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Effects of Recommended Fertilizer Application Strategies Based on Yield Goal and Nutrient Requirements on Drip-Irrigated Spring Wheat Yield and Nutrient Uptake

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Abstract: Excessive application of fertilizers in drip-irrigated wheat production can suppress yields, lower nutrient utilization efficiency, and lead to economic and environmental issues such as nitrogen residues in the soil. Based on a recommended fertilizer application (RF) strategy that takes into account target yield and nutrient requirements, this study explores the responses of wheat plant traits, changes in topsoil and subsoil nutrients, fertilizer utilization, and economic benefits under this strategy. From 2022 to 2023, a field experiment was conducted in a typical oasis spring wheat production area at the northern foot of the Tianshan Mountains in Xinjiang. The treatments included no fertilizer control (CK), the farmer's conventional practice (FP), recommended fertilizer (RF), RF with nitrogen omission (RF-N), phosphorus omission (RF-P), and potassium omission (RF-K). The results showed that compared with FP, the RF reduced 91 kg N ha^{-1} (30.3%) and 33 kg P_2O_5 ha^{-1} (24.8%) in 2022, and 69 kg N ha^{-1} (23.0%) and 2 kg P_2O_5 ha^{-1} (1.5%) in 2023. The effect in 2023 was better; RF also decreased the $NO_3{}^{-1}$-N residue in the 0–100 cm soil layer by 40.1 kg N ha^{-1} compared with FP, with no significant difference in wheat grain yield (RF: 5382.9 kg ha^{-1}) or economic benefit (RF: USD 1613.1 ha^{-1}). Furthermore, there were no significant differences between RF and FP in pre-anthesis NP transport or post-anthesis NP accumulation; however, RF significantly increased pre-anthesis potassium transport volume (15.8%) and transport rate (12.5%). RF led to a 16.3% increase in nitrogen utilization efficiency (NUE), while there was no significant difference in phosphorus utilization efficiency (PUE) compared with FP. The fertilizer yield effect for RF was evaluated as N > P > K. Correlation analysis indicated that grain yield was significantly positively correlated with pre-anthesis NPK transport and post-anthesis NP accumulation. It was also positively correlated with organic matter, alkali-hydrolyzed nitrogen, and Olsen-P content in both the topsoil (0–20 cm) and subsoil (20–40 cm), but not with available potassium in the soil. Therefore, conducting soil tests and determining fertilizer recommendations based on the proposed RF method at harvest can reduce fertilizer usage and achieve a balance between the conflicting objectives of environmental protection, increased crop yields, nutrient utilization efficiency, and improved economic benefits in oasis agricultural areas facing excessive fertilizer application.

Keywords: drip irrigation; wheat yield; nutrients uptake; soil nutrients; NPK remobilization; fertilizer use efficiency

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1. Introduction

Wheat (*Triticum aestivum* L.) is one of the major staple crops, with a total global production of 770 million tons, ranking as the third largest food crop after maize and rice [1]. The application of chemical fertilizers plays a crucial role in increasing wheat yield and ensuring global food security [2]. In reality, due to the low capacity of farmers to bear economic risks, economic profit is of greater concern than environmental costs [3]. This has led wheat farmers to adopt either excessive fertilizer or under-fertilization practices. Nevertheless, there are significant disparities in perceptions of fertilizer use among farmers in China [4–6] and other parts of the world [7,8], resulting in soil nutrient deficiencies and excesses. Unsustainable soil management practices and inaccurate fertilizer application strategies in past agriculture have led to a series of environmental issues and significant spatiotemporal changes in soil properties [9–11]. The current challenge in agricultural production is to ensure stable growth in food yield while minimizing the negative environmental impacts of fertilizers. Therefore, there is an urgent need to apply suitable strategies to scientifically utilize chemical fertilizers, achieving sustainable development of both agriculture and the environment.

Oases are generally located in arid and semi-arid regions, situated between mountains and deserts. Oasis agriculture plays an important role in ensuring sustainable human development and ecological succession in oases, making it a crucial component of terrestrial ecosystems [12]. This study was conducted in the largest oasis farming area in Xinjiang, which is located in the middle section of the northern foothills of the Tianshan Mountains, adjacent to the Tianshan Mountains and the Gurbantunggut Desert, with the Manas River running through the entire region. With the development of oasis agriculture, artificial oases are gradually replacing natural oases, but desertification is also increasing [13]. The production of food crops such as wheat is subject to more severe climate challenges [14]. This is mainly due to the irrational use of water resources and soil degradation in farmlands [15]. The overuse of fertilizer is harmful to soil health, so scientific use of fertilizer is of great significance to improve the soil environment.

Most fertilizer recommendation methods focus solely on the response of crop yield to fertilizer application [16,17] or nutrient absorption by the soil [18], without adequately considering the levels of soil nutrients or residue. Cao et al. [19] and Huang et al. [20] developed an optimized fertilizer recommendation method based on soil testing at the time of the previous crop harvest to recommend appropriate amounts of N, P, and K fertilizers. The aim of the method was to reduce fertilizer application to reasonable levels while maintaining or enhancing crop yield and economic benefits, improving nutrient use efficiency, and decreasing nitrate nitrogen residue in the soil at harvest time. This strategy has been proven by most studies to promote increases in crop yield and economic benefits while reducing environmental risks [3,21,22]. On the other hand, irregular rainfall and low precipitation are major factors hindering stable crop yields in Northwest China [23,24]. Particularly in Xinjiang, the evaporation rate (1700–2200 mm) far exceeds the precipitation (200 mm), compelling farmers to adopt drip irrigation systems, which are more efficient in water and nutrient use, for crop cultivation [25–28]. Numerous studies have shown a significant coupling effect between water and nutrients during crop growth [29–31]. However, research on the water and nutrient benefits to drip-irrigated wheat based on this strategy has not yet been conducted.

Due to the ability of drip irrigation cultivation practices to directly or indirectly affect soil nutrient cycling, coordinate soil water, nutrients, gas, heat, and crop growth, and enhance the availability of soil nutrients and crop absorption capacity, this study hypothesizes that a recommended fertilizer application strategy based on yield and nutrient requirements can effectively improve the accumulation and transport of NPK, increase yield, and ultimately enhance fertilizer utilization efficiency and economic benefits compared with the conventional fertilizer strategies used by farmers. The objectives of this work were (1) to study the effects of different fertilizers on wheat growth and quantify dry matter accumulation and nutrient transport and accumulation, (2) to investigate the dynamic changes of soil physicochemical factors, and (3) to elucidate the response characteristics of wheat growth to different fertilizers and its relationship with soil environmental factors. The findings of this research will contribute to understanding the yield-increasing effects of recommended fertilizer application strategies under drip irrigation, providing a basis for promoting the green, efficient, and sustainable development of wheat production and ensuring food security and ecological security in Xinjiang.

2. Materials and Methods

2.1. Experimental Site

A field experiment was conducted in Shihezi (44°19′ N, 85°59′ E, Figure 1), Xinjiang, in the oasis region of Northwest China. The study site has a typical temperate continental climate, with an annual average temperature of 7.7 °C, an annual average precipitation of 200 mm, and an average annual evaporation of 1700–2200 mm. The frost-free period is 168–171 days. The daily maximum temperature, minimum temperature, and precipitation during the spring wheat growing period from 2022 to 2023 are shown in Figure 1b. The soil type in the test area was gray desert soil, and the basic physical and chemical properties of the topsoil (0–20 cm) were as follows: pH 8.33, organic matter 16.73 g kg^{-1}, alkali-hydrolyzed nitrogen 50.78 mg kg^{-1}, available phosphorus 13.17 mg kg^{-1}, available potassium 213.40 mg kg^{-1}.

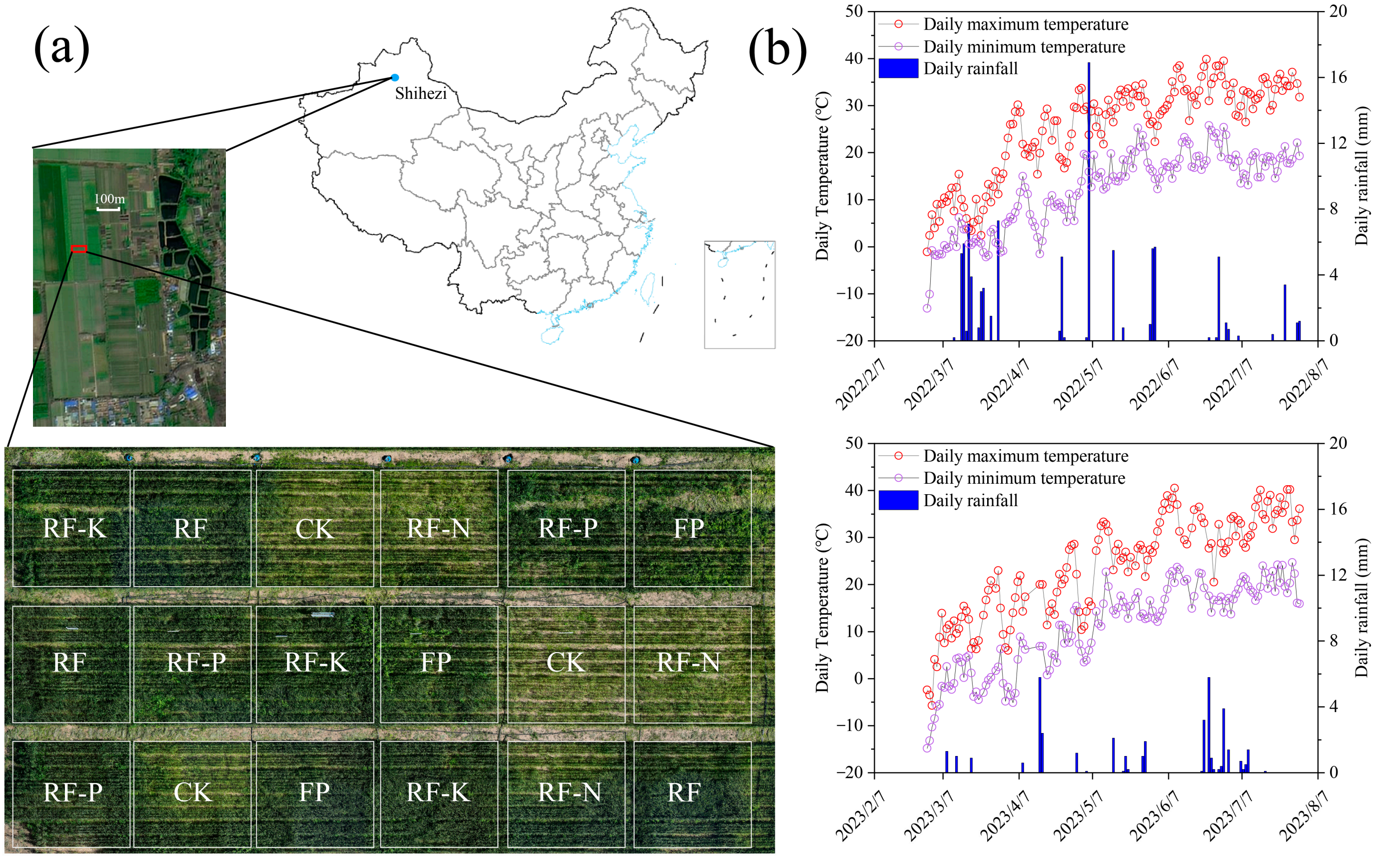

Figure 1. The experimental site and the arrangement of each treatment plot (**a**). Daily maximum temperature, minimum temperature and precipitation during the spring wheat growing season in 2022–2023 (**b**). CK, no fertilizer; FP, farmer's conventional practice; RF, recommended fertilizer application; RF-N, N omission for RF; RF-P, P omission for RF; RF-K, K omission for RF.

2.2. Experimental Design

From April 2022 to July 2023, a field plot experiment was conducted with spring wheat as the test crop. The specific variety was Xin Chun 38 (this variety has been selected by local farmers for a long time because of its stable yield and strong disease resistance). A total of six treatments were established: no fertilizer control (CK), farmer's conventional practice (FP), recommended fertilizer application (RF), RF-N (nitrogen omission from RF), RF-P (phosphorus omission from RF), and RF-K (potassium omission from RF). The fertilizer amounts for the RF treatment were calculated based on fertilizer monitoring techniques, resulting in a reduction of 30.3% nitrogen and 24.8% phosphorus in 2022, and a reduction of 23.0% nitrogen and 1.5% phosphorus in 2023. The amount of fertilizer applied for each treatment over the two years is shown in Table 1. The reduction in fertilizer amounts was referenced from the studies by Cao et al. [19] and Yang et al. [22], considering the nutrient requirements for the target yield, the nitrate nitrogen content in 1 m of soil, and the available phosphorus and potassium content in the 0–40 cm soil layer. In this experiment, the fertilizer amount for 2022 was based on the baseline soil nutrient assessment conducted prior to the experiment, while the fertilizer amount for 2023 was determined based on the soil nutrient content after the harvest in 2022 (Figure S1a–d).

Table 1. Fertilizer doses of different treatments (kg ha^{-1}).

Year	Treatment	Base Fertilizer			Top Dressing			Total Doses		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
2022	CK	0	0	0	0	0	0	0	0	0
	FP	60	26.6	0	240	106.4	0	300	133	0
	RF	41.8	20	6	167.2	80	24	209	100	30
	RF-N	0	20	6	0	80	24	0	100	30
	RF-P	41.8	0	6	167.2	0	24	209	0	30
	RF-K	41.8	20	0	167.2	80	0	209	100	0
2023	CK	0	0	0	0	0	0	0	0	0
	FP	60	26.6	0	240	106.4	0	300	133	0
	RF	46.2	26.2	6	184.8	104.8	24	231	131	30
	RF-N	0	26.2	6	0	104.8	24	0	131	30
	RF-P	46.2	0	6	184.8	0	24	231	0	30
	RF-K	46.2	26.2	0	184.8	104.8	0	231	131	0

Note: CK, no fertilizer; FP, farmer's conventional practice; RF, recommended fertilizer application; RF-N, N omission for RF; RF-P, P omission for RF; RF-K, K omission for RF.

The experiment adopted a randomized block design (Figure 1a), with three replicates for each treatment, on a total of 18 plots, each with an area of 29.7 m^2 (5.5 m × 5.4 m). Mechanical strip sowing was carried out on 4 April 2022 and 31 March 2023, respectively, with a seeding rate of approximately 300 kg ha^{-1} and an equal row spacing of 15.0 cm. The irrigation method was drip irrigation, and the drip irrigation belt was placed in the middle of the four rows of wheat, with a total irrigation volume of 4000 m^3 ha^{-1}. A flank labyrinth drip irrigation belt was used in this experiment. The inner pipe diameter was 16 mm, the wall thickness was 0.18 mm, the drop hole spacing was 300 mm, the rated flow rate of the irrigator was 2.1 L h^{-1}, and the working pressure was 0.05~0.1 Mpa. Irrigation during the whole growth period was carried out via groundwater drip irrigation, pumped through the main pipeline of the pump house and then into the test plot. The groundwater quality parameters in this area are shown in Table S1. In this experiment, 20% of the total fertilizer was applied as basal fertilizer (including urea, calcium superphosphate, and potassium sulfate), and the remaining fertilizer was applied with water during the wheat seedling stage, jointing stage, heading stage, flowering stage, and filling stage (including urea, ammonium phosphate, and potassium sulfate). The fertilizer types and contents were as follows: urea (N ≥ 46%), calcium superphosphate (P_2O_5 ≥ 46%), ammonium phosphate (N ≥ 12%, P_2O_5 ≥ 61%), and potassium sulfate (K_2O ≥ 52%). The proportions of the topdressing amount at each growth stage to the remaining fertilizer were 12.5%, 37.5%, 25.0%, 12.5%, and 12.5%, respectively. Irrigation was carried out according to the different growth stages of crops, and the actual drip water was controlled by the installed small rotary vane water meter. The total water consumption and fertilizer amounts were consistent with the customary amounts used by local farmers. For specific fertilizer application and irrigation strategies, see Table 2. Other field management measures were consistent with local conventional management methods.

Table 2. Fertilizer and irrigation schedules during 2022 and 2023 wheat growing seasons.

Stages	Seedling	Jointing	Booting	Flowering	Filling
2022	26 April	7 May	22 May	7 June	19 June
2023	24 April	6 May	22 May	6 June	18 June
Topdressing proportion (%)	10	30	20	10	10
Irrigation amount (%)	20	20	20	15	15

2.3. Sample Collection and Measurement Indicators

2.3.1. Soil Sample Collection

Before sowing, soil samples were collected from the 0–20 cm layer of the experimental site to measure the basic physical and chemical properties of the soil. During the wheat seedling stage (late April), jointing stage (mid-May), flowering stage (early June), filling stage (late June), and harvesting stage (mid-July), a soil auger was used to collect 0–20 cm (topsoil) and 20–40 cm (subsoil) samples from each plot using the five-point sampling method. The collected soil samples were divided into two parts: one part was immediately stored in a refrigerator at 4 °C for determination of inorganic nitrogen (ammonium nitrogen and nitrate nitrogen) content; the other part was naturally air-dried, ground, and passed through 1 mm and 0.15 mm sieves, and stored at room temperature for determination of soil nutrients.

2.3.2. Plant Sample Collection and Yield Measurement

Ten wheat plants with uniform growth were selected from each plot and divided into stems, leaves, grains, and glumes (different organ classification in the early growth stage) according to their organs. The samples were then dried in an oven at 105 °C for 30 min and at 75 °C until they reached a constant weight. The dry matter weight was weighed, and the dried wheat samples were crushed according to their organs and used to determine their nitrogen, phosphorus, and potassium content. At wheat harvest, three 1 m^2 quadrats were randomly selected from each experimental plot to measure the yield, including the number of spikes, number of grains per spike, thousand-grain weight, and yield.

2.3.3. Sample Measurement

The alkali hydrolysis diffusion method was used to determine the alkali-hydrolyzed nitrogen content of the soil at each growth stage; the $NaHCO_3$ extraction–molybdenum antimony colorimetric method was used to determine the available phosphorus content of the soil; the NH_4OAc extraction–flame photometry method was used to determine the available potassium content of the soil; the potassium dichromate–external heating method was used to determine the soil organic matter content; the semi-micro Kjeldahl method was used to determine the total nitrogen content of the soil; a continuous flow analyzer was used to determine the nitrate nitrogen and ammonium nitrogen content of the 0–100 cm soil layer at the harvesting stage after 0.5 mol L^{-1} KCl extraction. The plant samples were digested with H_2SO_4-H_2O_2, and the total nitrogen was determined using the Kjeldahl method, the total phosphorus was determined using the vanadium molybdate colorimetric method, and the total potassium was determined using the flame photometer method [32].

2.4. Data Analysis

2.4.1. Nitrogen, Phosphorus, and Potassium Translocation and Accumulation

N, P, and K uptake and translocation in wheat plants were calculated as follows [33,34]:

$$\text{Plant N, P, K uptake}\left(\text{kg ha}^{-1}\right) = \text{Plant dry matter} \times \text{Plant N, P, K concentration} \quad (1)$$

$$\text{Pre} - \text{anthesis N, P, K translocation amount}\left(\text{PrNt, PrPt, PrKt kg ha}^{-1}\right) = \text{NU}_{\text{va}} - \text{NU}_{\text{vm}} \quad (2)$$

$$\text{N, P, K translocation efficiency}(\text{PrNtE, PrPtE, PrKtE \%}) = \frac{\text{PrNt(PrPt, PrKt)}}{\text{NU}_{\text{va}}} \times 100 \quad (3)$$

$$\text{Contribution rate of N, P translocation amount to grain}(\text{PrNtC, PrPtC \%}) = \frac{\text{PrNt(PrPt)}}{\text{NU}_{\text{gm}}} \times 100 \quad (4)$$

$$\text{Post} - \text{anthesis N, P accumulation amount}\left(\text{PoNa, PoPa kg ha}^{-1}\right) = \text{NU}_{\text{sm}} - \text{NU}_{\text{sa}} \quad (5)$$

$$\text{Contribution rate of N, P accumulation amount to grain}(\text{PoNaC, PoPaC\%}) = \frac{\text{PoNt(PoPt)}}{\text{NU}_{\text{gm}}} \times 100 \quad (6)$$

where NU_{va} and NU_{vm} represent N, P, and K uptake in vegetative organs at anthesis stage and N, P, and K uptake in vegetative organs at maturity stage, respectively. NU_{sa}, NU_{sm}, and NU_{gm} represent N and P nutrient uptake by plant shoots at anthesis stage, N and P nutrient uptake by plant shoots at maturity stage, and N, P, and K uptake in grains at maturity stage, respectively.

2.4.2. Increasing Effect of N, P, and K Fertilizer on Wheat Yield

Relative yield was defined as the ratio of yield from NPK fertilized plots to N/P/K omitted plots and was calculated as follows [22] (Equations (7)–(9)):

$$\text{Relative yield of N fertilization}(\text{RYN \%}) = \frac{\text{Y}_{\text{RF}}}{\text{Y}_{\text{RF}-\text{N}}} \times 100 \quad (7)$$

$$\text{Relativey ield of P fertilization}(\text{RYP \%}) = \frac{\text{Y}_{\text{RF}}}{\text{Y}_{\text{RF}-\text{P}}} \times 100 \quad (8)$$

$$\text{Relative yield of K fertilization}(\text{RYK \%}) = \frac{\text{Y}_{\text{RF}}}{\text{Y}_{\text{RF}-\text{K}}} \times 100 \quad (9)$$

where Y_{RF} is the wheat grain yield of the RF treatment, and $Y_{RF\text{-}N}$, $Y_{RF\text{-}P}$, and $Y_{RF\text{-}K}$ are the wheat grain yields of the RF-N, RF-P, and RF-K treatments, respectively.

2.4.3. Nutrient Use Efficiency

Nutrient use efficiency (including NUE, PUE, and KUE) was calculated as follows [35,36]:

$$\text{NUE(PUE, KUE\%)} = \frac{\text{NU}_{\text{F}} - \text{NU}_0}{\text{AF}} \times 100 \quad (10)$$

where NU_0 and NU_F are the aboveground nutrient (N, P, and K) uptake at wheat harvest in the no-fertilizer (CK) and fertilizer treatments (FP, RF, RF-N, RF-P, and RF-K), respectively, and AF is the amount of N, P, and K fertilizer applied.

2.4.4. Benefits Calculation

The benefits of fertilizer inputs were calculated as follows [22]:

$$\text{Benefits}\left(\text{USD ha}^{-1}\right) = \text{Y}_{\text{g}} \times \text{P}_{\text{g}} - \text{F}_{\text{N}} \times \text{P}_{\text{N}} - \text{F}_{\text{P}} \times \text{P}_{\text{P}} - \text{F}_{\text{K}} \times \text{P}_{\text{K}} \quad (11)$$

where Y_g is wheat grain yield, F_N, F_P, and F_K are the fertilizer rates for N, P_2O_5, and K_2O (kg ha^{-1}), respectively, and P_g (USD 0.340 kg^{-1}), P_N (Urea, USD 0.281 kg^{-1}; monoammonium phosphate, USD 0.983 kg^{-1}), P_P (superphosphate, USD 0.840 kg^{-1}), and P_K (potassium sulfate, USD 0.702 kg^{-1}) are the prices of wheat grain and the N, P, and K fertilizers, respectively.

2.4.5. Data Processing and Mapping

Microsoft Excel 2021 and Origin 2022 were used for data processing and mapping. SPSS 21.0 software was used for statistical analysis, and Duncan's method was used for the difference test between different treatments ($p < 0.05$). Two-way analysis of variance

(ANOVA) was used to determine the effects of fertilizer treatment (F), year (Y), and their interaction on plant and soil indicators. All results are expressed as mean values. The error bars in the results represent the standard deviation (n = 3).

3. Results

3.1. Changes in Dry Matter and Nutrient Uptake

In 2022 and 2023, the dry matter and aboveground nitrogen and phosphorus uptake of all treatments gradually increased with wheat growth and development, while the potassium uptake gradually decreased after the flowering stage (Figure 2). In 2022 and 2023, the total dry matter of FP was significantly ($p < 0.05$) higher than that of other treatments at the harvesting stage. Specifically, FP was 9.7% and 9.4% higher than RF and RF-K, respectively, and 4.5% and 5.0% higher than RF and RF-K, respectively, but there was no significant difference between RF and RF-K. The trends of dry matter in each organ were consistent with the total dry matter (Figure 2a,b). Among them, the grain dry matter of FP, RF, and RF-K in 2023 was significantly ($p < 0.05$) higher than that of other treatments (Figure 2b). RF-N and RF-P significantly affected the N (Figure 2c,d) and P (Figure 2e,f) uptake of the treatment in each growth stage in 2022 and 2023, respectively. Although the uptake was higher than that of CK in each period, it was lower than that of FP, RF, and RF-K. RF-K did not affect the K uptake of the treatment (Figure 2g,h).

3.2. Grain Nutrient Uptake, Yield, and Yield Components

The results (Table 3) showed that, in 2022 and 2023, the grain number, grain N, P, and K uptake, and grain yield of the fertilized treatments (FP, RF, RF-N, RF-P, and RF-K) were significantly ($p < 0.05$) higher than those of CK. Among them, the number of spikes and the weight of 1000 grains of RF-N showed no significant differences compared with CK. Compared with FP, the grain yields of RF and RF-K were reduced by 9.1% and 10.5% in 2022 and 4.9% and 5.8% in 2023, respectively. Compared with RF, the grain yields of RF-N, RF-P, and RF-K were reduced by 12.50%, 8.16%, and 1.30% in 2022, respectively, and by 21.0%, 10.5%, and 1.0% in 2023, respectively. Compared with FP, RF affected only the grain N uptake, while the P and K uptake showed no significant differences compared with FP (except for grain K uptake in 2023). Two-way ANOVA showed that year (Y), fertilizer treatment (F), and their interaction (Y × F) all significantly ($p < 0.01$) affected the number of grains per spike, as well as N and K uptake at the harvesting stage, and Y and F both significantly ($p < 0.05$) affected the yield and its components and grain N, P, and K uptake (Table 3).

Table 3. Effects of different treatments on wheat yield components, grain nutrient uptake, and yield, from 2022 to 2023.

Year	Fertilizer Treatment	Spike Number Plant m^{-2}	1000-Grain Weight g	Grain Number $spike^{-1}$	Grain N Uptake kg ha^{-1}	Grain P Uptake kg ha^{-1}	Grain K Uptake kg ha^{-1}	Grain Yield kg ha^{-1}
2022	CK	439.67 ± 6.43 ^{c}	31.85 ± 0.56 ^{d}	31.37 ± 0.38 ^{c}	70.00 ± 1.52 ^{d}	20.51 ± 2.07 ^{b}	21.56 ± 1.13 ^{c}	4392.37 ± 112.36 ^{d}
	FP	483.00 ± 4.58 ^{a}	35.67 ± 0.35 ^{a}	35.23 ± 0.71 ^{ab}	133.32 ± 4.15 ^{a}	33.22 ± 1.76 ^{a}	35.69 ± 1.34 ^{a}	6069.93 ± 165.07 ^{a}
	RF	458.00 ± 8.19 ^{b}	34.07 ± 0.12 ^{b}	35.67 ± 0.55 ^{a}	124.34 ± 2.82 ^{b}	31.46 ± 4.16 ^{a}	36.12 ± 2.73 ^{a}	5563.86 ± 11.57 ^{b}
	RF-N	440.33 ± 4.16 ^{c}	32.37 ± 0.55 ^{cd}	34.70 ± 0.61 ^{b}	111.66 ± 3.06 ^{c}	30.40 ± 2.52 ^{a}	33.34 ± 1.34 ^{ab}	4945.61 ± 135.92 ^{c}
	RF-P	445.67 ± 3.06 ^{bc}	33.13 ± 0.32 ^{c}	34.83 ± 0.76 ^{ab}	116.18 ± 4.39 ^{bc}	29.63 ± 1.95 ^{a}	32.49 ± 1.44 ^{ab}	5144.29 ± 162.41 ^{c}
	RF-K	452.67 ± 9.07 ^{bc}	33.97 ± 0.65 ^{b}	35.73 ± 0.64 ^{a}	124.22 ± 7.35 ^{b}	29.72 ± 4.35 ^{a}	31.30 ± 2.25 ^{b}	5492.48 ± 67.59 ^{b}
2023	CK	416.67 ± 2.89 ^{e}	30.23 ± 0.68 ^{c}	30.23 ± 0.68 ^{c}	89.80 ± 3.21 ^{e}	22.22 ± 0.65 ^{c}	26.34 ± 1.01 ^{e}	4042.43 ± 78.36 ^{e}
	FP	458.00 ± 11.27 ^{a}	33.20 ± 0.20 ^{a}	33.20 ± 0.20 ^{a}	150.48 ± 2.20 ^{a}	36.78 ± 0.97 ^{a}	44.51 ± 0.72 ^{a}	5625.96 ± 18.52 ^{a}
	RF	451.33 ± 12.34 ^{ab}	32.50 ± 0.44 ^{a}	32.50 ± 0.44 ^{a}	144.14 ± 2.70 ^{b}	36.12 ± 0.94 ^{a}	43.07 ± 0.33 ^{b}	5382.85 ±147.13 ^{ab}
	RF-N	424.33 ± 5.86 ^{de}	30.83 ± 0.15 ^{bc}	30.83 ± 0.15 ^{bc}	120.32 ± 6.69 ^{d}	30.48 ± 1.86 ^{b}	38.10 ± 0.78 ^{d}	4434.63 ± 46.13 ^{d}
	RF-P	433.67 ± 4.04 ^{cd}	31.57 ± 0.60 ^{b}	31.57 ± 0.60 ^{b}	122.49 ± 0.79 ^{d}	31.77 ± 2.62 ^{b}	40.32 ± 0.78 ^{c}	4854.12 ± 29.83 ^{c}
	RF-K	440.33 ± 2.08 ^{bc}	33.03 ± 0.42 ^{a}	33.03 ± 0.42 ^{a}	134.75 ± 3.34 ^{c}	32.78 ± 2.46 ^{b}	41.92 ± 1.05 ^{b}	5315.50 ± 225.19 ^{b}

Table 3. *Cont.*

Year	Fertilizer Treatment	Spike Number Plant m^{-2}	1000-Grain Weight g	Grain Number $spike^{-1}$	Grain N Uptake kg ha^{-1}	Grain P Uptake kg ha^{-1}	Grain K Uptake kg ha^{-1}	Grain Yield kg ha^{-1}
Two-way ANOVA								
Year (Y)		**	**	**	**	**	**	**
Fertilizer Treatment (F)		**	**	**	**	**	**	**
Y × F		ns	ns	**	**	ns	**	ns

Note: CK, no fertilizer; FP, farmer's conventional practice; RF, recommended fertilization; RF-N, N omission for RF; RF-P, P omission for RF; RF-K, K omission for RF. The data are shown as the means ± SD (n = 3). Means in a column for the same fertilizer treatment and same year followed by different lowercase letters indicate a significant difference at $p < 0.05$. ** indicate the significance level at $p < 0.01$. ns means not significant.

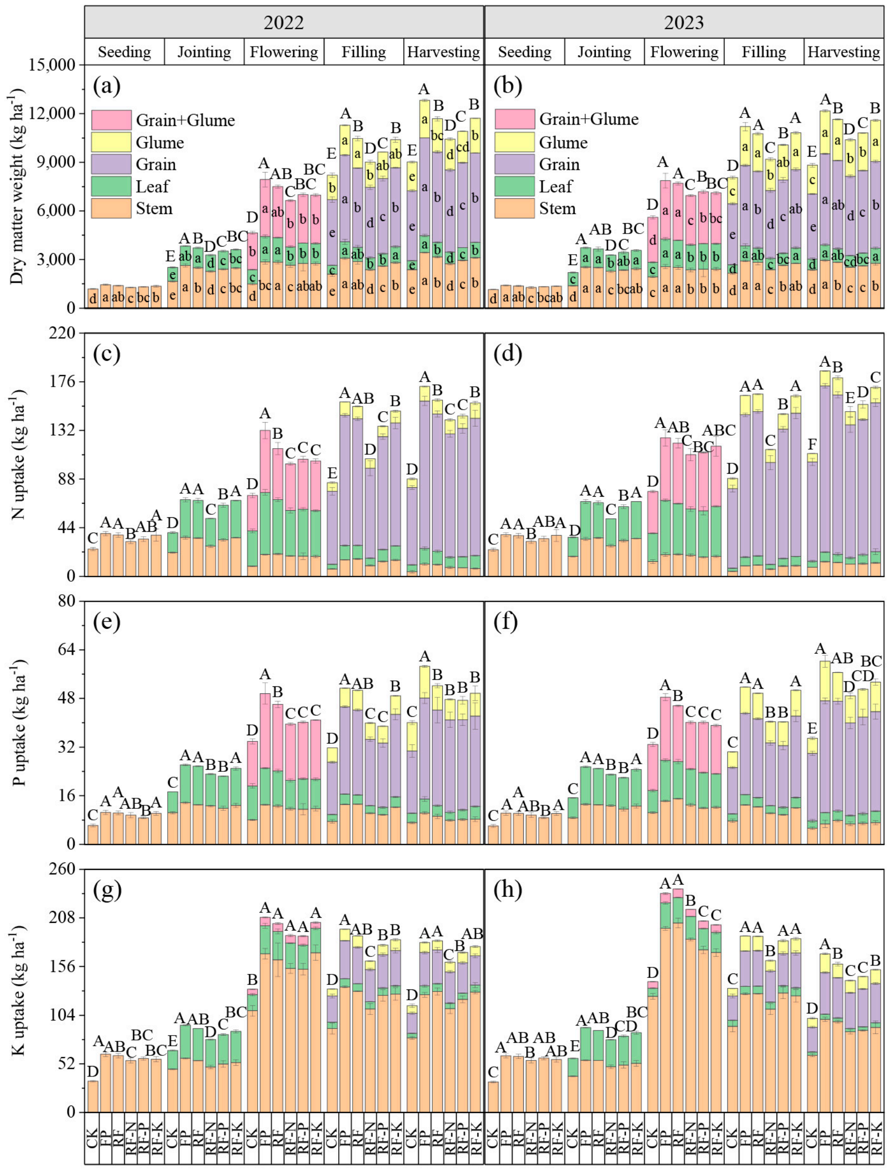

Figure 2. Dry matter accumulation (**a**,**b**), N (**c**,**d**), P (**e**,**f**), and K (**g**,**h**) uptake in the shoots of wheat at each growth stage in 2022–2023 under each fertilizer treatment. CK, no fertilizer; FP, farmer's conventional practice; RF, recommended fertilizer; RF-N, N omission for RF; RF-P, P omission for RF; RF-K, K omission for RF. The values presented in the figures are given as mean ± SD (n = 3). Different color fillings represent different organs of wheat, and different lowercase letters in the column represent significant differences between different fertilizer treatments of the same organ in the same period ($p < 0.05$). The different capital letters on the columns represent significant differences between the different fertilizer treatments of the aboveground wheat in the same period ($p < 0.05$).

3.3. Changes in Soil Nutrients in Different Soil Layers During the Growth Period

From the seedling to maturity stage in 2022–2023, the SOM in topsoil (0–20 cm) showed a trend of first decreasing and then increasing. Compared with CK, the SOM of FP and RF increased more significantly in the later stages (filling stage to maturity stage) ($p < 0.05$, Table S2); subsoil (20–40 cm) showed a similar trend (Figure 3a,b). Compared with FP, RF reduced topsoil SAN content by 0.60–2.31%, and RF-N reduced topsoil SAN content by 5.82–11.99%. In 2022, compared with FP, the RF reduced the SAN in subsoil by 3.34–19.23%. In 2023, compared with FP, the RF increased the SAN in subsoil by 0.74–4.05% (jointing–maturity stage) (Table S3). From the seedling stage to the maturity stage in 2022–2023, compared with the FP, the RF reduced topsoil Olsen-P from the seedling stage to the maturity stage by 0.31–30.15%, and the RF-P reduced topsoil Olsen-P from the seedling stage to the maturity stage by 31.78–61.73% (Figure 3e,f) (Table S4). In 2022–2023, at the maturity stage, compared with FP, RF increased the SAK in topsoil by 25.70–28.21%, and compared with RF, RF-K reduced the SAK in topsoil by 23.53–28.21%; at the maturity stage, compared with FP, RF reduced the SAK in subsoil by 12.83–17.94% (Table S5).

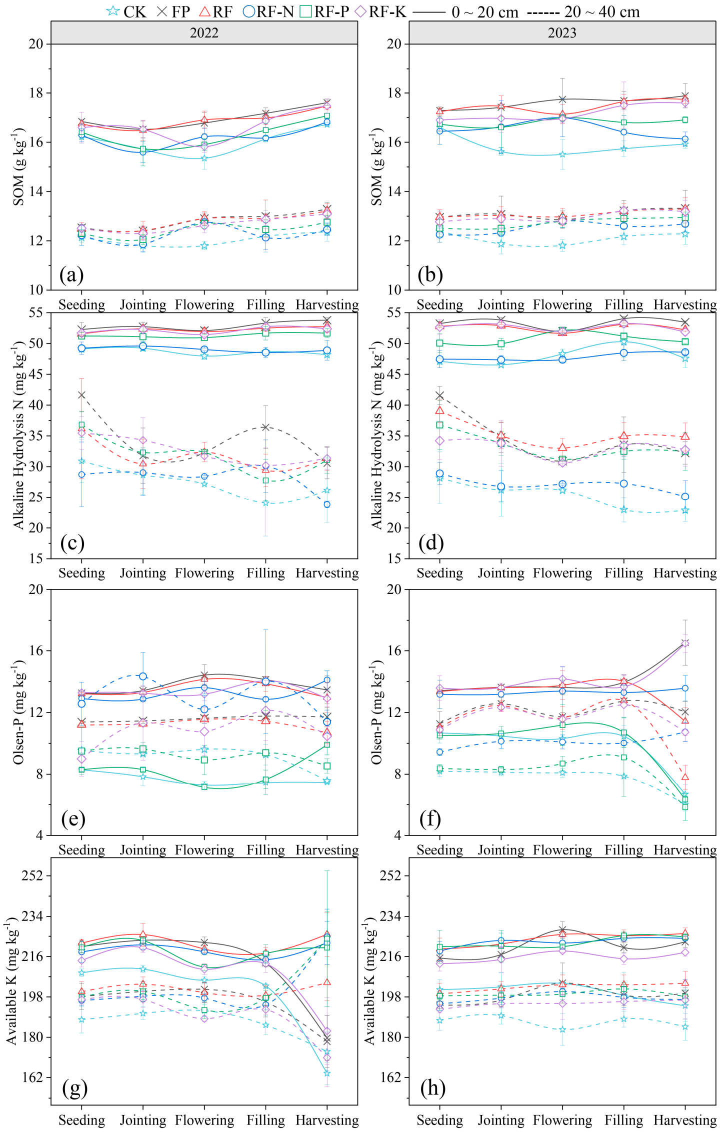

Figure 3. Effects of different fertilizer treatments on 0–20 cm and 20–40 cm soil properties of wheat at different growth stages in 2022–2023. CK, no fertilizer; FP, farmer's conventional practice; RF, recommended fertilizer; RF-N, N omission for RF; RF-P, P omission for RF; RF-K, K omission for RF. SOM, soil organic matter (**a**,**b**); Alkali-hydrolyzable N (**c**,**d**); Olsen-P (**e**,**f**); Available K (**g**,**h**).

3.4. Nutrient Transport and Accumulation Before and After Flowering

In 2022 and 2023, compared with CK, the fertilizer treatments (F) significantly ($p < 0.05$) affected the NPK transport, accumulation, and distribution before and after wheat flowering (Table 4). Specifically, the transport, accumulation, and distribution of N were as follows: compared with FP, RF showed no significant difference (except for PoNaC in 2022 and PrNt in 2023); compared with RF, RF-N, RF-P, and RF-K had no significant effect on PrNt and PrNtE, but RF-N and RF-P significantly ($p < 0.05$) reduced PoNa by 10.3%, 11.9% (2022) and 51.6%, 35.7% (2023). The transport and accumulation of P were as follows: there was no significant difference between RF and FP (except for PrPtE in 2022); RF-N, RF-P, and RF-K all significantly ($p < 0.05$) reduced PrPt compared with RF, by 13.1%~21.2% and 15.8%~35.9% in 2022 and 2023, respectively. The K uptake of wheat plants in 2022 and 2023 showed a trend of first increasing and then decreasing with the advancement of the growth stage. Therefore, only the K transport rate and transport capacity before wheat flowering were analyzed. It is worth noting that compared with FP, the PrKt and PrKtE of RF in 2023 increased by 15.8% and 12.5%, respectively ($p < 0.05$). Compared with RF, RF-K significantly ($p < 0.05$) reduced PrKt by 28.2% and PrKtE by 14.3% in the second year (2023). Two-way ANOVA showed that year (Y), fertilizer treatment (F), and their interaction (Y $\times$ F) all significantly ($p < 0.05$) affected PrNtE, PrNtC, PoNa, PoNaC, PrPtE, PoPa, and PrKtE. Y and F both significantly ($p < 0.05$) affected the transport and accumulation of N, the rate of P and K transport, and the accumulation of P (Table 4).

3.5. Nutrient Utilization and Economic Benefits

In 2022, there were no significant differences in NPK utilization among the fertilizer treatments. In 2023, the NUE of RF was significantly ($p < 0.05$) higher than that of the other treatments. Compared with FP, RF increased NUE by 16.3%; PUE was not significantly different from FP; KUE was significantly ($p < 0.05$) higher than RF-N and RF-P. In 2022, the economic benefit of FP was significantly ($p < 0.05$) higher than that of other treatments. In 2023, there was no significant difference between FP, RF, and RF-K, and all of them were higher than the other treatments. Two-way ANOVA showed that year (Y), fertilizer treatment (F), and their interaction (Y $\times$ F) all significantly ($p < 0.05$) affected NUE. Both Y and F significantly ($p < 0.05$) affected benefits, and F significantly ($p < 0.01$) affected only KUE (Table 5).

3.6. Increasing Effects of N, P, and K Fertilizers on Wheat Yield in the Recommended Fertilizer Application Strategy

The same trend was observed in 2022 and 2023: the yield-increasing effect of N fertilizer in the recommended fertilizer application strategy was significantly ($p < 0.05$) greater than that of P and K fertilizers, and the effect in 2023 was better than that in 2022. Two-way ANOVA showed that year (Y), fertilizer treatment (F), and their interaction (Y $\times$ T) all significantly ($p < 0.05$) affected the relative yield-increasing effect of fertilizers (shown in Figure 4).

Table 4. Effects of fertilizer treatments on pre-anthesis NPK transport, post-anthesis NP accumulation, and grain contribution in 2022 and 2023.

Year	Fertilizer Treatment	N					P					K	
		PrNt kg ha^{-1}	**PrNtE** %	**PrNtC** %	**PoNa** kg ha^{-1}	**PoNaC** %	**PrPt** kg ha^{-1}	**PrPtE** %	**PrPtC** %	**PoPa** kg ha^{-1}	**PoPaC** %	**PrKt** kg ha^{-1}	**PrKtE** %
2022	CK	22.94 ± 2.53 ^{e}	55.74 ± 4.10 ^{a}	32.81 ± 4.14 ^{a}	14.99 ± 2.97 ^{c}	21.40 ± 4.03 ^{c}	14.31 ± 2.20 ^{c}	42.11 ± 4.77 ^{c}	69.97 ± 10.42 ^{a}	6.20 ± 2.30 ^{a}	30.03 ± 10.42 ^{a}	44.95 ± 6.38 ^{c}	32.61 ± 3.37 ^{b}
	FP	37.68 ± 1.35 ^{a}	49.36 ± 1.34 ^{bc}	28.58 ± 2.02 ^{ab}	39.86 ± 6.09 ^{b}	27.20 ± 0.38 ^{c}	25.52 ± 0.75 ^{a}	47.96 ± 3.80 ^{b}	72.82 ± 12.02 ^{a}	8.96 ± 4.07 ^{a}	27.18 ± 12.02 ^{a}	120.45 ± 1.16 ^{a}	45.32 ± 0.80 ^{a}
	RF	34.23 ± 1.49 ^{ab}	49.34 ± 1.53 ^{bc}	27.55 ± 1.73 ^{b}	43.88 ± 9.67 ^{ab}	35.19 ± 6.93 ^{b}	25.34 ± 1.20 ^{a}	54.99 ± 1.34 ^{a}	80.59 ± 3.69 ^{a}	6.12 ± 1.28 ^{a}	19.41 ± 3.69 ^{a}	107.23 ± 18.76 ^{ab}	41.90 ± 4.56 ^{a}
	RF-N	29.60 ± 2.55 ^{cd}	49.72 ± 3.24 ^{bc}	26.56 ± 3.02 ^{b}	39.79 ± 4.90 ^{b}	35.57 ± 3.49 ^{b}	22.28 ± 0.50 ^{b}	56.32 ± 1.14 ^{a}	73.75 ± 8.11 ^{a}	8.12 ± 3.02 ^{a}	26.25 ± 8.11 ^{a}	93.18 ± 10.95 ^{b}	42.18 ± 3.79 ^{a}
	RF-P	31.79 ± 4.29 ^{bc}	52.21 ± 4.70 ^{ab}	27.41 ± 4.05 ^{b}	39.23 ± 4.84 ^{b}	33.70 ± 2.97 ^{b}	22.41 ± 0.45 ^{b}	55.84 ± 2.90 ^{a}	75.79 ± 3.65 ^{a}	7.22 ± 1.59 ^{a}	24.21 ± 3.65 ^{a}	84.79 ± 21.14 ^{b}	37.55 ± 5.85 ^{ab}
	RF-K	26.75 ± 1.56 ^{de}	45.08 ± 2.51 ^{c}	21.55 ± 1.02 ^{c}	52.59 ± 4.41 ^{a}	42.30 ± 1.29 ^{a}	20.91 ± 1.85 ^{b}	51.10 ± 4.44 ^{ab}	70.85 ± 5.97 ^{a}	8.81 ± 3.02 ^{a}	29.15 ± 5.97 ^{a}	94.19 ± 3.66 ^{ab}	39.19 ± 0.58 ^{ab}
2023	CK	17.72 ± 2.14 ^{d}	45.31 ± 3.95 ^{b}	19.76 ± 2.61 ^{b}	34.42 ± 3.23 ^{d}	38.28 ± 2.51 ^{ab}	20.18 ± 1.53 ^{bc}	61.38 ± 3.99 ^{a}	90.77 ± 4.30 ^{a}	2.03 ± 0.90 ^{c}	9.23 ± 4.30 ^{c}	58.61 ± 5.35 ^{e}	44.03 ± 2.96 ^{c}
	FP	35.18 ± 0.18 ^{a}	48.47 ± 2.67 ^{ab}	23.54 ± 0.01 ^{ab}	60.58 ± 3.35 ^{a}	40.31 ± 2.60 ^{a}	24.48 ± 0.46 ^{a}	51.41 ± 0.52 ^{bc}	66.05 ± 2.63 ^{bc}	12.81 ± 1.26 ^{ab}	33.95 ± 2.63 ^{ab}	98.64 ± 0.52 ^{bc}	44.17± 0.68 ^{c}
	RF	30.36 ± 3.44 ^{bc}	46.11 ± 4.70 ^{ab}	21.04 ± 2.00 ^{b}	59.14 ± 3.20 ^{ab}	41.03 ± 2.16 ^{a}	25.15 ± 0.62 ^{a}	55.16 ± 0.76 ^{b}	69.68 ± 3.56 ^{b}	10.97 ± 1.56 ^{ab}	30.32 ± 3.56 ^{b}	114.24 ± 5.31 ^{a}	49.69 ± 1.07 ^{ab}
	RF-N	32.22 ± 1.48 ^{ab}	52.98 ± 4.19 ^{a}	26.84 ± 2.09 ^{a}	39.00 ± 1.90 ^{cd}	32.44 ± 1.35 ^{b}	21.72 ± 1.07 ^{b}	54.13 ± 2.18 ^{b}	71.45 ± 5.69 ^{b}	8.76 ± 2.15 ^{b}	28.55 ± 5.69 ^{b}	106.64 ± 4.07 ^{ab}	50.86 ± 1.58 ^{a}
	RF-P	26.21 ± 4.55 ^{c}	44.18 ± 6.12 ^{b}	21.41 ± 3.84 ^{b}	43.58 ± 5.20 ^{c}	35.56 ± 4.06 ^{ab}	20.86 ± 0.42 ^{b}	52.03 ± 0.74 ^{b}	65.96 ± 5.48 ^{bc}	10.91 ± 2.54 ^{ab}	34.04 ± 5.48 ^{ab}	91.57 ± 4.04 ^{c}	46.56 ± 0.97 ^{bc}
	RF-K	27.15 ± 1.61 ^{c}	42.91 ± 2.95 ^{b}	20.18 ± 1.68 ^{b}	53.23 ± 4.39 ^{b}	39.56 ± 4.01 ^{a}	18.51 ± 0.82 ^{c}	47.33 ± 2.59 ^{c}	56.79 ± 6.43 ^{c}	14.27 ± 3.20 ^{a}	43.21 ± 6.43 ^{a}	81.99 ± 7.37 ^{d}	42.56 ± 3.54 ^{c}
							Two-way ANOVA						
Year (Y)		**	**	**	**	**	ns	*	ns	**	ns	ns	**
Fertilizer Treatment (F)		**	*	**	**	**	**	**	**	**	**	**	**
Y × F		ns	*	**	**	**	**	**	**	*	**	*	*

Note: CK, no fertilizer; FP, farmer's conventional practice; RF, recommended fertilizer; RF-N, N omission for RF; RF-P, P omission for RF; RF-K, K omission for RF. PrNt, PrPt, PrKt represent the pre-anthesis NPK translocation. PrNtE, PrPtE, PrKtE represent the pre-anthesis NPK transport rate. PrNtC and PrPtC represent the contribution rate of NP translocation to grain at pre-anthesis. PoNa and PoPa represent NP accumulation at pro-anthesis. PoNaC and PoPaC represent the contribution rate of NP accumulation to grain at pro-anthesis. Means in a column for the same fertilizer treatment and same year followed by different lowercase letters indicate a significant difference at $p < 0.05$. * and ** indicate the significance level at $p < 0.05$ and $p < 0.01$. ns means not significant.

Table 5. Effects of fertilizer treatments on nutrient use efficiency and economic benefits of wheat in 2022 and 2023.

Year	Fertilizer Treatment	NUE	PUE	KUE	Benefits
			%		USD ha^{-1}
2022	CK	-	-	-	1493.40 ± 38.20 ^{d}
	FP	21.11 ± 1.82 ^{a}	9.56 ± 2.02 ^{a}	-	1852.62 ± 56.12 ^{a}
	RF	26.00 ± 2.00 ^{a}	10.95 ± 6.18 ^{a}	48.53 ± 12.71 ^{a}	1716.54 ± 3.93 ^{b}
	RF-N	-	9.89 ± 4.50 ^{a}	39.25 ± 6.99 ^{a}	1565.02 ± 46.21 ^{c}
	RF-P	22.10 ± 2.08 ^{a}	-	36.43 ± 1.29 ^{a}	1669.31 ± 55.22 ^{b}
	RF-K	25.95 ± 3.07 ^{a}	9.21 ± 3.64 ^{a}	-	1713.33 ± 22.98 ^{b}
2023	CK	-	-	-	1374.42 ± 26.64 ^{c}
	FP	20.23 ± 1.25 ^{b}	10.95 ± 0.49 ^{a}	-	1701.67 ± 49.52 ^{a}
	RF	23.53 ± 1.64 ^{a}	10.61 ± 0.22 ^{a}	55.74 ± 4.48 ^{a}	1613.09 ± 79.08 ^{ab}
	RF-N	-	6.31 ± 1.82 ^{b}	39.18 ± 0.91 ^{c}	1361.71 ± 15.68 ^{c}
	RF-P	14.15 ± 1.19 ^{c}	-	46.60 ± 3.28 ^{b}	1564.48 ± 10.14 ^{b}
	RF-K	19.46 ± 1.08 ^{b}	8.06 ± 1.76 ^{ab}	-	1617.40 ± 76.56 ^{ab}
Two-way ANOVA					
Year (Y)		**	ns	ns	**
Fertilizer Treatment (F)		**	ns	**	**
Y × F		*	ns	ns	ns

Note: CK, no fertilizer; FP, farmer's conventional practice; RF, recommended fertilizer; RF-N, N omission for RF; RF-P, P omission for RF; RF-K, K omission for RF. Nitrogen use efficiency (NUE), phosphorus use efficiency (PUE), and potassium use efficiency (KUE). Means in a column for the same fertilizer treatment and same year followed by different lowercase letters indicate a significant difference at $p < 0.05$. * and ** indicate the significance level at $p < 0.05$ and $p < 0.01$. ns means not significant.

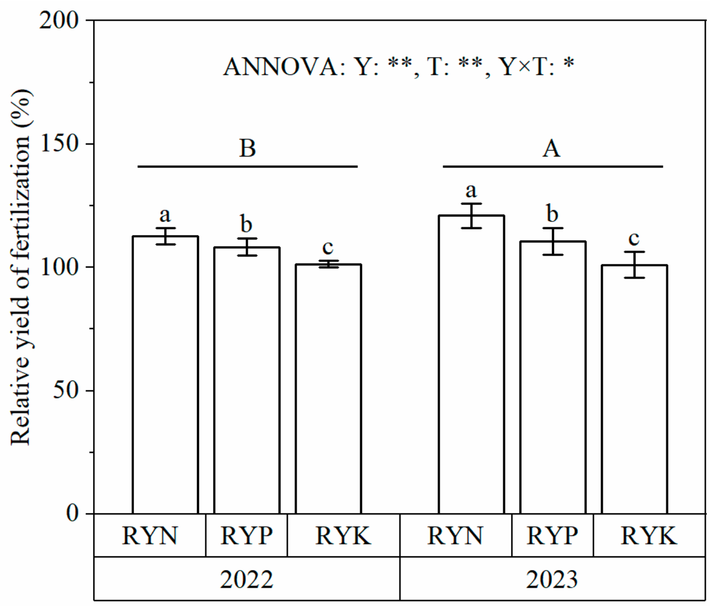

Figure 4. Effects of N, P, and K fertilizers on wheat relative yield in 2022 and 2023 under the recommended fertilizer strategy. RYN, RYP, and RYK are the increasing effects of NPK fertilizer on wheat yield, respectively. Different lowercase letters indicate that the difference between different treatments is significant level at $p < 0.05$. Different capital letters indicate that the difference between different years is significant level at $p < 0.05$. * and ** indicate the significance level at $p < 0.05$ and $p < 0.01$.

4. Discussion

4.1. Effects of Recommended Fertilizer Application on NPK Nutrient Uptake, Transport, and Distribution in Wheat

This study demonstrated that nitrogen absorption by plants progressively increased throughout the growth period, reaching its peak at maturity. Grain nitrogen absorption is sourced from two primary pathways: pre-anthesis nitrogen transport (PrNt) and post-anthesis nitrogen accumulation (PoNa). In the second year of this study, the PrNt with the recommended fertilizer (RF) treatment was significantly lower than that with the farmer's practice (FP). This variation may be attributed to the high temperatures and drought conditions experienced during the flowering period of 2023 (Figure 1b). Xu et al. [37] reported that moderate soil drought enhances PrNt under high nitrogen treatments, whereas nitrogen reduction treatments are associated with lower sensitivity to drought due to smaller root transpiration area and reduced water requirements [37]. Previous studies have shown that moderate soil drought does not seriously damage the nitrogen transport of phloem, and phloem transport is less susceptible to drought than leaf photosynthesis [38]. Weather factors play an important role in wheat yield and protein content [39,40], especially in arid regions. Notably, the RF strategy did not affect post-anthesis N accumulation in 2022 and 2023 (Table 4). These results indicate that RF strategy could effectively improve post-anthesis nitrogen transport and grain nitrogen accumulation. Nitrogen absorption, transport, and assimilation directly affect nitrogen accumulation and nitrogen utilization in grains. In this study, compared with FP, RF significantly improved the nitrogen use efficiency of wheat, and too much nitrogen application in FP would reduce the nitrogen use efficiency. RF was able to improve the nitrogen use efficiency and reduce nitrogen loss at the same time (Table 5). This was mainly because increasing the nitrogen application rate increased nitrogen accumulation and nitrogen loss in vegetative organs, and more nitrogen was stored in stems, leaves and other parts at maturity, leading to an increase in the ineffective use of nitrogen.

Phosphorus plays a crucial role in regulating the growth and development of wheat [41,42]. The results of this study indicated that the phosphorus content in the stems and leaves of wheat continuously decreased throughout the growth period, reaching its lowest level at maturity. This phenomenon can be attributed to the fact that the biomass of different plant parts steadily increased during the growth period, while the rate of phosphorus absorption by the plants was significantly lower than the rate of biomass accumulation. As a result, a dilution of phosphorus occurred within the wheat plants, leading to a continual decrease in phosphorus content throughout the growth period.

It was similarly observed that during the flowering to grain-filling period, the phosphorus content within the plants exhibited a negative growth trend. This indicates that the primary role of phosphorus during this stage was to enhance grain plumpness, resulting in the highest phosphorus concentration within the grains compared with all the other plant organs, consequently leading to a decline in the phosphorus content of the plant [43]. The findings of this study demonstrated that the jointing to flowering stage was a critical period for the rapid accumulation of phosphorus in the plants, with a continuous increase in phosphorus accumulation throughout the wheat growth period. Additionally, both the farmer's practice (FP) and recommended fertilizer (RF) strategies were found to enhance pre-anthesis phosphorus transport and its contribution to grain phosphorus content, thereby promoting the accumulation of phosphorus in the grains. This effect was attributed to the ability of phosphorus fertilizers to influence the amount of pre-anthesis phosphorus transport in the wheat plants, while appropriate nitrogen levels facilitated increased absorption and accumulation of phosphorus within the plants [44]. Furthermore, RF effectively coordinated the relationship between pre-anthesis phosphorus transport and post-anthesis phosphorus accumulation, thereby enhancing the transport of phosphorus to the grains.

The majority of potassium fertilizers applied to soil are converted into non-exchangeable potassium, with only a small portion being available for plant uptake [45]. The results of this study indicate that the nitrogen and phosphorus absorption in the aboveground parts of the wheat gradually increased throughout its growth period, while potassium absorption progressively decreased at pro-anthesis [46]. Research conducted by Kausar and Gull [46] showed that potassium uptake in wheat followed a "low–high–low" unimodal curve, peaking during the transition from flowering to the grain-filling period, with potassium absorption at the jointing stage being crucial for the later stages of growth. This study confirms that the period from jointing to flowering is a key phase for rapid accumulation of potassium (Figure 2). The potassium content and accumulation in the wheat plants initially increased and then declined as the growth period progressed, with the highest potassium absorption occurring during flowering. This trend was closely related to the changes in dry matter accumulation throughout the growth period. Furthermore, nitrogen fertilizer application influenced the plants' ability to absorb potassium, to some extent. Other studies [45,47] have noted that applying nitrogen fertilizer along with potassium can significantly enhance the productivity of nitrogen and potassium fertilizers and improve wheat's absorption of these nutrients. The results of this study suggest that the combined application of NPK fertilizers (RF) significantly increased the potassium content in nutritional organs during the jointing, flowering, and maturity stages compared with treatments without potassium (FP). This enhancement can primarily be attributed to the ability of NPK application to improve potassium transport and transport efficiency before flowering (Table 4), thereby promoting the plants' absorption of potassium.

4.2. The Impact of Recommended Fertilizer Application on Dry Matter, Yield, and Economic Benefits

Variation in dry matter quality is closely related to yield formation, and different fertilizer treatments significantly influence the dry matter quality during the growth period of wheat. In this study, the RF (recommended fertilizer) treatment resulted in a significant reduction in yield compared with the conventional fertilizer, with a decrease of 30.3% in nitrogen and 24.8% in phosphorus in the first year of the experiment. This finding is inconsistent with previous research results [21,48]. Two primary factors may explain this discrepancy: first, while the Olsen-P content in alkaline soils is not low, only a small portion of the applied phosphorus fertilizer is absorbed by the crops, due to high fixation rates resulting from binding with Ca^{2+} [49]. This situation complicates the evaluation of fertilizer application strategies. Secondly, in a drip-irrigated wheat system where 20% of the nutrients come from base fertilizer and 80% from top dressing, excessive reduction of phosphorus fertilizer can be detrimental to later-stage wheat growth, leading to insufficient nutrient supply and significantly reduced absorption after the jointing stage (Figure 2e,f), ultimately impacting dry matter accumulation. Notably, compared with the FP (conventional fertilizer) treatment, the RF treatment in the second year of the experiment (2023), which involved a 23% reduction in nitrogen and a 1.5% reduction in phosphorus, showed no significant difference in grain yield or yield components. Optimizing fertilizer application in the second year can effectively reduce chemical fertilizer usage, increase farmers' incomes, and ensure stable wheat yield (Table 5). Moreover, research by Yang et al. [22] indicates that optimized fertilizer application techniques not only reduce the input of chemical fertilizers but also lower production costs in wheat farming, thereby enhancing farmers' profits.

4.3. The Impact of Recommended Fertilizer Application Strategies on Soil Properties and Their Relationship with Nutrient Transport and Grain Yield

Soil is the primary source of nutrient uptake for crops, and its nutrient availability directly affects yield responses to fertilizers [16,50]. In our study, grain yield showed significant positive correlations with PrNt, PoNa, PrPt, PoPa, and PrKt (Figure 5a,d,f,i,k). Furthermore, surface (0–20 cm) and subsurface (20–40 cm) soil organic matter, available nitrogen, and phosphorus significantly influenced grain yield (Figure 5m,n,o), whereas available potassium showed no significant impact (Figure 5p). This indicates that plants can absorb and utilize soil nutrient reserves despite their direct acquisition from fertilizer sources [51,52]. Therefore, fields with higher soil fertility or increased fertilizer inputs can potentially enhance crop yield while reducing fertilizer usage [53], facilitating nutrient transport and accumulation in grain production. However, in our study, grain yield was not correlated with soil available potassium, possibly due to the inherently high baseline values of available potassium in the region. Nevertheless, this situation may introduce subtle issues related to grain quality. He et al. [54] found similar trends, noting that due to the minimal application of potassium fertilizer by local farmers, the average soil available potassium in Northwest China would significantly decrease from 153.5 mg kg^{-1} in the 1990s to 116.5 mg kg^{-1} by the 2050s. Adequate potassium supplementation can alleviate soil potassium depletion and improve grain quality [54]. In this study, the recommended fertilizer application strategy primarily affected NUE, while PUE and KUE showed no significant change across years; hence, we have focused on yield and nitrogen application effects. Jia et al. [55] and Shi et al. [56] reported that 34–55% of the nitrogen absorbed by wheat originates from fertilizer nitrogen, with 45–66% derived from soil nitrogen. Other studies indicate that plant uptake of soil nitrogen accounts for over 70% of nitrogen accumulation [57,58]. Factors like soil fertility, irrigation amount and timing, nitrogen application rates, and the ratio of base to top-dressed nitrogen significantly influence plant nitrogen accumulation [55]. Our findings align with this perspective, showing that relative nitrogen yield (RYN) increased with two consecutive years of the recommended fertilizer (RF) strategy (Figure 4). This is consistent with many studies indicating that increased food production often leads to a reduction in nitrogen content within grains [59,60]. Therefore, under moderate nitrogen absorption levels, enhancing nitrogen fertilizer yield by increasing overall productivity and grain nitrogen content may serve as an effective strategy to achieve higher NUE alongside nitrogen yield [59].

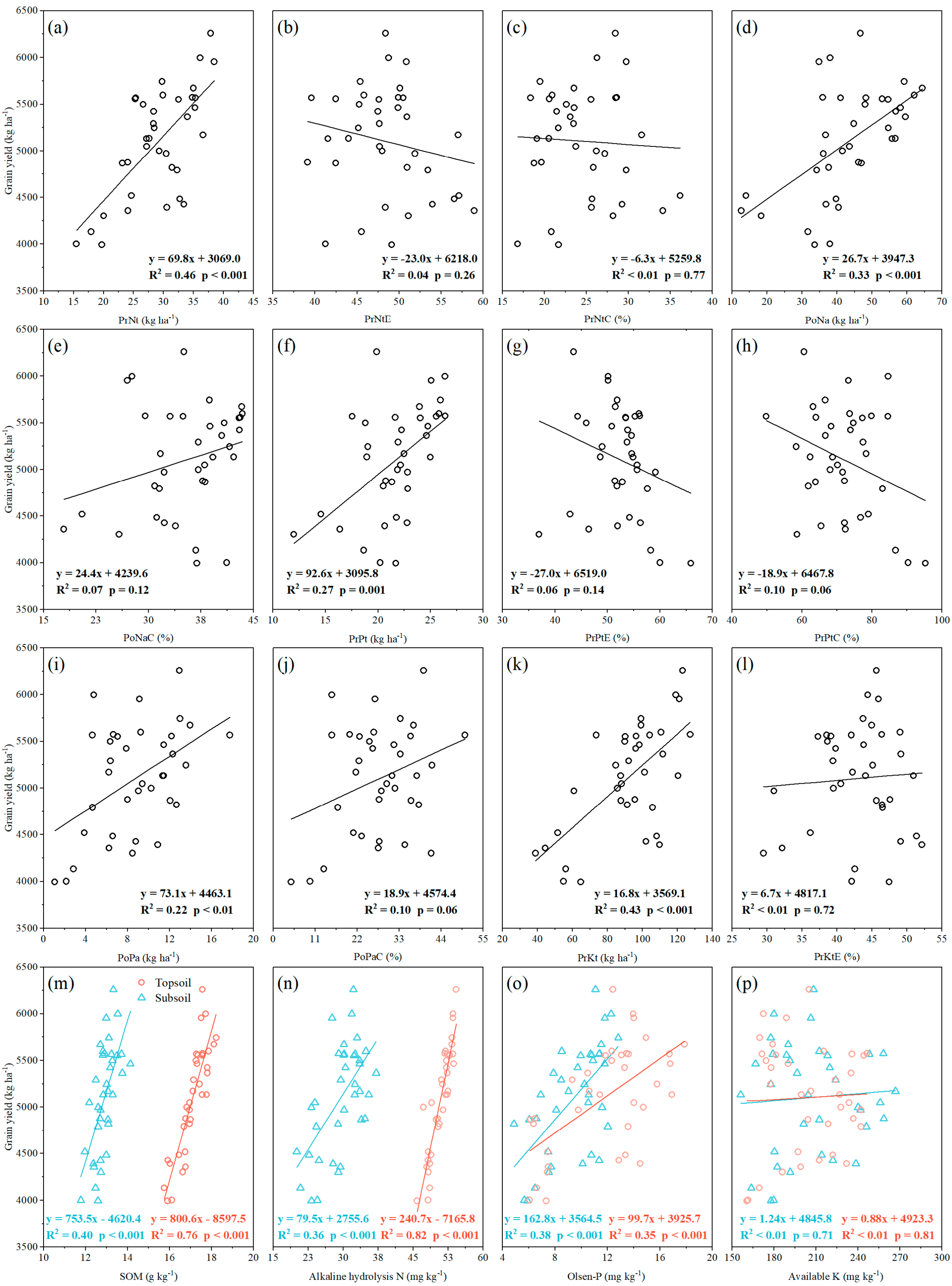

Figure 5. Relationship between pre-anthesis nutrient transport and post-anthesis nutrient accumulation, topsoil (0–20 cm) and subsoil (20–40 cm) traits, and wheat grain yield in 2022–2023. PrNt (**a**), PrPt (**f**), PrKt (**k**) represent the pre-anthesis NPK translocation. PrNtE (**b**), PrPtE (**g**), PrKtE (**l**) represent the pre-anthesis NPK transport rate. PrNtC (**c**) and PrPtC (**h**) represent the contribution rate of NP translocation to grain at pre-anthesis. PoNa (**d**) and PoPa (**i**) represent NP accumulation at pro-anthesis. PoNaC (**e**) and PoPaC (**j**) represent the contribution rate of NP accumulation to grain at pro-anthesis. SOM, soil organic matter (**m**); Alkali-hydrolyzable N (**n**); Olsen-P (**o**); Available K (**p**).

5. Conclusions

Two consecutive years of field trials have confirmed that in the oasis agricultural area at the northern foot of the Tianshan Mountains in Xinjiang, the recommended fertilizer application strategy (RF) for drip irrigation wheat production can not only reduce the dose of chemical fertilizers used but also lower production costs and increase nitrogen utilization efficiency. Compared with the farmer's conventional practice (FP), RF significantly improved pre-anthesis potassium transport volume and transport efficiency, while there were no significant differences in pre-anthesis NP transport and post- anthesis accumulation. Additionally, although RF resulted in lower dry matter accumulation compared with FP, there were no differences in grain yield or economic benefits between the two treatments. The yield-increasing effect of nitrogen fertilizer in RF was greater than that of phosphorus, which in turn was greater than that of potassium. Grain yield was significantly positively correlated with organic matter, alkali-hydrolyzed nitrogen, and Olsen-P content in both the topsoil and subsoil, but not with available potassium in the soil. Although potassium fertilizer application did not show significant effects in this trial, further research on aspects of the grains' quality is needed. In summary, the recommended fertilizer application strategy is crucial for farmers to stabilize grain yield, improve nitrogen utilization efficiency and economic benefits, and reduce environmental burdens. It represents a viable fertilizer plan for drip irrigation wheat production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14112491/s1, Figure S1. Effect of recommended fertilization in 2022 and 2023 on available nutrient content in 0–100cm soil layer during wheat harvest; Table S1. The groundwater hydrochemical characteristics of the experimental site; Table S2. Effects of different fertilization treatments on soil organic matter (g kg^{-1}) in different soil layers at different growth stages of wheat; Table S3. Effects of different fertilization treatments on alkali-hydrolyzed N (mg kg^{-1}) in different soil layers at different growth stages of wheat; Table S4. Effects of different fertilization treatments on Olsen-P (mg kg^{-1}) in different soil layers at different growth stages of wheat; Table S5. Effects of different fertilization treatments on available K (mg kg^{-1}) in different soil layers at different growth stages of wheat.

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Data Availability Statement: The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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