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EFFECTS OF REDUCED COMPOUND FERTILIZER APPLICATION COMBINED WITH BIOCHAR SUPPLEMENTATION ON ACCUMULATION AND TRANSPORT OF DRY MATTER AND NITROGEN IN WINTER WHEAT

JIAHUI LU[1], YUN LI[2], XUEJUN REN[1], ZHENQING GUO[1], HAOLIANG LI[1], YUCUI HAN[1]* AND XIAOHU LIN[1]*

[1]College of Agronomy and Biotechnology/Hebei Key Laboratory of Crop Stress Biology, Hebei Normal University of Science and Technology, Qinhuangdao 066000, China.
[2]Research Center of Rural VitalizWinter Wheatation, Hebei Normal University of Science and Technology, Qinhuangdao 066000, China

*Corresponding author's email: yucuihan84@163.com; xiaohulin2008@163.com

Abstract

Compound fertilizer application with biochar supplementation may be an effective and environment-friendly strategy to improve nitrogen accumulation and utilization in winter wheat. This study set up main plots of biochar (B1-B3), and sub-plots of compound fertilizer (F1-F4). Then, the effects of different treatments on winter wheat yield, soil nitrogen content, dry matter and nitrogen accumulation, transport rate, contribution rate to grains, and nitrogen use efficiency in eastern Hebei Province were analyzed in two consecutive years. B2F3 treatment resulted in the highest winter wheat yield in the two years (7505.61 kg·hm^{-2} and 7600.35 kg·hm^{-2}), which were significantly higher than those of BIF4 by 3% and 11%, respectively. Pre-anthesis dry matter transfer volume (1.10 kg·hm^{-2}), transfer rate (0.40%), and contribution rate to grains (0.72%) reached the maximum value under B2F3 treatment, which were all significantly higher than those under B1F4 treatment. The post-anthesis nitrogen accumulation under B3F3 treatment was significantly higher than that under B1F4 treatment. Compound fertilizer application combined with biochar could improve the nitrogen use efficiency of winter wheat in general. The nitrogen agronomic use efficiency of the first-year B2F3, B3F3, and B2F2 treatment, and the second-year B2F2 and B2F3 treatment were all significantly higher than those under B1F4 treatment. The optimal combination of 450 kg·hm^{-2} compound fertilizer and 7500 kg·hm^{-2} biochar is recommended for reducing compound fertilizer application, increasing the efficiency, and promoting the yield of winter wheat in the studied area.

Key words: Winter wheat; Compound fertilizer; Biochar; Dry matter; Nitrogen; Yield

Introduction

Wheat is one of the most important food crops, providing people with not only carbohydrates, but also part of proteins. China has a large planting area and yield of winter wheat. Nitrogen is an essential element in the growth and development of winter wheat. Rational application of nitrogen fertilizer can not only promote the growth and development of vegetative organs such as leaves, sheaths, and culms of winter wheat, but also increase the number of ears at the reproductive growth stage, thereby improving the seed setting rate and directly contributing to the yield of winter wheat (Kubar *et al*., 2021). However, excessive nitrogen application will lead to ineffective tillering, resulting in decreased ear number and late maturing of green wheat, thus negatively affecting the yield of winter wheat (Zhang *et al*., 2018). In addition, it can also result in low nitrogen utilization efficiency and leaching of nitrate and ammonium salts to cause adverse effects such as soil, groundwater, and atmosphere (Robertson *et al*., 2013; Yang *et al*., 2021; An *et al*., 2020). Slow-release compound fertilizers can provide crops with nutrients for a longer time due to their slow release properties, thus improving crop yield and quality and reducing nitrogen emissions at the same time. Compared with mineral fertilizers, compound fertilizers have improvement of nitrogen utilization efficiency (Bai *et al*., 2022). Ma *et al*., (2021) found that increased application of phosphorus fertilizer can promote the accumulation and absorption of nitrogen in wheat plants. Deng *et al*., (2019) and Liu *et al*., (2021) found that the application of slow controlled release fertilizers with different NPK proportions can improve the nitrogen utilization rate of wheat, which can save the cost, increase the fertilizer efficiency, and stabilize the yield. China accounts for about 30.7% of chemical fertilizer consumption in the world, but the utilization rate of chemical fertilizer is relatively low (Ju *et al*., 2009). With the problems caused by excessive application of chemical fertilizer becoming increasingly prominent, it is urgent to reduce the application amount of chemical fertilizer and improve its utilization efficiency.

In recent years, biochar has received great attention for its potential in soil improvement and environmental remediation (Zhao *et al*., 2021; An *et al*., 2020). Biochar is a carbon-rich product obtained by pyrolysis of straw and other organic materials (Wang *et al*., 2019; Wang *et al*., 2019). It has the advantages of large specific surface area, strong adsorption capacity, high stability, and high contents of various nutrients (Abdul *et al*., 2017; Borchard *et al*., 2012). Application of biochar can also significantly increase the contents of soil potassium, phosphorus, and calcium, as well as greatly improve soil pH, soil aggregates,

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activated carbon components, soil total porosity, soil microbial biomass, and soil nutrient cycling and reduce nutrient loss, thereby improving soil fertility and quality, crop yield and quality to improve the nitrogen use efficiency (Laird *et al*., 2010; Liu *et al*., 2021; Dong *et al*., 2022). Some studies have demonstrated that combined application of biochar and chemical fertilizer can reduce soil nutrient leaching and delay nutrient release, thereby improving the crop yield and fertilizer utilization rate (Peng *et al*., 2015; Singh *et al*., 2019; Shrestha *et al*., 2017). Zahra *et al*., (2021) showed that combined application of biochar with compost significantly increased both the maize grain yield (by 46.29%) and biomass yield (by 13.4%) by increasing soil organic carbon compared with compost application alone, respectively. To date, there have been few reports on the effects of slow-release compound fertilizer combined with biochar on the dry matter accumulation and transport, nitrogen index, yield, and yield components of winter wheat. In this study, winter wheat was planted for two consecutive years, and the effects of compound fertilizer combined with biochar supplementation on the above indices were evaluated. The aim is to explore the optimal combination of compound fertilizer and biochar for winter wheat planting, and provide a theoretical basis for reducing fertilizer application, increasing fertilizer efficiency, and promoting the yield of winter wheat.

Materials and Methods

Field conditions: The experiment was conducted at the Experimental Station of College of Agronomy and Biotechnology, Hebei Normal University of Science and Technology, China (39.70°N, 119.15°E) for two consecutive years from October 2021 to June 2023. The experimental station is located in a temperate continental monsoon climate, and the soil type of the experimental site is loam. The soil nutrient status of 0–20 cm before the first year of planting is soil organic matter 17.56×10^3 $mg\cdot kg^{-1}$, total N 2.30×10^3 $mg\cdot kg^{-1}$, total P 2.06×10^3 $mg\cdot kg^{-1}$, alkaline hydrolyzed N 75.67 $mg\cdot kg^{-1}$, available P 19.47 $mg\cdot kg^{-1}$, available K 129.32 $mg\cdot kg^{-1}$, PH 7.61.

Experimental design: The winter wheat variety tested was "Zhongmai 886". The area of each plot was 6 m^2 and the row spacing was 20 cm. The biochar was wheat straw biochar, provided by Henan Sanli New Energy Company. The wheat straw was prepared under anaerobic pyrolysis at 500°C, organic carbon=492.33×10^3 $mg\cdot kg^{-1}$, N (total nitrogen) =5.90×10^3 $mg\cdot kg^{-1}$, P (total potassium) =23.87×10^3 $mg\cdot kg^{-1}$, K (total kalium) =0.83×10^3 $mg\cdot kg^{-1}$. *w* (C/N) =87.37, pH 10.02. Compound fertilizer was a slow release fertilizer with a total NPK content of 43% (N 25%, P_2O_5 12%, K_2O 6%). A split block test design was adopted, and the main plots (B) were set as 0 $kg\cdot hm^{-2}$ (B1), 7500 $kg\cdot hm^{-2}$ (B2), 15000 $kg\cdot hm^{-2}$ (B3) with biochar; and the sub-plots (F) were established as 0 $kg\cdot hm^{-2}$ (F1), 225 $kg\cdot hm^{-2}$ (F2), 450 $kg\cdot hm^{-2}$ (F3), 675 $kg\cdot hm^{-2}$ (F4) with compound fertilizer, with three repetitions. Biochar and compound fertilizer were applied to winter wheat before sowing in the first year. Since the effects of biochar last for many years after a single application, only compound fertilizer was applied to winter wheat before sowing in the second year. Each fertilization was applied to the soil in the form of basal fertilizer, and other management was the same as that of general field. The planting date of the first year winter wheat was October 17, 2021, and the harvest date was June 18, 2022; the planting date of the second year winter wheat was October 7, 2022, and the harvest date was June 15, 2023.

Determination items and methods: The above-ground parts of 10 winter wheat plants with uniform growth were selected at the joint stage, booting stage, flowering stage, and maturity stage, respectively. After determination of the fresh weight of the plants, they were put into the oven at 105℃ for 30 min, and then dried in the oven at 80℃ until constant weight. After measuring the dry weight of plants at the stage of joint, booting, flowering and maturity, the dried plant samples were crushed and boiled with concentrated sulfuric acid. The nitrogen content of plants was determined by automatic Kjeldahl nitrogen analyzer. The soil nitrogen content in each growth stage was determined at the joints stage, booting stage, flowering stage and maturity stage, and the soil samples at each growth stage were air-dried and ground to a depth of about 20 cm. The soil nitrogen content was determined by alkaline diffusion method, and the soil total nitrogen content was determined after the soil samples were boiled.

For determination of yield and related indices, at the maturing stage of winter wheat, 20 wheat ears were captured in each plot to determine the number of grains per spike. From each plot, a representative 1 m2 area was selected, and the number of ears was measured. The harvest wheat grains were naturally dried and threshed, followed by determination of 1000 grain weight weighed 1000 grains. Then, the moisture content was measured. The yield was then converted into the yield and 1000-grain weight at 13% water content.

Calculation of related indices of nitrogen utilization:

Plant nitrogen accumulation ($kg\cdot hm^{-2}$) = plant dry weight × nitrogen content;

Dry matter transfer before anthesis ($kg\cdot hm^{-2}$) = plant dry weight at flowering stage – vegetative organ dry weight at maturity stage;

Dry matter accumulation after anthesis ($kg\cdot hm^{-2}$) = plant dry weight at mature stage – plant dry weight at flowering stage;

Nitrogen transfer before anthesis ($kg\cdot hm^{-2}$) = plant nitrogen accumulation at flowering stage – vegetative organs nitrogen accumulation at maturity stage;

Post-anthesis nitrogen accumulation ($kg\cdot hm^{-2}$) = plant nitrogen accumulation at mature stage – plant nitrogen accumulation at flowering stage;

$$\text{Dry matter transfer rate before anthesis (\%)} = \frac{\text{Dry matter transfer before flowering}}{\text{Plant dry weight at flowering stage}} \times 100$$

$$\text{Contribution rate of dry matter before anthesis to grain (\%)} \quad \frac{\text{Dry matter transfer before flowering}}{\text{Grain dry weight at maturity}} \times 100$$

$$\text{Contribution rate of dry matter to grain after anthesis (\%)} = \frac{\text{Dry matter accumulation after anthesis}}{\text{Grain dry weight at maturity}} \times 100$$

$$\text{Nitrogen transfer rate before anthesis (\%)} = \frac{\text{Nitrogen transfer before flowering}}{\text{Nitrogen accumulation at flowering stage}} \times 100$$

$$\text{Contribution rate of pre-anthesis nitrogen to grain nitrogen (\%)} = \frac{\text{Pre-flowering nitrogen transfer volume}}{\text{Grain nitrogen accumulation at maturity}} \times 100$$

$$\text{Contribution rate of post-anthesis nitrogen to grain nitrogen (\%)} = \frac{\text{Post-flowering nitrogen accumulation}}{\text{Grain nitrogen accumulation at maturity}} \times 100$$

$$\text{Nitrogen harvest index (\%)} = \frac{\text{Nitrogen accumulation in grains}}{\text{Nitrogen accumulation in mature plants}} \times 100$$

$$\text{Nitrogen fertilizer agronomic use efficiency (\%)} = \frac{\text{(Yield in N application zone – Yield in no N application zone)}}{\text{N application amount}}$$

$$\text{Nitrogen uptake efficiency (kg·kg}^{-1}\text{)} = \frac{\text{Plant nitrogen accumulation}}{\text{Nitrogen application}}$$

$$\text{Nitrogen partial productivity (kg·kg}^{-1}\text{)} = \frac{\text{Grain yield}}{\text{Nitrogen application amount}}$$

Data processing and statistical analysis: Data were organized using Microsoft Excel 2019. Statistical analyses, including two-way ANOVA and post-hoc tests, were performed using IBM SPSS Statistics 26.0. Different letters indicate significant differences at the 0.05 level among the treatment ($p<0.05$).

Results

Effect of compound fertilizer combined with biochar on yield of winter wheat in two years : We analyzed the results of winter wheat yield under 12 treatments in the two-year test (Fig. 1). The yield of winter wheat in the first year reached a maximum of 7505.61 kg·hm^{-2} under B2F3 treatmentBoth B2F3 and B1F4 treatments resulted in significantly higher yields than other treatments. The yield in the second year reached a maximum of 7600.35 kg·hm^{-2} also under B2F3 treatment, which was significantly higher than that under all other treatment except for B2F4 and B3F3, and was 10.61% higher than the B1F4 treatment. Overall, the yield of winter wheat in the second year was higher than that in the first year under the same fertilization treatment. Under single application of compound fertilizer (B1F1, B1F2, B1F3, and B1F4), the yield in the first year gradually increased with increasing compound fertilizer application amount, reaching the maximum value of 7303.24 kg·hm^{-2} under B1F4 treatment, which was significantly higher than that under other treatments. Under single application of biochar (B1F1, B2F1, and B3F1), the yield decreased with increasing biochar application, and reached the maximum value of 5497.10 kg·hm^{-2} under B1F1 treatment, which was not significantly different from that under B2F1 treatment. Both B1F1 and B2F1 treatments resulted in significantly higher yields than B3F1 treatment. When the application amount of compound fertilizer was F2 (B1F2, B2F2, and B3F2), the yield of winter wheat continuously decreased with increasing application amount of biochar. There was no significant difference between B1F2 and B2F2 treatments, with a maximum value of 6230.3 kg·hm^{-2}, and both treatments had significantly higher yields than B3F2 treatment. When the application amount of compound fertilizer was F3 (B1F3, B2F3, and B3F3), with increasing application amount of biochar, the yield showed a first increasing and then decreasing trend, and the maximum value of 7505.61 kg·hm^{-2} was observed under B2F3 treatment, which was significantly higher than that under other treatments. When the application amount of compound fertilizer was F4 (B1F4, B2F4, and B3F4), the winter wheat yield showed a trend of continuous decreases with increasing application amount of biochar, and the maximum value of 7303.24 kg·hm^{-2} was observed under B1F4 treatment, which was significantly higher than that under other treatments. The yield of winter wheat in the second year under single application of compound fertilizer showed a gradually increasing trend with increasing compound fertilizer application amount, and reached the maximum value of 6871.14 kg·hm^{-2} under B1F4 treatment, which was not significantly different from that under B1F2 treatment and B1F3 treatment, and the three treatments resulted in significantly higher yields than B1F1 treatment. In the case of single application of biochar, the yield increased continuously with increasing amount of biochar, and reached a maximum value of 6113.84 kg·hm^{-2} under B3F1 treatment, with no significant difference among different treatments. When the application amount of compound fertilizer was F2, with the increase in application amount of biochar, the yield of winter wheat showed a first increasing and then decreasing a trend, reaching the maximum value of 6832.86 kg·hm^{-2} under B2F2 treatment, and the difference among different treatments was not significant. When the application amount of compound fertilizer was F3, with increasing application amount of biochar, the winter wheat yield also exhibited a first increasing and then decreasing trend, reaching the maximum value of 7600.35 kg·hm^{-2} under B2F3 treatment, which was not significantly different from that under B3F3 treatment, but significantly higher than that under B1F3 treatment. When the application amount of compound fertilizer was F4, the winter wheat yield showed a first increasing and then decreasing trend as well, reaching the maximum value of 7072.31 kg·hm^{-2} under B3F4 treatment, and the differences among different treatments were not significant.

Effects of compound fertilizer combined with winter wheat on soil total N content： We analyzed the soil total N content in each growth stage of winter wheat revealed that in the first year at the maturity stage, B3F4 treatment resulted in the maximum soil total N content (3.52 mg·kg^{-1}), which was significantly higher than that of single application of compound fertilizer and significantly increased by 63.72% relative to conventional B1F4 treatment (Table 1). At the jointing stage in the second year, the maximum value was found under B1F4 treatment (4.26×10^{3} mg·kg^{-1}), which was significantly different from that of other treatments except for B1F3, B2F3, and B3F4. At the booting stage, the maximum value was found under B3F2 treatment (6.95×10^{3} mg·kg^{-1}), which was significantly higher than that under B2F2 and B2F3 treatments. At the flowering stage, a maximum soil total N content of 9.70×10^{3} mg·kg^{-1} was observed under B2F4 treatment, which was significantly higher than that under B1F4 and B3F1 treatments. At the maturity stage, the soil total N content reached a maximum value of 5.34×10^{3} mg·kg^{-1} under B3F2 treatment, which was not significantly different from that under B3F3 treatment, and both were higher than those under other treatments; moreover, B3F3 treatment resulted in a higher value than B1F4 treatment. With increasing compound fertilizer application amount, the soil total N content showed continuous increases at the jointing stage, and a maximum value of 4.26×10^{3} mg·kg^{-1} was observed under B1F4 treatment. At both booting stage and flowering stage, the soil total N content showed a gradually decreasing trend with increasing application amount of compound fertilizer, and reached the maximum value under B1F1 treatment, which was 5.58×10^{3} mg·kg^{-1} and 9.59×10^{3} mg·kg^{-1}, respectively. When only biochar was applied, soil total N content of winter wheat showed a continuously decreasing trend with the application amount of biochar at the jointing stage, and reached a maximum value of 2.73×10^{3} mg·kg^{-1} under B1F1 treatment, and there was no significant difference among treatments. At both the booting stage and maturity stage, the soil total N content first decreased and then increased with biochar amount, and both reached the maximum value of 5.58×10^{3} mg·kg^{-1} and 4.00×10^{3} mg·kg^{-1} under B1F1 treatment, respectively, and there was no significant difference between the two treatments. At the flowering stage, the soil total N content showed a gradually decreasing trend with biochar amount.

Effects of compound fertilizer combined with biochar on soil alkali-hydrolyzed N content of winter wheat：

In terms of alkaline hydrolyzed N content in 0–20 cm soil layer at different growth stages of winter wheat (Table 2), there were great differences among different growth stages. In the first-year maturity stage, B3F4 treatment obtained the maximum value (114.94 × 10^{3} kg·hm^{-2}), which was significantly higher than that under other treatments except for B2F4. B3F4 significantly increased the alkaline hydrolyzed N content by 32.91% compared with B1F4 treatment. At the second-year jointing stage, the maximum value (90.30 mg·kg^{-1}) was observed under B3F2 treatment, which was significantly higher than that under other treatments except for B3F1, and was significantly increased by 43.33% relative to that under conventional treatment B1F4. B3F1 treatment significantly increased the alkaline hydrolyzed N content by 37.03% compared with B1F4 treatment. At the booting stage, the maximum value was observed under B2F2 treatment (154.47 mg·kg^{-1}), which was significantly higher than that under other treatments except for B1F3, and was significantly elevated by 29.56% compared with that of conventional treatment B1F4. At the flowering stage, the maximum value was found under B1F4 treatment (116.67 mg·kg^{-1}), which was significantly higher than that under B1F1, B2F4, B3F1, and B3F4 treatment. At the maturity stage, the maximum value was found under B3F2 treatment (88.67 mg·kg^{-1}), which was significantly higher than that under B1F1, B2F1, B2F3, and B2F4 treatments. In the case of single application of compound fertilizer, with increasing compound fertilizer application amount, the alkaline hydrolyzed N content in 0–20cm soil layer showed a continuously increasing trend at the jointing, flowering, and maturity stages, and reached the maximum value at B1F4, which were 63.00, 116.67, and 80.50 mg·kg^{-1}, respectively. B1F4 treatment resulted in significantly higher alkaline hydrolyzed N content than B1F1 treatment at the jointing and flowering stages. At the booting stage, the alkaline hydrolyzed N content showed a first increasing and then decreasing trend, and reached the maximum value of 145.37 mg·kg^{-1} under B1F3 treatment, with no significant difference among different treatments. When biochar was applied alone, with increasing application amount, the alkaline hydrolyzed N content first decreased and then increased at the jointing stage, reaching the maximum value of 86.33 mg·kg^{-1} under B3F1 treatment. At both the booting stage and flowering stage, the alkaline hydrolyzed N content first increased and then decreased, both reaching the maximum value under B2F1 treatment, which was 120.17 mg·kg^{-1} and 102.90 mg·kg^{-1}, respectively. At the maturity stage, the alkaline hydrolyzed N content showed a gradually increasing trend, reaching a maximum value of 70.00 mg·kg^{-1} under B3F1 treatment, and the differences among different treatments were not significant.

Effects of compound fertilizer combined with biochar on dry matter accumulation in winter wheat plants: We analyzed the results of the accumulation of dry matter in winter wheat under 12 treatment conditions at each growth stage (Table 3). The results showed that the maximum value was 5.26 × 10^3 kg·hm^{-2} under B3F4 treatment at the jointing stage in the second year, which was significantly higher than that under other treatments. B1F2, B1F3, B2F3, B2F4, and B3F4 treatments resulted in significantly higher dry matter accumulation than B1F4 treatment. The maximum values at the second-year booting and flowering stage and two-year maturity stage under B2F3 treatment were 10.98 × 10^3, 18.82 × 10^3, 21.72 × 10^3, and 17.06 × 10^3 kg·hm^{-2}, respectively. B2F3 treatment at the second-year flowering stage and first-year maturity stage had significantly higher dry matter accumulation than other treatments. B2F3 treatment at the second-year booting stage led to significantly higher dry matter accumulation than other treatments except for B1F3. At the second-year maturity stage, the dry matter accumulation of the B2F3 treatment was 20% higher than that of the B1F4 treatment.At all stages mentioned above, B2F3 treatment resulted in significantly higher dry matter accumulation than B1F4 treatment. Under single application of compound fertilizer, the dry matter accumulation in winter wheat at each growth stage first increased and then decreased with increasing compound fertilizer at the second-year jointing, booting, and maturity stages, reaching the maximum value under B1F3 treatment (4.54 × 10^3, 10.75 × 10^3, and 19.90 × 10^3 kg·hm^{-2}, respectively). At the flowering stage, it showed a continuously increasing trend, and reached a maximum value of 14.74 × 10^3 kg·hm^{-2} under B1F4 treatment. In the first year, the dry matter accumulation at the maturity stage first decreased and then increased, reaching a maximum value of 16.51 × 10^3 kg·hm^{-2} under B1F4 treatment. When biochar was applied alone, with increasing biochar application amount, the dry matter accumulation in winter wheat continuously decreased at the second-year jointing stage and first-year maturity stage, and reached the maximum value under B1F1 treatment (3.15 × 10^3 and 14.21×10^3 kg·hm^{-2}, respectively). The dry matter accumulation first increased and then decreased at the second-year booting stage and maturity stage, reaching the maximum value under B2F1 treatment (9.07 × 10^3 and 16.76 × 10^3 kg·hm^{-2}, respectively. At the second-year flowering stage, the dry matter accumulation first decreased and then increased, reaching the maximum value of 12.11 × 10^3 kg·hm^{-2} under B1F1 treatment.

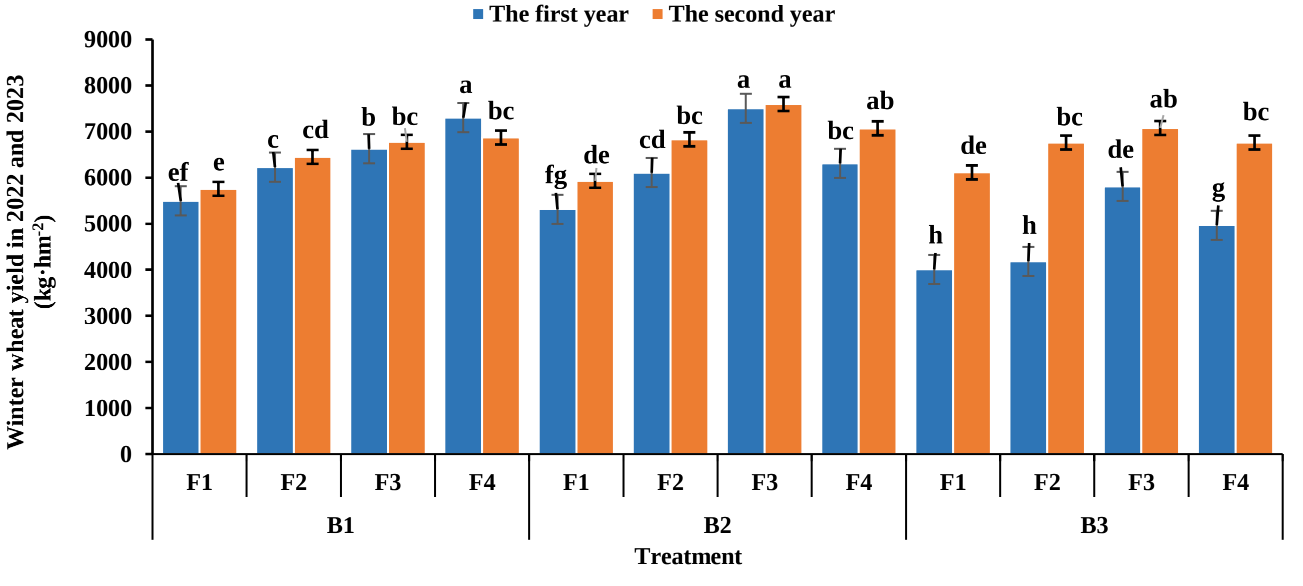

Fig. 1. Two-year winter wheat yield.

Table 1. Total N content in 0–20 cm soil layer at each growth stage of winter wheat (×10^3 mg·kg^{-1}).

Treatment	The first year	The second year			
	Maturity	Jointing stage	Booting stage	Flowering stage	Maturity
B1F1	2.05 ± 0.08c	2.73 ± 0.02bcd	5.58 ± 0.36ab	9.59 ± 0.54a	4.00 ± 0.23bc
B1F2	2.03 ± 0.06c	3.25 ± 0.10e	5.33 ± 0.22ab	9.57 ± 0.82a	3.12 ± 0.61cd
B1F3	2.15 ± 0.26bc	3.64 ± 0.15ab	5.31 ± 0.14ab	9.54 ± 0.92a	4.08 ± 0.31bc
B1F4	2.15 ± 0.24bc	4.26 ± 0.30a	5.23 ± 0.53ab	6.43 ± 1.67bc	4.17 ± 0.17bc
B2F1	2.51 ± 0.15abc	1.72 ± 0.41de	5.41 ± 0.49ab	8.22 ± 0.31abc	3.24 ± 0.41cd
B2F2	3.2 ± 0.54ab	2.64 ± 0.22bcd	4.53 ± 0.81b	9.34 ± 0.85ab	3.80 ± 0.60bc
B2F3	3.27 ± 0.57a	4.15 ± 0.22a	4.72 ± 0.68b	8.28 ± 0.84abc	2.16 ± 0.28d
B2F4	3.31 ± 0.59a	2.43 ± 0.73cd	5.47 ± 0.65ab	9.70 ± 0.96a	2.63 ± 0.15d
B3F1	3.33 ± 0.3a	1.34 ± 0.18b	5.47 ± 0.82ab	5.63 ± 0.07c	3.94 ± 0.21bc
B3F2	3.41 ± 0.32a	2.74 ± 0.20bcd	6.95 ± 0.02a	9.64 ± 0.65a	5.34 ± 0.23a
B3F3	3.49 ± 0.3a	2.49 ± 0.10cd	6.05 ± 0.92ab	7.71 ± 1.12abc	4.69 ± 0.50ab

B3F4	3.52 ± 0.36a	3.41 ± 0.51abc	6.39 ± 0.34ab	8.75 ± 1.07ab	4.02 ± 0.21bc

Different letters in the same column indicate significant differences between different nitrogen application rates ($p<0.05$). The same below

Table 2. Alkali hydrolyzed N content in 0–20cm soil layer at each growth stage of winter wheat ($mg \cdot kg^{-1}$).

Treatment	The first year	The second year			
	Maturity	Jointing stage	Booting stage	Flowering stage	Maturity
B1F1	71.31 ± 1.06g	43.17 ± 3.09def	116.55 ± 9.90bcd	89.83±9.34bcd	60.67±2.33b
B1F2	80.36 ± 0.36f	52.50 ± 3.50bcd	120.75 ± 9.09bc	105.70 ± 4.04ab	73.50±2.02ab
B1F3	88.27 ± 0.78e	55.53 ± 2.44bcd	145.37 ± 17.07ab	106.17 ± 3.44ab	74.67±2.33ab
B1F4	86.48 ± 0.86e	63.00 ± 8.08b	119.23 ± 2.03bcd	116.67 ± 2.37a	80.50±2.02ab
B2F1	98.82 ± 0.39d	28.00 ± 4.04g	120.17 ± 9.55bcd	102.90 ± 1.21abc	63.00±4.04b
B2F2	103.22 ± 0.53c	46.67 ± 4.67de	154.47 ± 14.24a	105.23 ± 7.88ab	70.00±17.62ab
B2F3	106.38 ± 1.78bc	59.50 ± 2.02bc	123.90 ± 0.81bc	100.10 ± 14.36abcd	67.67±6.17b
B2F4	113.93 ± 1.7a	38.50 ± 2.02efg	120.40 ± 2.46bcd	96.25 ± 0.61bcd	63.00±0.00b
B3F1	106.95 ± 0.81b	86.33 ± 2.37a	86.57 ± 7.51e	85.40 ± 0.00cd	70.00±4.04ab
B3F2	103.5 ± 1.08c	90.30 ± 0.00a	90.77 ± 3.44de	105.23 ± 0.23ab	88.67±4.67a
B3F3	109.63 ± 1.87b	50.40 ± 5.30cde	104.30 ± 4.66cde	100.10 ± 0.01abcd	79.33±2.33ab
B3F4	114.94 ± 0.68a	33.83 ± 3.09fg	116.20 ± 9.8bcd	83.30 ± 0.00d	72.33±2.33ab

Table 3. Dry matter accumulation in winter wheat at different growth stages under different treatments ($\times 10^3$ $kg \cdot hm^{-2}$).

Treatment	The first year	The second year			
	Maturity	Jointing stage	Booting stage	Flowering stage	Maturity
B1F1	14.21 ± 0.11f	3.15 ± 0.03f	7.94 ± 0.17de	12.11 ± 0.56cde	16.38 ± 0.43d
B1F2	14.67 ± 0.09d	4.33 ± 0.13cd	10.15 ± 0.31ab	13.25 ± 0.27bcd	18.91 ± 0.77bc
B1F3	14.39 ± 0.09ef	4.54 ± 0.38bc	10.75 ± 0.69a	13.88 ± 0.52bc	19.90 ± 1.28ab
B1F4	16.51 ± 0.05b	3.68 ± 0.23e	7.91 ± 0.49de	14.74 ± 0.10b	18.10 ± 1.29bcd
B2F1	13.54 ± 0.03g	3.13 ± 0.16f	9.07 ± 0.43bcd	10.45 ± 0.60e	16.76 ± 0.84cd
B2F2	14.53 ± 0.05de	2.62 ± 0.75f	9.40 ± 0.25bc	13.53 ± 0.47bc	20.32 ± 0.67ab
B2F3	17.06 ± 0.03a	4.35 ± 0.70cd	10.98 ± 0.36a	18.82 ± 0.86a	21.72 ± 0.67a
B2F4	14.70 ± 0.04d	4.95 ± 0.31ab	8.78 ± 0.52cd	14.23 ± 1.77bc	19.90 ± 1.01ab
B3F1	11.36 ± 0.01i	2.81 ± 0.17f	6.96 ± 0.14e	11.40 ± 0.46de	16.24 ± 0.42d
B3F2	12.24 ± 0.09h	2.89 ± 0.13f	8.99 ± 0.18cd	11.30 ± 0.20de	18.00 ± 0.65bcd
B3F3	15.36 ± 0.08c	3.93 ± 0.56de	9.26 ± 0.13bc	14.00 ± 1.24bc	19.26 ± 0.10abc
B3F4	13.63 ± 0.15g	5.26 ± 0.63a	8.55 ± 0.10cd	12.87 ± 0.61bcd	19.57 ± 0.16ab

Table 4. Nitrogen accumulation in winter wheat plants at different growth stages ($kg \cdot hm^{-2}$)

Treatment	The first year	The second year			
	Maturity	Jointing stage	Booting stage	Flowering stage	Maturity
B1F1	342.84 ± 3.15de	86.04 ± 7.60ef	102.23 ± 0.95c	245.90 ± 5.88cd	292.32 ± 11.88d
B1F2	350.87 ± 2.38cd	108.37 ± 1.88de	173.05 ± 8.44a	278.98 ± 2.10abc	352.77 ± 7.08bcd
B1F3	364.75 ± 1.58bc	172.81 ± 8.42b	132.26 ± 15.11b	261.93 ± 17.02bc	370.05 ± 14.87bc
B1F4	367.60 ± 3.34bc	227.08 ± 18.50a	123.37 ± 6.24bc	293.08 ± 2.47ab	406.90 ± 18.61bc
B2F1	331.34 ± 5.10e	96.17 ± 1.30def	144.77 ± 8.09b	208.23 ± 3.08d	305.18 ± 16.55d
B2F2	372.27 ± 0.15b	76.37 ± 2.66f	133.57 ± 6.32b	255.68 ± 17.10bc	372.78 ± 13.59bc
B2F3	371.80 ± 11.97b	122.56 ± 16.68cd	174.78 ± 4.47a	317.68 ± 24.31a	480.84 ± 22.88a
B2F4	376.17 ± 6.69a	143.65 ± 2.31bc	143.39 ± 12.17b	288.59 ± 3.36ab	398.93 ± 20.58bc
B3F1	305.55 ± 5.07f	83.71 ± 10.44ef	70.91 ± 1.34d	265.54 ± 19.00bc	345.05 ± 26.59cd
B3F2	308.59 ± 6.95f	222.65 ± 11.75a	133.97 ± 5.85b	261.72 ± 5.77bc	389.20 ± 8.58bc
B3F3	362.29 ± 3.69bc	165.05 ± 1.99b	132.66 ± 1.88b	238.03 ± 5.78cd	417.00 ± 24.14b
B3F4	344.09 ± 5.30de	157.75 ± 8.05b	147.17 ± 2.39b	293.87 ± 14.72ab	403.54 ± 35.36bc

Effects of compound fertilizer combined with biochar on nitrogen accumulation in winter wheat plants： We analyzed the results of nitrogen accumulation in winter wheat plants at each growth stage under 12 different treatment conditions (Table 4). The maximum nitrogen accumulation reached 376.17 $kg \cdot hm^{-2}$ under B2F4 treatment at the first-year maturity stage, which was significantly higher than that under other treatments. Nitrogen accumulation at the second-year jointing stage was the maximum (227.08 $kg \cdot hm^{-2}$) under B1F4 treatment, which was significantly higher than that under other treatments except for B3F2 treatment. Under B2F3 treatment, the maximum values at the second-year booting stage, flowering stage, and maturity stage were 174.78, 317.68, and 480.84 $kg \cdot hm^{-2}$, respectively. In addition, except for the jointing stage and flowering stage, the maximum value in other growth stages was significantly higher than that in B1F4 treatment. In the case of single application of compound fertilizer, nitrogen accumulation showed an overall gradually increasing trend with increasing compound fertilizer application amount at the first-year maturity stage, second-year jointing stage, flowering stage, and maturity stage, all of which reached the maximum value under B1F4 treatment (367.60, 227.08, 293.06, and 406.90 kg·hm^{-2}, respectively. Nitrogen accumulation first increased and then decreased at the booting stage, and reached the maximum value of 173.05 kg·hm^{-2} under B1F2 treatment, which was significantly different from that under other treatments. When biochar was applied alone, with increasing biochar application amount, nitrogen accumulation first increased and then decreased at the jointing stage and booting stage, reaching the maximum values under B2F1 treatment (96.17 and 144.77 kg·hm^{-2}, respectively). Nitrogen accumulation first decreased and then increased at the flowering stage, and reached a maximum value of 265.54 kg·hm^{-2} under B3F1 treatment. In the second-year maturity stage, nitrogen accumulation continuously increased with increasing application of biochar and reached the maximum value of 345.05 kg·hm^{-2} under B3F1 treatment. Nitrogen accumulation in the first-year maturity stage showed a trend of continuous decline, and the maximum value of 342.84 kg·hm^{-2} was observed under B1F1 treatment.

Effects of compound fertilizer combined with biochar on dry matter transport of winter wheat：We analyzed the transport characteristics of dry matter in winter wheat under 12 treatment conditions at each growth stage (Table 5). The results showed that B2F3 treatment resulted in significantly higher pre-anthesis dry matter transport volume (1.10 kg·hm^{-2}), transport rate (0.40%), and contribution rate to grains (0.72%) than other treatments. Compared with B1F4 treatment, it significantly increased by 0.57% and 29%. The post-anthesis dry matter accumulation amount reaches its maximum value of 1.25 kg·hm^{-2} under the B3F2 treatment. Compared with B1F4 treatment, it significantly increased by 47%. In the single application of compound fertilizer, the pre-anthesis dry matter transport volume, transport rate and contribution rate to grains showed a gradually increasing trend with increasing compound fertilizer application amount, and all reached the maximum values at B1F4 (0.70 kg·hm^{-2}, 0.31%, and 0.45%, respectively). Post-anthesis dry matter accumulation and contribution rate to grains showed a gradually decreasing trend, both of which were the lowest under B1F4 treatment (0.85 kg·hm^{-2} and 0.55%, respectively). In the case of single application of biochar, with increasing biochar application amount, the pre-anthesis dry matter transfer volume, transfer rate and contribution rate to grains showed a first decreasing and then increasing trend, and reached the maximum value under B3F1 treatment (0.66 kg·hm^{-2}, 0.28%, and 0.44%, respectively). Post-anthesis dry matter accumulation and contribution rate to grains showed a first increasing and then decreasing trend. Both of them reached the maximum values of 1.19 kg·hm^{-2} and 0.79% under B2F1 treatment.

Effects of compound fertilizer combined with biochar on nitrogen transport of winter wheat：We analyzed the nitrogen transport characteristics under 12 treatments results of winter wheat at different growth stages (Table 6). The results showed that pre-anthesis nitrogen transport and transport rate reached the maximum under B3F2 treatment (136.53 kg·hm^{-2} and 0.52%, respectively), followed by B2F3 treatment (131.88 kg·hm^{-2} and 0.46%, respectively, and there was no significant difference between the two treatments. Post-anthesis nitrogen accumulation and contribution rate to grains were the highest under B3F3 treatment (178.97 kg·hm^{-2} and 0.68%), and the second highest under B2F3 treatment (163.16 kg·hm^{-2} and 0.56%), with no significant difference between the two treatment. Under single application of compound fertilizer, pre-anthesis nitrogen transfer, transport rate, contribution rate of nitrogen to grains and post-anthesis nitrogen accumulation and contribution rate to grains all showed a first decreasing and then increasing trend with increasing compound fertilizer application amount, and all reached the maximum value under B1F4 treatment, which were 130.47 kg·hm^{-2}, 0.45%, 0.54%, 113.81 kg·hm^{-2}, and 0.46%, respectively. With increasing biochar application amount, the pre-anthesis nitrogen transfer, transport rate and contribution rate to grains first decreased and then increased, and reached the maximum values of 130.73 kg·hm^{-2}, 0.45% and 0.62% under B3F1 treatment. Post-anthesis nitrogen accumulation and contribution rate to grains first increased and then decreased, and reached the maximum value of 83.00 kg·hm^{-2} and 0.50% under B2F1.

Effect of compound fertilizer combined with biochar on nitrogen use efficiency of winter wheat grain: We analyzed the results of nitrogen use efficiency under 12 treatments in two years (Fig. 2). The results revealed that nitrogen harvest index (NHI) and nitrogen partial productivity (NPFP) in the second year were generally higher than those in the first year. NHI reached a maximum of 77.50% under B3F2 treatment in the second year, which was 38.79% higher than that in the first year; NPFP reached the maximum value of 121.47 kg·kg^{-1} under B2F2 treatment in the second year, which was 9.67% higher than the maximum value under B1F2 treatment in the first year, and significantly higher than that under conventional treatment B1F4 in both years. Nitrogen agronomic use efficiency (NAE) reached the maximum value of 19.48 kg·kg^{-1} under B2F3 treatment in the first year, and the second highest value of 16.02 kg·kg^{-1} under B2F2 treatment in the second year, and the difference between the two was not significant. Nitrogen absorption efficiency (NUPE) reached a maximum of 6.62 kg·kg^{-1} under B2F2 treatment in the first year and the second highest value of 6.57 kg·kg^{-1} under B3F2 treatment in the second year, with no significant difference between the two. In the first year of single application of compound fertilizer, NHI showed a first decreasing and then increasing trend with increasing compound fertilizer application amount, and reached the maximum value of 55.59% under B1F3 treatment, with no significant difference among treatments. With increasing application amount of biochar alone, NHI increased first and then decreased, reaching the maximum value of 55.76% under

B2F1 treatment. Upon single application of compound fertilizer, with increasing application amount, NAE first decreased and then increased, reaching the maximum value of 13.03 kg·kg^{-1} under B1F2 treatment. Both NUPE and NPFP continuously decreased with increasing compound fertilizer application amount during single application, and reached the maximum value of 6.24 kg·kg^{-1} and 110.76 kg·kg^{-1} under B1F2 treatment. In the second year, with increasing compound fertilizer application amount, NHI first decreased and then increased, and reached the maximum value of 57.67% under B1F4 treatment, which was significantly higher than that under B1F2 treatment. In the second year, in the case of single application of biochar, NHI first decreased and then increased with increasing biochar application, and reached the maximum value of 70.98% under B3F1 treatment. In the case of single application of compound fertilizer, NAE, NUPE, and NPFP all showed a gradually decreasing trend with the increases in compound fertilizer application amount, and reached the maximum values of 12.16, 6.34, and 114.69 kg·kg^{-1} under B1F2 treatment.

Table 5. Dry matter transport characteristics of winter wheat under different treatments in the second year.

Treatment	Pre-anthesis dry matter			Post-anthesis dry matter	
	Translocation amount/ (×10^3 kg·hm^{-2})	Translocation rate / %	Contribution rate to grain /%	Accumulation amount/ (×10^3 kg·hm^{-2})	Contribution rate to grain/ %
B1F1	0.65 ± 0.07bc	0.27 ± 0.02bcd	0.40 ± 0.05b	0.98 ± 0.10bc	0.60 ± 0.05c
B1F2	0.58 ± 0.02bc	0.24 ± 0.01d	0.38 ± 0.02bc	0.96 ± 0.04bcd	0.62 ± 0.02bc
B1F3	0.62 ± 0.06bc	0.26 ± 0.02bcd	0.40 ± 0.04b	0.93 ± 0.06bcd	0.60 ± 0.04c
B1F4	0.70 ± 0.04b	0.31 ± 0.02b	0.45 ± 0.01b	0.85 ± 0.02cd	0.55 ± 0.01c
B2F1	0.32 ± 0.02e	0.16 ± 0.01e	0.21 ± 0.02e	1.19 ± 0.03a	0.79 ± 0.02a
B2F2	0.42 ± 0.04de	0.19 ± 0.01e	0.28 ± 0.03d	1.08 ± 0.08ab	0.72 ± 0.03a
B2F3	1.10 ± 0.05a	0.40 ± 0.01a	0.72 ± 0.03a	0.43 ± 0.05e	0.28 ± 0.03d
B2F4	0.71 ± 0.05b	0.29 ± 0.02bc	0.43 ± 0.04b	0.96 ± 0.10bcd	0.57 ± 0.04c
B3F1	0.66 ± 0.02bc	0.28 ± 0.01bcd	0.44 ± 0.02b	0.84 ± 0.06de	0.56 ± 0.02c
B3F2	0.51 ± 0.02cd	0.26 ± 0.01cd	0.29 ± 0.01cd	1.25 ± 0.05a	0.71 ± 0.01ab
B3F3	0.62 ± 0.04bc	0.27 ± 0.01bcd	0.39 ± 0.02b	0.95 ± 0.02bcd	0.61 ± 0.02c
B3F4	0.63 ± 0.04bc	0.28 ± 0.01bcd	0.45 ± 0.03b	0.78 ± 0.04d	0.55 ± 0.03c

Table 6. Nitrogen transport characteristics of winter wheat under different nitrogen treatments in the second year.

Treatment	Pre-anthesis N			Post-anthesis N	
	Translocation amount/ (kg·hm^{-2})	Translocation rate / %	Contribution rate to grain /%	Accumulation amount/ (kg·hm^{-2})	Contribution rate to grain/ %
B1F1	102.10 ± 0.56ab	0.36 ± 0.02ef	0.66 ± 0.04a	46.42 ± 6.04e	0.29 ± 0.02e
B1F2	104.21 ± 2.17ab	0.37 ± 0.01ef	0.56 ± 0.03ab	73.80 ± 8.43de	0.40 ± 0.04cde
B1F3	96.15 ± 18.55ab	0.34 ± 0.03f	0.51 ± 0.11ab	108.11 ± 31.83bcd	0.56 ± 0.16abcd
B1F4	130.47 ± 3.36a	0.45 ± 0.01bc	0.54 ± 0.05ab	113.81 ± 20.84bcd	0.46 ± 0.05de
B2F1	69.78 ± 3.63b	0.34 ± 0.02f	0.42 ± 0.05b	83.00 ± 0.99cde	0.50 ± 0.06a
B2F2	107.74 ± 3.94ab	0.38 ± 0.00def	0.52 ± 0.11ab	117.10 ± 30.47bcd	0.55 ± 0.11abcd
B2F3	131.88 ± 23.12a	0.46 ± 0.01b	0.44 ± 0.05ab	163.16 ± 2.48ab	0.56 ± 0.05abcd
B2F4	127.61 ± 3.92a	0.42 ± 0.01bcd	0.54 ± 0.05ab	110.34 ± 17.80bcd	0.46 ± 0.06bcde
B3F1	130.73 ± 18.97a	0.45 ± 0.01bc	0.62 ± 0.03ab	79.51 ± 9.89de	0.38 ± 0.03cde
B3F2	136.53 ± 7.62a	0.52 ± 0.02a	0.52 ± 0.03ab	127.48 ± 8.82abcd	0.48 ± 0.03bcde
B3F3	115.07 ± 8.84a	0.40 ± 0.02cde	0.46 ± 0.04ab	178.97 ± 28.45a	0.68 ± 0.04ab
B3F4	130.89 ± 17.05a	0.44 ± 0.01bc	0.57 ± 0.13ab	140.62 ± 11.45abc	0.60 ± 0.06abc

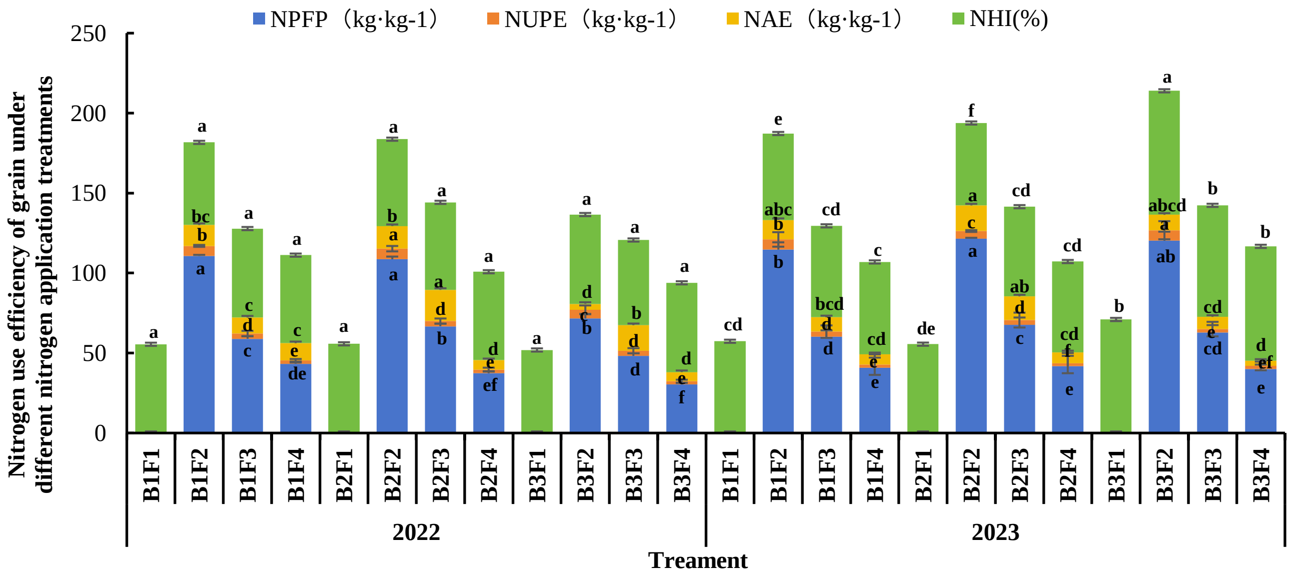

Fig. 2. Nitrogen use efficiency of winter wheat under different treatments.
NHI: Nitrogen harvest index (%); NAE: Nitrogen agronomic use efficiency (%); NUPE: Nitrogen absorption efficiency; NPEP: Nitrogen partial productivity.

Discussion

Effect of compound fertilizer combined with biochar on winter wheat yield: Rational nitrogen management is crucial to the reduction of nitrogen loss, promotion of crop growth, and enhancement of crop yield. Previous studies have found that the combined application of biochar and nitrogen fertilizer can contribute to a higher yield of winter wheat than single application of compound fertilizer (Sadaf *et al*., 2017), which is consistent with the findings of this study. In this study, the yield of winter wheat in both years reached the maximum value of 7505.61 kg·hm^{-2} and 7600.35 kg·hm^{-2} under B2F3 treatment, both of which were higher than that under single application of compound fertilizer. Similarly, Li *et al*., (2019) found that the combined application of 20 t/ha biochar and 120 kg/ha nitrogen fertilizer increased wheat biomass. Malik *et al*., (2024) found that the application of biochar could increase wheat yield by 10%. Li (2023) reported that the combined application of biostimulant and compound fertilizer could reduce the amount of nitrogen fertilizer by 20% and achieve stable yield, which also supports our conclusion. Kamal *et al*., (2024) research found that the combined use of biochar and half-dose NPK not only increased the yield but also enhanced soil organic matter and total nitrogen. Baronti *et al*., (2010) found that biochar application to reduce nutrient leaching and to improve crop yields. These findings indicate that the addition of biochar can increase wheat yield to a certain extent while reducing the demand for nitrogen. However, our results also showed that under the same application conditions of compound fertilizer, the application of 7500 kg·hm^{-2} biochar (B2) resulted in a higher winter wheat yield than 15000kg·hm^{-2} biochar (B3) for two consecutive years, indicating that application of excessive biochar would reduce the yield.

Effects of compound fertilizer combined with biochar on soil total nitrogen and alkali-hydrolyzed nitrogen contents of winter wheat: Due to its advantages such as large specific surface area and high porosity, biochar can improve the physical and chemical properties of soil and increase the efficiency of nutrient utilization. Soil nitrogen content is an important source of plant nitrogen supply Previous studies have found that the total nitrogen absorbed by wheat from soil in the North China Plain ranges from 45%-66%, and about 15%-31% of the total nitrogen absorbed by wheat is derived from fertilizer, while the nitrogen absorbed from soil accounts for more than 70% (Jia *et al*., 2011; Wu *et al*., 2019), and about 26.8%-32.4% of the total nitrogen absorbed by maize is derived from fertilizer, while the nitrogen absorbed from soil accounts about 67.6%-73.2% (Wang *et al*., 2016). This might be because the maximum rooting depth of summer corn is only about 1.2 meters, while the maximum root depth of winter wheat can reach up to 2 meters. Winter wheat, with its deeply rooted system, is able to more effectively capture the fertilizer nitrogen from the lower soil layer (Wu *et al*., 2005). Therefore, the nitrogen fertilizer utilization rate of wheat is relatively high. In this study, our results showed that the soil total nitrogen accumulation of winter wheat at the two-year maturity stage increased with increasing nitrogen application, and reached the maximum values of 2.15 and 4.17×10^3 mg·kg^{-1} under B1F4 treatment. The soil alkali-hydrolyzed nitrogen content of winter wheat at the two-year maturity stage increased with increasing application amount of biochar alone, and reached the maximum value under B3F1 treatment, which is similar to the results of Chen (2014). The total nitrogen accumulation under the application of compound fertilizer combined with biochar was generally higher than that under single application of compound fertilizer or biochar, probably because the addition of biochar can activate residual nitrogen and increase available nitrogen in soil, which is conducive to crop nitrogen absorption. This is also consistent with the study of Hui *et al*., (2022).

Effects of compound fertilizer combined with biochar on dry matter accumulation and transport of winter wheat: Wheat produces carbohydrates under photosynthesis. Dry matter is the final form of carbohydrates, and its accumulation rate at different growth stages directly affects the yield formation (Lv *et al*., 2020). The accumulation and transport of dry matter from flowering to maturity is a key factor affecting wheat grain yield (Zhang *et al*., 2019). Our results revealed that under single application of compound fertilizer, pre-anthesis dry matter transfer, transport rate, and contribution rate to grains all showed an increasing trend with increasing compound fertilizer, reaching the maximum value of 0.70 kg·hm^{-2}, 0.31%, and 0.45%, under B1F4 treatment, while post-anthtesis dry matter accumulation and contribution rate to grains were the lowest under B1F4 treatment, which were 0.85 kg·hm^{-2} and 0.55%, respectively. These results indicate that the application of compound fertilizer can improve the accumulation, transport, and utilization of dry matter in the vegetative organs of winter wheat, which is consistent with the conclusion of Ni *et al*., (2017). Zhang *et al*., (2014) found that the application of biochar promotes dry matter accumulation in summer maize. As a whole, the results of this study showed that post-anthtesis dry matter accumulation under the application of compound fertilizer combined with biochar was higher than that under single fertilizer treatment, indicating that combining biochar with compound fertilizer could increase post-anthtesis dry matter accumulation and transport of winter wheat, which is generally the same as previous research results.

Effects of compound fertilizer combined with biochar on nitrogen accumulation and transport in winter wheat: Nitrogen accumulation and transport in wheat plants can reflect plant nitrogen uptake and affect plant growth. Previous studies have found that increasing nitrogen application rate can increase nitrogen accumulation in winter wheat, which is generally consistent with the results of this study (Chen *et al*., 2016; Tran *et al*., 2000). Our results revealed that increasing application amount of compound fertilizer alone could promote plant nitrogen accumulation, pre-anthesis nitrogen transfer and transfer rate, all of which reached the maximum value under B1F4 treatment. In this study, the pre-anthesis nitrogen accumulation and nitrogen transfer under the combined fertilizer and biochar treatment were higher than those under single application of fertilizer or biochar. In the second year, nitrogen accumulation at the booting stage, flowering stage, and maturity stage reached the maximum under B2F3 treatment, which were 174.78, 317.68 and 480.84 $kg \cdot hm^{-2}$, respectively. The pre-anthesis nitrogen transfer reached the maximum under B3F2 treatment (136.53 $kg \cdot hm^{-2}$). These results indicate that combined application of compound fertilizer with biochar can increase plant nitrogen accumulation and pre-anthesis nitrogen transfer compared with single application of fertilizer or biochar, but application of excessive compound fertilizer will decrease plant nitrogen accumulation instead of increasing it. This is similar to the results of Jia *et al*., (2011) who showed that a high nitrogen application rate causes more nitrogen loss than low nitrogen application rate. Hui *et al*., (2022) found that when the applied amount of biochar reached 30 $t \cdot hm^{-2}$, the nitrogen accumulation and transport in spring wheat organs would be significantly inhibited, which is consistent with the results of this study. The maximum pre-anthesis contribution rate to grains of nitrogen was 0.52% under B3F2 treatment, and the maximum post-anthesis contribution rate to grains of nitrogen was 0.68% under B3F3 treatment, both of which were higher than that under single application of fertilizer or biochar, indicating that nitrogen contributes more to grains and could better promote grain growth under the combined application conditions. It also has a positive promoting effect on the production, which is consistent with the study of Wu *et al*., (2019). Biochar plays a role in reinforcing the soil structural stability, particularly by promoting aggregate formation and reducing the bulk density. Stable soil aggregates limit macro-pore connectivity and improve the physical entrapment of water and solutes, creating a more diffusive transport environment that reduces nitrate leaching. Stable soil aggregates limit macro-pore connectivity and improve the physical entrapment of water and solutes, creating a more diffusive transport environment that reduces nitrate leaching (Okebalama *et al*., 2023; Ghorbani *et al*., 2024). In soils, pH increases induced by biochar can reduce aluminum toxicity, enhance root nutrient uptake, and shift microbial communities toward pathways that are less conducive to rapid nitrification, thereby achieving the improvement of nitrogen absorption (Karimi *et al*., 2020; Cao *et al.*, 2018).

Effects of compound fertilizer combined with biochar on nitrogen use efficiency of winter wheat: The utilization rate of nitrogen fertilizer can be used to measure the rationality and effect of nitrogen fertilizer application. Previous studies have shown that the nitrogen use efficiency of wheat treated with urea alone is lower than that treated with biochar combined with urea (Aula *et al*., 2016), which is consistent with this study. Our results showed that nitrogen use efficiency in the second year was higher than that in the first year. In the first year, both NPFP and NUPE showed a first increasing and then decreasing trend, reaching the maximum value of 110.76 $kg \cdot kg^{-1}$ and 6.24 $kg \cdot kg^{-1}$ under B3F2 treatment, respectively. NAE also showed a similar trend, reaching the maximum value of 13.03 $kg \cdot kg^{-1}$ under B2F3 treatment. In the second year, both NHI and NUPE reached the maximum values of 77.50% and 6.57 $kg \cdot kg^{-1}$ under B3F2 treatment, which were significantly higher than those under other treatments. Both NPFP and NAE reached their maximum values under B2F2 treatment, which were 121.47 $kg \cdot kg^{-1}$ and 16.02 $kg \cdot kg^{-1}$, respectively. These results indicate that excessive N application will not improve the N use efficiency, and may even decrease the efficiency, which is consistent with the findings of Ayadi *et al*., (2016) that NAE will decrease when the N application rate is too high. Huo *et al*., (2004) also found that N use efficiency of winter wheat will decrease under excessive N application rate.

Economic benefits and environmental benefits: Calculate the production benefits based on the most suitable fertilization combination treatment B2F3.The wheat yield was 7600.35 $kg \cdot hm^{-2}$. The unit price is 2.5 $yuan \cdot kg^{-1}$ and the total value was 19,000.88 yuan. The cost of the compound fertilizer was 1530 yuan, and the cost of biochar was 20,625 yuan. The yield at the conventional fertilization level was 6871.14 $kg \cdot hm^{-2}$, the unit price was 2.5 $yuan \cdot kg^{-1}$, the total value was 17,177.85 yuan, and the total profit was 14882.85 yuan. Because biochar has long-lasting effects, it remains effective for 3 to 5 years after application. When the effect lasts for 3 years with biochar, the total cost of compound fertilizer and biochar each year is 8405 yuan, and the total profit is 19,000.88-8,405.00=10,595.88 yuan, which is 4286.98 yuan less than the profit from compound fertilizer alone. When using biochar for four and five years, the profits were respectively 2,567.68 yuan and 1,536.98 yuan less than when using only compound fertilizer alone. Biochar contains a large amount of high-molecular, high-density carbohydrates and various mineral nutrients, and has the characteristic of low density. During the entire life cycle of biochar, through its own "carbon sequestration", it can effectively increase the total amount of soil carbon pool by 64.3% (Chagas *et al*., 2022). In addition, biochar also has the ability to adsorb nitrate nitrogen, which can reduce nitrogen fertilizer loss. At the same time, it has water retention capacity, thereby enhancing the stability of the ecosystem. (Liang *et al*., 2014). However, it makes a significant contribution to the environment. Due to the high cost of biochar, currently only a small number of farmers are using it (Tongzhanxinyv, 2025). In the long run, as the cost of biochar decreases, farmers may show greater interest in using biochar, and their acceptance will increase. The application area will also expand significantly.

Conclusion

Soil is an important source of nitrogen supply for wheat plants. Compound fertilizer combined with biochar can increase the content of total N and alkali-hydrolyzed N in soil, thus promoting the absorption and utilization of soil nitrogen by plants, improving the accumulation and transfer of dry matter and nitrogen in plants, as well as enhancing the nitrogen use efficiency, so as to promote the rapid transfer of nutrients to grains and increase wheat yield. Finally, it is recommended that the optimal fertilizer level of 450 kg·hm^{-2} compound fertilizer combined with 7500 kg·hm^{-2} biochar should be applied to reduce the fertilizer use, increase efficiency, and promote the yield of winter wheat in this area.It should be noted that this study is site-specific, that results may vary under different soils/climates.

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