Optimized fertilization strategy for improving grain yield, nutrient uptake, and fertilizer use efficiency of drip-fertigated winter wheat in Northern Xinjiang, China

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Abstract: Excessive fertilizer application is common in the management of winter wheat (*Triticum aestivum* L.) in northwest China. However, this practice does not necessarily guarantee higher wheat yield and also causes a waste of resources and environmental pollution. The nitrogen (N), phosphorus (P), and potassium (K) fertilizer application rates need to be optimized to reduce the nitrate residue in the soil while maintaining a high wheat yield. Field experiments were conducted in three consecutive growth seasons (2018-2021) on winter wheat in Northern Xinjiang of China with four reduced fertilization (N-P_2O_5-K_2O) rates (FS1: 166-80-30 kg/hm^2, FS2: 0-80-30 kg/hm^2, FS3: 166-0-30 kg/hm^2, FS4: 166-80-0 kg/hm^2) and the local fertilization rate (CK: 240-105-38). The soil nutrients, nutrient uptake content of organ, dry matter accumulation, yield, and fertilization use efficiency were investigated. The results showed increasing NH_4^+–N concentrations in the soil over the three growing seasons, while NO_3^-–N concentrations decreased in the later experimental years. High soil NH_4^+–N concentration and low soil NO_3^-–N residues were observed in FS3. When the control fertilization (CK) was applied, the grains had a higher proportion of N and P, while the N content in grains was relatively low at the high fertilization rate. When the fertilizer supply was insufficient (FS2, FS3, and FS4), the proportion of vegetative organs to the total biomass was relatively low. Lower fertilization rates resulted in higher N, P, and K use efficiencies in 2019-2020 and 2020-2021, in comparison to those at higher rates, while FS2 exhibited the highest fertilizer use efficiency. When fertilization (CK) was sufficient, the dry matter accumulation decreased by 3.33%-17.08%, and the harvest index increased by 0.87%-47.40%. FS1 had the highest spike number, which significantly increased by 17.98%, 17.80%, and 9.64% compared with CK during 2018-2019, 2019-2020, and 2020-2021, respectively. In conclusion, a reduction in fertilizer application compared with CK could provide excellent production results. The optimal drip fertigation approach for winter wheat production in the arid regions of northwest China was determined to be the N-P_2O_5-K_2O application rate of 166-80-30 kg/hm^2 when comprehensively considering the winter wheat yield, soil NH_4^+–N, and NO_3^-–N, N use efficiency, P use efficiency, and K use efficiency. This research can provide a scientific basis for the responses of winter wheat production to nutrient uptake of drip-irrigated winter wheat in arid and semi-arid regions.
Keywords: winter wheat, soil nutrients, yield, fertilizer application rate, nutrient content and use efficiency
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1 Introduction

Winter wheat (*Triticum aestivum* L.), a major staple crop in Xinjiang of China and abroad, has been widely cultivated to ensure national and global food security[1,2]. Nevertheless, farmers often excessively apply fertilizers to achieve high yields and maximize profits[3-5], which not only results in low fertilizer use efficiency[6] but also exacerbates fertilizer losses by leaching in the soil and volatilization[7,8]. Specifically, the leaching of soluble inorganic matter (such as nitrate) due to excessive fertilization is considered the main cause of increased inorganic salts in groundwater, which directly disrupts soil hydrological ecosystems[9,10]. Consequently, maintaining high yields and increasing nutrient and fertilizer use efficiency is crucial for achieving sustainable food production[4,11].

Growth, yield, and fertilizer use efficiency in winter wheat have been studied extensively to determine how different rates of fertilizer application affect the crop[12,13]. Notably, although increasing the fertilization rate increased winter wheat yield, the

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efficiency of the fertilizer used declined drastically[1,14]. Guo et al.[15] discovered that under drip irrigation, increased N fertilization rate led to an increase in both residual soil N and water use efficiency. Zhu et al.[16] observed that elevated P fertilization rate resulted in increased grain yield and P use efficiency. Previous studies indicated that excessive N accumulated in the soil profile. However, the balanced application of N and P fertilizer could remarkably enhance yield and lower nitrate–N residue in comparison to N fertilization alone[17,18]. Shi et al.[19] reported that the use of N increased winter wheat yield, and a combined treatment with P fertilizer further enhanced this effect. Similarly, K fertilizer applied to the soil can directly increase crop yield[20]. Liu et al.[21] reported that N and K fertilization significantly increased yields. Therefore, it is critical to establish suitable N, P, and K fertilizer ratios in winter wheat production in Xinjiang, China.

The supply of fertilizer will directly or indirectly affect biomass distribution and assimilate production through the availability of macronutrients (N, P, and K) to the soil, and the nutrient content of plant will directly or indirectly affect biomass distribution and assimilate production[22,23]. The amount of macronutrients absorbed directly influences wheat yield[24]. Many studies have shown that suitable fertilizer ratios (nitrogen, phosphorus, and potassium) can improve wheat growth and yield[25-27] and reduce fertilizer input[28]. In addition, the combined N, P, and K fertilization can result in higher grain yield, protein, nitrogen, phosphorus, and potassium uptake and utilization efficiency[1]. When the fertilization rate was N-P_2O_5-K_2O (162-72-57 kg/hm^2), sustainable wheat production and environmental safety could be achieved, as reported by Xu et al.[29]. When N, P, and K were in limited supply, the winter wheat growth and yield were significantly affected[30,31]. Additionally, researchers have studied the effects of applying fertilizer on the yield and quality of winter wheat[32]. In conclusion, the suitable application of N, P, and K benefits wheat growth and enhances fertilizer utilization efficiency under drip fertigation[33].

Reducing fertilizer application is essential for sustainable intensification, thus promoting sustainable agriculture[34]. Effectively combining N, P, and K application at appropriate rates can help achieve higher wheat yields, improve fertilizer use efficiency, and control soil nitrate–N residue[35,36]. Consequently, the study objectives were to: 1) examine how dry matter accumulation and nutrient absorption in winter wheat are affected by the combined application of N, P, and K, and 2) determine a suitable N, P, and K application ratio to maximize winter wheat yield and fertilizer use efficiency and to reduce soil nitrate–N. In arid regions, drip-fertigated winter wheat production may be optimized by using the scientific basis derived from this study to optimize N, P, and K fertilization.

2 Materials and methods

2.1 Experimental site

Field experiments were conducted in three consecutive growth seasons (from 2018 to 2021) at the Unity Farm, 9th Division, Xinjiang Production and Construction Corps (46°31′3″N, 83°29′40″ E; 1521.0 m a.s.l). The climate is classified as temperate continental, characterized by lengthy and cold winters as well as short and hot summers. It is prone to drought and has an annual mean potential evaporation of 1810 mm. The precipitation and daily average temperature distributions during the three consecutive growth seasons are displayed in Figure 1. The soil texture at this site is sand loamy. Additionally, soil bulk density is 1.24-1.58 g/cm^3 in the 0-100 cm soil layer. Table 1 presents other primary characteristics and features of the topsoil. Winter wheat was planted for three seasons on October 8, 2018, October 10, 2019, and October 6, 2020, and harvested on June 24, 2019, June 20, 2020, and June 25, 2021.

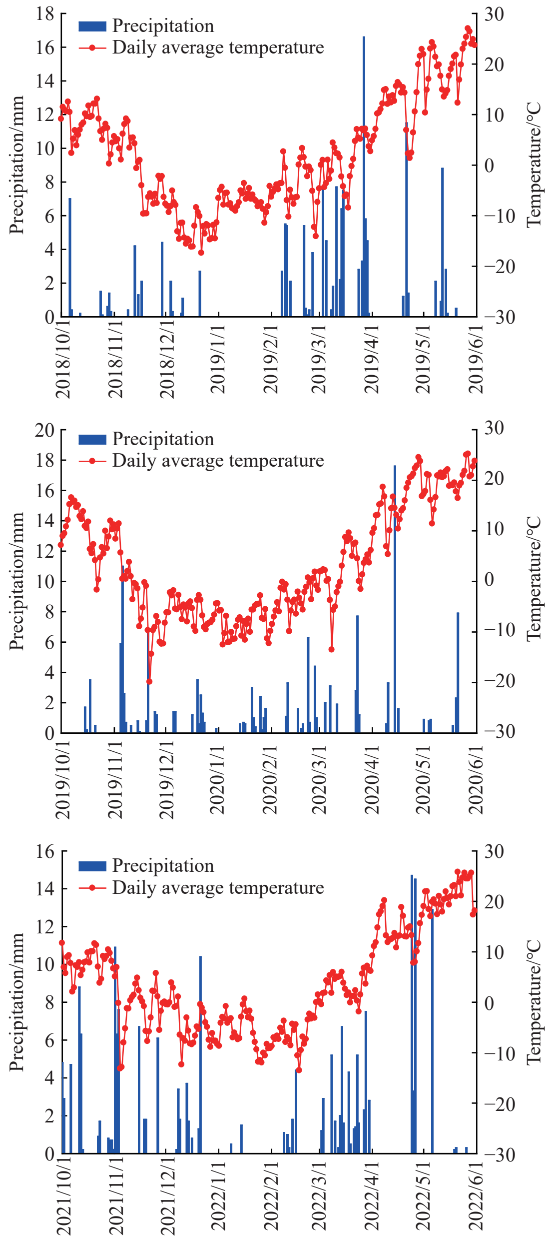


Figure 1 The distributions of precipitation and temperature at the experiment site during the three growing seasons

Table 1 Chemical properties of the soil (0-100 cm layer) before the experiment in 2018

Soil depth/ cm	Properties						
	Organic matter/ g·kg^{-1}	Total nitrogen/ g·kg^{-1}	NO_3^-–N/ g·kg^{-1}	NH_4^+–N/ mg·kg^{-1}	AP/ mg·kg^{-1}	AK/ mg·kg^{-1}	pH
0-100	19.5	0.7	30.5	1.7	23	219.5	8.2

Note: AP: available phosphorus; AK: available potassium.

2.2 Experimental design and field management

To examine how fertilizer reduction affects nutrient allocation ratio on soil nutrient content, winter wheat yield, and fertilizer utilization efficiency, this study used local production practices as a control treatment and referred to previous research results[37,38]. The field experiment included five distinct fertilization applications and was set up with completely randomized design (CK: fertilizer applied by local farmers [N-P_2O_5-K_2O: 240-105-38], FS1: reduced fertilization [N-P_2O_5-K_2O: 166-80-30], FS2: reduced N fertilization

[N-P_2O_5-K_2O: 0-80-30], FS3: reduced P fertilization [N-P_2O_5-K_2O: 166-0-30], FS4: reduced K fertilization [N-P_2O_5-K_2O: 166-80-0]). The treatments were performed in three replicates. The fertilization application rates are detailed in Table 2. The nitrogen as urea [$(NH_2)_2CO$; 46% N], phosphate as superphosphate [$Ca_2PH_4O_8$; 14% P_2O_5], and potassium as [K_2SO_4; 50% K_2O] (Table 2) were used to fertilize the experimental plots. Each experimental planting plot had an area of 40 m^2 (5×8 m). The application of each fertilizer was conducted using a drip irrigation system. The water source for irrigation was groundwater. The water amount applied to winter wheat with drip irrigation was 295 mm for the entire cultivation period, and the drip irrigation dates were 145, 160, 178, 195, 210, 225, and 240 days after sowing, corresponding to drip irrigation water amounts of 30, 35, 60, 60, 35, 35, and 40 mm, respectively. Winter wheat was sown at a rate of 400 kg/hm^2, with a row spacing of 15 cm and a sowing depth of 5 cm (Figure 2). Aphids and Hylemya coarctata were the most prominent types of pests that caused damage to the winter wheat in the experimental regions, and wheat stripe rust was the most common type of disease. Pests and diseases were effectively managed throughout the experiment with the use of agrochemicals like cyhalothrin, thiophanate-methyl, and others. Manual hoeing was used to control the weeds. Furthermore, other common planting management techniques mirrored those used by the local farmers.

Table 2 Fertilizer treatments and application rates used in the field experiment

Treatment	Fertilization			Fertilization/kg·hm^{-2}		
	N fertilizer/ kg N·hm^{-2}	P fertilizer/ kg P_2O_5·hm^{-2}	K fertilizer/ kg K_2O·hm^{-2}	Urea [$(NH_2)_2CO$; 46% N]	Superphosphate ($Ca_2PH_4O_8$; 14% P_2O_5)	Potassium sulfate (K_2O_4; 50% K_2O)
CK	240	105	38	522	750	76
FS1	166	80	30	361	571	60
FS2	0	80	30	0	571	60
FS3	166	0	30	361	0	60
FS4	166	80	0	361	571	0

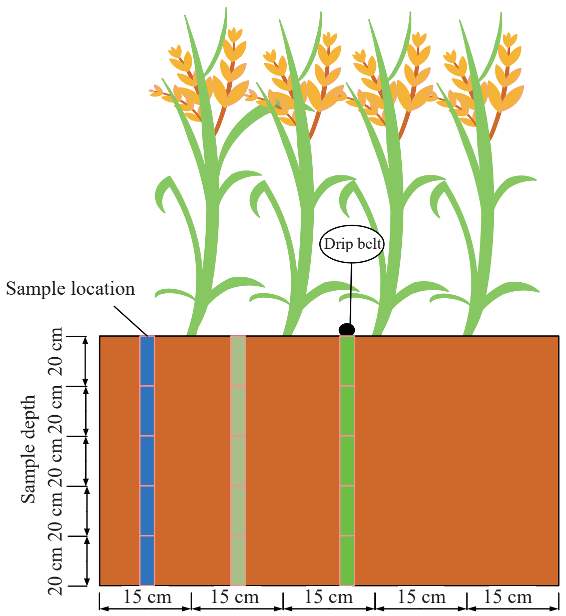


Figure 2 Planting pattern and soil sampling locations

2.3 Sampling and measurements

2.3.1 Soil NO_3^-–N and NH_4^+–N concentration and residue determination

At the wheat maturity stages (i.e., June 15, 2019, June 17, 2020, and June 16, 2021), the concentrations of NO_3^-–N and NH_4^+–N were measured in the soil layer depth ranges of 0-20, 20-40, 40-60, 60-80, and 80-100 cm. Figure 2 depicts the sites used for soil samples. A hand-held soil iron drill (5 cm diameter) was used to take samples of the soil. The drilled soil samples from each experimental plot were sealed in their corresponding aluminum case and were returned to the laboratory for further analysis. After air milling and fine sifting (1 mm), the soil samples were extracted using a 2 mol/L KCl solution (5 g dry soil and 1:10 soil-to-liquid ratio). A flow analyzer (Bran+Luebbe AutoAnalyzer-III, SEAL company, Norderstedt, Germany) was used to estimate the concentrations of NO_3^-–N and NH_4^+–N in the extracts. Soil NO_3^-–N and NH_4^+–N residues were calculated as follows[39]:

$$\text{Soil } NO_3^- - N \text{ and } NH_4^+ - N \text{ residue (kg/hm}^2) = 0.1 \times CN \times \gamma \times h \quad (1)$$

where, CN is the NO_3^-–N and NH_4^+–N concentration (mg/kg); γ represents the bulk density (g/cm^3); h represents the soil depth (cm).

2.3.2 Dry matter, total N, P, and K concentration

Four plants in each experiment plot were collected with completely randomized design during the harvest period. Following a 120-minute drying period at 105°C, the stem in an oven, leaf, husk, and grain were further dried at 75°C to a consistent weight. The dry matter accumulation was the mean weight of four plants multiplied by the planting density. After pulverizing the dried plant samples, they were subsequently filtered through a 1 mm sieve. Nutrient concentration was determined by digesting the particulates with H_2SO_4–H_2O_2. Thereafter, a continuous flow analyzer was employed to obtain total N and P, whereas the atomic absorption spectrometry (Z–2000, Tokyo, Japan) was employed to obtain total K.

2.3.3 N, P, and K use efficiency

N, P, and K use efficiency (kg/kg) were calculated as:

$$\text{N use efficiency (NUE)} = Y/\text{FN} \quad (2)$$

$$\text{P use efficiency (PUE)} = Y/\text{FP} \quad (3)$$

$$\text{K use efficiency (KUE)} = Y/\text{FK} \quad (4)$$

where, Y represents the winter wheat yield (kg/hm^2). Total amounts of N, P, and K accumulation (kg/hm^2) at maturity are denoted by FN, FP, and FK, respectively[40].

2.3.4 Harvest index

The harvest index was calculated as the ratio of the grain yield/aboveground dry matter accumulation[41].

2.3.5 Yield and partial factor productivity

At harvest, three areas of 1 m^2 (1 m×1 m) were chosen at random from each experimental field, and the plants that corresponded to those random areas were threshed using a hand–driven thresher to obtain the yield of wheat grain. The weight of 1000 grains was determined from three subsamples of 1000 random grains[24].

Nitrogen partial factor productivity (NPFP), Phosphorus partial factor productivity (PPFP), and Potassium partial factor productivity (KPFP) were derived as indicated below:

$$\text{NPFP} = \text{Grain yield (kg/hm}^2\text{)/nitrogen application rate (kg/hm}^2\text{)} \tag{5}$$

$$\text{PPFP} = \text{Grain yield (kg/hm}^2\text{)/phosphorus application rate (kg/hm}^2\text{)} \tag{6}$$

$$\text{KPFP} = \text{Grain yield (kg/hm}^2\text{)/potassium application rate (kg/hm}^2\text{)} \tag{7}$$

2.4 Statistical analysis

SPSS 18.0 and Microsoft Excel 2010 were used to carry out the analysis of the data. An analysis of variance (ANOVA) was conducted, and Duncan's method was used to evaluate multiple comparisons among the treatment means. The least significant difference (LSD) method was applied to split-plot ANOVA. A general linear model was applied to investigate the influence of each treatment on soil NH_4^+–N, soil NO_3^-–N, total N content of winter wheat of various organs, total P content of winter wheat of various organs, total K content of winter wheat of various organs, dry matter accumulation, winter wheat yield, and partial factor productivity using the SPSS environment version 18.0. Across the two years, to examine whether or not variance (ANOVA) between treatments were related to soil NH_4^+–N, soil NO_3^-–N, total N content of winter wheat of various organs, total P content of winter wheat of various organs, total K content of winter wheat of various organs, dry matter accumulation, winter wheat yield, and partial factor productivity, this study set treatments and growing year as fixed factors, and three replicates were considered as random factors. Differences were considered statistically significant at the p<0.01 and p<0.05 levels. Sigma plot 14.0 was used to generate the figures.

3 Results

3.1 Soil NH_4^+–N and NO_3^-–N concentrations and residues

Different fertilization strategies had varying influences on the concentrations of soil NH_4^+–N and NH_4^+–N at different soil depths (Figure 3). The highest average soil NH_4^+–N content over three years (0-100 cm depth) was observed in CK (1.76 mg/kg), but the lowest NH_4^+–N was in FS2 treatment (0.79 mg/kg). The highest three–year average NH_4^+–N and NH_4^+–N concentrations were measured in the 0-40 cm soil layer. FS2 decreased the NH_4^+–N concentration in the layers of soil ranging from 0 to 100 cm compared with the other treatments. Specifically, the NH_4^+–N concentration in FS2 was 55.38%, 32.53%, 26.46%, and 31.61% higher compared to CK, FS1, FS3, and FS4, respectively. In addition, CK led to an increase in the soil NO_3^-–N concentration in the top 0-100 cm soil layer, being 51.22%, 124.12%, 64.82%, and 53.29% higher as compared to FS1, FS2, FS3, and FS4, respectively. Similar results were obtained for soil NH_4^+–N and NH_4^+–N residues under various fertilization strategies (Figure 4). Overall, there was an increasing and then decreasing trend of soil NH_4^+–N concentrations over the three seasons (Figure 3g), while NO_3^-–N concentrations decreased (Figure 3h).

3.2 N, P, and K concentrations in various plant organs

The total N content of winter wheat decreased as a result of the reduction in fertilization rates over the three growing seasons (Figure 5a-5c). During the three growing seasons, CK, FS2, FS3, and FS4 treatments decreased the total N content by 19.63%, 15.85%, 11.06%, and 15.92% relative to FS1, respectively. Total N content differed significantly between CK and FS1 (p<0.05), while the difference was insignificant between FS1 and FS2 and between FS3 and FS4 during 2018–2019 and 2019–2020 (p>0.05). Furthermore, the average distribution percentages of total N in the stem+leaves, spikes+hulls, and the grains over the three seasons ranged from 14.05%-16.27%, 14.32%-18.31%, and 65.42%-71.62%, respectively. When fertilization was sufficient, the N content in grain was relatively low.

Total P concentration increased as a result of the reduction in fertilization rate over the three growing seasons (Figure 5d-5f). FS1 increased total P content by 13.46%, 14.51%, and 6.89% compared with CK during 2018–2019, 2019–2020, and 2020–2021, respectively. The difference in the total P content between CK, FS1, FS2, FS3, and FS4 was insignificant (p>0.05). Furthermore, the average distribution percentages of total P in the stem+leaves, spikes+halls, and the grain over the three seasons ranged from 15.95%-18.74%, 9.52%-18.13%, and 64.74%-71.74%, respectively.

The total K concentration increased as a result of the reduction in fertilization rate over the three growing seasons (Figure 5g-5i). FS1 increased the total K concentration by 37.16%, 40.64%, and 35.57% compared with CK during 2018-2019, 2019-2020, and 2020-2021, respectively. Furthermore, the average distribution percentages of total K in the stem+leaves, spikes+hulls, and the grains over the three seasons ranged from 71.75%-75.90%, 12.16%-14.05%, and 10.96%-15.42%, respectively.

3.3 N, P, and K use efficiency

Significant (p<0.05) effects on NUE were observed for fertilization, year, and fertilization×year interaction (Table 3). CK significantly increased NUE by 4.95% and 18.31% and by 16.31% and 13.07% as compared to FS1 and FS4 during 2018-2019 and 2019-2020, respectively. During 2020-2021, CK significantly increased NUE by 24.78% compared with FS1, and the difference between CK and FS1 was significant in NUE (p<0.01) (Table 3).

Table 3 Effects of various fertilization strategies on N, P, and K use efficiency (NUE, PUE, and KUE) during 2018-2019, 2019-2020, and 2020-2021

Treatments	NUE/kg(yield)·kg^{-1} N			PUE/kg(yield)·kg^{-1} P			KUE/kg(yield)·kg^{-1} K		
	2018-2019	2019-2020	2020-2021	2018-2019	2019-2020	2020-2021	2018-2019	2019-2020	2020-2021
CK	36.5^a±5.41	32.5^b±3.07	36.4^a±3.33	153.6^b±17.02	220.4^b±23.82	176.8^{bc}±13.50	45.0^a±3.28	66.1^b±6.59	39.7^b±5.41
FS1	34.8^a±5.91	28.0^b±0.31	29.2^b±1.75	200.5^{ab}±11.11	187.1^b ±17.71	150.8^c±12.64	39.6^a±2.87	47.1^c±4.30	25.4^c±5.41
FS2	42.2^a±6.02	46.7^a±4.16	35.6^a±6.89	252.2^a±15.58	289.3^a±21.20	321.6^a±18.58	48.3^a±4.09	88.3^a±3.15	54.5^a±5.41
FS3	41.2^a±2.03	29.5^b±2.24	34.8^a±2.80	250.0^a±18.67	189.5^b±10.93	184.0^{bc}±18.63	40.1^a±3.27	40.5^c±2.12	36.8^b±5.41
FS4	30.9^a±4.02	28.8^b±0.82	38.0^a±4.70	181.3^{ab}±9.28	188.3^b±6.27	197.8^b±21.36	36.6^a±3.32	44.6^c±3.34	37.8^b±5.41
Fertilization (F)	**			**			*		
Years (Y)	*			NS			**		
F×Y	**			**			**		

Note: NUE, PUE, and KUE represent the N use efficiency, P use efficiency, and K use efficiency. Values within a column followed by the different lowercase letters indicate a significant difference at p<0.05 using the LSD method. * significant p<0.05; ** significant p<0.01; NS not significant p>0.05. The value of each treatment in the table is the average effect value. ±: Standard deviation.

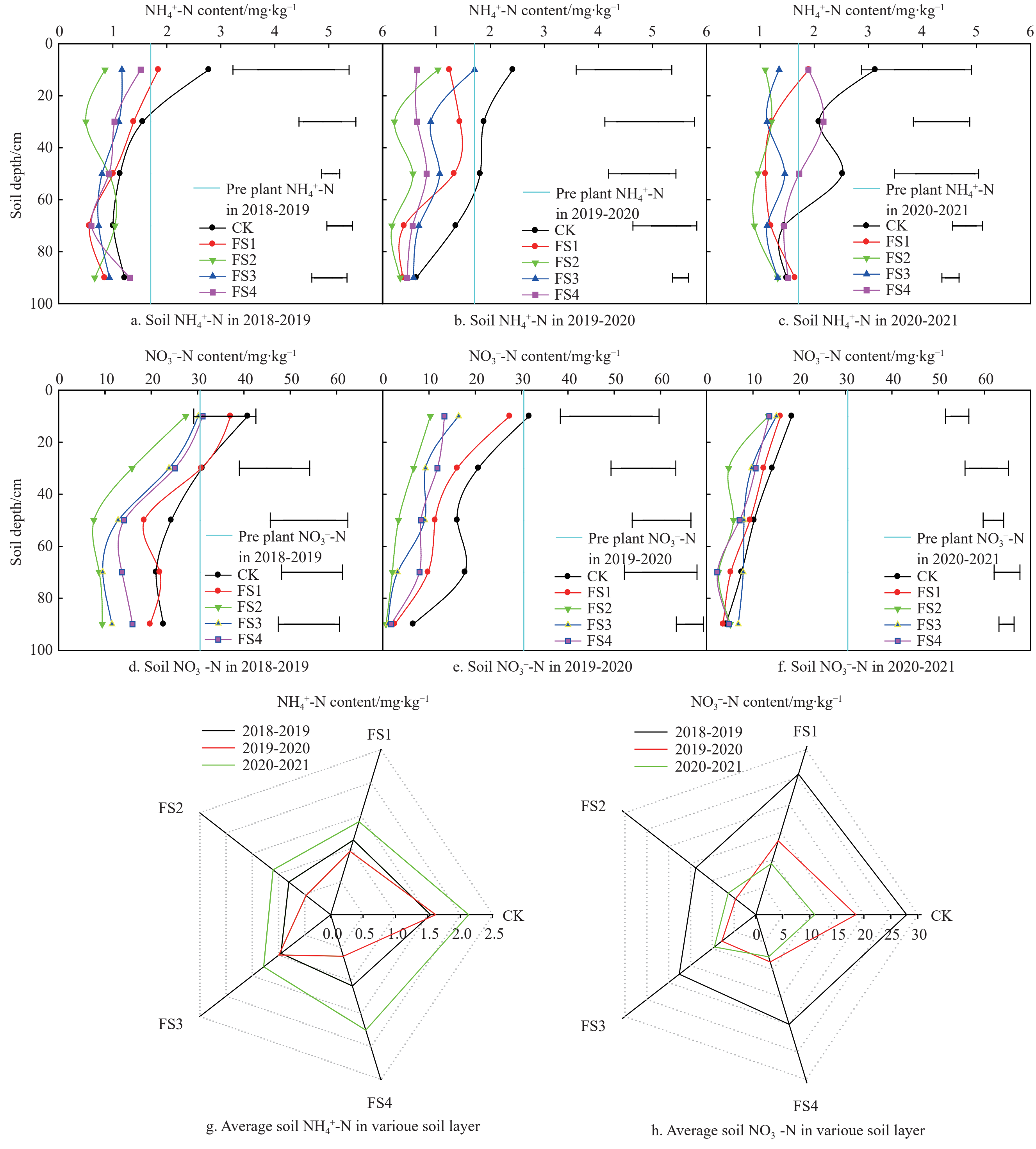


Figure 3 Changes of soil ammonium nitrogen (NH_4^+–N) and nitrate nitrogen (NO_3^-–N) concentration at different soil depths under different fertilization strategies in 2018–2019, 2019–2020, and 2020–2021

The FS2 had a higher NUE, which suggested that the lack of nitrogen fertilizer promoted and improved nitrogen use efficiency.

Fertilization and fertilization×year exhibited highly significant (p<0.01) effects on PUE (Table 3). Among the three growing seasons, FS2 had the highest PUE, which was increased by 25.77%-64.25%, 31.23%-54.60%, and 62.58%-113.32% compared with other treatments during 2018-2019, 2019-2020, and 2020-2021, respectively. There was a significant difference in PUE between FS2 and CK during 2019-2020 and 2020-2021 (p<0.01). Generally, the FS2 treatment had a higher PUE, possibly due to P accumulation mainly in wheat grains under low fertilization conditions. Fertilization, year, and fertilization×year significantly (p<0.05) affected KUE (Table 3). The CK significantly increased KUE by 13.78%, 12.30%, and 44.88% in 2018-2019, 40.43%, 63.37%, and 48.14% in 2019-2020, and 55.94%, 7.80%, and 5.26% in 2020-2021 in comparison with FS1, FS3, and FS4, respectively. On the other hand, CK significantly decreased KUE by 6.72%, 25.13%, and 27.16% compared to FS2 during 2018–2019, 2019–2020, and 2020–2021, respectively. Additionally, there was a significant difference in KUE between CK and FS2 during 2019-2020 and 2020-2021 (p<0.05). In summary, KUE was high in the CK treatment, which may be a result of K accumulation mainly in the vegetative organs of wheat under high fertilization conditions (Table 3).

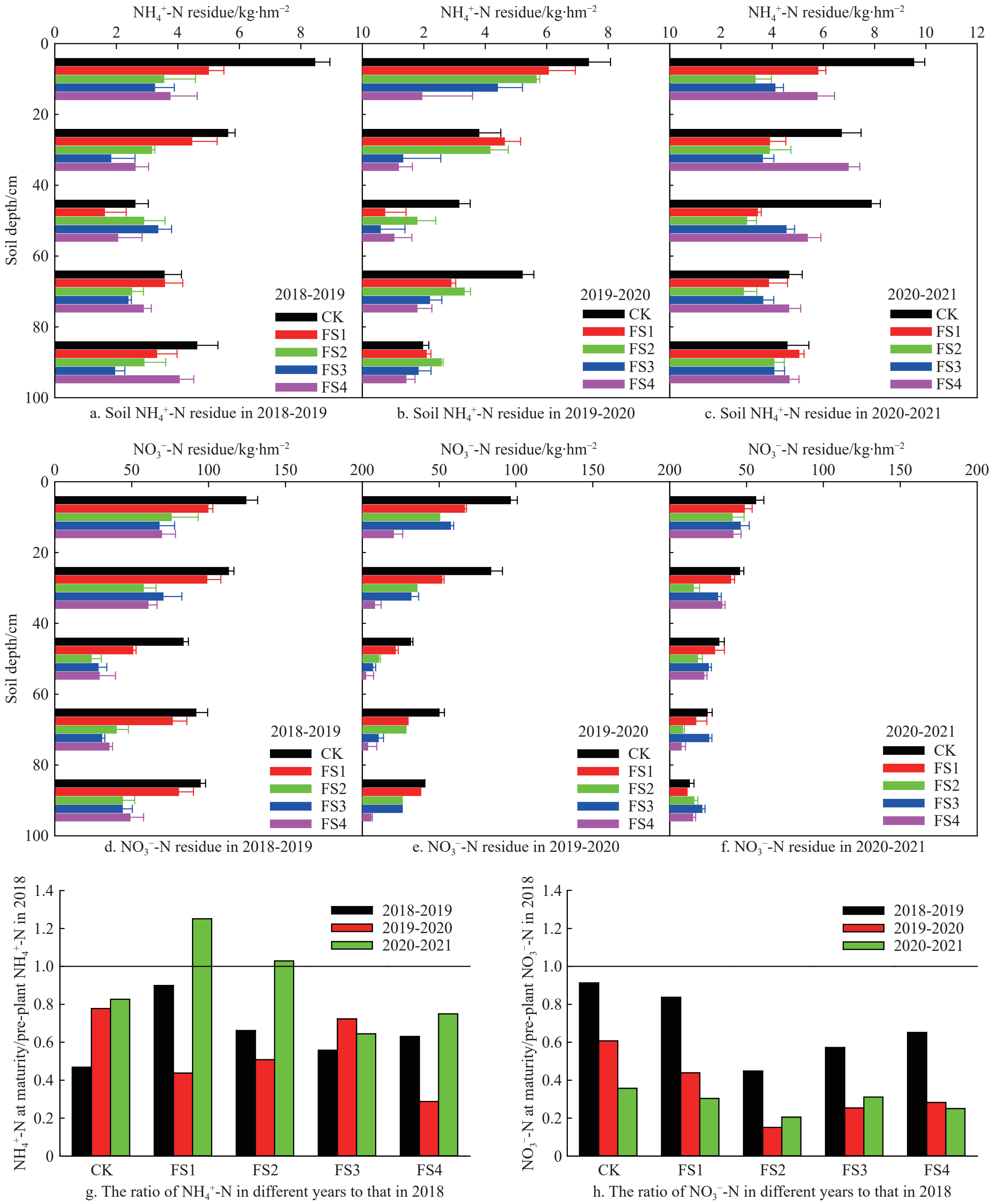
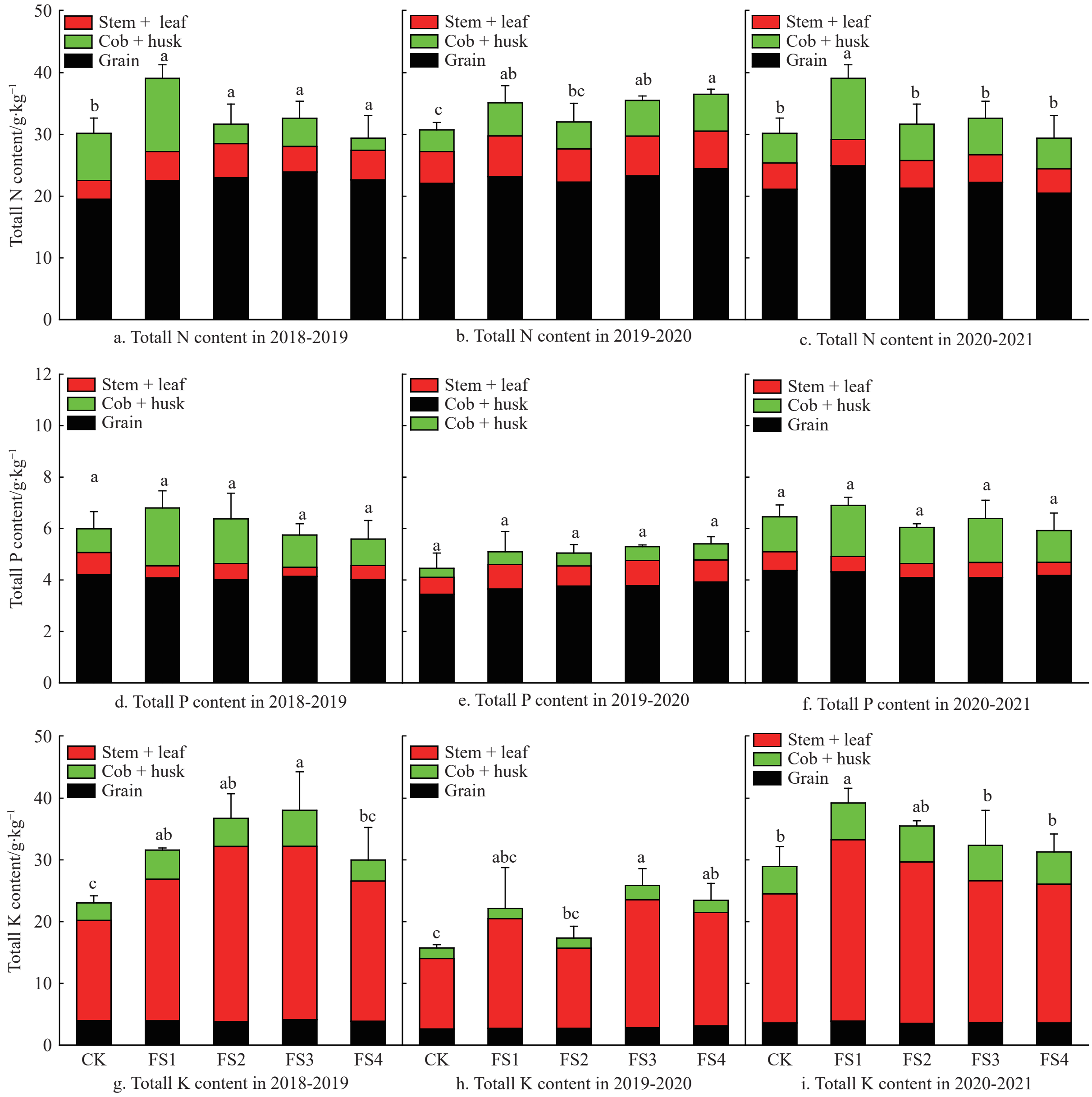


Figure 4 Changes of soil NH_4^+–N and NO_3^-–N residue at different soil depths under different fertilization strategies in 2018–2019, 2019–2020, and 2020–2021

3.4 Dry matter accumulation and harvest index

The fertilization, year, and year×fertilization all exhibited a significant impact on dry matter accumulation (p<0.05) (Figure 6c). The grain at maturity constituted the majority of the total dry matter (41.01%-44.50%). The stems and leaves represented 38.50%-40.00% of total dry matter, and spikes and hulls accounted for the lowest proportion of total dry matter (16.99%-20.00%). The dry matter of CK treatment decreased by 11.20%, 3.80%, and 11.08% in 2018-2019, 9.27%, 3.33%, and 3.79% in 2019-2020, and 16.21%, 12.39%, and 17.08% in 2020-2021 as compared with FS1, FS3, and FS4, respectively. On the other hand, CK increased dry matter by 11.20%, 3.80%, and 11.08% compared to FS2 during 2018–2019, 2019–2020, and 2020–2021, respectively. Moreover, significant differences were observed in dry matter between CK, FS2, and FS4 over the three growing seasons (p<0.05). The dry matter increased due to the proper reduction of fertilizer application over the three growing seasons (Figure 6a-6c).

The fertilization, year, and fertilization×year all exhibited a significant impact on the harvest index (p>0.05) (Figure 4f). CK increased the harvest index by 43.91%, 39.46%, and 6.37% in 2018-2019, 47.40%, 1.33%, and 7.97% in 2019-2020, and 21.63%, 0.76%, and 0.87% in 2020-2021 as compared to FS2, FS3, and FS4,



Note: Bars are the means+one standard error of the mean (n=3). Different letters above the bars indicate a significant difference at p<0.05 according to an LSD test.

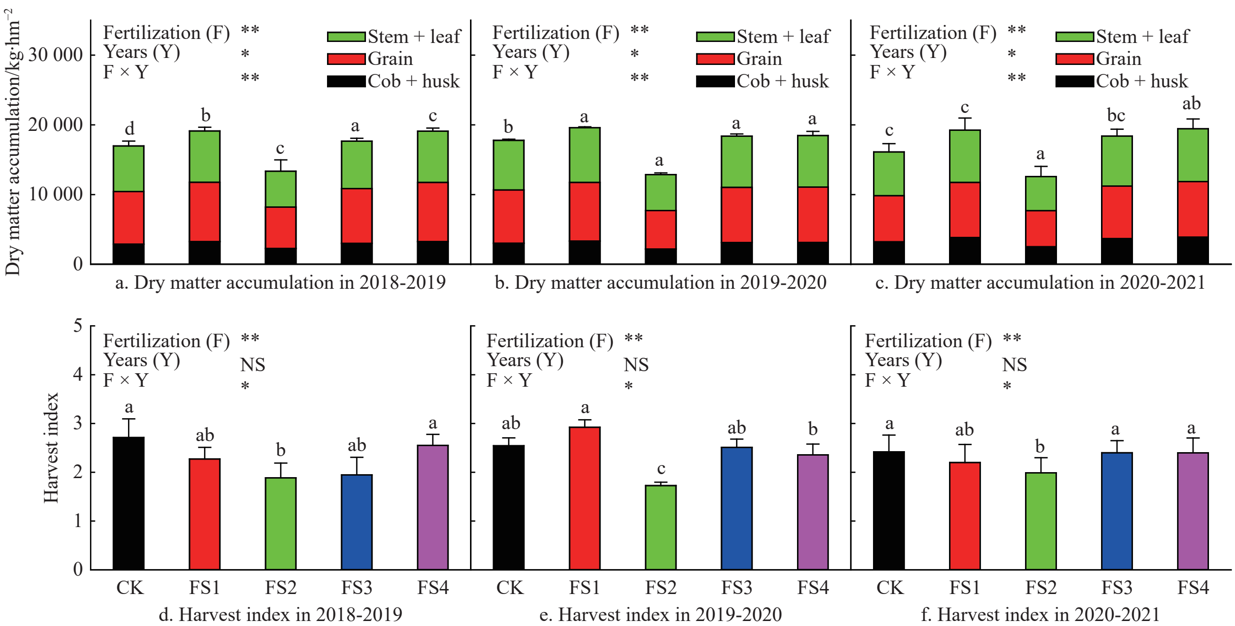
Figure 5 Effects of different fertilization strategies on total N, P, and K concentrations of winter wheat during 2018-2021

respectively. Interestingly, FS1 increased the harvest index by 14.99% compared to CK during 2019-2020, and decreased it by 16.29% and 9.13% during 2018-2019 and 2020-2021, respectively (Figure 6d-6f). The high harvest index during 2019-2020 could be explained by the occurrence of drought, which caused lower wheat yields (Table 4).

3.5 Grain yield and partial factor productivity

In the three growth seasons, fertilization significantly affected the grain yield (p<0.01). Year did not significantly affect wheat yield (p>0.05), but highly significantly affected the spike number, grains per spike, and 1000-grain weight (p<0.01). Fertilization×year exhibited a significant impact on the yield and the 1000-grain weight (p<0.01) (Table 4). Compared with CK, FS1, FS3, and FS4 increased yield by 6.73%-31.50%, 4.95%-15.00%, and 6.11%-21.49% during 2018-2021, respectively. This indicated that appropriate fertilization reduction would not decrease winter wheat yield. In addition, the yield in the FS2 treatment showed an increasing trend in the later years, while a reasonable effective reduction in fertilizer application rate (i.e., FS3) increased the yield (Table 4). Among the three growing seasons, FS1 resulted in the highest number of spikes, which increased by 17.98%, 17.80%, and 9.64% compared with CK during 2018-2019, 2019-2020, and 2020-2021, respectively. Interestingly, FS2 increased the spike number by 1.05% compared with CK during 2018-2019, while reducing it by 8.26% and 3.79% during 2019-2020 and 2020-2021, respectively. In agreement with the spike number results, FS1 had the highest number of grains per spike. This explained its high yield across the growing seasons due to the high number of spikes and grains per spike. Nevertheless, FS3 showed a positive effect in terms of 1000-grain weight, with increases of 2.37%, 2.35%, and 9.17% compared with CK during three growth seasons (Table 4). This suggested that P fertilizer application improved the 1000-grain weight across the growing seasons.

Fertilization and fertilization×year exhibited highly significant (p<0.01) effects on NPFP, PPFP, and KPFP. Year significantly affected NPFP, PPFP, and KPFP (p<0.05) (Table 5). FS1 positively affected NPFP, PPFP, and KPFP across the three growing seasons, which increased by 54.33%-90.10%, 40.10%-72.58%, and 35.21%-66.57% compared with CK during three growth seasons, respectively (p<0.01). Furthermore, FS4 increased NPFP by 5.67%,



Note: Bars are the means+one standard error of the mean (n=3). Different letters above the bars indicate a significant difference at p<0.05 according to an LSD test. * significant p<0.05; ** significant p<0.01; NS not significant p>0.05.

Figure 6 Effects of different fertilization strategies on dry matter accumulation and harvest index during 2018–2021

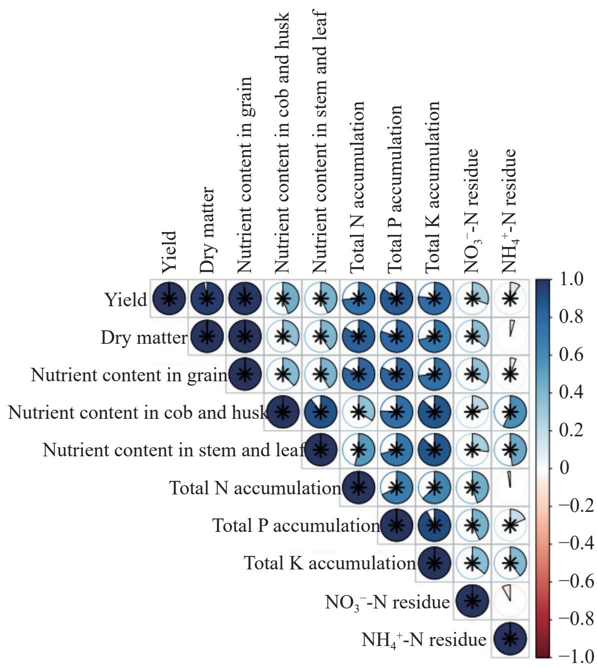
Table 4 Grain yield and its components of winter wheat under different fertilization strategies during 2018-2019, 2019-2020, and 2020-2021

Treatments	Yield/ kg·hm^{-2}	Spikes/ 10^{4}·hm^{-2}	Grains per spike/No.	1000-grain weight/g
		2018-2019		
CK	6466^{d}±383	573^{bc}±29	30.2^{a}±2.9	59.1^{a}±3.2
FS1	8419^{b}±685	676^{a}±38	35.0^{a}±3.8	59.8^{a}±6.8
FS2	6562^{c}±894	579^{bc}±29	34.9^{a}±4.1	60.0^{a}±7.4
FS3	7081^{a}±879	632^{ab}±46	33.8^{a}±1.9	60.5^{a}±4.9
FS4	7481^{c}±956	654^{c}±34	34.7^{a}±3.2	58.6^{b}±3.7
Fertilization (F)	**	**	NS	**
Years (Y)	NS	**	**	**
F×Y	**	NS	NS	**
		2019-2020		
CK	6984^{b}±606	545^{bc}±36	32.6^{b}±3.6	54.4^{ab}±5.1
FS1	7454^{a}±749	642^{a}±49	37.7^{a}±4.2	53.2^{b}±5.3
FS2	6478^{c}±569	500^{bc}±38	37.7^{a}±2.8	55.2^{a}±4.8
FS3	7330^{a}±883	600^{ab}±42	36.5^{a}±2.5	55.7^{a}±5.6
FS4	7411^{a}±418	626^{c}±39	37.5^{a}±3.4	48.4^{c}±4.5
Fertilization (F)	**	**	**	**
Years (Y)	NS	**	**	**
F×Y	**	NS	NS	**
		2020-2021		
CK	6667^{c}±511	633^{b}±52	40.0^{a}±3.4	53.1^{c}±3.8
FS1	8767^{a}±660	694^{a}±49	40.6^{a}±4.3	54.2^{bc}±4.2
FS2	6334^{c}±665	609^{a}±43	42.0^{a}±3.7	51.5^{a}±5.1
FS3	7667^{b}±970	681^{a}±51	36.4^{a}±3.2	58.0^{abc}±4.9
FS4	8100^{b}±920	654^{a}±45	40.6^{a}±3.6	58.7^{ab}±3.5
Fertilization (F)	**	NS	NS	*
Years (Y)	NS	**	**	**
F×Y	**	NS	NS	**

1.11%, and 5.65% compared with FS3 during 2018-2019, 2019-2020, and 2020-2021, respectively. This explained the increase in NPFP due to P fertilizer application across the three growing seasons. The appropriate combinations of fertilizers could also increase partial factor productivity (i.e., PPFP and KPFP) (Table 5).

3.6 Correlation analysis of grain yield, dry matter, N, P, and K accumulation, and soil nutrient content

A correlation analysis was performed between grain yield, dry matter, nutrient uptake in the grain, spikes, hulls, stems, and leaves, as well as the total N accumulation, total P accumulation, total K accumulation NO_3^-–N, and NH_4^+–N (Figure 7).



Note: Nutrient content in grain: the sum of N, P, and K content in grain. Nutrient content in cob and husk: the sum of N, P, and K content in cob and husk. Nutrient content in stem and leaf: the sum of N, P, and K content in stem and leaf. Total N, P, and K accumulation: the sum of grain, cob+husk, and stem + leaf. * significant p<0.05.

Figure 7 Correlation analysis of grain yield, dry matter, total N, P, and K accumulation, nutrient content in different plant organs and soil NO_3^-–N and NH_4^+–N

Table 5 Partial factor productivity of winter wheat under different fertilization strategies during 2018-2019, 2019-2020, and 2020-2021

Treatments	Nitrogen partial factor productivity/NPFP			Phosphorus partial factor productivity/PPFP			Potassium partial factor productivity/KPFP		
	2018–2019	2019–2020	2020–2021	2018–2019	2019–2020	2020–2021	2018–2019	2019–2020	2020–2021
CK	$27.0^{d}\pm2.6$	$29.1^{b}\pm2.9$	$27.8^{c}\pm1.9$	$61.6^{c}\pm5.2$	$66.5^{c}\pm6.1$	$63.5^{d}\pm6.1$	$170.2^{d}\pm15.6$	$183.8^{c}\pm16.2$	$175.5^{d}\pm15.2$
FS1	$50.7^{a}\pm3.8$	$44.9^{a}\pm3.5$	$52.8^{b}\pm4.2$	$105.2^{a}\pm8.7$	$93.2^{a}\pm8.9$	$109.6^{c}\pm9.8$	$280.6^{b}\pm26.3$	$248.5^{a}\pm23.1$	$292.2^{a}\pm27.1$
FS2	-	-	-	$94.5^{b}\pm7.6$	$84.3^{b}\pm7.9$	$79.2^{b}\pm7.2$	$252.2^{c}\pm24.1$	$224.8^{b}\pm20.8$	$211.1^{c}\pm20.6$
FS3	$42.7^{c}\pm3.1$	$44.2^{a}\pm4.1$	$46.2^{ab}\pm2.6$	-	-	-	$302.7^{a}\pm29.7$	$244.3^{a}\pm23.5$	$255.6^{b}\pm24.3$
FS4	$45.1^{b}\pm3.5$	$44.6^{a}\pm3.9$	$48.8^{a}\pm3.4$	$93.5^{b}\pm6.9$	$92.6^{a}\pm9.2$	$101.3^{a}\pm9.9$	-	-	-
Fertilization (F)	**			**			**		
Years (Y)	**			*			**		
F×Y	**			**			**		

Grain yield had a high positive correlation coefficient of 0.969 and 0.983 with dry matter and nutrient uptake in the grains. The dry matter exhibited the strongest positive link to their nutrient uptake in the grains (R=0.998), while nutrient uptake in the grains was highly linked to total N accumulation (R=0.817) and total P accumulation (R=0.817). Total K accumulation positively correlated with nutrient uptake in the spikes and hulls (R=0.877) and nutrient uptake in the stems and leaves (R=0.876).

4 Discussion

4.1 Nitrogen concentration and residues in the soil

The crucial significance of soil mineral nitrogen concentration on crop growth has been widely recognized[19,42-45]. However, nitrate is highly vulnerable to leaching into groundwater under inappropriate fertigation management[46], which can lead to groundwater pollution[47]. Therefore, a reasonable fertilizer reduction could maintain the soil mineral N content for efficient crop yield while reducing the harm of nitrate leaching in the soil and groundwater. Previous studies have indicated that appropriate combined fertilizer application significantly increased winter wheat yields by improving the absorption and utilization of N fertilizer[19]. Moreover, the root is an important organ of the plant for absorbing water and nutrients from the soil. The efficiency of water and fertilizer absorption in plants is significantly influenced by the spatial distribution of root systems[48-50]. There have been studies showing that reducing N fertilizer inputs (i.e., soil nitrate) can improve crop root growth by increasing nutrient availability in the rhizosphere[51,52]. An intriguing phenomenon which emerged from this study was that, compared with FS1, FS2, FS3, and FS4, CK significantly increased the concentrations of NO_3^-–N (by 18.83% to 132.30%) and NH_4^+–N (by 51.22% to 124.12%) in the 0-100 cm soil layer. In addition, applying P fertilizers rationally has been found to enhance crop growth by increasing N uptake[16,53]. The soil NO_3^-–N residues were primarily accumulated in the surface layer of the soil (Figure 3). Therefore, additional studies are recommended to elucidate how irrigation and fertilization affect NO_3^-–N leaching over a longer time.

4.2 N, P, and K concentration and use efficiency

The uptake of nutrients in wheat is related to fertilization levels[54]. According to Cao et al.[55], higher wheat yields could be achieved by acquiring sufficient N, P, and K based on multiple years of data experimentation and observations. In the present study, N was transported to wheat grains due to the senescence and abscission of leaves at maturity[1]. Additionally, Bogard et al.[56] and Sandaña et al.[57] found a negative correlation between grain N content and crop yield. However, a positive correlation between grain N concentration and winter wheat yield was found in the current study (Figure 7), and consistent findings were reported by Yan et al.[58]. This interesting phenomenon could be related to environmental factors[59]. In addition, Liu et al.[60] also identified a linear correlation between wheat yield and P and K concentration using the QUEFTS model. This is highly consistent with this study's findings, indicating that a reduction in fertilizer supply facilitates N, P, and K accumulation by the crop, and a reduction in N, P, and K supply improves the transport from vegetative organs to the grains and increases yield. The fertilizer treatment with the highest nutrient amount (CK, N-P_2O_5-K_2O: 240-105-38 kg/hm^2) resulted in a lower wheat N, P, and K content. This interesting phenomenon was attributed to the fact that when the nutrient supply capacity of the soil exceeds the nutrient demand of the grain, the nutrients absorbed by the soil are not efficiently transported to the grain, contributing to higher contents of accumulated nutrients in the vegetative organs (leaves and stems)[1,61].

Proper fertilizer application is highly essential to enhancing wheat yield and efficiency in fertilizer use[40,62]. Fertilizer utilization efficiency (N, P, and K) has been demonstrated to decline when N, P, and K application rates have increased in previous research[1,63]. Li et al.[64] demonstrated that the increased application of nitrogen fertilizer decreased the nitrogen use efficiency under the same phosphorus and potassium fertilizer application rate. This study also obtained a result similar to that of previous studies. Nitrogen, phosphorus, and potassium utilization efficiency were higher under reduced N fertilizer applications than under higher application rates during 2018-2019, 2019-2020, and 2020-2021. However, nitrogen fertilizer application increased the utilization efficiency of phosphorus and potassium[40], contrary to this study's results (Table 3). This could be because reduced nitrogen fertilization could affect phosphorus and potassium accumulation, increasing the phosphorus and potassium fertilizer utilization efficiency. In addition, this study also observed that no application of nitrogen fertilizer could increase the efficiency of N, P, and K utilization. Similar results were reported in the study of Shi et al.[19].

4.3 Dry matter accumulation, grain yield, and fertilizer productivity

The fertility characteristics of the soil have a significant impact on the accumulation of dry matter. Moreover, high dry matter accumulation is the prerequisite for high wheat grain yield shown in prior research[65]. The translocation and assimilation of dry matter from the different wheat organs, influenced by fertilization, is the dominant contributor to wheat grain yield. Recently, numerous researchers have shown that fertilization increased wheat grain yield. This is mainly because fertilizer application regulates the canopy structure, photosynthetic rate, and sink-to-source ratio[66-68]. As observed in this study, the stem, leaf, and grain dry matter percentages tended to decrease at maturity due to N fertilizer reduction. The proportion of dry matter in the grains was greater under normal reduction conditions compared to fertilizer reduction and local fertilization practices. In addition, Duan et al.[69] identified that achieving high yield was mainly related to the spike dry matter. The results of the present study also demonstrated that wheat yield was positively and linearly related to dry matter accumulation (Figure 7).

Fertilizer application can enhance crop yield and modify soil nutrient supply capacity. An increase in the application rate of nitrogen fertilizer resulted in a rise in wheat yield; however, excessive nitrogen fertilization failed to increase the yield[70]. Mon et al.[71] and Fois et al.[72] revealed that nitrogen fertilization increased leaf photosynthetic rate and chlorophyll content and increased light energy interception and capture, resulting in higher dry biomass and yield. Similar results were observed in the present study. Nonetheless, among the various treatments of fertilizer reduction, grain yield was significantly decreased (p<0.05) in the CK treatment. This finding could be explained by the local environmental conditions in this arid area and by high fertilizer treatments that would increase the inorganic ion concentration, potentially causing soil salinization[73].

Higher fertilizer effectiveness can be obtained with high fertilizer application when nutritional and reproductive growth are in balance. However, Abdelkhalek et al.[74] observed that excessive fertilizer application disrupts the balance between the nutritional and reproductive growth of the crop and affects crop growth. This study demonstrated that higher crop productivity can also be obtained with moderate fertilizer application rates[75,76]. Fertilizer use efficiency decreased with increasing amounts of fertilizer applied. The NPFP and PPFP values were maximized when the amount of fertilizer was 166-80-30 (N-P_2O_5-K_2O). The results indicated that fertilizer reduction under this fertilizer application combination could improve the crop's ability to absorb nutrients and increase fertilizer use efficiency. Even though the reduced application rate of N, P, and K fertilizers resulted in higher PFP, the yield production was not meeting the standards (i.e., high yield and high PFP). Therefore, the appropriate ratio of N, P, and K nutrients applied at moderate rates was more favorable for both yield and fertilizer utilization.

5 Conclusions

Different fertilizer strategies significantly impacted soil N, plant N, P, and K content, dry matter accumulation, yield components, yield, and fertilizer productivity of winter wheat. Each fertilization strategy regulated the soil mineral N, P, and K concentrations in the root zone and nutrient uptake and distribution of winter wheat, thus affecting yield and fertilizer use efficiency. The optimal fertilizer application strategy was determined to be 166-80-30 (N-P_2O_5-K_2O) to obtain maximum benefits in the arid region of northwest China. The findings of this study will provide valuable insights for policymakers to devise optimum fertilizer application techniques for wheat yield optimization in the arid regions of northwest China.

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