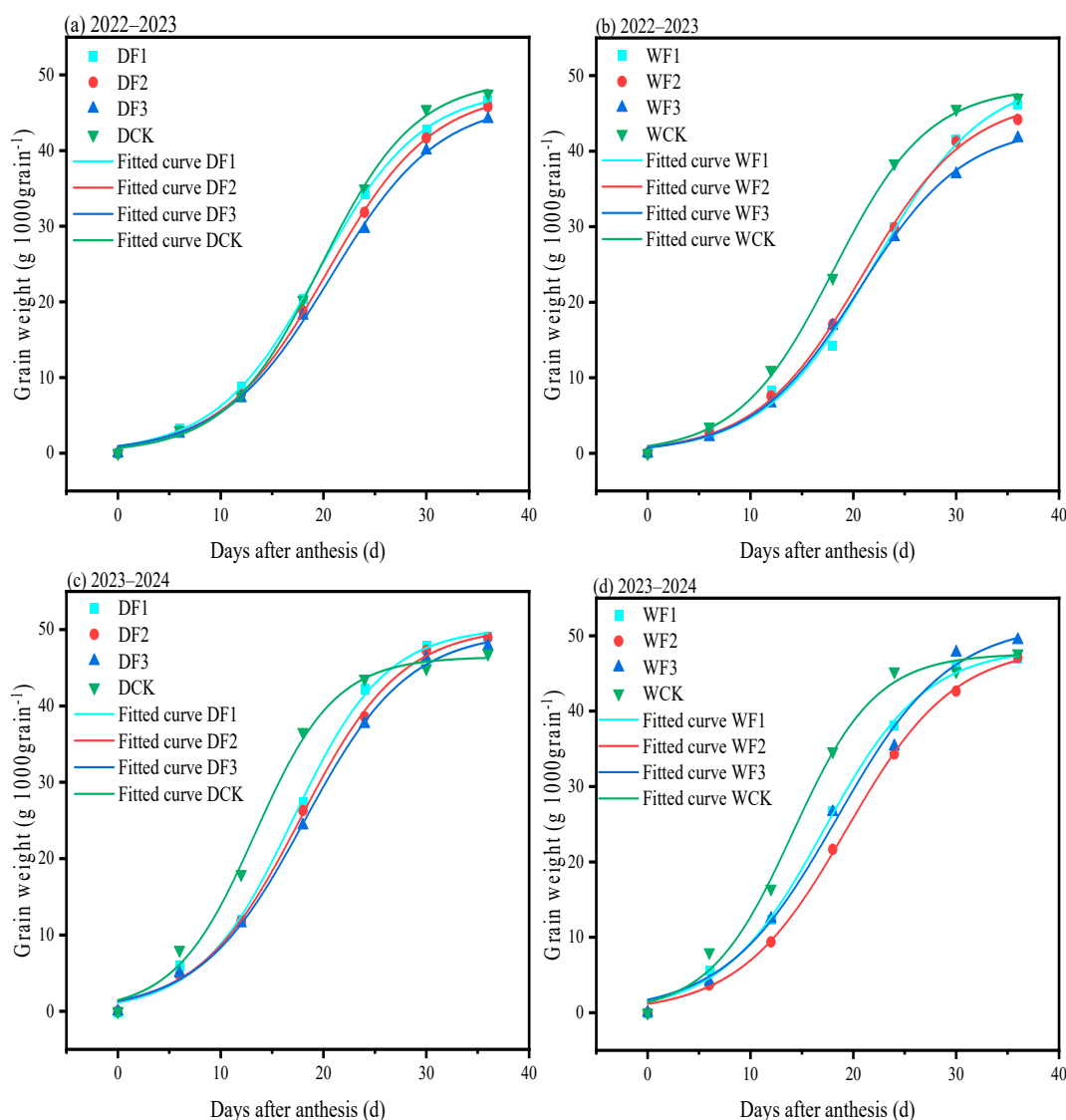


Figure 5. Effects of different treatments on grain filling of winter wheat in two wheat seasons from 2022–2024.

As shown in Table S3, year had a significant effect on G_{mean} , T_2 , G_{max} , ΔT , and T_{grain} ($p < 0.01$). The effects of soil fertility, irrigation, and their interaction on these parameters are generally consistent with the shown in Table 4. However, the effect of irrigation on ΔT differed from that reported in Table 4. A significant year and soil fertility interaction was observed for G_{mean} , T_2 , ΔT , and T_{grain} ($p < 0.05$), but not for G_{max} . Neither the year $\times$ irrigation interaction nor the three-way interaction among year, soil fertility, and irrigation had significant effects on G_{mean} , T_2 , G_{max} , ΔT , and T_{grain} , except that the three-way interaction significantly affected T_2 ($p < 0.05$).

3.6. Effect of Regulated Deficit Irrigation on Winter Wheat Yield Component, and Water and Nitrogen Use Efficiency at Different Soil Fertility Levels

As shown in Table S4 and Figure 6, soil fertility significantly affected winter wheat yield components ($p < 0.05$), whereas water deficit had no significant effect. Compared to the CK treatment, the thousand-kernel weight of the F1, F2, and F3 treatments reduced by 3.78%, 7.15%, and 7.47%, respectively. In contrast, grain number per spike increased by 120.15%, 125.16%, and 124.89%, while spike number increased by 93.78%, 115.40%, and 120.52%, respectively.

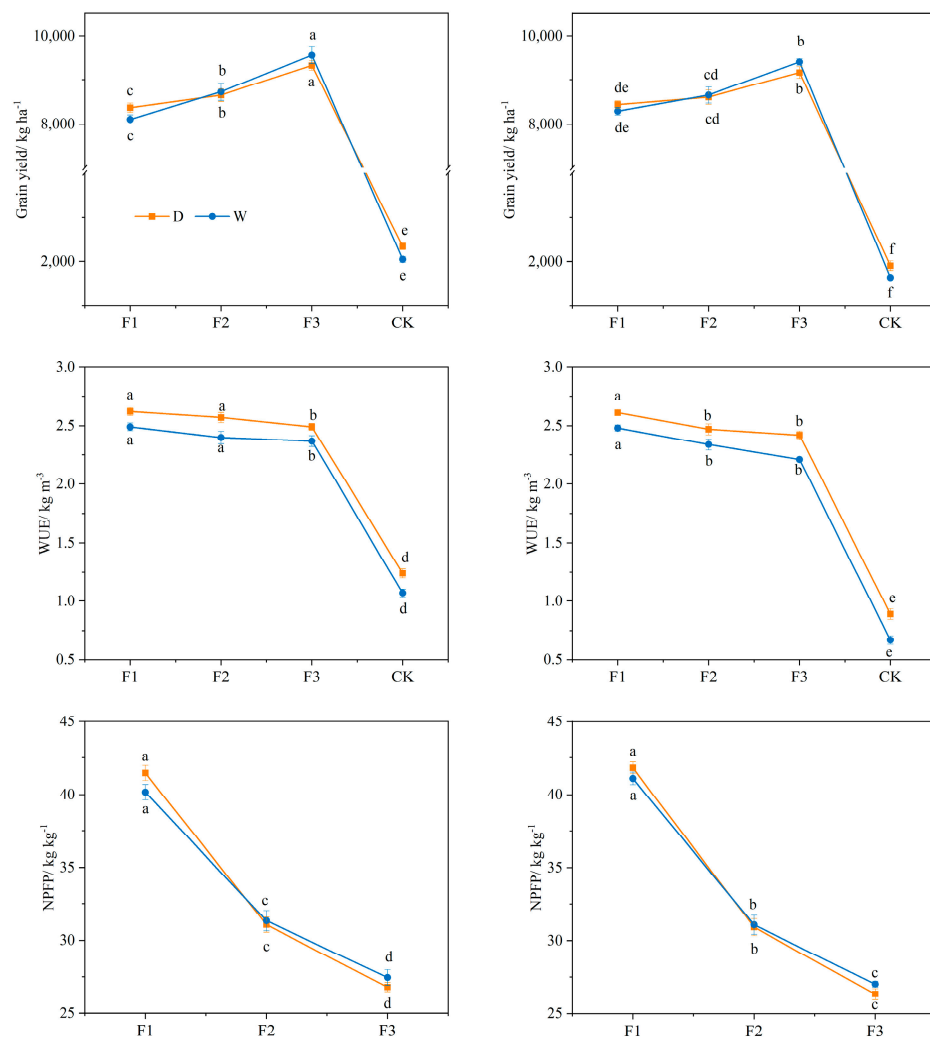


Figure 6. Grain yield, water use efficiency (WUE), and nitrogen partial factor productivity (NPFP) of winter wheat under the different water and fertilizer levels in 2022–2024. Different lowercase letters mean significant differences among treatments at $p < 0.05$.

Soil fertility and its interaction with water deficit had a marked impact on grain yield ($p < 0.05$), whereas water deficit alone had no significant influence. Compared to the CK treatment, the grain yield of the F1, F2, and F3 treatments enhanced by 275.87%, 296.41%, and 330.74% in 2022–2023, and by 371.40%, 386.35%, and 423.11%, respectively, in 2023–2024. Compared to the WCK and WF1 treatments, grain yield enhanced by 15.13% in the DCK treatment and 2.49% in the DF1 treatment. Meanwhile, the grain yield in the DF2 and DF3 treatments exhibited a decrease of 0.70% and 2.50%, respectively, relative to the WF2 and WF3 treatments.

Soil fertility and water deficit significantly affected WUE ($p < 0.05$); WUE initially enhanced and then reduced with the increase in soil fertility levels. Compared to the CK treatment, the WUE of the F1, F2, and F3 treatments showed an average reduction of 173.36%, 161.87%, and 153.37%, respectively, while the WUE of the D treatment increased by an average of 8.00% compared to the W treatment. Soil fertility and its interaction with water deficit had a marked impact on NPFP ($p < 0.05$), whereas water deficit alone had no significant effect. The NPFP reduced with the enhancement of soil fertility levels; the NPFP of the F1 and F2 treatments showed average increases of 53.19% and 15.78% relative to the F3 treatment. Additionally, the NPFP of the DF1 treatment increased by an average of 2.49% compared to the WF1 treatment, while the NPFP of the DF2 and DF3 treatments decreased by 0.69% and 2.24%, respectively, relative to the WF2 and WF3 treatments.

As shown in Table S5, year significantly influenced grain yield and WUE ($p < 0.01$), but had no significant effect on NPFP. The effects of soil fertility, irrigation, and their interaction on grain yield, WUE, and NPFP were consistent with those presented in Figure 6. Significant interactions between year and soil fertility were observed for grain yield, WUE, and NPFP ($p < 0.05$). However, neither the year $\times$ irrigation interaction nor the three-way interaction among year, soil fertility, and irrigation had significant effects on any of these parameters.

3.7. Comprehensive Evaluation

The TOPSIS method was employed to comprehensively evaluate key parameters, including the nitrogen, potassium, and phosphorus application rate; grain yield; total crop water requirement; WUE; and NPFP. The results reveal that the treatment ranking is DF1 > WF1 > DF2 > WF2 > DF3 > WF3 in both the 2022–2023 and 2023–2024 growing seasons (Table 5). This indicates that moderate water deficit enhanced the overall production benefits of winter wheat through optimized trade-off among grain yield, WUE, and NPFP. Although grain yield enhanced with the increase in soil fertility levels, it concurrently reduced WUE and NPFP. Therefore, implementing a moderate water deficit under the F1 soil fertility level during the anthesis to grain filling stage is considered the optimal water and fertilizer management strategy for winter wheat in this region, achieving the highest comprehensive benefits.

Table 5. TOPSIS-based comprehensive ranking values.

Year	Treatment	D^+	D^-	RC	Rank
2022–2023	DF1	0.282	0.941	0.769	1
	DF2	0.529	0.526	0.499	3
	DF3	0.867	0.344	0.284	5
	WF1	0.391	0.865	0.688	2
	WF2	0.608	0.418	0.407	4
	WF3	0.931	0.345	0.271	6
2023–2024	DF1	0.331	0.926	0.737	1
	DF2	0.564	0.476	0.458	3
	DF3	0.858	0.361	0.296	5
	WF1	0.395	0.880	0.690	2
	WF2	0.589	0.426	0.420	4
	WF3	0.916	0.381	0.294	6

Note: D^+ represents the distance between the evaluation object and the positive ideal solution, and D^- represents the distance between the evaluation object and the negative ideal solution; RC (relative closeness) is calculated as $RC = D^- / (D^+ + D^-)$.

4. Discussion

4.1. Effects of Regulated Deficit Irrigation on the Accumulation and Translocation of Aboveground Biomass and Total Nitrogen in Winter Wheat at Different Fertility Levels

Aboveground biomass accumulation is crucial for yield formation in winter wheat [22]. In the present study, dry matter mass increased significantly with increasing soil fertility levels ($p < 0.05$), which agreed with the findings of Si et al. [23], who demonstrated that nitrogen application significantly promoted dry matter accumulation. Similarly, total nitrogen content in aboveground tissues also increased with improved soil fertility ($p < 0.05$), indicating a continuous improvement in nitrogen supply capacity as fertility improved. This observation concurs with the results of Zhao et al. [17], who found that both plant nitrogen concentration and accumulation elevated significantly with higher nitrogen input. Moreover, soil fertility significantly modulated the impact of water deficit on dry matter accumulation ($p < 0.05$). Specifically, water deficit promoted the dry matter accumulation under low fertility conditions (CK and F1 treatment), whereas it inhibited

it under medium to high fertility levels (F2 and F3 treatment). This contrasting response may be attributed to greater transpiration rates and water consumption by wheat under high fertility conditions [24]. Interestingly, water deficit also enhanced nitrogen uptake and total nitrogen accumulation in the plants. This finding contrasts with the findings of Ye et al. [19], who suggested that sufficient irrigation improves nitrogen absorption. The apparent discrepancy may be explained by compensatory growth mechanisms following rehydration, which can mitigate or offset nitrogen loss during mild drought stress [25].

Dry matter allocation and translocation are critical factors for achieving high and stable wheat yields, and both irrigation and fertilization management play key roles in these processes [26]. Yan et al. [27] demonstrated that the applications of nitrogen, phosphorus, and potassium promoted the remobilization of nutrients from vegetative organs to grain, thereby increasing grain yield. In this study, higher soil fertility levels increased the proportions of dry matter in the spike and leaf, while reducing those in the stem at maturity. These findings agree with the results of Wu et al. [28], who concluded that nitrogen application enhanced dry matter translocation from the stem to grain, thereby increasing the demand for DM_T .

Soil moisture and nitrogen status also significantly influenced plant nitrogen accumulation, translocation, and allocation [29]. Our study reveals that increasing soil fertility decreased the proportion of nitrogen allocated to the spike, while significantly increased the proportion of total nitrogen in the stem and leaf. These findings are in line with the findings of Lemaire et al. [30], who concluded that both the accumulation and proportion of nitrogen in leaves elevated significantly with the enhancement of the nitrogen application rate, and the conclusion of Zhao et al. [16], who concluded that the proportion of nitrogen accumulation in nutrient organs elevated with increased nitrogen levels, thereby reducing the proportion of nitrogen apportioned to grains. Feng et al. [31] found that delayed supplementary irrigation during later growth stages, such as grain filling, could inhibit the translocation of assimilates to grain, ultimately diminishing the yield. Conversely, Fan et al. [32] reported that a certain degree of drought during critical growth phases can enhance assimilate remobilization and improve the harvest index. Yang et al. [33] observed that a water deficit during grain filling could increase the proportion of photosynthate allocated to the grain. These discrepancies are likely due to regional variation in climatic and soil conditions and cultivar characteristics. We observed that water deficit can improve the proportion of dry matter mass in the leaf and spike, and reduce that in the stem. This is basically in line with the conclusions of Zhuang et al. [10], who reported that under water deficit conditions, the proportion of dry matter allocated to the leaves and roots increases, whereas the proportion allocated to stems decreases.

Fertilization can increase yield by regulating the source–sink ratio [34]. This study demonstrated that DM_T , NA_T , DM_A , and NA_A all elevated significantly with the enhancement of soil fertility ($p < 0.05$), which agrees with the findings of Zhuang et al. [10], who reported that the DM_T and DM_A of winter wheat increase with the enhancement of nitrogen application rate; yield was determined by both DM_T and DM_A [35]. Yan et al. [36] and Zhang et al. [37] observed that reducing irrigation at anthesis promotes the photosynthate translocation to the spike, but significantly decreases the biomass accumulation and photosynthetic rate. Whereas, Bahrani et al. [38] concluded that drought stress enhances the translocation of photosynthate to the growth center, increases the pre-anthesis carbon pools, and improves the efficiency of post-anthesis dry matter translocation to the grain. Our study demonstrated that water deficit slightly increased DM_T , but suppressed NA_T , significantly during the 2022–2023 growing season ($p < 0.05$), which agrees with the findings of Li et al. [39], who revealed that water deficit impairs crop nitrogen use efficiency, thereby hindering plant nitrogen translocation and accumulation. Ali et al. [40] concluded

that the pre-anthesis dry matter translocation rate elevated with an increase in irrigation amount, whereas Lyu et al. [41] reported that both the pre-anthesis assimilate translocation rate and its contribution rate to grain reduce with the enhancing of the irrigation amount. Our results show that the effect of water deficit on $DM_T/GDM_{maturity}$ was affected by soil fertility level. Specifically, water deficit suppressed $DM_T/GDM_{maturity}$ under the CK and F1 treatments, but promoted it under the F2 and F3 treatments. Furthermore, water deficit suppressed $NA_T/GNA_{maturity}$, but significantly enhanced $NA_A/GNA_{maturity}$. These results may be due to the fact that water deficit inhibited the aboveground dry matter accumulation at anthesis, while it enhanced the post-anthesis nitrogen translocation from vegetative tissues to the grain [42].

4.2. Effect of Regulated Deficit Irrigation on Grain Filling Characteristics of Winter Wheat at Different Levels of Soil Fertility

Grain filling is a key agronomic trait of winter wheat, and both its duration and rate significantly affect the dynamic changes in grain weight [43]. Optimizing the quality of grain filling is essential for increasing grain weight and yield [44]. This process is influenced by soil moisture and nutrient management [45,46]. In the present study, we observed that T_1 , T_{max} , T_2 , ΔT , and T_{grain} initially increased and then gradually stabilized or slightly reduced with the increase in soil fertility level, which differed marginally from the conclusions of Yan et al. [27], who reported that T_{max} , T_2 , and T_{grain} increase with greater fertilizer input. Liang et al. [47] demonstrated that excessive nitrogen application could inhibit wheat grain filling, resulting in biomass and grain yield loss. Liu et al. [46] observed that G_{mean} reduces with the enhancement of nitrogen application, while G_{max} initially enhances and then slightly reduces with an increase in nitrogen application. In our study, both G_{mean} and G_{max} significantly decreased with increases in soil fertility levels ($p < 0.05$). These discrepancies among the studies may arise from the differences in crop varieties, irrigation approaches, and soil fertility levels. Shi et al. [48] found that water deficit would shorten the effective grain filling time and ultimately reduce the grain filling rate. Liu et al. [46] concluded that excessive irrigation would promote the vegetative growth of winter wheat, which was not conducive to source–sink conversion, and thus diminished the grain filling rate. In this study, we concluded that a moderate water deficit increased T_1 , slightly, shorten the ΔT , but significantly enhanced both G_{mean} and G_{max} ($p < 0.05$). These results are consistent with those of Ali et al. [49] and Zhang et al. [50], who revealed that a moderate deficit in irrigation effectively improved the G_{mean} and G_{max} of winter wheat, ultimately increasing grain yield.

4.3. Effect of Regulated Deficit Irrigation on Yield and Water and Nitrogen Use Efficiency of Winter Wheat at Different Fertility Levels

Water and fertilizer management are closely related to crop growth and development, as well as the yield component. Nitrogen fertilizer is of great significance for increasing crop yield; however, excessive or insufficient nitrogen application could reduce crop yield and nitrogen use efficiency [13,51]. Therefore, optimizing water and fertilizer strategies is critical for improving crop yield. This study demonstrated that the grain yield of winter wheat significantly elevated with the enhancement of soil fertility level ($p < 0.05$), primarily due to the increase in grain number per spike and total spike number. This finding basically concurs with the results of Li et al. [13], who concluded that high nitrogen application enhances the grain number per spike by elevating soil available nitrogen, ultimately improving wheat yield. The influence of water deficit on grain yield varied with soil fertility level; it increased yield under the CK and F1 treatments but diminished yield under the F2 and F3 treatments. This agrees with the conclusion of Zhao et al. [24], who found that plants under high-nitrogen conditions were more sensitive to drought stress due

to an increased transpiration area and higher water consumption. You et al. [52] observed that yield component (such as spike number, grain number per spike, and thousand-kernel weight) elevated with the enhancement of irrigation amount. However, our findings reveal that a moderate water deficit did not significantly diminish the yield components of winter wheat. This may be attributed to compensatory mechanisms triggered by rehydration following the water deficit period [53].

Resource use efficiency functions synergistically rather than independently, and there is an interaction between WUE and nitrogen use efficiency (NUE) in crops [54]. For winter wheat, both WUE and NUE are co-regulated by water management and soil fertility. Du et al. [55] demonstrated that WUE exhibits a parabolic change trend with the enhancement of nitrogen application, and that excessive nitrogen application is not conducive to improving WUE. Similarly, we revealed that WUE initially enhanced and then reduced with the increase in soil fertility levels. This may be attributed to the fact that a higher soil fertility level enhances water consumption to a greater extent than it increases yield [56]. The water deficit significantly increased WUE ($p < 0.05$), which was in line with the conclusions of Rathore et al. [57], Eissa et al. [58], Wang et al. [59], and Greaves et al. [60]. These studies concluded that the yield slightly decreases or even increases under moderate deficit irrigation, but the total irrigation amount is substantially reduced, ultimately improving WUE. This phenomenon primarily results from the ability of mild water stress to reduce transpiration rates while maintaining photosynthetic rate, thereby increasing WUE without significantly affecting yield [61,62].

As for nitrogen partial factor productivity (NPFP), our study found a significant decline with increasing soil fertility levels ($p < 0.05$), which concurs with the findings of Wang et al. [63] and Duan et al. [64]. Du et al. [65] demonstrated that a water deficit reduces the NUE, whereas, our results found that a water deficit increased NPFP under the F1 treatment, but decreased it under the F2 and F3 treatments. These results indicate that the effect of a water deficit on NPFP is significantly regulated by the soil fertility level ($p < 0.05$).

5. Conclusions

Increasing soil fertility significantly enhanced aboveground dry matter, total nitrogen content, and both pre- and post-anthesis dry matter accumulation ($p < 0.05$). Water deficit promoted DM_T and enhanced the allocation of dry matter and nitrogen to the spikes, while reducing their allocation to the stems. However, the effect of water deficit on the contribution of post-anthesis dry matter to the grain varied with soil fertility levels—increasing under the CK and F1 treatments, but decreasing under the F2 and F3 treatments. The contribution of post-anthesis nitrogen to the grain was significantly improved by the water deficit ($p < 0.05$). Higher fertility levels delayed the onset of grain filling, prolonged T_{grain} by 18.04%, and reduced G_{mean} by 15.05%. In contrast water deficit advanced the onset of grain filling, shortened T_{grain} by 3.28%, and increased G_{mean} by 12.83% ($p < 0.05$). The grain yield increased significantly with enhanced soil fertility ($p < 0.05$), reaching a maximum of 9505.42 kg ha⁻¹ under the WF3 treatment. Water deficit improved yield under the CK and F1 treatments, but reduced it under the F2 and F3 treatments. WUE showed a peak at moderate fertility levels and was significantly improved under deficit irrigation. NPFP declined with increasing fertility, but was enhanced by water deficit under the F1 treatment. TOPSIS revealed that applying a moderate water deficit during the heading to grain filling stage at an F1 fertility level achieved the optimal balance among grain yield, WUE, and NPFP. This provides a promising water–fertilizer management strategy for winter wheat production in the HHHP.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy15081874/s1>, Figure S1: Effects of different treatments on the allocation proportion of dry matter mass in different organs of winter wheat during different growth stages in 2022–2024; Figure S2: Effects of different treatments on the allocation proportion of total nitrogen content in different organs winter wheat during different growth stages in 2022–2024; Table S1: Yield component of winter wheat in 2022–2024.

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