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Straw Return Substituting Potassium Fertilizer Increases Crop Yield, Efficiency, and Quality in Maize-Wheat Rotation System

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Abstract: The application of potassium fertilizer application and straw return are effective agronomic measures for increasing crop productivity; however, information on how straw return—when substituting potassium fertilizer—affects crop yield, efficiency, and quality in dryland remains limited. In this study, an experiment on a dryland summer maize and winter wheat rotation system was initiated in 2007. This study included four treatments: CK (no fertilizer and no straw return), NP (nitrogen and phosphorus fertilizer application without straw return), NPK (nitrogen, phosphorus, and potassium fertilizer application without straw return), and NPS (NP treatment with straw return, substituting potassium fertilizer as used in the NPK treatment). These treatments were employed to assess grain yield and fertilizer agronomic efficiency in 2015–2020. Additionally, we evaluated the content of nitrogen (N), phosphorus (P), and potassium (K), as well as the protein content and protein yield in maize and wheat grains and the protein components in wheat grains in 2019–2020. The results showed that compared to the CK treatment, NP, NPK, and NPS treatments not only significantly increased the yield, protein yield, and fertilizer agronomic efficiency in both maize and wheat but also increased the content of protein and protein components in wheat grains. Compared to the NP treatment, the NPK treatment significantly increased the contents of N, K, globulin, and gluten in wheat grains by 5.11%, 21.59%, 10.06%, and 15.14%. Compared to NPK treatment, NPS treatment significantly increased the average yield of summer maize by 21.33% and 20.91%, respectively, as well as the annual yield by 9.99% and 13.59%, the N fertilizer agronomic efficiency of summer maize by 132.47%, and the annual N and P fertilizer agronomic efficiency by 42.83% and 64.36%, over the five-year period. The NPS treatment also significantly increased the summer maize protein yield and annual protein yield by 10.43% and 23.08%, as well as the content of protein components, the protein content, and P content in wheat grains by 4.93–13.58%, 7.81%, and 28.89%, respectively. In conclusion, NPS treatment can not only enhance crop yield, protein yield, and fertilizer agronomic efficiency in summer maize annually but also has the advantage of promoting wheat quality. NPS is an efficient strategy to improve crop yield, efficiency, and quality in a dryland maize–wheat rotation system.

Keywords: straw return; potassium; grain yield; nutrient content; protein components; fertilizer agronomic efficiency; maize-wheat rotation

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1. Introduction

Maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) are the main grain crops in China and worldwide [1]. Enhancing the yield and quality of maize and wheat plays

an important role in ensuring food security and optimizing people's dietary structure, particularly in terms of facing the challenge of rapid population growth and improving living standards [2,3]. Studies have acknowledged that the application of fertilizer has been one of the most common agricultural practices used to improve crop productivity in the last three decades [4,5]; however, in pursuit of high yield and quality, excessive and unreasonable amounts of fertilizers have been applied to maize and wheat production systems, resulting in low fertilizer utilization efficiency. For example, the nitrogen (N) fertilizer agronomic efficiency for maize is 9.8 kg kg^{-1} and for wheat is 8.0 kg kg^{-1}, with an N-use efficiency of 26.1% and 28.2%, far below the levels in developed countries [6]. Due to the mismatch of precipitation and crop water requirements, infertile soil, and insufficient water for topdressing fertilizers, fertilizer efficiency is particularly low and unstable in drylands [7]. Summer maize and winter wheat (maize–wheat) rotation is one of the main cropping systems used in drylands in China [8,9]. In this system, the overuse of NPK fertilizer has also been adopted to achieve high crop yields and has led to lower fertilizer use efficiency [9–12]. Therefore, it is essential to explore nutrient management measures that can synergistically enhance grain yield, quality, and fertilizer efficiency in dryland maize–wheat rotation systems.

Fertilization, which increases crop yield by at least 30–50%, is the main approach used to improve crop productivity [4,5]. Nitrogen (N), phosphorus (P), and potassium (K) fertilizers are the three essential elements for crop growth and development [13]. K is required by plants in a lot of crucial physiological processes, and its functions are vital for boosting crop quality and tolerance to adversity [14,15]; however, the study and application of K fertilizer lag behind N and P fertilizers, especially in dryland areas [16,17]. Long-term cropping without K fertilizer application leads to decreased soil-available K and crop K uptake in drylands [18]. Some studies have also found that, after long-term no-K application, soil-available K decreases in maize-wheat rotation systems under well-irrigated conditions [19]. In China, scant resources, high prices, and habitual ways of thinking limit K fertilizer application to field crops, especially in drylands [20]. Therefore, it is necessary to supplement K nutrition in the soil and explore alternative measures to substitute K fertilizers.

Crop straw is rich in K, and returning it to the field is an effective way to improve soil K content, enrich the soil K pool, and meet the K requirements for crop growth, thus reducing the crop's need for K fertilizer [20–23]. Some studies have shown that, in drylands, the effectiveness of K fertilizer application on crop yield is limited due to the inadequate water supply [24]; however, many studies have shown that straw return can improve the soil water status, which contributes to fully exerting the nutrient's functions and, finally, enhancing crop yield, quality, and efficiency [7,18,25,26]. A meta-analysis found that compared to no straw return, straw return can improve the water conservation capacity of the soil and can increase wheat yield by 11.80% [25]. It has been proven that straw return optimized soil moisture content and surface temperature and synergistically optimized the nutrient environment and crop nutrient uptake, resulting in a 9.56% and 21.30% increase in wheat yield and protein content, respectively, as well as a 9.50% and 7.30% increase in maize yield and N-use efficiency [26]. A study also demonstrated that, relative to the absence of straw return, the practice of returning straw to the soil led to a slight increase in yield; however, another study showed that compared to no straw return, straw return did not increase wheat yield significantly but decreased the protein and wet gluten content in grain by 2.50% and 6.10% [27]. In addition, straw return substituting the use of K fertilizer has been demonstrated as an alternative measure for the rational utilization of straw, reducing the environmental pollution caused by burning straw [28,29] and increasing annual crop yields by 1.5–3.2% in dryland [14] and the agronomic efficiency of K fertilizer by 1.3–2.9 fold in maize–rice rotation [14,30]. However, these studies only focused on straw return substituting K on the yield and efficiency of monoculture crop systems in rain-fed areas and rotation systems in irrigated areas.

To the best of our knowledge, previous research did not provide a comprehensive assessment of the effects of the application of K fertilizer and straw return substituting K fertilizer on grain yield, quality, and fertilizer agronomic efficiency in dryland maize-wheat rotation systems. In the present study, a long-term positioning experiment initiated in 2007 was used to determine the effects of K fertilizer application and straw return substituting chemical K input on grain yield, nutrient content, protein content, protein components, and fertilizer agronomic efficiency in a dryland maize-wheat rotation system. The objectives of the present study were as follows: (1) quantify the impact of straw return substituting potassium fertilizer on grains yields and fertilizer agronomic efficiency; (2) evaluate their effects on grains protein content, protein content and components in wheat; and (3) identify an optimal agronomic strategy that can increase crop yield, efficiency, and quality in dryland summer maize and winter wheat rotation systems.

2. Materials and Methods

2.1. Site Description

This experiment was performed from June 2007 to June 2020 at Luoyang Dryland Agriculture Test Site, Chinese Academy of Agricultural Sciences, Henan, China (112.39° E, 34.62° N). This site is located in a semi-arid region at the southeast edge of the Loess Plateau. In this region, the maize-wheat rotation is the predominant cropping system, and the climate is classified as temperate continental monsoon, with an annual precipitation of 400–800 mm, an average annual temperature of 14.6 °C, and an average frost-free period of 210 days. The annual precipitation from 2015 to 2020 was 429.5, 545.5, 618.0, 504.5, and 649.7 mm, and 211.3, 327.3, 295.3, 410.3, and 437.7 mm during the summer maize growing season, and 218.2, 218.5, 322.7, 93.7, and 212.0 mm during the winter wheat growing season (Figure 1). The soils at the experimental site are classified as yellow-brown earthy cinnamon (Udic Haplustalf in the USDA system). The properties of the 0–20 cm soil layer when the experiment was initiated are listed in Table 1.

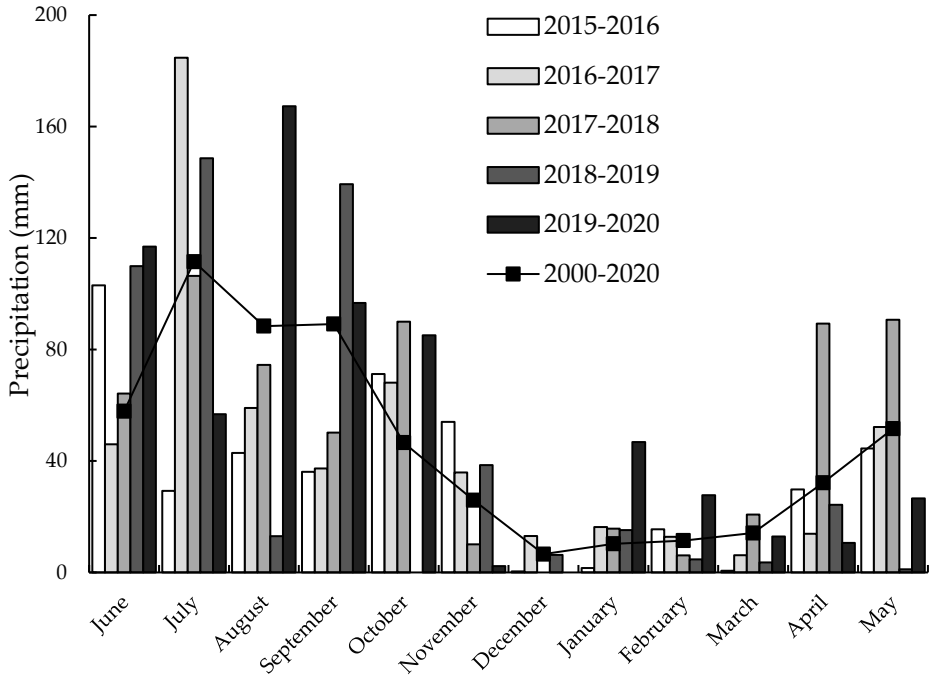

Figure 1. Monthly precipitation (mm) in the experimental years from June 2015 to May 2020. The broken line shows the average precipitation from 2000 to 2020.

Table 1. The physico-chemical properties of topsoil (0–20 cm) at the beginning of the experiment in June 2007.

Soil Characteristics	Value	Unit
Bulk density	1.53 ± 0.05	g cm^{-3}
Organic matter	15.80 ± 0.42	g kg^{-1}
Total nitrogen	0.90 ± 0.02	g kg^{-1}
Available phosphors	10.39 ± 0.31	mg kg^{-1}
Available potassium	166.0 ± 4.12	mg kg^{-1}
Field capacity	23.48 ± 0.91	%
pH	7.30 ± 0.26	-

Values indicate the mean ± standard error (n = 3).

2.2. Experimental Design and Management

The experiment was conducted as a randomized complete block design with three replications. The experiment included the following four treatments, namely, CK (no fertilizer and no straw return), NP (N and P fertilizer without straw return), NPK (N, P, and K fertilizer without straw return), and NPS (N and P fertilizers with crop straw return), which also express the effect of substituting potassium fertilizer with straw compared to the NPK treatment. Detailed information on each treatment is given in Table 2. The chemical fertilizers used in this study were urea (46% N), calcium superphosphate (12% P_2O_5), and potassium chloride (60% K_2O). Each plot size was 16 m^2 (4 m × 4 m). In general, winter wheat was sowed in early or middle October after rotary tillage at a seeding rate of 135 kg ha^{-1} and harvested in late May or early June of the following year. Summer maize was sowed in early June after a no-till tillage with a seedling density of 4.5 × 10^4 ha^{-1}, and harvested in late September. The varieties of maize and wheat were Luoyu 114 and Luohan 7, respectively. Based on the common practices of field management adopted by local farmers, herbicides and insecticides were used to control weeds, diseases, and pests.

Table 2. Fertilizer and straw management under different treatments.

Treatment	Fertilizer and Straw Management
CK	Zero fertilizer was applied, and straw of previous crops was removed from field during maize and wheat seasons
NP	207 kg N ha^{-1} was evenly applied when rainfall occurred around jointing stage of summer maize, and 150 kg N ha^{-1}, and 120 kg P_2O_5 ha^{-1} were manually broadcasted and thoroughly incorporated into the soil by plowing (25–30 cm) at the sowing of winter wheat, and straw was removed from the field during maize and wheat seasons
NPK	The management of N and P_2O_5 fertilizer and straw was the same as NP, and 90 kg K_2O ha^{-1} was manually broadcasted and thoroughly incorporated into the soil by plowing (25–30 cm) during sowing of winter wheat
NPS	All fertilizer management was the same as the NP, and 100% straw of the previous winter wheat was surface-mulched during the summer maize season, and 50% straw (length was ≤5.0 cm) of the previous summer maize was incorporated into the soil by plowing (25–30 cm) during sowing of winter wheat season.

2.3. Measurements and Methods

2.3.1. Grain Yield

At the maturity of maize and wheat from 2015 to 2020, all plants in each plot were manually harvested. After air-drying, the plants in each plot were threshed, and the weight of the grain was measured. In the lab, 50 ± 5 g of grains in each plot were oven-dried at 80 °C to a constant weight to measure the moisture content of the air-drying grains. The yield was calculated based on a grain moisture content of 13%.

2.3.2. Grain Nutrient Content

In the experimental year of 2019–2020, 50 g of maize and wheat grains were oven-dried and ground and then digested with H_2SO_4-H_2O_2 to determine the content of N, P, and K. The content of N and P was determined using a high-resolution digital colorimeter auto analyzer 3 (AA3, SEAL Company, Norderstedt, Germany), and the content of K was determined using a flame photometer (M410, Sherwood, Cambridge, UK) [31]. The content of N, P, and K in wheat and maize grains are expressed on a dry weight basis. Additionally, the content and yield of protein were calculated using the following equations [32].

$$\text{Protein content (\%)} = \text{Nitrogen content in grains} \times 5.7; \quad (1)$$

$$\text{Protein yield (kg ha}^{-1}\text{)} = \text{Grain dry weight} \times \text{protein content (\%)}. \quad (2)$$

2.3.3. Grain Protein Components

In 2019–2020, the content of protein components in wheat grains was determined as previously described [33]. Here, 0.50 g of whole meal flour was precisely weighed and subjected to albumin extraction. This extraction process involved mixing the flour with 5 mL of pure water in a plastic centrifuge tube, followed by oscillation (20 min) and centrifugation (4000 r, 7 min). This procedure was repeated four times, and the resulting extract was collected as albumin. Similarly, the residue remaining in the tube underwent extraction with separate solutions to isolate the fractions of globulin, gliadin, and glutenin. Specifically, 2% NaCl, 75% ethanol, and 0.2% NaOH solutions were employed for the extraction process, respectively. The extraction protocol mirrored that described above and was repeated four times for each fraction. Subsequently, the concentration of each protein fraction was determined using the Kjeldahl method (H8750, Haineng company, Shanghai, China).

2.3.4. N and P Fertilizer Agronomic Efficiency

The calculation of N (P) fertilizer agronomic efficiency was according to [34]:

$$\text{N fertilizer agronomic efficiency (kg kg}^{-1}\text{)} = \frac{GY - GY_{CK}}{N_{rate}}; \quad (3)$$

$$\text{P fertilizer agronomic efficiency (kg kg}^{-1}\text{)} = \frac{GY - GY_{CK}}{P_{rate}} \quad (4)$$

where GY is the grain yield of the NP, NPK, and NPS treatments, and GY_{CK} is grain yield of the CK treatment.

2.4. Statistical Analysis

Statistical methods were performed using one-way analysis of variance (ANOVA) to examine the grain yield, quality, and fertilizer agronomic efficiency. The least significant difference (LSD, at a 0.05 probability level) test was subsequently applied in SPSS software (version 23, IBM, New York, NY, USA) to determine significant differences among the treatments. The graphical presentation of the data was generated using Origin 2022 software (Origin Lab Corp., Northampton, MA, USA).

3. Results

3.1. Grain Yield

Table 3 shows that compared to CK, the yield in summer maize, winter wheat, and annual NP, NPK, and NPS treatments showed a significant increase in most years, with a 5-year average yield of 21.93–47.96%. These findings suggested that fertilization can greatly enhance crop yields in the dryland maize-winter rotation system. However, the effect of NP, NPK, and NPS on crop yields varied within years and crops. For summer maize, compared to NP, NPK did not affect grain yield over the consecutive five years, while NPS exhibited a substantial yield increase effect, except for 2018 (there was no significant difference among

NP, NPK, and NPS), with an increase of 19.3–215.3%. Compared to NPK, NPS significantly increased maize yields by 20.91% (16.0–154.7%) in all of the experimental years except for 2018.

Table 3. Effects of different treatments on crop yield in dryland maize-wheat rotation system in the experimental year of 2015–2020.

Year	Treatment	Summer Maize (kg hm^{-2})	Winter Wheat (kg hm^{-2})	Annual (kg hm^{-2})
2015–2016 (2015)	CK	4161.5 ± 165.85 ab	3404.7 ± 26.79 a	7566.2 ± 154.21 ab
	NP	3474.0 ± 383.37 b	3316.3 ± 81.03 ab	6790.2 ± 464.40 bc
	NPK	3423.6 ± 283.28 b	3198.5 ± 95.24 b	6622.2 ± 374.24 c
	NPS	4711.8 ± 455.69 a	3492.7 ± 113.55 a	8204.5 ± 394.72 a
2016–2017 (2016)	CK	3960.9 ± 78.67 c	2868.8 ± 145.44 b	6829.7 ± 196.94 c
	NP	4265.6 ± 106.82 b	4252.1 ± 347.15 a	8517.7 ± 448.92 ab
	NPK	4385.4 ± 18.54 b	4021.9 ± 333.79 a	8407.2 ± 327.33 a
	NPS	5088.5 ± 204.26 a	4096.9 ± 130.68 a	9185.4 ± 238.90 a
2017–2018 (2017)	CK	506.3 ± 0.0 b	3876.8 ± 1.84 b	4383.0 ± 1.84 c
	NP	403.1 ± 20.89 b	4791.5 ± 100.34 a	5194.6 ± 85.94 b
	NPK	499.0 ± 229.66 b	4300.5 ± 319.73 b	4799.5 ± 535.75 bc
	NPS	1270.8 ± 97.31 a	4813.5 ± 257.15 a	6084.3 ± 263.28 a
2018–2019 (2018)	CK	3735.9 ± 222.39 b	2108.3 ± 131.66 c	5844.2 ± 90.73 c
	NP	6041.8 ± 414.15 a	3693.0 ± 321.44 a	9734.8 ± 646.32 a
	NPK	6121.5 ± 466.51 a	2692.5 ± 219.49 b	8814.0 ± 365.85 b
	NPS	6238.3 ± 242.40 a	3184.5 ± 283.88 ab	9422.8 ± 109.89 ab
2019–2020 (2019)	CK	5354.5 ± 42.53 c	3196.9 ± 165.85 c	8551.0 ± 208.38 c
	NP	7423.6 ± 405.50 b	5591.7 ± 161.48 b	13,015.3 ± 453.04 b
	NPK	7253.5 ± 544.44 b	5983.3 ± 150.55 a	13,236.8 ± 647.75 ab
	NPS	8908.0 ± 679.05 a	5768.8 ± 127.88 ab	14,676.7 ± 574.81 a
5-year average	CK	3543.7 ± 43.89 c	3091.1 ± 69.05 b	6634.8 ± 82.97 c
	NP	4321.9 ± 147.90 b	4328.9 ± 117.57 a	8650.5 ± 288.16 b
	NPK	4336.6 ± 145.40 b	4039.4 ± 168.63 a	8375.9 ± 281.25 b
	NPS	5243.5 ± 196.15 a	4271.3 ± 44.04 a	9514.8 ± 219.50 a

Note: CK refers to no fertilizer and no straw return; NP refers to N and P fertilizer without straw return; NPK refers to N, P, and K fertilizer without straw return; NPS refers to N and P fertilizers with crop straw return. Different lowercase letters after the data within the same column indicate significant differences ($p < 0.05$) among treatments.

For winter wheat, compared to NP, NPK did not change the yield in 2015–2016 and 2016–2017, but significantly decreased the yield in 2017–2018 (10.25%) and 2018–2019 (27.09%) and significantly increased by 7.00% in 2019–2020. The yield of NPS did not differ significantly from NP in the 5 experimental years. Compared to NPK, NPS significantly increased the wheat yield by 9.20% and 11.93% in 2015–2016 and 2017–2018, respectively, but did not change the 5-year average yield.

In terms of annual yield, compared to NP, NPK did not change the yield, but NPS significantly increased the average yield by 9.99%, with significant increases of 20.83%, 17.13%, and 12.77% in 2015–2016, 2017–2018, and 2019–2020, respectively. Compared to NPK, the 5-year average yield of NPS significantly increased by 13.60%, with a significant increase in all years except 2018–2019. These results indicated that the regulatory effect of K fertilizer on the yield of the maize-wheat rotation system was inconsistent, while straw return substituting K fertilizer can effectively improve crop yield. However, this effect was mainly observed in summer maize.

3.2. N and P Fertilizer Agronomic Efficiency

As shown in Table 4, NPS treatment showed the highest N agronomic efficiency in summer maize, in five consecutive years, with N agronomic efficiency increases of 118.35%

and 132.47%, respectively, compared to NP and NPK. However, N agronomic efficiency showed no significant difference in terms of NP and NPK. For winter wheat, compared to NP, the N agronomic efficiency under NPK and NPS was significantly decreased by 63.13% and 32.09% in 2018–2019 but significantly increased by 199.53% and 142.70% in 2015–2016.

Table 4. Effect of different treatments on the agronomic efficiency for N and P_2O_5 in dryland maize–wheat rotation system.

Year	Treatment	Summer Maize	Winter Wheat		Annual	
		N (kg kg^{-1})	N (kg kg^{-1})	P_2O_5 (kg kg^{-1})	N (kg kg^{-1})	P_2O_5 (kg kg^{-1})
2015–2016 (2015)	NP	−3.32 ± 1.05 b	−0.5 ± 0.64 ab	−0.74 ± 0.80 ab	−2.17 ± 0.87 b	−6.47 ± 2.59 cb
	NPK	−2.37 ± 0.64 b	−1.66 ± 0.98 b	−2.07 ± 1.22 b	−2.07 ± 1.06 b	−6.16 ± 3.15 bc
	NPS	2.66 ± 1.68 a	0.59 ± 0.92 a	0.73 ± 1.15 a	1.79 ± 0.71 a	5.32 ± 2.12 a
2016–2017 (2016)	NP	1.47 ± 0.63 c	9.22 ± 1.36 a	11.53 ± 1.70 a	4.73 ± 0.85 ab	14.07 ± 2.54 ab
	NPK	3.12 ± 0.79 bc	6.25 ± 4.61 a	7.81 ± 5.77 a	4.43 ± 0.41 b	13.19 ± 5.24 b
	NPS	5.45 ± 0.85 a	8.19 ± 0.43 a	10.23 ± 0.53 a	6.60 ± 0.66 a	19.63 ± 1.96 a
2017–2018 (2017)	NP	−0.50 ± 0.10 c	6.10 ± 0.68 a	7.62 ± 0.85 a	2.27 ± 0.24 ab	6.76 ± 0.72 ab
	NPK	−0.77 ± 0.35 c	2.20 ± 6.64 a	2.74 ± 8.29 a	0.48 ± 2.98 b	1.42 ± 8.88 b
	NPS	3.69 ± 0.47 a	6.25 ± 1.70 a	7.81 ± 2.13 a	4.77 ± 0.73 a	14.18 ± 2.18 a
2018–2019 (2018)	NP	11.14 ± 2.42 a	10.57 ± 1.38 a	13.21 ± 1.73 a	10.90 ± 1.96 a	32.42 ± 5.84 a
	NPK	9.56 ± 1.23 a	6.36 ± 2.20 b	7.95 ± 2.75 b	8.22 ± 1.31 a	24.45 ± 3.69 ab
	NPS	12.09 ± 1.95 a	7.18 ± 2.19 ab	8.97 ± 2.74 ab	10.02 ± 0.53 a	29.82 ± 1.57 a
2019–2020 (2019)	NP	10.00 ± 1.77 b	15.97 ± 1.77 c	19.96 ± 2.21 c	12.50 ± 0.96 c	37.20 ± 2.85 c
	NPK	9.73 ± 2.96 b	18.72 ± 0.60 ab	23.39 ± 0.75 ab	13.50 ± 1.87 bc	40.18 ± 5.57 bc
	NPS	17.17 ± 3.09 a	17.15 ± 1.73 bc	21.43 ± 2.17 bc	17.16 ± 1.07 a	51.05 ± 3.17 a
5-year average	NP	3.76 ± 0.86 b	8.25 ± 0.36 a	8.60 ± 0.45 a	5.65 ± 0.68 b	16.80 ± 2.03 b
	NPK	3.85 ± 0.75 b	6.37 ± 0.86 a	6.64 ± 2.16 a	4.91 ± 1.30 b	14.61 ± 3.87 b
	NPS	8.21 ± 0.83 a	7.87 ± 1.73 a	8.20 ± 0.84 a	8.07 ± 0.45 a	24.00 ± 1.33 a

Note: NP refers to N and P fertilizer without straw return; NPK refers to N, P, and K fertilizer without straw return; NPS refers to N and P fertilizers with crop straw return. Different lowercase letters after the data within the same column indicate significant differences ($p < 0.05$) among treatments.

In terms of fertilizer agronomic efficiency, compared to NP, NPK did not change the agronomic efficiency of N and P, but NPS significantly increased the N and P fertilizer agronomic efficiency by 42.83% and 42.86%, respectively. Compared to NPK, the 5-year average agronomic efficiency for N and P in NPS significantly increased by 42.86% and 64.27%, with a significant increase in all years except for 2018–2019. In general, the annual N and P fertilizer agronomic efficiency was the highest in NPS, exceeding NP by 42.83% and 64.36% and NPK by 42.86% and 64.27%, respectively.

3.3. Soil Properties

Table 5 shows the effects of different treatments on soil fertility at the harvest of winter wheat in 2019–2020. Compared to the initial stage of the experiment (June 2007), CK led to a decrease in the contents of soil organic matter, total nitrogen, available phosphorus, and available potassium by 19.0%, 22.2%, 62.5%, and 1.2%, respectively. These reductions were statistically significant except for available potassium. In addition, compared to the initial value, NP, NPK, and NPS showed significant increases in nutrient content, with the increases ranging from 15.1% to 55.7% in organic matter, 4.4% to 33.3% in total nitrogen, 8.8% to 26.0% in available phosphors, and 31.32% to 117.9% in available potassium, respectively. Further analysis revealed that compared to NP, NPS significantly increased the content of soil organic matter, total nitrogen, available potassium, and available phosphorus by 35.2%, 27.7%, 15.9%, and 75.2%, respectively. Compared to NPK, NPS significantly increased the content of soil organic matter, total nitrogen, and available phosphorus by 13.9%, 20.0%, and 12.9%, respectively, while the content of soil available potassium

did not change significantly. Compared to the soil before the trial, all four fertilization treatments resulted in a significant increase in soil pH, with increases of 0.69, 0.36, 0.44, and 0.66 units, respectively.

Table 5. Soil fertility of each treatment at harvest of winter wheat in 2019–2020.

Treatment	Organic Matter (g kg^{-1})	Total Nitrogen (g kg^{-1})	Available Phosphors (mg kg^{-1})	Available Potassium (mg kg^{-1})	pH
Initial value	15.80 ± 0.42 c	0.90 ± 0.02 c	10.39 ± 0.31 c	166.00 ± 4.12 c	7.30 ± 0.26 c
CK	12.8 ± 0.51 d	0.7 ± 0.08 d	3.9 ± 0.26 d	198 ± 6.17 b	7.99 ± 0.36 a
NP	18.2 ± 0.45 b	0.94 ± 0.05 b	11.3 ± 0.30 b	218 ± 12.31 b	7.66 ± 0.29 b
NPK	21.6 ± 0.56 b	1.0 ± 0.12 b	11.6 ± 0.26 b	331 ± 13.24 a	7.74 ± 0.30 b
NPS	24.6 ± 0.68 a	1.2 ± 0.22 a	13.1 ± 0.52 a	382 ± 16.58 a	7.96 ± 0.34 a

Note: CK refers to no fertilizer and no straw return; NP refers to N and P fertilizer without straw return; NPK refers to N, P, and K fertilizer without straw return; NPS refers to N and P fertilizers with crop straw return. Different lowercase letters after the data within the same column indicate significant differences ($p < 0.05$) among treatments.

3.4. N, P, and K Content in Grain

Figure 2 illustrates that the long-term fertilization management of NP, NPK, and NPS significantly affected the N, P, and K content in grains of summer maize and winter wheat. For summer maize, compared to CK, NP, NPK, and NPS significantly increased the content of N by 7.26%, 5.65%, and 7.26%, as well as the content of P by 27.78%, 27.32%, and 25.93%, respectively. However, there were no significant differences in NP, NPK, and NPS treatments. For winter wheat, NPS did not affect the content of N compared to NPK. However, NPS significantly increased the content of N by 39.01% and 7.66% it significantly increased by 39.01% and 7.66% when compared to CK and NP. Additionally, compared to CK and NP, the content of grain K was significantly increased by 26.17% and 18.94% under NPS and by 28.97% and 21.58% under NPK; however, there was no significant difference between NPS and NPK. These findings indicated that the NPK and NPS had a positive impact in increasing the content of N in summer maize grains and the content of N and K in winter wheat grains.

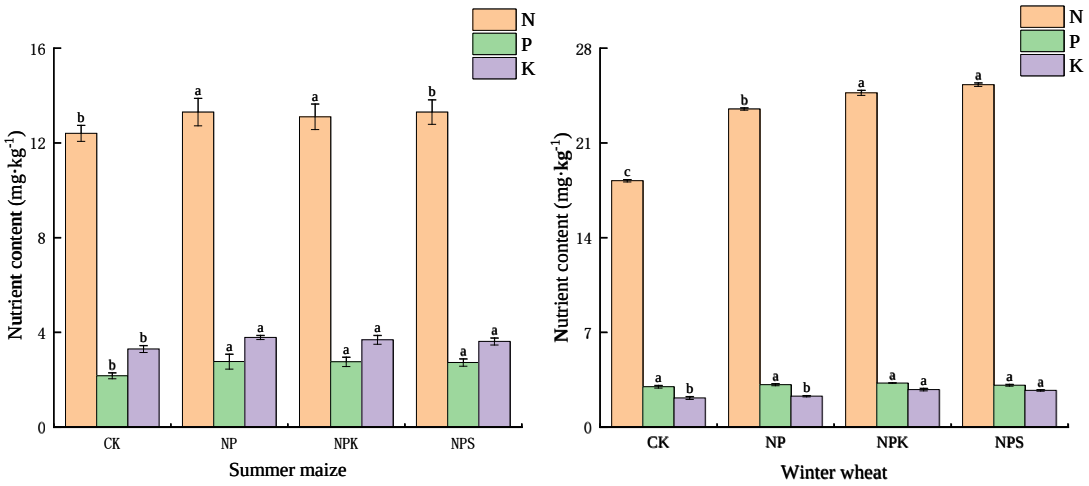

Figure 2. Effect of different treatments on the content of N, P, and K in grains in the dryland maize-wheat rotation system in the experimental year of 2019–2020. Note: CK refers to no fertilizer and no straw return; NP refers to N and P fertilizer without straw return; NPK refers to N, P, and K fertilizer without straw return; NPS refers to N and P fertilizers with crop straw return. Different lowercase letters above the column for the same nutrient indicate significant differences ($p < 0.05$) among treatments.

3.5. Protein Content and Protein Yield

Figure 3 shows that the fertilization treatments significantly increased the content of grain protein and the yield of protein in summer maize and winter wheat. For summer maize, the content of protein showed no statistical differences under NPS, NP, and NPK, but they were significantly increased by 7.8%, 7.53%, and 5.82% compared to CK. NPS leads to the highest yield of protein, exhibiting significant increases of 20.27% and 24.98% compared to NP and NPK, respectively. For winter wheat, compared to CK and NP, NPS significantly increased the content of protein by 39.29% and 7.69%, as well as the yield of protein by 151.3% and 11.13%, but it did not change compared to NPK. Likewise, compared to CK, NP, and NPK, NPS significantly increased the yield of protein by 212.9%, 11.51%, and 8.98%, respectively. These results strongly suggested that the NPS treatment had a positive impact on increasing the content of grain protein and the yield of protein in the dryland maize–wheat rotation system.

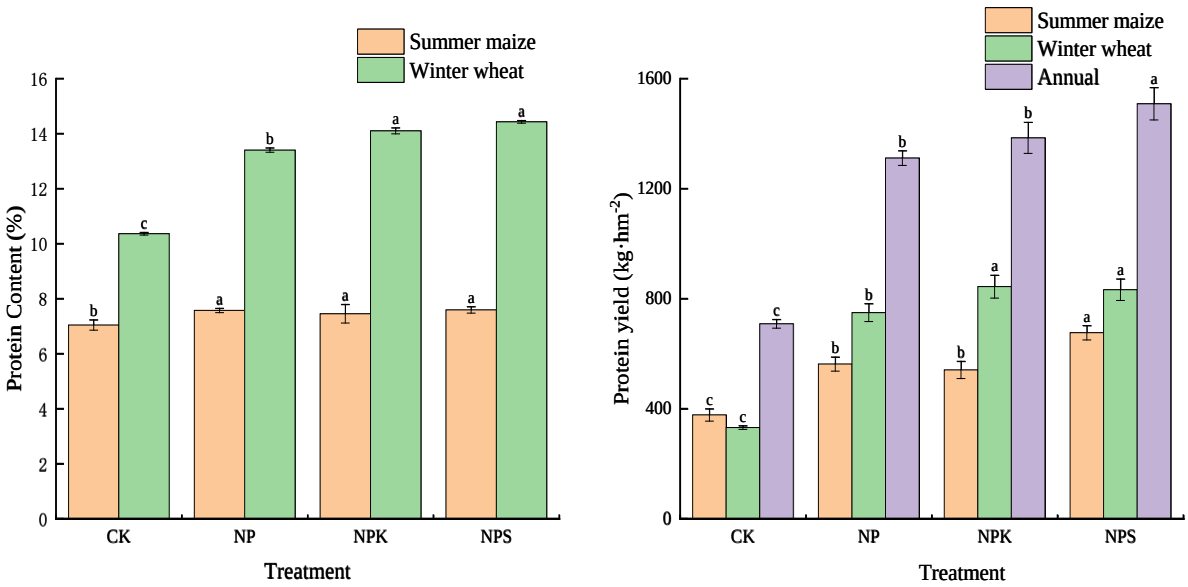

Figure 3. Effects of different treatments on the content and yield of grain protein in the dryland maize-wheat rotation system in the experimental year of 2019–2020. Note: CK refers to no fertilizer and no straw return; NP refers to N and P fertilizer without straw return; NPK refers to N, P, and K fertilizer without straw return; NPS refers to N and P fertilizers with crop straw return. Different lowercase letters above the column for the same nutrient indicate significant differences ($p < 0.05$) among treatments.

3.6. Protein Components

As shown in Figure 4, compared to CK, NP, NPK, and NPS can increase the contents of protein components in wheat grains. NPS caused the highest contents of albumin, globulin, gliadin protein, glutenin, and glutenin-to-gliadin ratio. Specifically, compared to NP and NPK, NPS significantly increased the content of albumin, gliadin, and glutenin by 8.24% and 13.58%, 6.98% and 4.93%, and 15.14% and 5.97%, respectively. Furthermore, compared to NPK, the globulin and gliadin contents in NPS were increased by 7.69% and 10.06%, respectively. For store protein content, compared to NP, the content of store proteins in NPK and NPS was increased by 11.90% and 11.38%, respectively. These findings indicated that the application of fertilizers and straw return substituting K fertilizer can enhance the contents of all protein composition in wheat grain, and the best performance was obtained under NPS.

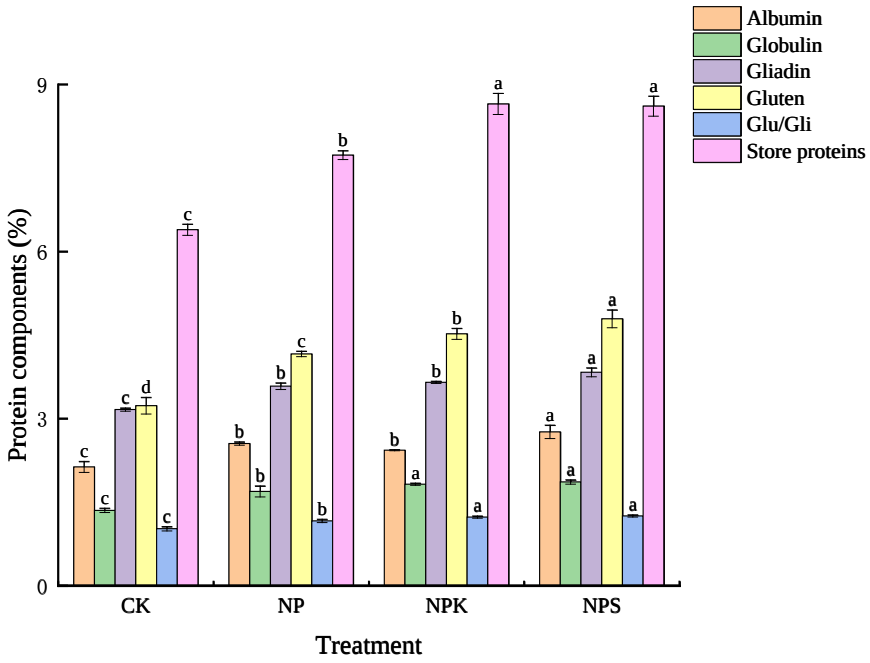

Figure 4. Effect of different treatments on the characteristics of protein components of winter wheat grains in dryland maize-wheat rotation system in the experimental year of 2019–2020. Note: CK refers to no fertilizer and no straw return; NP refers to N and P fertilizer without straw return; NPK refers to N, P, and K fertilizer without straw return; NPS refers to N and P fertilizers with crop straw return. Different lowercase letters above the column for the same nutrient indicate significant differences ($p < 0.05$) among treatments.

4. Discussion

4.1. Crop Yields and Fertilizer Agronomic Efficiency Affected by Straw Return Substituting K Fertilizer

Proper fertilization and straw return are important measures for increasing crop yields. Previous research has shown that straw return can increase wheat yields, particularly in drylands where water and nutrients are insufficient [35,36]. In this study, NPS significantly increased summer maize yield by 20.91% compared to NPK (Table 1), but it did not affect the winter wheat yield and annual yield. These results indicated that NPS can stabilize wheat yields and significantly increase summer maize yield in the drylands, which is consistent with the previous research reported by [9]. This may be mainly ascribed to two reasons. Firstly, water is the primary limiting factor for crop yields in drylands. The rainfall during the 3–4 months growing season of summer maize accounts for 47.8–81.4% of the annual precipitation, which can enhance the effect of the straw return on soil water retention and prevent soil water evaporation, thereby improving soil moisture and crop yields. Secondly, during the winter wheat growing season, the rainfall (ranging from 93.7 to 322.7 mm) is far below the wheat water requirement of 450 mm, especially during the critical water requirement stage from jointing to flowering (March to May, 29.0–75.0 mm), which weakens the capacity of straw return on fertilization and water-retention, resulting in a corresponding decrease in the ability for increasing yield. Therefore, the yield increases from straw return is better than that from K fertilizer application.

Enhancing fertilizer use efficiency is crucial for sustainable and environmentally friendly wheat production [9,18]. Previous research has shown that straw return was an important measure to improve fertilizer use efficiency [36,37]. The results of this long-term positioning experiment also showed that NPS enhanced the N fertilizer agronomic efficiency of summer maize by 132.47% and the annual N and P fertilizer agronomic efficiency by 64.36% and 64.27%, respectively. The discrepancy could be attributed to the positive effect of straw return on soil water, soil nutrients, and the soil micro-environment, which, in

turn, promoted the yield and efficiency of crops planted in the rainy summer season [38]. However, straw return did not affect the N and P fertilizer agronomic efficiency of winter wheat, indicating that employing the technique of straw return to achieve the target of high yield and efficiency in wheat still has some challenges, particularly in regions with low rainfall and susceptibility to drought stress during the critical stage of water demand.

4.2. Grain Quality Affected by Straw Return Substituting K Fertilizer

The content of nutrients and protein in crop grains directly determines the intake of dietary nutrients and plant proteins for humans. Previous research has shown that rice straw return can increase the content of protein and wet gluten, thus improving the quality of medium-strong gluten wheat [39]. This study further confirmed that potassium fertilizer can increase the K content in summer maize grains and the N content in winter wheat grains. Moreover, substituting potassium fertilizer with straw return can not only increase the N and K content in winter wheat grains but also enhance the protein content and protein yield of grain crops in the dryland maize–wheat rotation system. This may be due to the significant increase in the contents of soil organic matter and N, P, and K introduced by straw return [9], which has been proven to be a good foundation for plant nutrient accumulation and protein formation [40].

The content and ratio of protein composition in grains are closely related to wheat quality. The Glu/Gli ratio is an important indicator affecting the baking quality of bread and the quality of steamed buns. A higher Glu/Gli ratio can yield higher bread volume and bread scores [41,42]. This study showed that compared to CK, all three fertilizations increased the contents of most protein compositions and the Glu/Gli ratio in wheat grains with the order of NPS > NPK > NP. This suggested that potassium fertilizer application and straw return substituting potassium fertilizer had a positive effect in gaining a favorable processing quality of wheat in drylands. Additionally, NPS significantly increased the contents of various protein components (except globulin) but did not affect Glu/Gli ratio compared to NPK. This indicated that straw return, as a substitute for potassium fertilizer application, could be used as an alternative measure for improving the processing quality by increasing the protein composition. This is mainly because K fertilization is an essential nutrient in crop growth and development and plays an important role in improving crop resistance, increasing grain yield, and improving grain quality [21,22]. In addition, straw return helped to improve nutrient availability and K supply during the crop growing stage by increasing soil organic matter content and improving soil structure, thus improving grain quality [43,44].

5. Conclusions

Compared to CK, all the fertilization treatments, such as NP, NPK, and NPS, significantly increased crop yield, protein yield, and the contents of protein and protein components in wheat grains. Compared to NP, NPK did not affect yield and fertilizer agronomic efficiency but showed better increasing effects in the contents of N, K and globulin, and gluten in wheat grains. However, compared to NPK, NPS stabilized the yield, yield of protein, and fertilizer agronomic efficiency in wheat but significantly increased the yield, yield of protein, and fertilizer agronomic efficiency in maize annually, as well as increased the contents of all protein components, except for globulin in wheat grains. Therefore, substituting potassium fertilizer with straw return (NPS) was a suitable agronomic measure in terms of increasing maize, annual yield, efficiency and wheat quality in a dryland maize-wheat rotation system. In a future study, more focus should be given to examining the long-term effects of NPS on soil health and investigating its impact on other crops in rotation systems. Such research endeavors would help to explore the mechanisms underlying the observed improvements in crop yield and quality and to further optimize fertilization strategies for dryland maize–wheat rotation systems.

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