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ORIGINAL PAPER

Optimized Drip Fertigation Scheduling Improves Nitrogen Productivity of Winter Wheat in the North China Plain

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Abstract

Traditional methods of water and fertilizer application are the main cause of nitrogen (N) losses through ammonium volatilization, leaching, and greenhouse gas emissions. This problem could be addressed with the use of drip fertigation techniques, which ensure the integration of irrigation and fertilization technologies. However, current results on drip fertigation scheduling of winter wheat (*Triticum aestivum* L.) under a single nitrogen application rate are lacking. A 2-year field experiment was conducted to determine the responses of wheat yield, nitrogen uptake, and nitrogen use efficiency (NUE) indices to different fertigation schedules under a drip irrigation system. A total of 240 kg N ha^{-1} was split between sowing (basal N), jointing (first topdressing N), and booting (second topdressing N) stages. The treatments were N0-0 (0% basal and 0% topdressing), N0-100 (0% basal and 100% topdressing), N25-75 (25% basal and 75% topdressing), N50-50 (50% basal and 50% topdressing), N75-25 (75% basal and 25% topdressing), and N100-0 (100% basal and 0% topdressing). The grain yield (GY) obtained in the N50-50 was significantly higher than that in the N0-100 (11.24%), N25-75 (8.27%), N75-25 (9.00%), and N100-0 (22.13%). Similarly, the N50-50 improved total N uptake by 6.54% (N25-75), 9.36% (N75-25), 17.73% (N0-100), and 32.96% (N100-0). The agronomic efficiency (AE), apparent recovery efficiency (APE), and nitrogen partial factor productivity (PFP) were higher in N50-50. Moreover, a principal component analysis (PCA) showed that the N50-50 had the highest ranking at 91.20% over 2 years of study. Applying 50% of 240 kg ha^{-1} (urea) at sowing and splitting the balance between jointing and booting stages is desirable for maximum grain yield and proper utilization of nitrogen fertilizer.

Keywords Drip fertigation · Nitrogen scheduling · Split N application · Optimum N uptake · Nitrogen efficiency indices

1 Introduction

Providing food, energy, and water resources to the world's dynamic population is a global challenge, but more serious in areas with high food demand and low water available for agriculture. Water-scarce areas such as North China rely, heavily, on groundwater, with more than 70% used for agricultural activities (Du et al. 2015). Zain et al. (2021a) reported that the groundwater level in North China has decreased by about 0.5–3 m per year over the last 30~40 years. High-performance irrigation systems such as drip irrigation are encouraged to overcome the problem of water scarcity and increase irrigation efficiency. Drip irrigation provides the highest water productivity by maintaining the soil moisture at 50–60% of field capacity (Wang et al. 2013). Kumar et al. (2019) found that drip irrigation is the best water-saving irrigation technology for its high water and nitrogen use efficiencies. It can improve water use efficiency

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by up to about 8% as compared to surface irrigation methods (Mehmood et al. 2019). Wang et al. (2013) reported a 5–13% increase in wheat yield as compared with level basin irrigation. Therefore, adopting drip irrigation technologies for the integrated management of water and nitrogen applications is necessary under current climate and food demand challenges.

Winter wheat (*Triticum aestivum* L.) is an important grain crop widely grown in China and accounts for about 45% of the national grain production (Duan et al. 2014). In particular, the North China Plain (NCP) produces about 60 to 80% of wheat in the country (Si et al. 2021). Farmers traditionally applied more nitrogen fertilizers to improve wheat grain yield leading to excessive application and improper utilization (Chen et al. 2021). Recently, nitrogen application in wheat fields has increased rapidly, but low efficiencies were reported (Cui et al. 2010). While fertilizers play important role in facilitating the economic development and productivity of agricultural communities, they constitute a remarkably high threat to environmental conservation, which is equally important for sustainable production. Excessive nitrogen fertilizer application significantly reduces NUE and increases losses through leaching (causing groundwater pollution), ammonium volatilization, and greenhouse gas emissions, which contributes to global warming potential (Wang et al. 2016; Tian et al. 2017a, b). Therefore, knowledge-based nitrogen application scheduling is necessary for food production and environmental sustainability in the current challenges of climate variability and rapid population growth.

Nitrogen is the fundamental nutrient element for wheat growth, development, and grain production. Farmers use synthetic fertilizers (urea) because of their availability and affordability. However, improper fertilization practices, involved in traditional water application methods, were found to have adversely impacted the environment and resulted in a higher loss of input and decreased economic benefit to the farmers (Borzouei et al. 2020; Tan et al. 2017). Therefore, it has been documented that proper nitrogen management is critical for establishing a sustainable strategy that improves crop yield and reduces environmental risks (Trost et al. 2016). It was found that appropriate ratios of basal and topdressing nitrogen fertilizers were an important strategy for nitrogen management (Zain et al. 2021b). Considering the conclusion of Zain et al. (2021b), split N application which involves topdressing ratios at jointing and booting stages could help meet the wheat nitrogen demand, improving grain yield and NUE traits.

In recent years, the benefits of drip-fertigation, such as facilitating water and nitrogen savings, have gradually encouraged adoption in arid and semi-arid areas (Kumar et al. 2019). Drip-fertigation techniques enable the application of the appropriate amount of nutrients to the soil-wetted area, where most active roots are concentrated (Jiao et al. 2018; Wang et al. 2013). It improves nutrient utilization, yield, and quality of produce (Jat et al. 2011). Fertigation has shown an ability to save up to 25% of fertilizer loss (Rajasree et al. 2020). Other findings reported that fertigation ensures saving in fertilizer by 40 to 60% (Jat et al. 2011). Fertigation techniques have been used commonly in vegetables and orchard fields, but their application in grain crops such as wheat is currently rare (Priya et al. 2017; Rajasree et al. 2020; Li et al. 2021). Farmers in the NCP could be encouraged to adopt drip fertigation in wheat crops to improve water and fertilizer management as it can achieve proper timing and placement of required nutrients (Tian et al. 2017a). Furthermore, they can optimize nutrient use by targeting the key growth stages such as jointing and booting.

Most of the previous studies primarily focused on different application rates and their effects on grain yield and NUE (Zhang et al. 2021), but research on split scheduling of a particular N rate for winter wheat production using drip fertigation systems is grossly limited (Zhou et al. 2017). Typically, Zhang et al. (2021) and Belete et al. (2018) recommended 240 kg per hectare for wheat production, but the responses of the wheat yield and NUE indices to various scheduling of this particular rate under drip fertigation system were not reported. Additionally, the few researches conducted were more concerned with high yield and single index of NUE. However, based on the importance of high yield to farmers' economic benefits and NUE to the environment and resource management, it could be hypothesized that a comprehensive evaluation method could be used to provide a scientific conclusion on a particular N-fertigation that can associate the contribution of yield and NUE indices in the winter wheat production system. Therefore, the objective of this study was to evaluate the effect of N-fertigation on winter wheat yield and NUE indices and propose a comprehensive evaluation method for optimizing fertilization scheduling under a drip-fertigation system.

2 Materials and Methods

2.1 Common Field Practices of Winter Wheat Production in the North China Plain

Winter wheat in North China is grown between mid-October and early June of the following year. Land preparation is normally done by plowing the 20-cm soil layer with a tractor-drawn rotary cultivator, followed by harrowing to level the field to a flat surface using a cultivator. The wheat is sown by a planter at 180 kg per hectare. The common irrigation practice in the area is the border irrigation method, and most farmers applied a seasonal total of 300-mm depth of water. The common fertilization rate is 300 kg N ha^{-1}. The fertilizer is manually spread twice in a season. Other chemical application practices are as follows: for aphids, 10% Imidacloprid powder with 300 g ha^{-1}. For grass weeds, 36% grass spirit cream with 2.4 L ha^{-1} and 20% bromobenzonitrile emulsion with 1.5L ha^{-1}.

2.2 Description of Experimental Site

The 2-year field experiment was conducted at Qiliying experimental station (35° 08′ N, 113° 45′ E, 81 m altitude) of Farmland Irrigation Research Institute of Chinese Academy of Agricultural Sciences in Xinxiang county, Henan Province, in 2019/2020 and 2020/2021 winter wheat seasons. A map showing the location of the experimental site can be obtained in Zain et al. (2021a, b). The main characteristics of the soil in the field are as shown in Zain et al. (2021a, b). The soil is sandy loam (USDA-NRCS Soil survey division). Other chemical properties/parameters were total nitrogen (0.66 mg g^{-1}), phosphorus (7.7 mg kg^{-1}), and potassium (177.00 mg g^{-1}). Soil organic matter, pH value, and electrical conductivity were 14.25 g kg^{-1}, 8.80, and 115.00 μs cm^{-1}, respectively. An automatic weather station at the experimental site was used to collect daily meteorological data, such as atmospheric temperature (maximum and minimum), wind speed, rainfall, and solar radiation. The seasonal variations in daily rainfall and temperature of the two seasons are presented in Fig. 1. The average wheat season temperatures in 2019/2020 and 2020/2021 were 10.39 °C and 10.45 °C, respectively. Total rainfall recorded was 113.00 mm (October 18, 2019~June 1, 2020) and 87.00 mm (October 18, 2020~June 1, 2021).

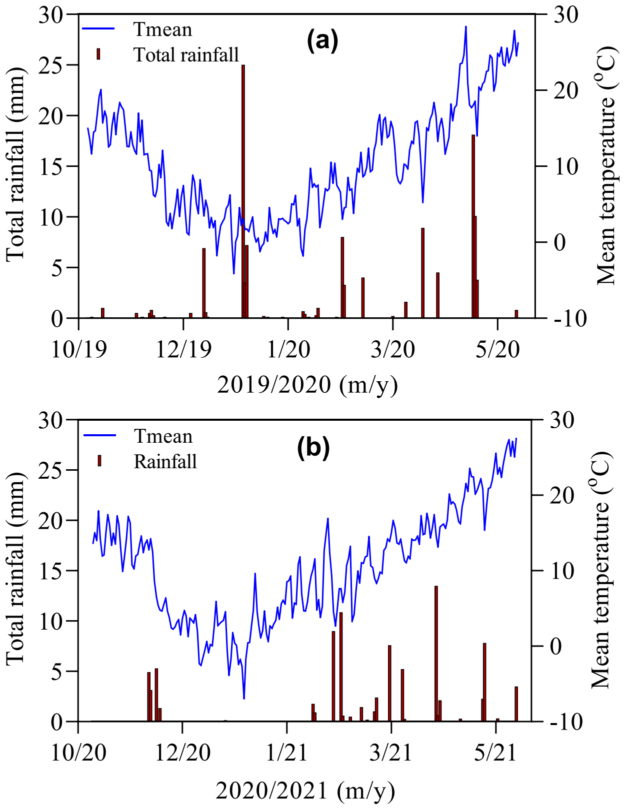

Fig. 1 Daily rainfall and mean daily temperature in (**a**) 2019/2020 and (**b**) 2020/2021 winter wheat seasons. T_{mean}, mean daily temperature

2.3 Experimental Design

The experiment was designed with six levels of split application of nitrogen fertilizer (urea) to a total of 240 kg ha^{-1} as recommended by Zhang et al. (2021) and Belete et al. (2018). The details of the experimental treatments are as shown in the supplementary material (Table S1). The three replicates of each treatment were arranged in a randomized complete block design (each replicate was randomly allocated to a block). The plot size was 3 m by 15 m. At sowing, the initial fertilizer proportions representing the basal dose were applied by manual spreading. The topdressing amounts were applied to the wheat field with the irrigation water (via fertigation) at jointing (March, 14–20) and booting (April, 25–30) stages in equal splits. The irrigation system, soil preparation, and agronomic practices used followed the work of Si et al. (2020).

Irrigation scheduling was done according to Eq. 1–2:

$$ET_c = K_c \times ET_o \tag{1}$$

where ET_c = crop evapotranspiration (mm/day), K_c = crop coefficients (early season $K_c = 0.36$; mid-season $K_c = 1.19$; late season $K_c = 0.28$ according to Gao et al. (2009)). The reference evapotranspiration (ET_o) was calculated according to Allen et al. (1998).

The amount of irrigation (I) was given as:

$$I = ET_c - Totalrainfall \tag{2}$$

The irrigation (I) amount should be 45 mm. The details of irrigation scheduling and total amount of water applied are as shown in the supplementary material (Table S2).

2.4 Irrigation and Fertigation Systems

Each treatment had a separate drip irrigation sub-system consisting of a fertigation tank, a water meter, and control valves. The drip laterals spacing was 60 cm, emitter spacing was 20 cm, and the discharge rate of the dripper was 2.2 L h^{-1} under a working pressure of 0.10–0.15 MPa. Flow meters were installed to determine the exact amount of irrigation water released to each experimental plot.

Fertigation was done using the closed tank system (Anjaly et al. 2016). The procedure was as explained in Ning et al. (2019). Water (10 mm) was applied before the fertilizer solution was injected into the irrigation water. The duration of fertigation was based on Amosteitch's empirical formula, i.e., T = ¼ 4V/Q (T is the time, V is the volume of the fertilizer tank, and Q is the flow rate of the drip irrigation system). Then, water was applied until the required amount (2025 l) of irrigation was applied (Table S2).

2.5 Measurement of Soil Inorganic Nitrogen

To determine the soil inorganic nitrogen, soil samples were taken from the 0–20-cm layer at the interval of 4 weeks. Three points were randomly selected from each plot for the sampling. The samples were then mixed and analyzed for nitrate and ammonium nitrogen concentrations with a flow analyzer (AAR-HR SEAL ANALYTICAL - USA). The inorganic nitrogen was taken as the sum of the nitrate and ammonium nitrogen.

2.6 Measurement of Grain Yield and Nitrogen Uptake

An undisturbed area of 1 square meter (m^2) was randomly selected from each plot for the measurement of GY and aboveground biomass. The harvesting, drying, and threshing of the samples were done manually. To determine the nitrogen uptake at maturity, plant samples were collected from each plot. The samples were dried in the oven at 75°C for 24 hours. The grain and straw were separated and ground. The total N content was determined by the micro-Kjeldahl method (Fageria 2014a). The N uptake was the product of total N (%) and weight of grain and straw. The total N uptake was the sum of grain and straw N uptake.

2.7 Determination of Nitrogen Use Efficiency Indices

The following nitrogen use indices were determined (Fageria 2014a; Fixen et al. 2015) using Eqs. 3 to 7:

1. Agronomic efficiency (AE)

$$AE = \frac{GY\ in\ treated\ pot - GY\ in\ control\ plot}{N_a} \times 100\% \tag{3}$$

2. Agro-physiological efficiency (APE)

$$APE = \frac{(GY\ intreated\ pot - GY\ in\ control\ plot)}{N_f - N_0} \tag{4}$$

3. Apparent N recovery efficiency (ARE)

$$APE = \frac{N_f - N_0}{N_a} \tag{5}$$

4. Nitrogen partial factor productivity (PFP)

$$PFP = \frac{GY}{N_a} \times 100\% \tag{6}$$

5. Nitrogen harvest index (NHI)

$$NHI = \frac{GNU}{TNU} \times 100\% \tag{7}$$

In the above equations: N_a = applied nitrogen (kg ha^{-1}); N_f = total nitrogen accumulation (kg ha^{-1}) in the fertilized plot; N_0 = total nitrogen accumulation in the control (N0-0) plot ((kg ha^{-1}); GNU = grain N uptake; TNU = total N uptake (for grain + straw).

2.8 Principal Component Analysis and Determination of Optimum N-Fertigation Schedule

The principal component analysis (PCA) was performed according to the standard procedure as presented by Liu et al. (2019). The optimum N-fertigation based on N uptake and efficiency indices was determined using Eqs. 8–17 (Li et al. 2021).

The steps of the PCA Comprehensive evaluation method are as follows:

1. Building a matrix X of the original data:

$$X = (x_{ij})_{n \times m} = \begin{bmatrix} x_{11} & x_{12} \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} \cdots & x_{nm} \end{bmatrix} \tag{8}$$

in which x_{ij} (I = 1, 2..., n; j = 1, 2..., m) is the j^{th} evaluation index for the i^{th} treatment; in which x_{ij} (I = 1, 2..., n; j = 1, 2..., m) is the evaluation index for the treatment.

2. Standardizing the original matrix:

To ensure that the evaluation indicators are in the same direction, the absolute value of each evaluation index was considered. The evaluation indices were then normalized to obtain the normalized values (A_{ij}) as follows:

$$A_{ij} = \frac{x'_{ij} - \overline{x'_{ij}}}{S_j} \tag{9}$$

$$x'_j = \frac{\sum_{i=1}^{n} x'_{ij}}{n} \tag{10}$$

$$S_j = \sqrt{\frac{\sum_{i=1}^{n} \left(x'_{ij} - \bar{x}'_j\right)^2}{n-1}} \tag{11}$$

3. Calculating the correlation matrix, R of the normalized indices:

$$A_j = \left(A_{1j}, A_{2j}, \ldots, A_{ij}\right)^T \tag{12}$$

$$R = \left(r_{ij}\right)_{m\times m} = \begin{bmatrix} r_{11} & r_{12} \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} \cdots & r_{mm} \end{bmatrix} \tag{13}$$

where r_{ij} is the correlation coefficient between x'_j and x'_k ; $k= 1, 2, \ldots, m$

4. Calculating the square root of R and the corresponding eigenvector α_k, and obtain the k^{th} principal component (f_{nk})

$$\left(R - \lambda_k I_m\right)\alpha_k = 0 \tag{14}$$

in which $\sum_{k=1}^{m} \lambda_k = m, k = 1, 2, \ldots, m$; $\alpha_k = \left(\alpha_{k1}, \alpha_{k2} \ldots \alpha_{km}\right)^T$

$$\begin{gathered} D_k = \frac{\lambda_k}{m}, k = 1, 2, \ldots, m \\ f_{nk} = \sum_{i=1}^{m} A_{ik}\alpha_{ik} \end{gathered} \tag{15}$$

The first main component, (f_{n1}), has the largest variance contribution of all data.

5. Calculating the Euclidean distances:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} w_j\left(f_{ij} - f_j^+\right)^2} \tag{16}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} w_j\left(f_{ij} - f_j\right)^2} \tag{17}$$

6. Calculating the performance score for treatments:

$$q_i = \frac{d_i^-}{d_i^+ + d_i^-}; i = 1, 2, \ldots, n \tag{18}$$

where w_j is the contribution rate of the j^{th} main component; f_{ij} is the principal component of the variable (x_{ij}) f_j^+; and f_j^- are the maximum and minimum values of the j^{th} main component. q_i is the performance score for each treatment; d_i^+ and d_i^- are the positive and negative Euclidean distances, respectively.

2.9 Determination of Marginal Efficiency

Marginal efficiency can be defined as the rate of increase in yield obtainable from an additional kilogram of nitrogen applied per hectare. In this study, it was used to analyze the optimum topdressing (fertigation) rate that balances wheat yield gain and nitrogen loss.

To determine the marginal efficiency, the optimum fertigation rate based on maximum GY was obtained by maximizing the quadratic relationship between wheat grain yield and the percentage of topdressing nitrogen (Cuong et al. 2017). The optimum fertigation rate was obtained by differentiating the general form of the quadratic equation ($0 = ax^2 + bx + c$) as given by Eq. 18

$$F_{opt} = -\frac{b}{2a} \tag{19}$$

The maximum grain yield Y_m was calculated using Eq. 19

$$Y_m = c - \frac{b^2}{4a} \tag{20}$$

Marginal efficiency is given by the differential equation (Eq. 19) (Tabak et al. 2020)

$$E_m = 2ax + b \tag{21}$$

where a and b are the coefficients of x in the quadratic equation.

2.10 Statistical Analysis

The data were statistically analyzed using the mixed model ANOVA and One-way ANOVA in SPSS 23.0 software (IBM SPSS Statistics for Windows, Version 23.0. Armonk, NY: IBM Corp). Mean separation was done using the Fisher's LSD at a confidence level of 95%, where applicable. The control was excluded to facilitate the factorial analysis where necessary. Linear regression analysis was conducted between grain yield and nitrogen uptake. Polynomial relationships between nitrogen uptake, wheat yield, and fertigation rate (independent variable) were established. The PCA was used to specify the best scheduling treatment.

3 Results

3.1 Seasonal Variations in Inorganic Nitrogen

The results of the dynamics of inorganic nitrogen in 2019/20200 and 2020/2021 are shown in Fig. 2. The treatments generally showed a similar pattern. As expected, high doses of nitrogen led to higher inorganic nitrogen flux at any given time. However, N50-50 maintained about an average profile in the two seasons. In both seasons, the N100-0 recorded the highest peak of inorganic nitrogen of 72.94 and 61.25 mg kg^{-1} at the sowing stages. After the

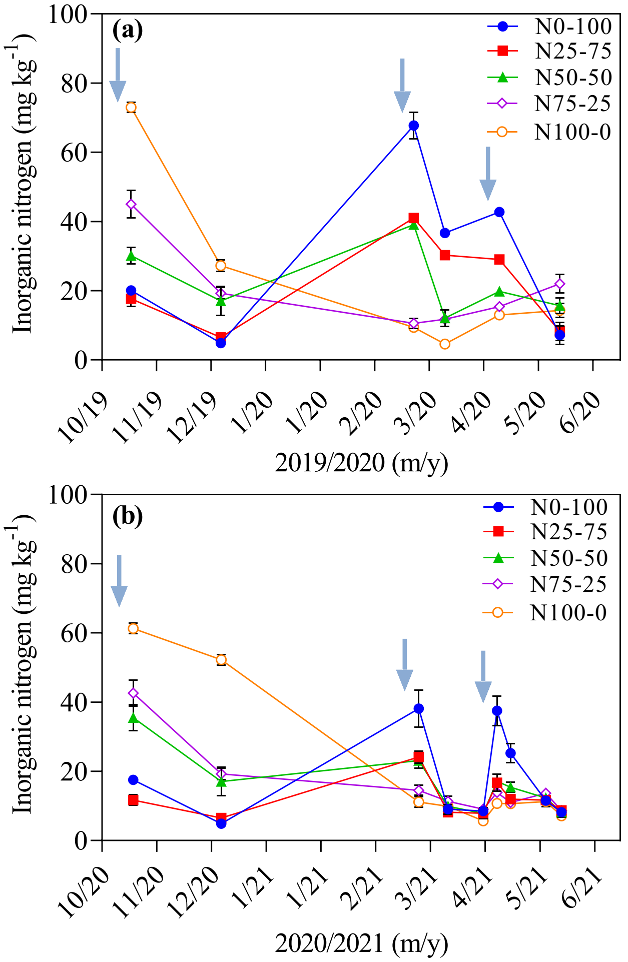

Fig. 2 Seasonal dynamics of soil inorganic nitrogen under different N-fertigation treatments in (**a**) 2019/2020 and (**b**) 2020/2021 winter wheat seasons. Note: Each data point represents the mean and standard error of three replicates. The downward arrows indicate fertilization/fertigation dates. N0-100 = 0% of basal nitrogen applied at sowing and 100% of topdressing nitrogen equally split at jointing and booting; N25-75 = 25% of basal nitrogen applied at sowing and 75% of topdressing nitrogen equally split at jointing and booting; N50-50 = 50% of basal nitrogen applied at sowing and 50% of topdressing nitrogen equally split at jointing and booting; N75-25 = 75% of basal nitrogen applied at sowing and 25% of topdressing nitrogen equally split at jointing and booting; N100-0 = 100% of basal nitrogen applied at sowing and 0% of topdressing nitrogen. Topdressing nitrogen was applied via a drip fertigation system

two topdressing applications (at jointing and booting), the N0-100 recorded the highest inorganic nitrogen of 67.72 and 38.12 mg kg^{-1}, respectively.

Analysis of the seasonal mean revealed that the N0-100 had the highest ($P < 0.05$) inorganic nitrogen as compared with other treatments. The highest means of inorganic nitrogen were recorded in the high topdressing treatments across the two seasons.

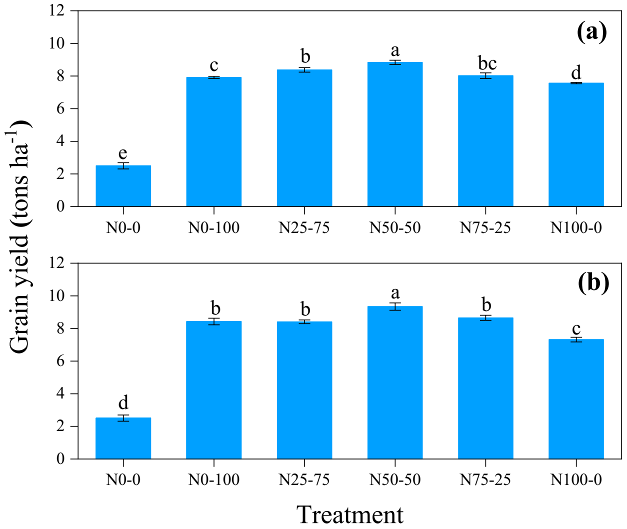

Fig. 3 Seasonal means of grain yield under different N-fertigation treatments in (**a**) 2019/2020 and (**b**) 2020/2021. Note: Each column represents the average value of three replicates. Error bars represent the standard errors. Different letters indicate a significant difference ($p < 0.05$) between treatments in a particular season. The mean separation was done with the Fisher's LSD. N0-0 = 0% of basal nitrogen applied at sowing and 0% of topdressing; N0-100 = 0% of basal nitrogen applied at sowing and 100% of topdressing nitrogen equally split at jointing and booting; N25-75 = 25% of basal nitrogen applied at sowing and 75% of topdressing nitrogen equally split at jointing and booting; N50-50 = 50% of basal nitrogen applied at sowing and 50% of topdressing nitrogen equally split at jointing and booting; N75-25 = 75% of basal nitrogen applied at sowing and 25% of topdressing nitrogen equally split at jointing and booting; N100-0 = 100% of basal nitrogen applied at sowing and 0% of topdressing nitrogen. Topdressing nitrogen was applied via a drip fertigation system

3.2 Grain Yield

The ANOVA revealed that grain yield (GY) was significantly ($P < 0.05$) affected by the N-fertigation treatments (Fig. 3). The highest yield was obtained when 50% nitrogen fertilizer was applied at sowing, followed by fertigated topdressing doses of 25% at jointing and booting stages, respectively. Compared with the N0-0, the N50-50 treatment improved the GY by 71.69% and 73.15% in 2019/2020 and 2020/2021, respectively. The N75-25 and N25-75 were statistically similar ($P > 0.05$) in GY during both seasons.

3.3 Nitrogen Uptake

The grain nitrogen uptake (GNU) and total nitrogen uptake (TNU) were influenced by N-fertigation treatments and their interaction with the sampling year, while the effects of the sampling year were not significant

(Table 1). Nitrogen uptake was highest in the N50-50 in both 2019/2020 and 2020/2021. Compared with the control (N0-0), the N50-50 improved GNU and TNU by 85.73 % and 73.75% in 2019/2020 and 83.98% and 65.40% in 2020/2021, respectively. The N75-25 and N25-75 had statistically similar ($P > 0.05$) GNU and TNU in both seasons (Fig. 4). Balancing N application in 50:50 ratios between basal and topdressing improved total nitrogen uptake by an average of 37.89% and 17.41% in both 2019/2020 and 2020/2021, respectively, as compared with the N0-100 treatment. A significant polynomial relation explaining the results of this work was observed between N uptake and N-fertigation rate (Fig. 5). It indicated that N uptake increases with an increase in N-fertigation (topdressing) rate until a maximum is reached at 50%, then it decreases as the rate of fertigation increases. However, grain yield

Table 1 Mixed model ANOVA results (*F*-values) of grain yield, nitrogen uptake and nitrogen use efficiency indices as affected by N-fertigation treatments, sampling seasons and their interactions

Source of variation	GY	GNU	TNU	AE	APE	ARE	NHI	PFP
T	316.672**	206.114**	81.867**	5.851**	0.349ns	4.198**	1.146ns	23.480**
y	13.998**	1.063ns	0.197ns	13.544*	3.668ns	0.650ns	5.050ns	13.852**
$y \times T$	5.138**	4.205**	4.068**	4.923**	7.598**	4.198*	4.258**	4.803*

T, N-fertigation treatment; *y*, season; *GY*, grain yield; GNU, grain n uptake; *TNU* total plant N uptake; *AE*, agronomic efficiency; *APE*, agro-physiological efficiency; *ARE*, Apparent recovery efficiency; *NHI*, Nitrogen harvest index; *PFP*, nitrogen partial factor productivity. *Significant at $p < 0.05$; **significant at $p < 0.01$; *ns*, not significant

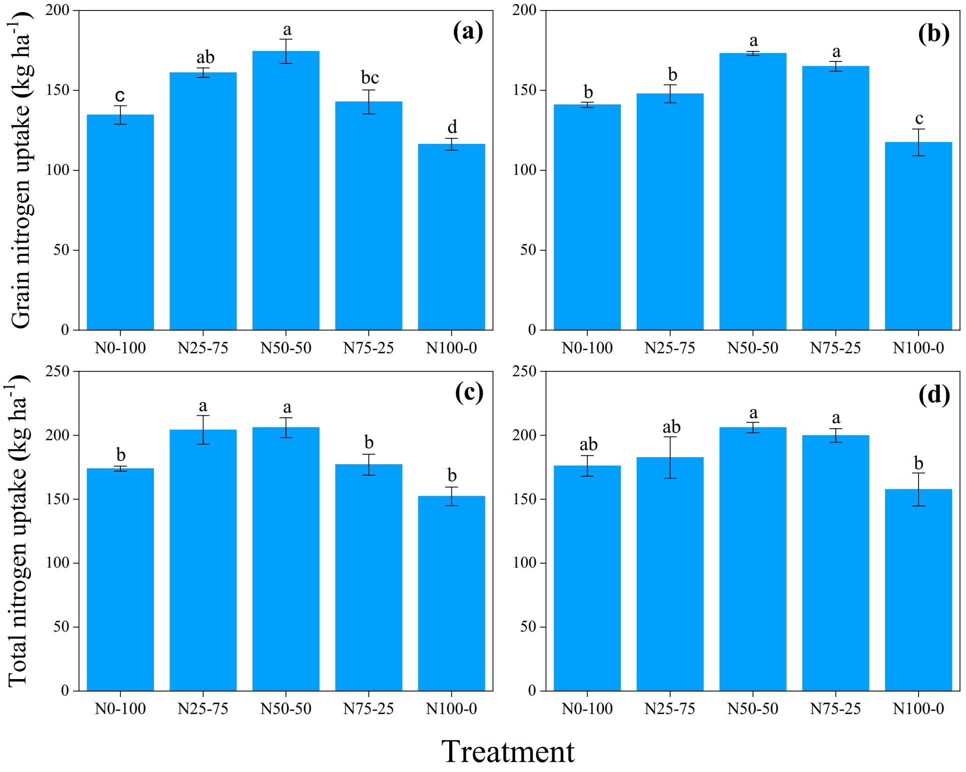

Fig. 4 Seasonal means of GNU (**a** and **b**) and TNU (**c** and **d**) under different N-scheduling treatments in 2019/2020 (a and c) and 2020/2021 (**b** and **d**). Note: Each bar represents the average value of three replicates. Error bars represent the standard errors Different letters indicate a significant difference ($p < 0.05$) between treatments in a particular season. The mean separation was done with the Fisher's LSD. N0-100 = 0% of basal nitrogen applied at sowing and 100% of topdressing nitrogen equally split at jointing and booting; N25-75 = 25% of basal nitrogen applied at sowing and 75% of topdressing nitrogen equally split at jointing and booting; N50-50 = 50% of basal nitrogen applied at sowing and 50% of topdressing nitrogen equally split at jointing and booting; N75-25 = 75% of basal nitrogen applied at sowing and 25% of topdressing nitrogen equally split at jointing and booting; N100-0 = 100% of basal nitrogen applied at sowing and 0% of topdressing nitrogen. Topdressing nitrogen was applied via a drip fertigation system

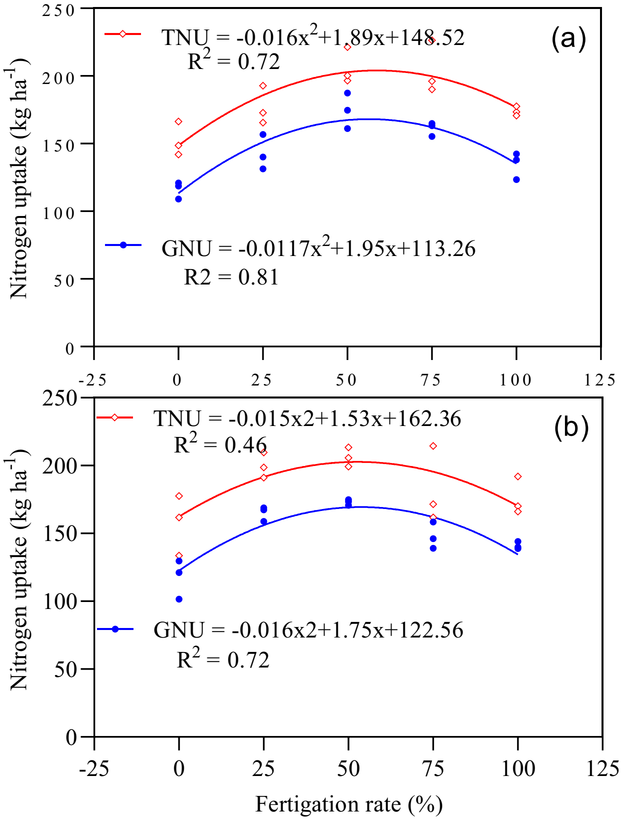

Fig. 5 Response of winter wheat nitrogen uptake to different fertigation levels of nitrogen fertilizer in (**a**) 2019/2020 and (**b**) 2020/2021. TNU, total plant N uptake; GNU, grain N uptake. Sample size = 15. $P < 0.01$

increased with an increase in nitrogen uptake as shown in Fig. 6. Therefore, the split application is more rational for high N uptake of the drip-irrigated winter wheat crop.

3.4 Nitrogen Use Efficiency Indices

3.4.1 Agronomic Efficiency

Nitrogen agronomic efficiency (AE) measures the plant's ability to produce an increased yield in response to nitrogen (Fixen et al. 2015). The N-fertigation treatment, sampling year, and their interaction affected the AE significantly ($P < 0.05$) as shown in Table 1. The N50-50 treatment produced the highest AE in 2019/2020 and 2020/2021 seasons. The lowest AE recorded in the N100-0 were 20.06% and 29.60% lower than the N50-50, respectively. While there was no significant difference between N75-25 and N0-100 in 2019/2020, N0-100, N25-75 and N75-25 recorded similar ($P > 0.05$) AE in 2020/2021 (Table 2).

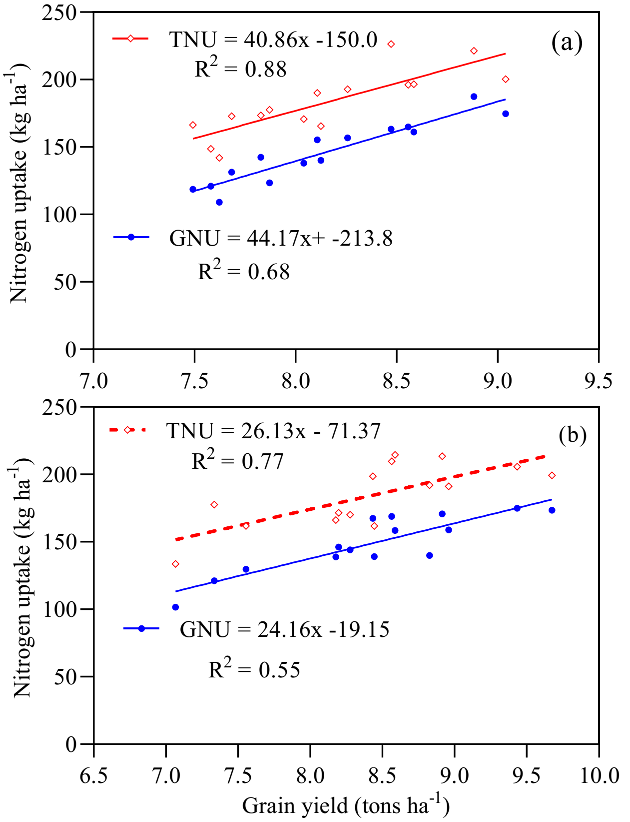

Fig. 6 Regression analysis of nitrogen uptake as a function of grain yield in (a) 2019/2020 and (b) 2020/2021. TNU, total plant N uptake; GNU, grain N uptake. Sample size = 15. $P < 0.01$

3.4.2 Agro-physiological Efficiency

The mixed model ANOVA revealed that the treatments and sampling year did not affect the response of agro-physiological efficiency (APE) to the various N-fertigation treatments (Table 1). However, the interaction of sampling year and N-fertigation affected the APE significantly ($P < 0.05$). In 2019/2020, the difference between the treatments was significant ($P < 0.05$), but N0-100, N50-50, and N75-25 produced similar results ($P > 0.05$). In 2020/2021, the five N-fertigation treatments had similar APE results.

3.4.3 Apparent Recovery Efficiency

The treatments significantly ($P < 0.05$) influenced the variations in apparent recovery efficiency (ARE), but the effect of the sampling year was not significant ($p > 0.05$) (Table 1). In 2019/2020 and 2020/2021, the highest ARE was obtained in the N50-50, and was 28.78% and 25.82% higher than the N100-0. However, the N0-100 and N75-25 were not significantly different (Table 2). On the other hand, the N50-50 improved the ARE by 17.20 and 15.9% compared with

Table 2 Seasonal means of nitrogen use efficiency indices under different N-fertigation treatments

Season	Treatment	AE (kg kg^{-1})	APE (kg kg^{-1})	ARE (%)	PFP (kg kg^{-1})	NHI (%)
2019/2020	N0-100	22.55 ± 0.55bc	35.03 ± 0.45ab	64.38 ± 1.42ab	33 ± 0.27cd	77.47 ± 4.03a
	N25-75	24.49 ± 0.87ab	31.96 ± 1.08b	77.01 ± 5.49a	35 ± 0.57b	79.24 ± 3.65a
	N50-50	26.39 ± 1.25a	34.01 ± 1.19ab	77.75 ± 4.13a	37 ± 0.55a	84.64 ± 1.49a
	N75-25	23.01 ± 1.16bc	35.13 ± 0.99ab	65.66 ± 4.33ab	33 ± 0.77bc	80.69 ± 2.53a
	N100-0	21.10 ± 0.92c	38.36 ± 2.99a	55.37 ± 2.54b	32 ± 0.16d	76.51 ± 2.91a
	N0-100	24.66 ± 1.25a	37.55 ± 0.79a	65.73 ± 3.65ab	35.11 ± 0.84b	80.34 ± 3.76a
	N25-75	24.59 ± 1.06ab	36.47 ± 2.41a	68.42 ± 7.71ab	35.04 ± 0.48b	81.68 ± 3.9a
2020/2021	N50-50	28.47 ± 1.59b	36.45 ± 2.36a	78.22 ± 1.42a	38.92 ± 0.93a	84.06 ± 2.09a
	N75-25	25.60 ± 0.24b	33.96 ± 1.32a	75.60 ± 2.81a	36.05 ± 0.66b	82.62 ± 1.08a
	N100-0	20.04 ± 1.18c	35.01 ± 3.15a	58.02 ± 5.08b	30.49 ± 0.59c	74.78 ± 3.48a

AE, agronomic efficiency; *APE*, agro-physiological efficiency; *ARE*, apparent recovery efficiency; *NHI*, nitrogen harvest index; *PFP*, nitrogen partial factor productivity. Each data represents the mean and standard error of three replicates. Means ± standard error followed by different letters in the same column are significantly different ($P < 0.05$). Mean separation was done with Fisher's LSD. N0-100 = 0% of basal nitrogen applied at sowing and 100% of topdressing nitrogen equally split at jointing and booting; N25-75 = 25% of basal nitrogen applied at sowing and 75% of topdressing nitrogen equally split at jointing and booting; N50-50 = 50% of basal nitrogen applied at sowing and 50% of topdressing nitrogen equally split at jointing and booting; N75-25 = 75% of basal nitrogen applied at sowing and 25% of topdressing nitrogen equally split at jointing and booting; N100-0 = 100% of basal nitrogen applied at sowing and 0% of topdressing nitrogen. Topdressing nitrogen was applied via a drip fertigation system

the N0-100, respectively. However, the N0-100 and N25-75 were not significantly different ($P > 0.05$).

3.4.4 Nitrogen Harvest Index

The nitrogen harvest index (NHI) was not affected by the treatments and the sampling year, as shown in Table 1. The highest NHI was recorded in the N50-50 at 84.64% and 84.06% in 2019/2020 and 2020/2021, respectively. The lowest values were recorded in the N100-0 treatment in both the growing seasons.

3.4.5 Nitrogen Partial Factor Productivity

The effects of the treatments, year of sampling and their interaction on the partial factor productivity (PFP) of nitrogen were significant ($P < 0.05$) (Table 1). The maximum PFP was obtained in the N50-50 in both 2019/2020 and 2020/2021 seasons. Compared with the N100-0, the N50-50 improved PFP by 14.38% and 21.65% in 2019/2020 and 2020/2021, respectively. The N25-75 and N75-25 were not significantly different in both seasons.

3.5 Maximum Grain Yield and Optimum Nitrogen Fertigation Schedule

The maximum yields obtained by maximizing the polynomial relationships (Fig. 7) were 8.48 and 9.02 tons ha^{-1} at optimum fertigation rates of 49.75 and 56.5 kg ha^{-1} for 2019/2020 and 2020/2021 seasons, respectively. The marginal efficiency analysis (Fig. 8) indicated that the fertigation rate of topdressing N dose should not exceed 50 kg ha^{-1} or 57 kg ha^{-1} according to the respective results of 2019/2020 and 2020/2021 seasons. Increasing the fertigation rate over the optimum did not increase yield but may increase operational costs from increased fertilizer input. On the other, a reduction in the fertigation rate could result in decreased input cost at the detriment of yield. Furthermore, the PCA method was used to obtain the best N-fertigation treatment by comprehensive evaluation of N-uptake and NUE indices as shown in Fig. 9. The PCA showed that N50-50, N25-75,

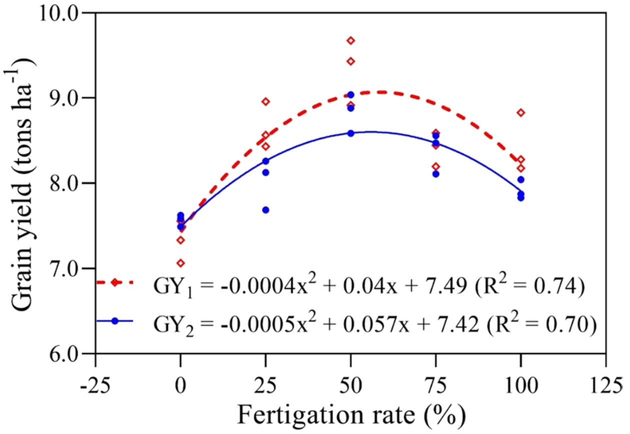

Fig. 7 Response of yield to fertigation levels of Nitrogen fertilizer. GY_1 and GY_2 are Grain yields in 2019/2020 and 2020/2021, respectively. The numerical solution of the quadratic equations revealed that the optimum fertigation rate of topdressing nitrogen was 50 and 57 kg ha^{-1} for 2019/2020 and 2020/2021, respectively. Sample size = 15. $P < 0.01$

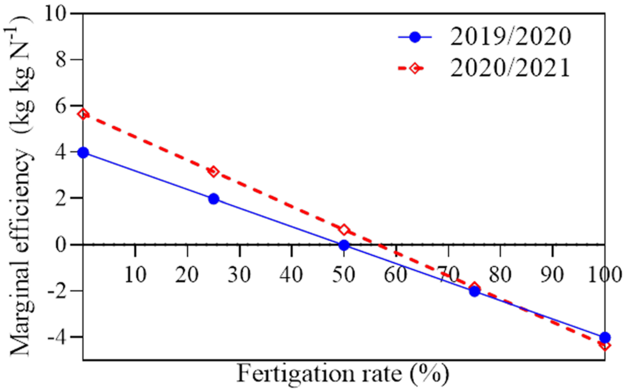

Fig. 8 Marginal efficiency of N-fertigation rate of topdressing nitrogen fertilizer. Fertigation rate represents the percentage of topdressing nitrogen

and N75-25 were strongly associated with the loadings of GNU, TNU, AE, ARE, PFP, and NHI in both seasons. The scores of the principal components and the ranking of each treatment are as shown in Table 3. The results of optimization by PCA revealed that N50-50 had the highest ranking. It could be deduced that the application of 50% of 240 kg ha^{-1} of urea at sowing and 25% each at jointing and booting stages through the drip fertigation technique is rational for improved N uptake and NUE.

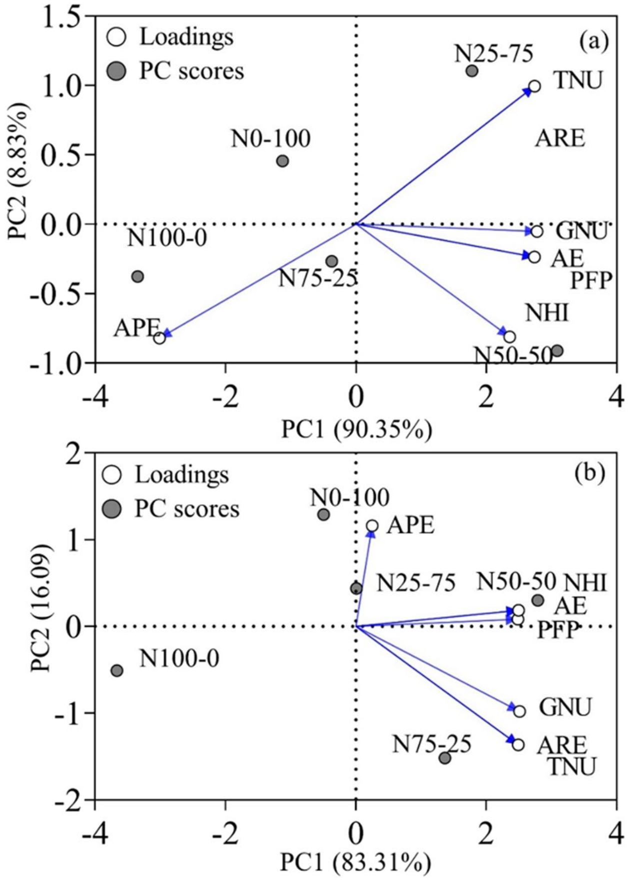

Fig. 9 Principal component analysis of N-fertigation scheduling in (**a**) 2019/2020 and (**b**) 2020/2021. Note: Blue arrows represent the factor loading coordinates for PC1 and PC2. GNU, grain N uptake; TNU, total plant N uptake; AE, agronomic efficiency; APE, agrophysiological efficiency; ARE, apparent recovery efficiency; PFP, nitrogen partial factor productivity; NHI, nitrogen harvest index. N0-100 = 0% of basal nitrogen applied at sowing and 100% of topdressing nitrogen equally split at jointing and booting; N25-75 = 25% of basal nitrogen applied at sowing and 75% of topdressing nitrogen equally split at jointing and booting; N50-50 = 50% of basal nitrogen applied at sowing and 50% of topdressing nitrogen equally split at jointing and booting; N75-25 = 75% of basal nitrogen applied at sowing and 25% of topdressing nitrogen equally split at jointing and booting; N100-0 = 100% of basal nitrogen applied at sowing and 0% of topdressing nitrogen. Topdressing nitrogen was applied via a drip fertigation system

4 Discussion

The components of the inorganic nitrogen; NO_3^--N and NH_4^+-N, are not only absorbed by the plants but also could be lost through nitrate leaching or ammonium volatilization, leading to the environmental risks of groundwater pollution and gas emissions (Geng et al. 2016). These losses could be minimized by proper scheduling of nitrogen fertilization as demonstrated by the results of this study. The pool of soil nitrogen is significantly connected to the plant growth stage characteristics based on the plant nutrient demand and supply gradient (Shi et al. 2012). The rapid hydrolysis of urea at the early stages of the wheat leads to the presence of high inorganic nitrogen content since the plants absorb a small amount of the fertilizer applied (Tian et al. 2017b). Therefore avoiding high nitrogen content in the soil when the plant uptake is low is logical for reducing nitrogen loss through volatilization or leaching (Grant et al. 2012; Yang et al. 2011). On the other hand, excessive nitrogen application at the later stages of wheat could provide a favorable environment for carbon dioxide release through ecosystem respiration (Mehmood et al. 2021). In this study, the N0-100 recorded the highest inorganic nitrogen content. The amount of nitrogen applied could have exceeded the optimal level required by the wheat, making the excess available for other processes such as leaching and gas emissions. The average inorganic nitrogen obtained in this work was within the ranges reported by other studies (Tian et al. 2017b; Geng et al. 2016).

Under water-scarce conditions, environmental and socioeconomical challenges, the ultimate aim of agricultural production systems is to achieve maximum yield per unit input applied. The nitrogen scheduling treatments employed in the current experiment significantly ($P < 0.05$) influenced the wheat GY. Split application of 240 kg ha^{-1} (the N50-50) was beneficial for its high GY. This agreed with the results

Table 3 Comprehensive evaluation of optimum N-fertigation treatment by principal components analysis (PCA)

Season	Treatments	f_1	f_2	d^+	d^-	q	Ranking
2019/2020	N0-100	− 0.526	0.457	2.863	4.664	0.621	4
	N25-75	− 0.096	0.245	2.811	4.930	0.635	3
	N50-50	2.453	0.479	0.837	6.119	0.887	1
	N75-25	1.268	− 0.378	1.796	5.454	0.752	2
	N100-0	− 3.099	− 0.804	5.068	4.698	0.484	5
2020/2021	N0-100	− 0.496	1.289	2.998	3.414	0.532	4
	N25-75	0.008	0.438	2.562	3.731	0.593	3
	N50-50	2.789	0.300	0.397	5.942	0.937	1
	N75-25	1.364	− 1.517	1.720	4.772	0.735	2
	N100-0	− 3.666	− 0.510	5.936	2.990	0.335	5

f_1, factor score by PC1; f_2, factor score by PC2; d^+, ideal best Euclidean distances; d^-, ideal worst Euclidean distance; q, performance score. N0-100 = 0% of basal nitrogen applied at sowing and 100% of topdressing nitrogen equally split at jointing and booting; N25-75 = 25% of basal nitrogen applied at sowing and 75% of topdressing nitrogen equally split at jointing and booting; N50-50 = 50% of basal nitrogen applied at sowing and 50% of topdressing nitrogen equally split at jointing and booting; N75-25 = 75% of basal nitrogen applied at sowing and 25% of topdressing nitrogen equally split at jointing and booting; N100-0 = 100% of basal nitrogen applied at sowing and 0% of topdressing nitrogen. Topdressing nitrogen was applied via a drip fertigation system

of Zhang et al. (2021) and Zain et al. (2021a, b) in a similar environment. However, the highest GY obtained exceeded the one reported by Si et al. (2020) even though they applied 60 kg ha^{-1} of N more than the total applied in this work. Excessive N applied at any stage of the wheat season was not beneficial to GY. The applied N in this situation was likely to be lost through leaching and greenhouse gas emission processes (Geng et al. 2016). The average yield (9.36 tons ha^{-1}) reported from the N50-50 was higher than that reported by Mehmood et al. (2019), Wang et al. (2016), and Kumar et al. (2019) under flood irrigation conditions in the same area. The increased yield reported in this study could suggest that the N50-50 was suitable for meeting the crop N demand at the time of application. Other studies reported improved wheat GY in response to three splits application of nitrogen at sowing, tillering, and flowering (Otteson et al. 2007; Singh et al. 2015). This finding could be an incentive for farmers to adopt the N application schedule used in this study.

Plant nitrogen content is an important component of the nitrogen cycle within agroecosystems. Poor nitrogen uptake leads to losses which could impact production as well as the environment. The split application of N employed in this study improved N uptake of the winter wheat plant. Additionally, the GY had a significant positive correlation with N uptake. This could be the consequence of the availability of sufficient nutrients at the critical stages of the crop. Researchers reported similar findings where N fertilizer was split three times between planting, tillering, and post-anthesis stages (Belete et al. 2018). This also agreed with the work of Fageria and Baligar (2005), who suggested that split application of N fertilizer improved N uptake in grain. Generally, works about N rates effects on N uptake indicated that N uptake tended to increase with increased application rates (Klikocka et al. 2017; Wang et al. 2010). However, they observed a decline in N uptake after increasing the N rate to about 300 kg ha^{-1}. This could explain the lower N uptake observed in the N0-100 and N100-0 treatments. These treatments tended to supply N exceeding the crop demand at application time leading to, probably, undesirable losses in the soil and atmosphere (Yong 2009). Therefore, this experiment proposes a split application of N to match the crop nutrient requirements and avoid losses through denitrification, ammonium volatilization, or leaching.

Nitrogen use efficiency indices, which could be influenced by fertilizer management, are an important basis for the evaluation of the production system. The nitrogen efficiency indices measured in this study indicated a significant response to the N-fertigation scheduling. The year 2020/2021, generally had a higher AE than 2019/2020. This is because of the difference in average GY across the treatments (De Oliveira Silva et al. 2020). Across the two seasons, higher AE was observed in the split application treatments than in single applications such as the N0-100 and N100-0. Research results concluded that AE decreases when excess N is applied in a single application (Dhillon et al. 2020). Therefore it could be believed that higher AE was obtained due to improve N uptake in the split application treatments (Kamble and Todmal 2020). The range of AE values reported in this work indicated the requirement for improvement as it was less than the common value for a perfectly managed system (Fixen et al. 2015). The agro-physiological efficiency (APE) measures the plant's ability to convert acquired N into economic yield (Fixen et al. 2015).

The results indicated that the treatments were not significant ($P > 0.05$) across the study years. However, other studies reported a significant effect for nitrogen application modes on APE under different climate conditions (Belete et al. 2018). The results might have been influenced by the residual effects of continuous fertilization in the experimental site. The range observed was relatively lower than the common values reported by Fixen et al. (2015), indicating the need to improve the system. The nitrogen apparent recovery efficiency (ARE) is defined as the ratio of the difference between the nutrient absorption of fertilized and unfertilized plots in the aboveground biomass to the amount of fertilizer applied (Fixen et al. 2015). The current results revealed that ARE increased with an increase in N uptake. The split application of N had a positive effect on ARE in line with the works of Haile et al. (2012) and Belete et al. (2018). Applying 50% basal N and fertigating the remaining 50% between jointing and booting stages could improve crop recovery and reduce losses. Yi et al. (2015) found a negative correlation between ARE and N application rates. The ARE of 68 and 69%, for 2019/2020 and 2020/2021, were higher than the prevailing average (Fixen et al. 2015) but lower than the 80% as expected from a well-managed system. The differences could be explained by the variations in local conditions such as soil type, crop, and climate. The nitrogen partial factor productivity (PFP) is the ratio of GY to the amount of fertilizer applied (Fixen et al. 2015). It measures the productivity of the cropping system. Generally, it decreases with an increase in N application rates (Pradhan et al. 2013). The results of this study indicated that PFP increased as wheat N uptake increased. It showed that the split application, which improved GY and N uptake produced the highest PFP. Nitrogen harvest index (NHI) is the ratio of grain N uptake to total N uptake by grain and straw (Fageria 2014b). It serves as an important indicator of crop yield potential. Nitrogen harvest index (NHI) is affected by N rates and the type and timing of fertilizer application (Fageria 2014b). However, it was not affected by the N-fertigation schedule used in this study. Similar results were reported by Xue et al. (2016) and López-Bellido et al. (2005), who found that split application of N did not affect NHI in wheat. The range of NHI values reported in this work agreed with that of Belete et al. (2018) and López-Bellido et al. (2005), although they used different application rates.

5 Conclusion

Drip fertigation can be a viable strategy for reducing losses and ensuring nitrogen productivity of winter wheat fields. Experimental results revealed that various schedules of a particular fertilization rate significantly influenced grain yield, nitrogen uptake, and nitrogen use efficiency (NUE) indices of winter wheat produced under drip irrigation conditions. The N50-50 treatments improved wheat grain yield, nitrogen uptake, and NUE indices over 2 years of study. This nitrogen fertigation mode allowed for the sufficient supply of required nutrients at the jointing and booting stages of the winter wheat growth. Numerical solutions by principal component analysis revealed that the fertilization rate of 240 kg N ha^{-1} should be split equally between basal and two topdressing fertigation events. The results of this study would be helpful in the management of drip fertigation practices of winter wheat in the North China Plain.

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Declarations

Conflict of Interest The authors declare no competing interests.

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