Effects of Timing in Irrigation and Fertilization on Soil NO$_3^-$-N Distribution, Grain Yield and Water–Nitrogen Use Efficiency of Drip-Fertigated Winter Wheat in the North China Plain

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Abstract: In the North China Plain, drip irrigation is gradually used in winter wheat production, and the improper management of water and fertilizer aggravates the risk of crop instability and groundwater pollution. A lysimeter experiment with three levels of fertilization timing (T1 = beginning; T2 = middle; and T3 = end of the irrigation cycle) and two irrigation rates (W1 of 30 mm and W2 of 20 mm) was carried out to investigate the effects of irrigation rate and fertilization timing on the soil NO$_3^-$-N distribution, crop development, yield, and water–nitrogen usage efficiency of winter wheat. The results indicated that, under the condition of delayed fertilization timing (T2 and T3), the trend of NO$_3^-$-N migration to the edge of moist soil became more apparent. The treatments of irrigation rate and fertilization timing significantly affected the plant height, water–nitrogen utilization efficiency, aboveground biomass, grain yield, and leaf area index. The maximum grain yield of 7688.67 kg ha$^{-1}$ was found at W1T2, which had a nitrogen partial factor productivity (NPFP) of 32.04 kg kg$^{-1}$. Moreover, W1T2 did not result in a significant reduction in irrigation water use efficiency (IWUE) (4.27 kg m$^{-3}$) in comparison with other treatments (4.00–5.43 kg m$^{-3}$). Based on crop growth, N uptake, yield, IWUE, and NPFP, the irrigation rate of 30 mm combined with fertilization in the middle of the irrigation duration could be considered as suitable irrigation and nitrogen timing for drip-irrigated wheat.

Keywords: drip irrigation; winter wheat; fertilization timing; grain yield; irrigation water use efficiency; nitrogen partial factor productivity

1. Introduction

The North China Plain (NCP) is China’s major agricultural production and wheat growing area, and winter wheat is an important irrigated crop in China, making it essential to the country’s food security [1,2]. However, the annual rainfall can only provide 25–40% of the winter wheat’s water requirements [3]. Groundwater depletion caused by irrigation threatens the sustainability of agricultural production [4]. Poor grain yield, nitrogen (N) absorption, and nitrogen-use efficiency (NUE) could be attributed to the soil water deficit [5]. According to studies, excessive N application wastes resources and causes economic losses, as well as polluting the groundwater [6]. Therefore, appropriate water and N management is critical for increasing N absorption, water–nitrogen use efficiency, and grain yield [2,7,8].

Drip irrigation as one of the crucial water-saving irrigation technologies is advantageous in saving water and fertilizer resources [9–13]. Moreover, drip irrigation increases crop yield, decreases crop water requirement, and reduces tillage costs and fertilizer application rates [14]. Fang, et al. [15] found that drip irrigation could provide sufficient...
moisture to the crop root zone, thereby improving water use efficiency (WUE) and grain yield. According to recent studies, irrigation and nitrogen management measures are needed to boost winter wheat production and WUE in the NCP [16]. Several studies suggested that drip irrigation significantly reduced the application of water and fertilizers and increased crop yields and WUE [2,16]. These studies indicated that drip irrigation has great potential for the sustainable development of agriculture in the NCP.

Nitrogen is an important input in agricultural production and significantly contributes to improving nutrient utilization and yield formation [17]. However, the use of nitrogen has been demonstrated to instigate NO\textsubscript{3}−-N leaching in the NCP, which can adversely affect the environment and groundwater [18]. Li, et al. [19] investigated the process of soil N movement and distribution under drip irrigation and indicated that after fertilization, NO\textsubscript{3}−-N concentrated near the borders of wetted soil spaces. Shang Shilong, et al. [20] confirmed this view in the study of a two-point source of drip irrigation that mainly focused on soil water–nitrogen transport with less emphasis on the fertigation strategies, crop nitrogen uptake, and utilization. Therefore, it is essential to understand the effects of drip irrigation and fertilization timing on crop yield, the utilization efficiency of water and N, and nitrate–nitrogen distribution in the soil profile.

However, the ideal irrigation water and fertilization timing for drip-fertigated winter wheat remains unknown, and more research is needed to establish a water–nitrogen management strategy for winter wheat cultivation in the NCP. Therefore, the objectives of this study were to (1) examine the effects of different irrigation rates and fertilization times on the plant height, leaf area index (LAI), aboveground biomass, grain yield and water–nitrogen usage efficiency; and to (2) develop an ideal irrigation and fertilization timing for drip-fertigated wheat cultivation that can boost winter wheat yield while reducing N loss.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted from October 2020 to May 2021 at the Experimental Station of the Institute of Farmland Irrigation, CAAS. The station is located in Qiliying town, Xinxiang city of Henan Province (35°08′ N, 113°54′ E and 81 m altitude). With an annual average temperature of 14 °C, the location’s climate is temperate, continental, and monsoonal. The frost-free period is 210 days, sunshine duration is 2399 h, and evaporation is 2000 mm.

2.2. Experimental Design

The experiment was carried out in lysimeters under a movable rain shelter. The rain shelter was used to protect the plots against rainfall and effectively control the influence of rainfall on the experimental results. Three lysimeters were used per treatment, each lysimeter had an area of 2.0 m (width) by 3.33 m (length), and the soil depth was 2.0 m. The lysimeters were filled with a loam soil with a bulk density of 1.51 g cm\textsuperscript{-3} and field capacity of 0.311 cm\textsuperscript{3} cm\textsuperscript{-3}. The average soil organic mass and available N, P, and K in the 0–100 cm soil layer were 7.8 g kg\textsuperscript{-1}, 21.62 mg kg\textsuperscript{-1}, 4.96 mg kg\textsuperscript{-1}, and 79.24 mg kg\textsuperscript{-1}, respectively.

The experiment consisted of two factors, i.e., irrigation rate and fertilization timing. The irrigation rate was designed with two levels: W1-30 mm and W2-20 mm, respectively. The timing of fertilization was divided into three levels, as shown in Figure 1: T1—fertilizer applied at 15 min after the irrigation; T2—fertilizer applied in the middle of the irrigation cycle; and T3—fertilizer applied at 15 min before the end of the irrigation cycle, respectively. There were six treatments in total and each treatment was repeated three times. The irrigation duration of W1 and W2 was 3 and 2 h, respectively, and the fertilization duration was 20 min. Nitrogen fertilizer was mixed with irrigation water using a fertilization pump.

The wheat variety (Zhoumai 22) was planted in the lysimeters with 10 rows spaced at 20 cm. The wheat was irrigated by a surface drip irrigation system with a 30 cm emitter spacing, a discharge rate of 2.2 L h\textsuperscript{-1}, and a lateral spacing of 60 cm. Urea (46.7% N), calcium superphosphate (14% P\textsubscript{2}O\textsubscript{5}), and potassium sulfate (50% K\textsubscript{2}O) were used as N, P,
and K fertilizers, respectively. Phosphorous and potassium were applied at rates of 120 kg ha$^{-1}$ and 105 kg ha$^{-1}$ as basal fertilizers. The seasonal amount of N fertilizer was 255 kg ha$^{-1}$ (applied four times), of which 40% was base fertilizer and the remaining 60% was split three times through top-dressing after the wheat returning green. The scheduling of drip fertigation during the wheat season is shown in Table 1.

![3 h irrigation cycle](image)

**Figure 1.** The specific scheduling of irrigation and fertilization at W1 and W2: W1 = irrigation rate of 30 mm; W2 = irrigation rate of 20 mm; T1 = fertilization time at the beginning of irrigation; T2 = fertilization time in the middle of irrigation; T3 = fertilization time at the end of irrigation.

| Treatment | 17 October 2020 | 9 December 2020 | 3 March 2021 | 22 March 2021 | 8 April 2021 | 25 April 2021 | 6 May 2021 |
|-----------|----------------|----------------|-------------|--------------|-------------|-------------|-----------|
| W1 T1 Basal dressing | Irrigate 30 mm | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N |
| W1 T2 Basal dressing | Irrigate 30 mm | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N |
| W1 T3 Basal dressing | Irrigate 30 mm | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N | Irrigate 30 mm and apply N |
| W2 T1 Basal dressing | Irrigate 20 mm | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N |
| W2 T2 Basal dressing | Irrigate 20 mm | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N |
| W2 T3 Basal dressing | Irrigate 20 mm | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N | Irrigate 20 mm and apply N |

Note: W1 = irrigation rate of 30 mm; W2 = irrigation rate of 20 mm; T1 = fertilization time at the beginning of irrigation; T2 = fertilization time in the middle of irrigation; T3 = fertilization time at the end of irrigation.

2.3. Methods of Sampling and Analysis

2.3.1. Soil Nitrate Nitrogen ($\text{NO}_3^-$-N)

Soil samples were taken 6 h after each irrigation and fertilization scenario. The sampling points were placed 10 cm away from the emitter. The samples were taken in vertical and horizontal directions in reference to the lateral direction. The soil was extracted using an auger with a diameter of 2 cm. The plan for soil sampling points is shown in Figure 2. The soil samples were collected from the 60 × 60 cm area at three different depths (0–20, 20–40, and 40–60 cm) and were used to determine the $\text{NO}_3^-$-N content via an AAR flow analyzer (AAR-HR SEAL ANALYTICAL—USA).

2.3.2. Plant Height and Leaf Area Index (LAI)

After the wheat returning green, plant height and leaf area were determined manually every 7 to 10 days. At each sampling date, ten plants were selected from each lysimeter for the measurement of plant height and leaf area. Then, the LAI was calculated based on leaf area and population density, as described by Zain, Si, Li, Gao, Mehmood, Rahman, Mounkaila Hamani and Duan [16].
2.3.3. Aboveground Biomass and Total Nitrogen Content

The plant samples were collected on the same day as the plant height measurement to determine aboveground biomass and total N content. Fresh samples were dried in the oven at 105 °C for 0.5 h then at 75 °C for 12 h. The plant samples were boiled with H2SO4-H2O2 and the total N content was determined using the AA3 flow analyzer (Seal, Germany).

2.3.4. Grain Yield and Yield Compositions

Three replications of the sample within a 1 m² area of wheat were taken at grain maturity to determine grain yield and composition. After natural air drying, the grains were weighed and translated into yield per acre. A 1 m row of wheat plants was taken from each plot to count the number of spikes and kernels per spike. Weighing 1000 seeds from the yield measurement samples yielded the 1000-grain weight.

2.4. Irrigation Water–Nitrogen Use Efficiencies

Irrigation water use efficiency and nitrogen use efficiency were calculated as follows:

\[ \text{IWUE} = 0.1Y/I \]  \hspace{1cm} (1)

\[ \text{NPFP} = \frac{Y}{N} \times 100\% \]  \hspace{1cm} (2)

where IWUE = irrigation water use efficiency (kg m⁻³); Y = grain yield (kg ha⁻¹); I = irrigation water applied (mm); NPFP = nitrogen partial factor productivity (kg kg⁻¹); and N = nitrogen application rate (kg ha⁻¹).

2.5. Statistical Analyses

The collected data were organized and calculated in Excel 2016 and a 2D contour map of the soil nitrate–nitrogen distribution was created using the Kriging interpolation method. To evaluate the impacts of water application rates and fertilization timing on wheat growth, grain yield, IWUE, and NPFP, an analysis of variance (ANOVA) was performed in SPSS 24.0 using the general linear model procedure. Duncan’s multiple range test was used to separate significant means at the 5% and 1% significance levels.

3. Results

3.1. Distribution of Soil Nitrate Nitrogen

After the application of irrigation water and N fertilizer, soil nitrate–nitrogen tended to migrate to the edge of moist soil, as shown in Figure 3. With the advance of fertilization timing, the trend of NO₃⁻-N migration to the humid edge became increasingly obvious. Under the fertilization timing of T1, the 40–60 cm soil layer distributed a higher proportion of soil nitrate–nitrogen, i.e., 28.68% and 31.55% at W1T1 and W2T1 (Table 2), respectively,
compared with the timings of T2 and T3. As soil water and nitrate-nitrogen continued to move to the deeper soil, the risk of N leaching was relatively high for the fertilization timing of T1. However, in the treatments at T2 and T3, the NO$_3^-$-N content within the 40–60 cm soil layer was less than 20%, indicating a lower risk of N leaching.

Table 2. Soil NO$_3^-$-N ratios at different layers in different treatments at the wheat jointing stage.

| Treatment | Soil Layer      | 0–20 cm | 20–40 cm | 40–60 cm |
|-----------|----------------|---------|----------|----------|
| W1 T1     |                | 45.32%  | 26.00%   | 28.68%   |
| W1 T2     |                | 46.26%  | 34.77%   | 18.96%   |
| W1 T3     |                | 65.30%  | 22.70%   | 11.99%   |
| W2 T1     |                | 45.33%  | 23.12%   | 31.55%   |
| W2 T2     |                | 57.95%  | 26.52%   | 15.53%   |
| W2 T3     |                | 58.38%  | 29.94%   | 11.68%   |

Note: W1 = irrigation rate of 30 mm; W2 = irrigation rate of 20 mm; T1 = fertilization time at the beginning of irrigation; T2 = fertilization time in the middle of irrigation; T3 = fertilization time at the end of irrigation.

The soil NO$_3^-$-N accumulation zone at T3 ranged between 15 and 30 cm from the drip line horizontally (Figure 3). Under W1T3 and W2T3, the fraction of the soil NO$_3^-$-N content distributed within the 0–20 cm soil layer was 65.30% and 58.38%, respectively (Table 2), indicating the high potential of nitrogen loss through emissions. Under the fertilization timing of T2, the soil NO$_3^-$-N content in the topsoil was greater than that at T1 but lower than that at T3. Moreover, at T2, the soil NO$_3^-$-N distribution within the 0–60 cm soil layer was more uniform as compared to T1 and T2 (Figure 3).
3.2. Plant Height, Leaf Area Index and Aboveground Biomass

The winter wheat plant height, LAI, and aboveground biomass were significantly affected by irrigation levels (Figure 4). The irrigation treatment, W1, was higher in plant height, LAI, and aboveground biomass, W2. Fertilization timing (T) and irrigation rate (W), as well as T × W, had significant effects on aboveground biomass. The plant height, LAI, and aboveground biomass at T2 were greater than those at T1 and T3 to varying degrees. Plant height was significantly affected by the interaction between irrigation and fertilization timing. The maximum plant height, LAI, and aboveground biomass values were 74.4 cm, 4.7, and 14,337.9 kg ha⁻¹, respectively, which were measured at W1T2.

![Figure 4](image)

3.3. Grain Yield and Composition

Irrigation and fertilization timing significantly affected the grain yield, spike number, kernels per spike, and the 1000-grain weight (Table 3). These indexes were greater at W1 than at W2. The grain yield, spike number, kernels per spike, and 1000-grain weight at T2 were higher than those at T1 and T3. However, there was no significant difference between T1 and T3. The interaction between irrigation and fertilization timing only significantly affected kernels per spike (Table 3). The grain yield, spike number, kernels per spike, and the 1000-grain weight at W1T2 were higher than those in other treatments, and the yield at W1T2 was 7688.67 kg ha⁻¹. The lowest grain yield of 6103.83 kg ha⁻¹ was obtained at W2T3.
Table 3. Effects of different treatments on grain yield and its components of winter wheat.

| Treatment | Grain Yield (kg ha\(^{-1}\)) | Spike Number (10\(^4\) ha\(^{-1}\)) | Kernels per Spike | 1000-Grain Weight (g) |
|-----------|-------------------------------|---------------------------------|------------------|----------------------|
| W1 T1     | 7204.93 b                     | 512.33 b                        | 39.50 bc         | 48.41 b              |
| W1 T2     | 7688.67 a                     | 596.00 a                        | 46.00 a          | 52.13 a              |
| W1 T3     | 7270.37 b                     | 518.33 b                        | 41.10 b          | 48.47 b              |
| Average   | 7387.99                       | 542.22                          | 42.2             | 49.67                |
| W2 T1     | 6119.50 d                     | 422.67 c                        | 37.6 c           | 45.25 c              |
| W2 T2     | 6512.27 c                     | 506.33 b                        | 40.03 bc         | 47.88 b              |
| W2 T3     | 6103.83 d                     | 422.33 c                        | 34.33 d          | 46.94 bc             |
| Average   | 6245.2                        | 450.44                          | 37.32            | 46.69                |

Note: W1 = irrigation rate of 30 mm; W2 = irrigation rate of 20 mm; T1 = fertilization time at the beginning of irrigation; T2 = fertilization time in the middle of irrigation; T3 = fertilization time at the end of irrigation. Values are means (n = 3). Different letters represent significant differences at p < 0.05. NS means p > 0.05, the difference is not significant. * and ** means significant difference at the p < 0.05 and p < 0.01 levels, respectively.

3.4. N Uptake, IWUE, and NPFP

Irrigation and fertilization timing significantly affected N uptake by stems and leaves, total N uptake by the aboveground straw, NPFP, and IWUE of winter wheat (Table 4). Except for IWUE, all indexes at W1 were higher than the values at W2. IWUE at W2 was greater than that at W1, indicating that appropriate deficit irrigation could enhance the utilization efficiency of irrigation water. Across all fertilization timings, either at W1 or W2, N uptake by stems and leaves, total N uptake by aboveground straw, NPFP, and IWUE of T2 were greater than those at T1 and T3 (Table 4). The peak values of N uptake by stems and leaves, total N uptake by aboveground straw, and NPFP (W1T2) were 69.13 kg ha\(^{-1}\), 332.55 kg ha\(^{-1}\), and 32.04 kg kg\(^{-1}\), respectively, and the maximum value of IWUE was 5.43 kg m\(^{-3}\) (W2T2). The interaction between irrigation and fertilization timing significantly affected the N uptake by stems and leaves and total N uptake by aboveground straw.

Table 4. Effects of irrigation rate and fertilization timing on N uptake, irrigation water use efficiency (IWUE), and nitrogen partial factor productivity (NPFP) of winter wheat.

| Treatment | N Uptake by Stems and Leaves (kg ha\(^{-1}\)) | N Uptake by Total Aboveground (kg ha\(^{-1}\)) | NPFP (kg kg\(^{-1}\)) | IWUE (kg m\(^{-3}\)) |
|-----------|-----------------------------------------------|-----------------------------------------------|------------------------|----------------------|
| T1        | 58.66 b                                       | 272.44 b                                      | 30.02 b                | 4.00 d               |
| W1 T1     | 69.13 a                                       | 332.55 a                                      | 32.04 a                | 4.27 c               |
| W1 T2     | 49.94 c                                       | 263.15 b                                      | 30.29 b                | 4.04 d               |
| Average   | 59.24                                         | 289.38                                        | 30.78                  | 4.10                 |
| T2        | 36.42 de                                      | 187.50 d                                      | 25.50 d                | 5.10 b               |
| W2 T1     | 41.41 d                                       | 234.98 c                                      | 27.13 c                | 5.43 a               |
| W2 T2     | 34.55 e                                       | 188.59 d                                      | 25.43 d                | 5.09 b               |
| Average   | 37.46                                         | 203.69                                        | 26.02                  | 5.21                 |

Note: W1 = irrigation rate of 30 mm; W2 = irrigation rate of 20 mm; T1 = fertilization time at the beginning of irrigation; T2 = fertilization time in the middle of irrigation; T3 = fertilization time at the end of irrigation. Values are means (n = 3). Different letters represent significant differences at p < 0.05. NS means p > 0.05, the difference is not significant. * and ** means significant difference at the p < 0.05 and p < 0.01 levels, respectively.

4. Discussion

4.1. Distribution of Soil Nitrate Nitrogen

Soil is the main domain of nitrogen absorption and utilization by crops, and nitrate-nitrogen (NO\(_3^-\)-N) affects plants’ absorption of water and nutrients [21]. Previous research has shown that the appropriate timing of nitrogen application can promote water-nitrogen
absorption and utilization in winter wheat fields [16,22], while the excessive application of nitrogen has negative effects on the soil–plant system, leading to N fertilizer waste, as well as environmental and groundwater resource pollution [23]. In this study, the soil NO$_3^-$-N concentration at the edge of moist soil was quite high, but the NO$_3^-$-N concentration inside the moist soil was low (Figure 2). The results indicated that NO$_3^-$-N usually accumulates at the edge of moist soil, which agrees with the findings of Badr, M. et al. [24] and Zhang, Y. et al. [25]. Nitrate–nitrogen can easily dissolve in water and it is rarely absorbed by the soil particles, but usually moves with the soil water during the convection process. In addition, during the irrigation and fertilization event, the soil water content below the emitter was the maximum, and a local anaerobic environment was formed, which led to the decrease in NO$_3^-$-N content at these points [26]. Our results also indicated that, as the fertilization sequence proceeded, the proportion of NO$_3^-$-N in the topsoil decreased, and the trend of NO$_3^-$-N migration to the edge of the moist soil became increasingly obvious (Figure 2). Weihao, et al. [27] found that for sandy, loam, and clay soil, the best timing for fertilization under drip fertigation was 3/8 way after the irrigation has commenced in the first half and the middle half, reducing the risk of nitrogen leaching. In a study of dual point sources of drip irrigation, Shang et al. [20] reported that fertilization in the middle of the irrigation duration can reduce the leaching loss of NO$_3^-$-N and improve NUE. Excessive irrigation causes deep percolation, which leads to the leaching of NO$_3^-$-N into the deep soil layers, potentially increasing the danger of groundwater contamination [28,29]. Consequently, appropriate irrigation and timing of fertilization could reduce the risk of groundwater contamination by slowing NO$_3^-$-N migration to deep soil.

4.2. Crop Growth and Grain Yield

The plant height, LAI, and aboveground biomass are key measures of crop development and growth. Previous studies have revealed that water and fertilizers are necessary for crop growth [30,31], and N availability had a positive effect while water stress had a negative effect on crop growth [32]. In agreement with these facts, our results showed that increasing irrigation rate could significantly improve wheat height, LAI, and aboveground biomass. As N application has a characteristic pattern of impacts on crop growth and yield regulation [33,34], the quantity of fertilizer available for absorption can directly influence crop growth and development, and hence the crop yield [35].

The goal of the current study was to quantify the appropriate irrigation rate and fertilization timing for drip-irrigated wheat that enhances the grain yield. Based on the results of the current study, it is proposed that an irrigation rate of 30 mm could be regarded as an ideal irrigation scheduling to achieve a high grain yield, mainly due to the greater yield components (Table 3). This finding supports the results of Si et al. [2], which demonstrated that yield attributes, such as spike length, number of grains per spike, and 1000-grain weight, increased at a higher irrigation rate. Liu et al. [31] suggested that a higher irrigation quota might increase the root growth and root weight density and promote the absorption of water and fertilizer by roots, which could be responsible for improved grain yield. The timing of fertilization also played an important role in improving yield. The results showed that fertilization at the middle stage of each irrigation event was beneficial to the yield of winter wheat, and the main reason for this was that the spike number, grain number per spike, and 1000-grain weight were significantly increased (Table 3). Li, et al. [36] also stated that fertilization at the middle stage of the irrigation duration might increase root weight density and promote photosynthesis, which could be responsible for improving yield. It could be observed that grain yield at W1T2 was only 5–7% greater than that of other treatments, which may be due to the fact that our test site was conducted in the pit and the test area was small, so the difference was not very large.

4.3. NPFP, IWUE, and Their Combined Effects

Improving water–nitrogen utilization efficiency is advantageous to the rational use of agricultural resources. In our research, we found that water–nitrogen management at
W1T2 significantly improved the N absorption and NPFP of winter wheat (Table 4). Soil moisture can significantly influence the availability of soil nitrogen, and the presence of a precise amount of water content in the soil promotes N absorption while also improving the absorption and use of soil water storage [37], which generally supports our results. In our study, as the increasing irrigation improved grain yield, IWUE decreased as irrigation water increased; this result is in agreement with Si et al. [22] and Dar et al. [10]. Although the treatment with a low irrigation rate had a high value of IWUE, significant decreases in aboveground biomass, yield, and NPFP were observed.

5. Conclusions

The combination of fertilization at the middle stage of the irrigation event and at an irrigation rate of 30 mm consistently improved wheat growth and resulted in high grain yield, IWUE, and NPFP. With the objective of improving yield while conserving water and fertilizer, as well as reducing the risk of groundwater pollution, fertilization at the middle stage of the irrigation event could be considered as the best nitrogen management scheme. More research is needed to investigate the interactions between irrigation and nitrogen application strategies for drip-irrigated winter wheat in the NCP and other locations with various kinds of irrigation quotas and timings of fertilization in different soils.

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