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Impact of straw return and nitrogen fertilizer on photosynthesis and yield of red kidney beans

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Red kidney bean (*Phaseolus vulgaris* L.) is widely cultivated and consumed globally. Exploring the effects of straw return and nitrogen fertilizer on the growth and yield of red kidney beans is essential for developing optimal straw return and nitrogen management practices to increase grain yield for food security. Field experiments were conducted for three consecutive years (2022–2024) to study the effects of two straw return methods and four nitrogen fertilization levels on the chlorophyll content, photosynthetic characteristics, dry matter accumulation, yield and its components of red kidney beans. The results showed that chlorophyll content, photosynthetic characteristics, dry matter accumulation, yield and its components improved significantly under straw return (ST) compared to no straw return (NST). Increasing nitrogen supply can promote the effect of straw return. Across all three seasons, the ST + N135 treatment produced the highest values for all measured traits. Chlorophyll content, Pn, Gs, Tr, dry matter accumulation, and yield increased increased 28.91-34.60%, 22.40-28.65%, 27.83-30.67%, 25.68-27.89%, 23.45-28.62%, and 17.08-21.05% under ST + N135 treatment. The ST + N90 treatment yielded the highest planting profit at $6378.84 per hectare. Our findings demonstrated the ST + N90 treatment was an effective way to achieve stable, high yields of red kidney beans and maximize farmers' income, which could be promoted and applied in Inner Mongolia.

Keywords Dry matter, Kidney bean, Nitrogen fertilizer management, Photosynthetic characteristics, Straw return

Red kidney bean (*Phaseolus vulgaris* L.) is a general term for common kidney bean and multi-flowered kidney bean[1]. It is rich in protein, minerals, and vitamins, which plays an important role in human nutrition[2]. It has the advantages of a short growth period, wide adaptability, strong drought resistance, ease of cultivation and management, and high economic value. It is primarily cultivated in cold, high-altitude regions in northern and southwestern China[3]which is a major grain crop with a large consumer population in China[4].

Red kidney bean yield is influenced by chlorophyll content, photosynthesis, dry matter accumulation, fertilizer application, and cultivation practices[5–10]. Proper nitrogen fertilization is key to enhancing photosynthetic efficiency and increasing yields[11]. Song[12] found that moderate application of nitrogen fertilizer was beneficial for the photosynthetic production, dry matter accumulation, and yield improvement of spring wheat. The optimal effect was achieved with the treatment of biochar combined with 255 kg/ha of nitrogen fertilizer. Liang[13] showed that applying an appropriate amount of nitrogen fertilizer can significantly improve the photosynthetic physiological characteristics and yield of maize. The optimal nitrogen application rate was 300 kg/ha of nitrogen fertilizer. Zhang[14] found that increasing nitrogen fertilizer application during the flowering period was beneficial for increasing the formation of dry matter accumulation, and laying a good foundation for soybean high yield. Nitrogen fertilizer is crucial for the growth and development of crops. While nitrogen fertilizer has made significant contributions to global food security, despite its importance, nitrogen fertilizer use is often inefficient due to overapplication, poor timing, and insufficient fertilization technologies[15]resulting in a large loss of fertilizer nitrogen, low nitrogen fertilizer utilization efficiency, decline in soil structure and fertility, and nutrient pollution leading to eutrophication of water bodies. Thus, optimizing fertilization strategies is essential for improving soil health, increasing crop productivity, and minimizing environmental impacts[16].

Recently, integrated fertilization practices, such as straw return combined with nitrogen application, have gained attention[17]. Straw return is a sustainable practice that improves nutrient recycling and soil quality. Straw

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contains a large amount of nutrients such as nitrogen, phosphorus, and potassium[18]and returning it to the field is an effective measure to improve soil structure[19,20]. Returning straw to the field recycles plant-derived nitrogen into the soil, improving nutrient availability[21]. Improving soil structure and nutrient levels provides favorable conditions for high-yield red kidney bean cultivation. Guo[22] found that straw return had greater chlorophyll relative content, net photosynthetic rate, transpiration rate, and yield of maize by 7.9–17.5%, 7.7–19.2%, 5.5–12.1%, and 6.2–6.7% than the control, respectively. Straw return increased maize yield by 15.6% compared to the control. Fan[23] showed that straw return combined with potash fertilizer had significant effects on maize yield. It was an effective way to ensure a stable and high yield of corn and enhance economic returns for farmers. Pn, Gs, Tr, dry matter accumulation, and yield of maize increased most under SFK60 treatment, which were 7.31–11.44 μmol·m^{-2}·s^{-1}, 0.20–0.22 mmol·m^{-2}·s^{-1} and 1.74–1.99 mmol·m^{-2}·s^{-1}, 4961.45-10,071.83 kg/ha, and 24.46-%25.76%. Ni[24] found that straw returning could increase winter wheat yield by 4.3-12.7%. Gao[25] indicated that straw return and 250 kg/ha nitrogen fertilizer supply resulted in better chlorophyll content and photosynthesis process for higher maize grain yield. Ebaid[26] found that the combination of straw returning and inorganic nitrogen fertilizer significantly affects the yield traits of broad beans in saline soil. Therefore, establishing standardized straw return and nitrogen application protocols is vital for improving red kidney bean yields.

In summary, previous studies have mainly focused on the effects of straw returning and nitrogen fertilizer on crops such as wheat, maize, and soybean. However, limited research exists on the combined effects of straw return and nitrogen fertilizer application on red kidney beans. Therefore, based on previous research, we conducted a three-year field experiment to determine the effects of straw return and nitrogen fertilizer on the chlorophyll content, photosynthetic characteristics, dry matter accumulation, yield, and yield component of red kidney beans.

The main purpose of this study was to understand how straw return and nitrogen fertilizer could affect the growth and development of red kidney beans. Specifically, we tested (1) How straw return and nitrogen fertilizer affected the chlorophyll content, photosynthetic characteristics, dry matter accumulation, yield, and yield component of red kidney beans. (2) What was the best treatment for achieving a high yield of red kidney beans? (3) What was the highest income red kidney bean planting technique for farmers? The information generated by this study will help screen cultivation measures for red kidney beans that can achieve high yields and maximize profits.

Materials and methods
Site description
Three field experiments were carried out at the experimental base of the Inner Mongolia Academy of Agricultural and Animal Husbandry Sciences during the seasons from 2022 to 2024. The experimental base is located in Hohhot City, Inner Mongolia Autonomous Region (40°48’ N, 111° 48’ E). The three-year experiments were carried out in the same plot. The surface soil fertility (0–20 cm) and the climatic conditions during the growth period of red kidney beans were shown in Table 1, and soil properties were determined using standard methods. Weather data was provided by the local weather station.

The experimental research and field studies on plants (either cultivated or wild), including the collection of plant material, comply with relevant institutional, national, and international guidelines and legislation. The field study was carried out on the official land which belonged to the key laboratory of crop cultivation and genetic improvement of Inner Mongolia Autonomous Region, permission was given after the research application passed verification, and the studies complied with local and national regulations. During the field study, our test did not involve endangered or protected species. No specific permissions were required for conducting the field study because it was not carried out in a protected area.

Experimental design
The test material was ‘British red kidney bean’. British red kidney beans were introduced to China from England in the early 21 st century and were promoted after trial planting in areas such as Heilongjiang and Shanxi. We purchased British red kidney bean seeds at the agricultural market in Hohhot City, Inner Mongolia Autonomous Region.

A split-plot design with five replications was used. The two straw return methods were assigned in the main plots, which were straw return (ST) and no straw return (NST). The four nitrogen fertilization levels (0, 45, 95, and 135 kg/ha) were allocated in the sub-plots, which were expressed by N0, N45, N90, and N135. Each sub-plot consisted of 10 rows with 5 m length and 0.6 m width, and each sub-plot area was 30 m^2 in the three years. The experimental treatment was shown in Table 2. NST + N0 was the control treatment (CK).

The designated tillage practices were performed each autumn after the harvest of red kidney beans. Straw return treatment: Straw return treatment used the straw secondary crushing technology. Firstly, the John Deere

Year	Organic matter (g/kg)	Total *N* (g/kg)	Available *N* (mg/kg)	Available *P* (mg/kg)	Available K (mg/kg)	pH	Sunshine hours (h)	Average temperature (℃)	Average rainfall (mm)
2022	24.37	1.2	94.53	9.4	120.35	7.3	1700.2	8.2	469.8
2023	24.65	1.2	95.62	9.5	121.53	7.3	1735.7	7.3	452.5
2024	25.13	1.3	96.86	9.7	122.67	7.3	1728.5	7.8	497.7

Table 1. Soil fertility and Climatic conditions during red kidney bean growth (2022–2024).

Straw return methods	Nitrogen fertilization levels (kg/ha)	Treatment
No straw return (NST)	0	NST + N0
	45	NST + N45
	90	NST + N90
	135	NST + N135
Straw return (ST)	0	ST + N0
	45	ST + N45
	90	ST + N90
	135	ST + N135

Table 2. Different experimental treatments.

W210 combine harvester was used to crush maize straw for the first time in autumn. Then, the 4Q-1.5-type Straw Stalk Grinder was used to crush maize straw for the second time. The maize straws were mechanically chopped into 3–6 cm long pieces and returned to the field with a depth of 40 cm. The John Deere W210 combined harvester with power rake was used to rake and compact the soil. The above operations were to ensure proper soil compaction and prevent poor seedling emergence. Land preparation is carried out in the spring of the second year, and different amounts of nitrogen fertilizer are applied before sowing red kidney beans. No straw return treatment: In the autumn after the first year of harvesting red kidney beans, the soil was plowed with a depth of 40 cm without returning straw. Land preparation was carried out in spring, and different amounts of nitrogen fertilizer were applied before sowing red kidney beans.

The red kidney bean was seeded on May 15, 13, and 14, and was harvested on August 22, 19, and 20 in 2022, 2023, and 2024, respectively. Base fertilizers applied at the seeding were urea, DAP, and KCl. We applied P_2O_5 at the rate of 90 kg/ha, K_2O at the rate of 75 kg/ha, and N at different application levels of 0, 45, 90, and 135 kg/ha. No fertilization treatment was carried out in the later stage. A series of cultivation and management measures such as irrigation and weeding were carried out according to the local high-yield cultivation. The above treatments were consistent except for the measures of returning maize straw to the field and the application of nitrogen fertilizer.

Measurements

Chlorophyll content[27]. In the flowering stage (R3), we selected 5 individual plants with uniform growth from each community and measured the chlorophyll content of red kidney bean leaves by using a portable chlorophyll analyzer (SPAD-502 plus, Konica Minolta, Japan).

Photosynthetic parameters[28]. In the flowering stage (R3), five healthy and uniform plants in each plot were selected, and the third to last fully unfolded leaf of each plant was measured by using a portable photosynthesis system (LI-6400XT, USA) from 9 to 11 am on sunny days. Before starting measuring, I adopted the open-air path and built-in light source, and the light intensity was set to 1500 μ mol CO_2 m^2 s^{-1}. The net photosynthetic rate (Pn), stomatal conductance (Gs), transpiration rate (Tr), and intercellular CO_2 concentration (Ci) of red kidney bean leaves could be measured within about one minute.

Dry matter accumulation[29]. Red kidney bean plants were taken in each plot during the pod setting stage (R6) with five replicates. Red kidney bean plants were dried at 105 ℃ for 30 min for enzyme deactivation, then dried at 80 ℃ to constant weight, and weighed the dry matter weight.

Yield and yield component[29]. Ten consecutive red kidney bean plants with uniform growth were selected and labeled each treatment separately. During the mature period (R8), the ten red kidney beans listed were tested for the number of pods per plant, number of seeds per pod, and 100-seed weight. Eight rows of red kidney beans from each treatment were harvested. Impurities were removed manually, and the yield per hectare was calculated.

Statistics analysis

All data were analyzed using SPSS version 17 (SPSS Inc., Chicago, IL, USA). Independent variables included straw return methods (ST, NST), nitrogen levels (0, 45, 90, 135 kg/ha), and year (2022–2024). Dependent variables included chlorophyll content, photosynthetic traits, dry matter, and yield. Under straw return methods, nitrogen fertilization levels, and test years, we examined chlorophyll content, photosynthetic characteristics, dry matter accumulation, yield, and yield components using GLM based on the model for a split-plot design[30,31]. The values were all the F-values of the ANOVA. To determine the impact of independent variables on dependent variables, statistical significance was assessed using ANOVA, and treatment means were compared using LSD at $P < 0.05$[32]. Figures were generated using SigmaPlot version 12.5. Different lowercase letters indicated statistically significant differences (LSD test, $\alpha = 0.05$).

Results

Significance tests of straw return methods, nitrogen fertilization levels and their interactions

Analysis of variance (ANOVA) results showed that straw return methods and nitrogen fertilization levels had significant effects on the chlorophyll content, photosynthetic characteristics, dry matter accumulation, yield, and yield component of red kidney beans from 2022 to 2024 (Table 3). Significant interactions between straw return methods and nitrogen fertilization levels were found on Tr of 2024, Ci of 2024, Number of pods

Year	Source	Chlorophyll content	Pn (μmol·m^{-2}·s^{-1})	Gs (mmol·m^{-2}·s^{-1})	Tr (mmol·m^{-2}·s^{-1})	Ci (μmol·mol^{-1})	Dry matter in R6(kg/ha)	Number of pods per plant	Number of seeds per pod	100- seed weight (g)	Yield (kg/ha)
2022	S	120.97**	9.02**	16.00**	47.08**	38.68**	31.37**	56.10**	12.11**	28.28**	32.59**
	N	242.43**	20.46**	51.04**	111.92**	82.44**	86.40**	76.93**	37.10**	59.68**	95.01**
	S×N	14.03**	0.64ns	0.36ns	2.81ns	1.16ns	2.06ns	6.73**	0.44ns	1.51ns	1.19ns
2023	S	30.58**	23.60**	39.70**	40.38**	54.54**	15.08**	94.81**	42.69**	93.24**	95.14**
	N	77.34**	46.22**	101.59**	72.53**	111.91**	30.09**	110.00**	104.20**	184.93**	263.11**
	S×N	2.08ns	0.69ns	0.60ns	2.33ns	2.17ns	0.21ns	8.57**	2.24ns	5.35**	7.82**
2024	S	32.06**	15.46**	56.48**	82.91**	106.19**	17.44**	62.26**	27.14**	43.44**	67.83**
	N	77.70**	29.27**	128.81**	143.11**	235.24**	32.65**	72.22**	67.77**	68.26**	181.43**
	S×N	1.47ns	0.50ns	2.02ns	5.06**	4.22*	1.25ns	4.47*	2.94ns	4.53*	7.75**

Table 3. Significance of the effects of straw return methods, nitrogen fertilization levels, and their interactions on red kidney bean growth and yield using ANOVA. Note: Numbers were F-values. Stars indicated the level of significance (*= $p<0.05$, **= $p<0.01$), and ns represented insignificant. S represented straw return methods, including NST and ST; N represented nitrogen fertilization levels, including N0, N45, N90, and N135 kg/ha.

per plant of 2022–2024, 100-seed weight of 2023–2024, and yield of 2023–2024. Through the comparison of three-year F-values, it could be found that the effect of nitrogen fertilization levels on the chlorophyll content, photosynthetic characteristics, dry matter accumulation, yield, and yield component of red kidney beans was greater than that of straw return methods.

Effects of straw return and nitrogen fertilizer on chlorophyll content of red kidney beans

It can be seen from Fig. 1, straw return and nitrogen fertilizer significantly increased ($p \leq 0.05$) the chlorophyll content of red kidney beans.

Compared with CK, under the treatments of NST + N45, NST + N90, NST + N135, ST + N0, ST + N45, ST + N90, and ST + N135 in the R3 stage increased by 5.40%, 11.88%, 17.19%, 2.38%, 8.81%, 22.03%, and 28.91% in 2022; the chlorophyll content increased by 6.98%, 16.85%, 21.51%, 3.86%, 11.46%, 25.62%, and 33.35% in 2023; the chlorophyll content increased by 8.20%, 17.10%, 23.25%, 4.93%, 12.99%, 26.11%, and 34.60% in 2024.

The comprehensive management of straw return and nitrogen fertilizer played a key role in improving the chlorophyll content and enhancing the stress adaptation ability of red kidney beans.

Effects of straw return and nitrogen fertilizer on photosynthesis of red kidney beans

The straw return methods and nitrogen fertilization levels significantly influenced ($p \leq 0.05$) the photosynthesis of red kidney beans compared to CK, resulting in Pn, Gs, and Tr values that were higher than those of CK, and Ci values that were lower than that of CK.

Straw return and nitrogen supply increased Pn, Gs, and Tr. From 2022 to 2024, compared with CK, Pn increased by 5.95-8.70% under NST + N45, 11.19-14.95% under NST + N90, 14.62-18.98% under NST + N135, 2.07-5.25% under ST + N0, 9.57-13.02% under ST + N45, 18.23-22.71% under ST + N90, and 22.40-28.65% under ST + N135 (Fig. 2a). Gs increased by 9.57-12.44% under NST + N45, 17.39-20.00% under NST + N90, 21.30-26.67% under NST + N135, 3.91-9.33% under ST + N0, 13.91-18.22% under ST + N45, 25.22-28.89% under ST + N90, and 27.83-30.67% under ST + N135 (Fig. 2b). Tr increased by 6.60-8.54% under NST + N45, 13.83-15.80% under NST + N90, 16.99-18.22% under NST + N135, 4.02-7.65% under ST + N0, 9.35-10.46% under ST + N45, 21.26-23.83% under ST + N90, and 25.68-27.89% under ST + N135 (Fig. 2c).

Straw return and nitrogen supply decreased Ci. From 2022 to 2024, compared with CK, Ci decreased by 7.94-8.11% under NST + N45, 11.63-12.27% under NST + N90, 13.34-13.68% under NST + N135, 5.24-5.77% under ST + N0, 9.89-10.03% under ST + N45, 15.66-15.96% under ST + N90, and 17.85-18.24% under ST + N135 (Fig. 2d).

Integrated management of straw return and nitrogen fertilizer optimized photosynthetic performance, and provided technical support for high-efficiency cultivation of red kidney beans.

Effects of straw return and nitrogen fertilizer on dry matter of red kidney beans

It can be seen from Fig. 3, the straw return methods and nitrogen fertilization levels significantly increased ($p \leq 0.05$) the dry matter accumulation of red kidney beans.

Compared with CK, under the treatments of NST + N45, NST + N90, NST + N135, ST + N0, ST + N45, ST + N90, and ST + N135 in the R6 stage increased by 5.47%, 11.84%, 15.89%, 2.27%, 8.84%, 18.54%, and 23.45% in 2022; the dry matter increased by 8.36%, 15.30%, 17.82%, 5.65%, 12.71%, 21.43%, and 25.59% in 2023; the dry matter increased by 12.45%, 17.19%, 20.11%, 9.15%, 14.13%, 23.12%, and 28.62% in 2024.

The comprehensive management of straw return and nitrogen fertilizer enhanced dry matter accumulation, providing a physiological basis for the high-yield cultivation of red kidney beans and guiding the development of regional planting plans.

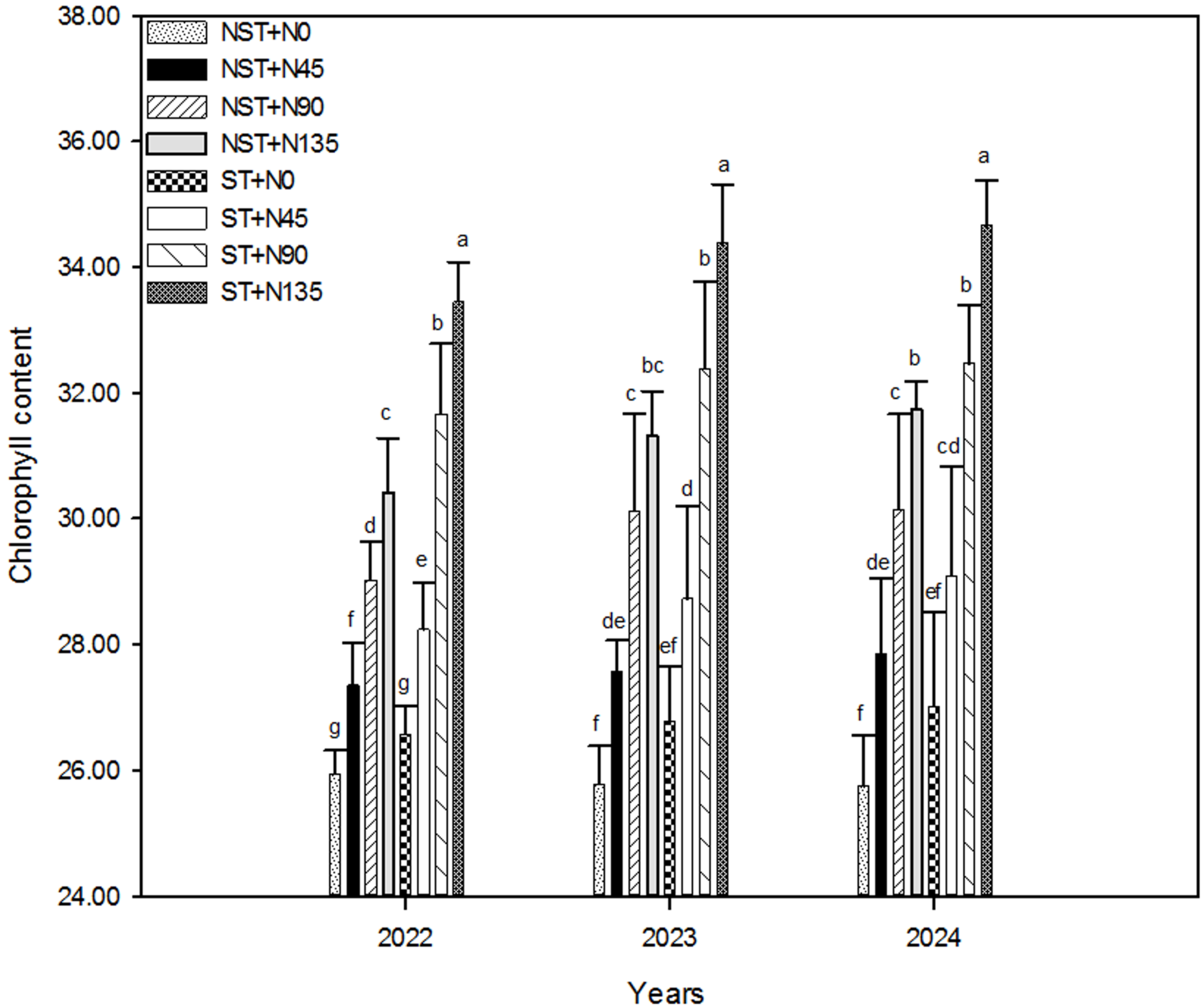

Fig. 1. Effects of straw return methods and nitrogen fertilization levels on chlorophyll content of red kidney beans. Note: Values followed by different letters in the same year indicated indicate statistical significance at α = 0.05 under different treatments. The same was below.

Effects of straw return and nitrogen fertilizer on yield and yield component of red kidney beans

Straw return and nitrogen supply significantly influenced ($p \leq 0.05$) the yield and yield component of red kidney beans. The yield and yield component of red kidney beans among treatments were as follows: ST + N135 > ST + N90 > NST + N135 > NST + N90 > ST + N45 > NST + N45 > ST + N0 > NST + N0 (Fig. 4).

The treatment of ST + N135 recorded the highest average yield in the three-year test, which was 3304.99 kg/ha. From 2022 to 2024, compared with CK, under ST + N135 conditions, the number of pods per plant increased by 28.33-32.26% (Fig. 4a), 100-seed weight increased by 15.88-20.53% (Fig. 4b), the number of seeds per pod increased by 15.29-19.39% (Fig. 4c), and yield increased by 17.08-21.05% (Fig. 4d).

The comprehensive management of straw return and nitrogen fertilizer increased yield potential, and the yield improvement verified the feasibility of this mode of production, which had practical guidance significance for ensuring the production capacity of legume crops.

Correlation analysis of chlorophyll content, photosynthetic characteristics, dry matter accumulation, yield component, and yield of red kidney beans

Chlorophyll content, Pn, Gs, and Tr were positively correlated with dry matter, while Ci was negatively correlated with dry matter. Dry matter was positively correlated with the number of pods per plant, number of seeds per pod, 100-seed weight, and yield. The correlation coefficients of chlorophyll content, Pn, Gs, Tr, Ci, dry matter in the R6 stage, number of pods per plant, number of seeds per pod, and 100-seed weight with yield were 0.926, 0.952, 0.979, 0.942, −0.985, 0.964, 0.914, 0.979 and 0.979 (Table 4). The results showed that the increase of chlorophyll content, Pn, Gs, and Tr and the decrease of Ci significantly improved dry matter. The increase in dry

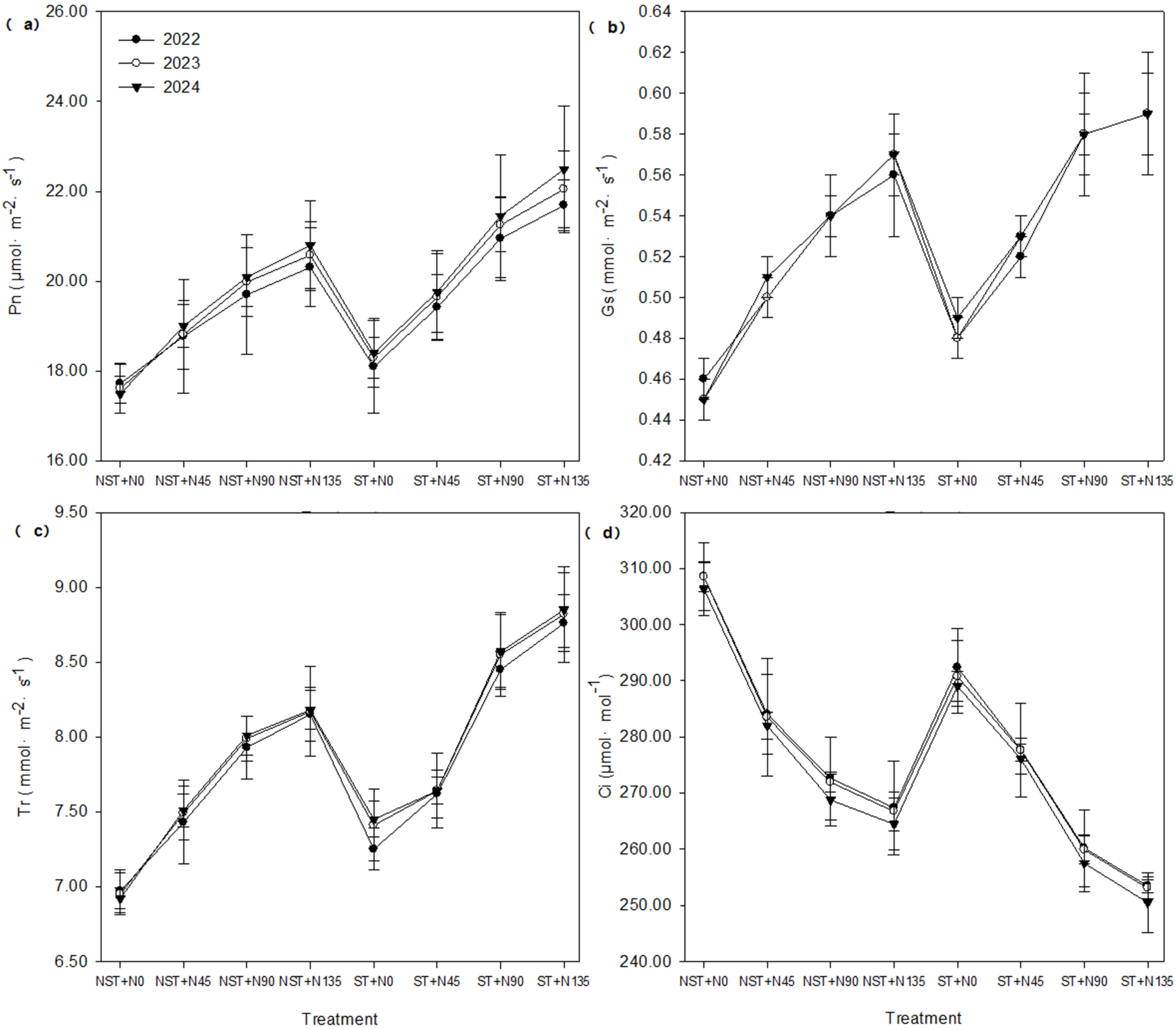

Fig. 2. Effects of straw return methods and nitrogen fertilization levels on photosynthesis of red kidney beans.

matter accumulation significantly enhanced the number of pods per plant, number of seeds per pod, and 100-seed weight, thereby increasing the yield of red kidney beans.

Effects of straw return and nitrogen fertilizer on the profit of red kidney bean planting

According to the average selling price of red kidney bean (15 yuan/kg) from 2022 to 2024, the net income of red kidney bean planting of different treatments was as follows: ST + N90 > ST + N135 > NST + N135 > NST + N90 > ST + N45 > NST + N45 > ST + N0 > NST + N0 (Table 5).

Compared to CK. the average net profit of red kidney bean planting in the three-year test increased by 3860.40, 5582.25, 6428.55, 2172.35, 4365.20, 6574.70, and 6545.75 yuan/ha between the treatments of NST + N45, NST + N90, NST + N135, ST + N0, ST + N45, ST + N90, and ST + N135. The treatment of ST + N90 achieved the maximum profit of 46528.80 yuan/ha for the cultivation of red kidney beans, an increase of 16.46% compared to CK.

Integrated management of straw return and nitrogen fertilizer improved economic net profit, avoided resource waste and environmental risks caused by excessive fertilization, and provided data support for optimizing fertilizer policies.

Discussion

Chlorophyll content, Pn, Gs, and Tr increased most under ST + N135 treatment, which increased 28.91-34.60%, 22.40-28.65%, 27.83-30.67%, and 25.68-27.89%. Ci decreased most under ST + N135 treatment, which was 17.85-18.24%. This may be due to the effect of chlorophyll content and photosynthesis improved significantly with the increase of nitrogenous fertilization levels under the same straw return method. Straw return improved chlorophyll content and photosynthesis under the same nitrogen supply. This suggests that straw return and

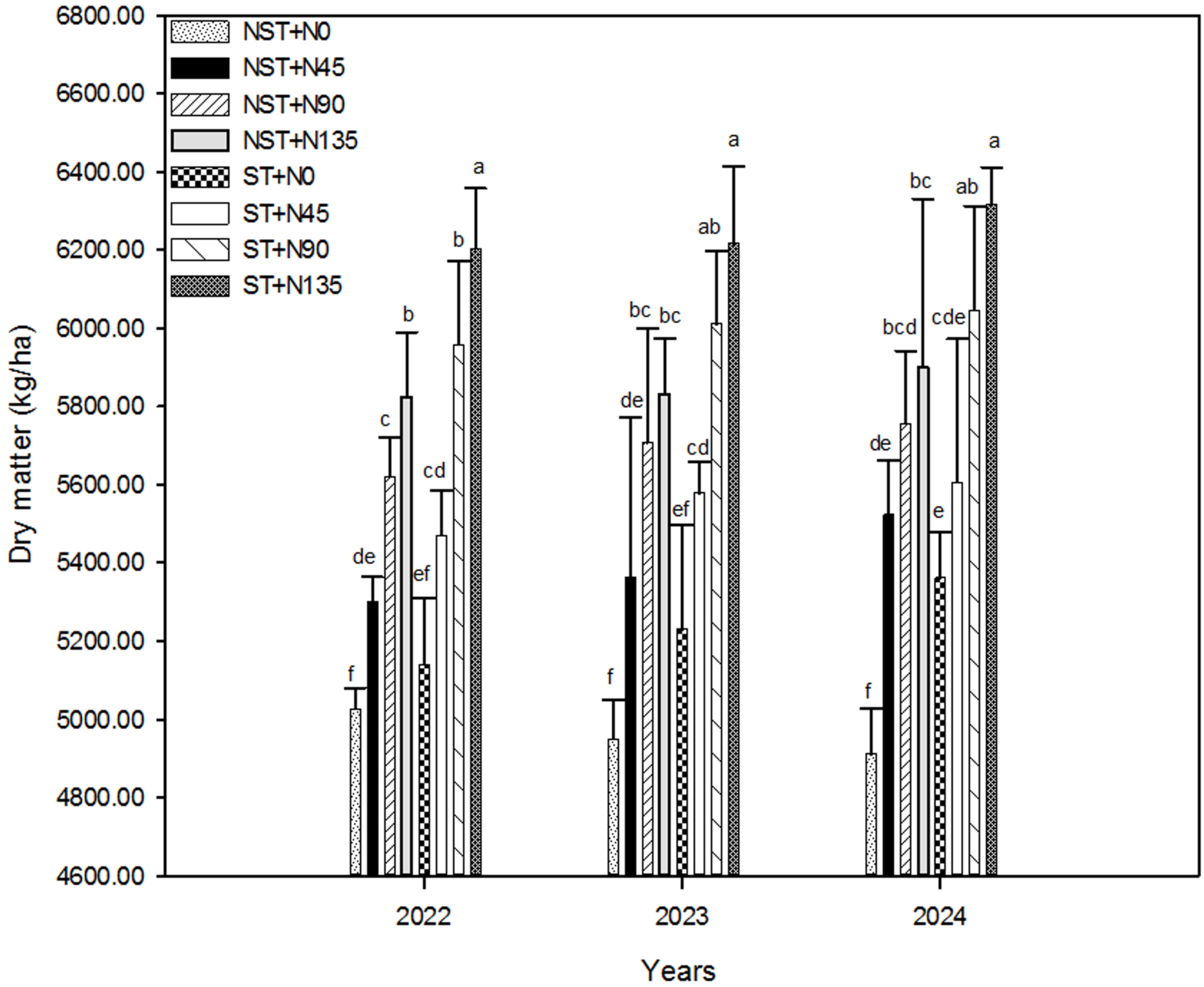

Fig. 3. Effects of straw return methods and nitrogen fertilization levels on dry matter of red kidney bean. Note: Values followed by different letters in the same year indicated indicate statistical significance at α = 0.05 under different treatments. The same was below.

nitrogen fertilizer can promote chlorophyll content and photosynthesis of red kidney beans, and the promotion effect increases year by year. The experimental results were similar to the research results of Gao. Gao[33] showed that the application of nitrogen fertilizer can improve the photosynthetic performance of kidney beans. The comprehensive performance of kidney beans was relatively better under a nitrogen application rate of 135 kg/ha. Straw returning significantly increases the photosynthetic rate, transpiration rate, and chlorophyll content of crops such as maize, wheat, and rice[34–36]. This was basically consistent with the research results of returning straw to the field on kidney beans in this article, which may be due to nitrogen fertilizer levels and cultivation management measures significantly affecting physiological activities such as chlorophyll content and photosynthesis in crop leaves, ultimately regulating dry matter accumulation and yield formation[37,38].

Dry matter accumulation increased most under the ST + N135 treatment, increasing by 23.45–28.62%, which may be due to the dry matter of red kidney beans improved with the nitrogen level under the same straw return method. Dry matter increased after the treatment of straw return under the same nitrogen supply. This suggests that straw return and nitrogen fertilizer can promote the dry matter accumulation of red kidney beans, and the promotion effect increases year by year. The experimental results were similar to the research results of Chang and Song[39,40]. Nitrogen application promoted the material accumulation, yield, and yield component of red kidney beans. Straw return promoted dry matter accumulation in crops such as maize, rice, and soybeans[41,42]. This was basically consistent with the research trends of returning straw to the field on kidney beans in this article, straw return improved dry matter accumulation of red kidney beans. Wang[43] showed that the dry matter accumulation of soybean increased by 9.70-26.80% compared with the control by increasing the amount of maize straw returned to the field. There were differences between the experimental data and the data in this study, which may be due to the varying effects of straw return on different crops.

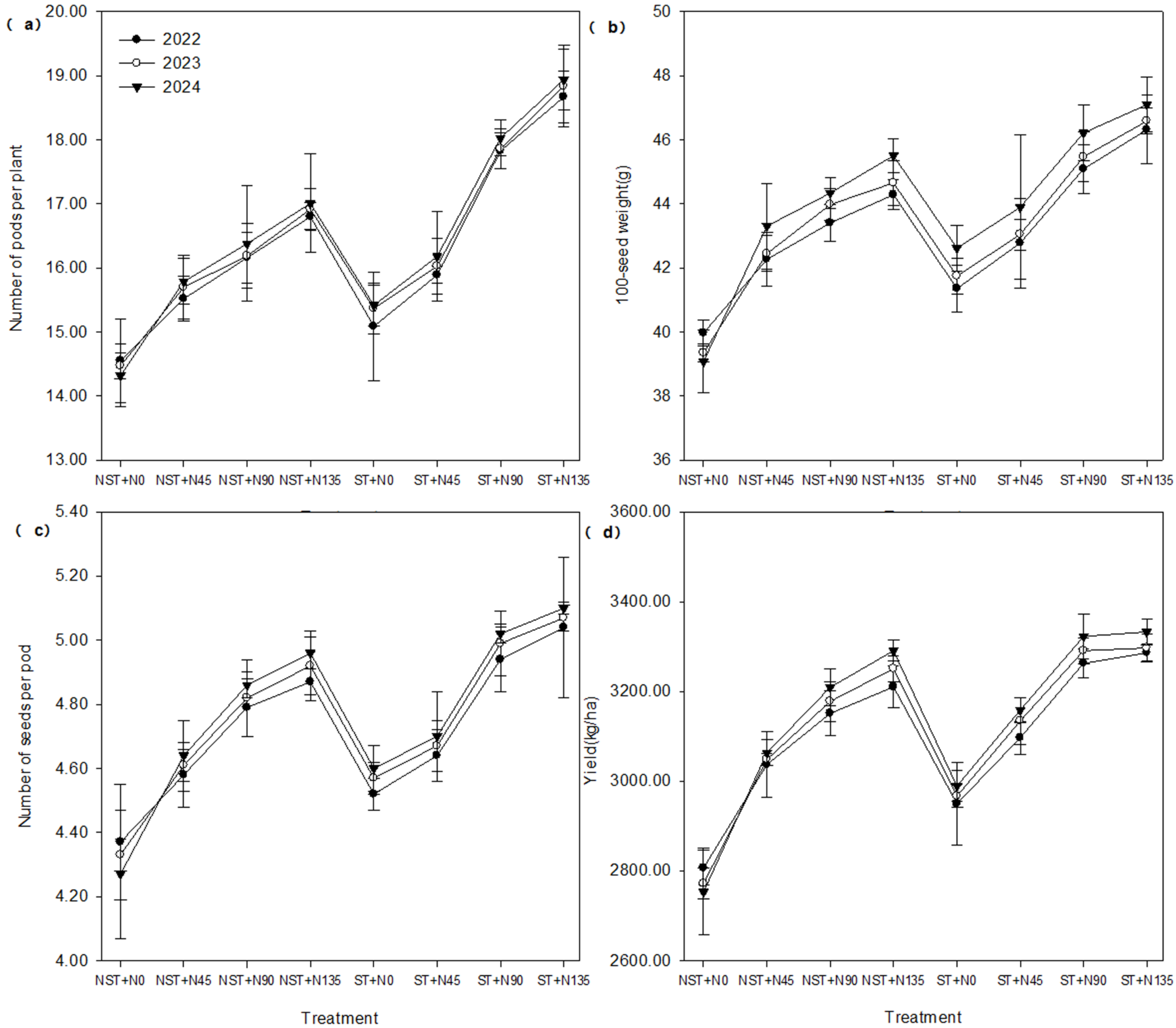

Fig. 4. Effects of straw return methods and nitrogen fertilization levels on yield and yield component of red kidney beans.

Compared with CK, the yield of red kidney beans increased most under ST + N135 treatment, which was 17.08-21.05%. The Net profit of red kidney beans was the largest under ST + N90 treatment, which was 46528.80 yuan/ha ($6378.84 per ha). This suggests that straw return and nitrogen fertilizer could all promote the yield and net profit of red kidney bean planting. Xiang[44] showed that the number of pods per plant of kidney beans improved with the increase of nitrogen application rate within the range of 0–180 kg/ha. Tang[45] found that excessive application of nitrogenous fertilizer reduced the yield and benefits of kidney beans, and the most suitable nitrogenous application rate for kidney bean cultivation was 178 kg/ha. The research trend of Xiang and Tang was consistent with this research trend, with the difference being the appropriate amount of nitrogen fertilizer applied. This may be because returning straw to the field could reduce the amount of nitrogen fertilizer applied, or it may be due to the different nitrogen fertilizer requirements of kidney beans in different experimental areas.

Conclusion

Chlorophyll content, Pn, Gs, Tr, dry matter accumulation, and yield increased most, which were 28.91-34.60%, 22.40-28.65%, 27.83-30.67%, 25.68-27.89%, 23.45-28.62%, and 17.08-21.05% under ST + N135 treatment. Under the ST + N90 treatment, the above indicators increased second only to the ST + N135 treatment, with increases of 22.03-26.11%, 18.23-22.71%, 25.22-28.89%, 21.26-23.83%, 18.54-23.12%, and 16.25-20.68%, respectively. While the ST + N90 treatment could maximize farmers' net profit from planting red kidney beans, the net profit could reach 46528.80 yuan/ha, which was equivalent to $6378.84 per ha. Overall, based on the comprehensive evaluation of agronomic performance and economic return, ST + N90 was recommended for red kidney bean cultivation. ST + N90 treatment was an effective way to achieve stable, high yields of red kidney beans and

Index	Chlorophyll content	Pn (μmol·m^{-2}·s^{-1})	Gs (mmol·m^{-2}·s^{-1})	Tr (mmol·m-2·s^{-1})	Ci (μmol·mol^{-1})	Dry matter in R6 (kg/ha)	Number of pods per plant	Number of seeds per pod	100-seed weight (g)	Yield (kg/ha)
Chlorophyll content	1									
Pn (μmol·m^{-2}·s^{-1})	0.993**	1								
Gs (mmol·m^{-2}·s^{-1})	0.967**	0.981**	1							
Tr (mmol·m^{-2}·s^{-1})	0.986**	0.987**	0.976**	1						
Ci (μmol·mol^{-1})	−0.958**	−0.977**	−0.986**	−0.977**	1					
Dry matter in R6 (kg/ha)	0.983**	0.992**	0.985**	0.987**	−0.985**	1				
Number of pods per plant	0.983**	0.983**	0.956**	0.987**	−0.959**	0.978**	1			
Number of seeds per pod	0.969**	0.976**	0.985**	0.984**	−0.987**	0.987**	0.958**	1		
100-seed weight (g)	0.958**	0.973**	0.973**	0.968**	−0.985**	0.987**	0.958**	0.988**	1	
Yield (kg/ha)	0.926**	0.952**	0.979**	0.942**	−0.985**	0.964**	0.914**	0.979**	0.979**	1

Table 4. Correlation analysis of chlorophyll content, photosynthesis, dry matter accumulation, yield and yield component of red kidney beans under two straw return methods.

Treatment	Expenditure(yuan/ha)				Total expenditure (yuan/ha)	Yield (kg/ha)	Gross income (yuan/ha)	Net profit (yuan/ha)
	Straw returning	Nitrogenous fertilizer	Seed	Hoeing and watering				
NST + N0	0	0	1000	700	1700	2776.94	41654.10	39954.10
NST + N45	0	225	1000	700	1925	3049.30	45739.50	43814.50
NST + N90	0	450	1000	700	2150	3179.09	47686.35	45536.35
NST + N135	0	675	1000	700	2375	3250.51	48757.65	46382.65
ST + N0	700	0	1000	700	2400	2968.43	44526.45	42126.45
ST + N45	700	225	1000	700	2625	3129.62	46944.30	44319.30
ST + N90	700	450	1000	700	2850	3291.92	49378.80	46528.80
ST + N135	700	675	1000	700	3075	3304.99	49574.85	46499.85

Table 5. Effects of straw return methods and nitrogenous fertilization levels on the profit of red kidney bean planting.

maximize farmers' income. This treatment provided a scientific basis for the cultivation and management of red kidney beans and a practical reference for optimizing regional fertilization policies, which could be promoted and applied in Inner Mongolia.

Data availability

All data generated or analysed during this study are included in this published article.

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Declarations

Competing interests
The authors declare no competing interests.

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