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The impact of the combined application of biochar and organic fertilizer on the growth and nutrient distribution in wheat under reduced chemical fertilizer conditions

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Organic fertilizer can help replenish fertility in cropland and reduce the use of chemical fertilizers, with biochar is an important soil conditioner. Under the premise of chemical fertilizer reduction, whether the application of biochar and organic fertilizer affect the yield and nutrient absorption and utilization of wheat? In this experiment, 7 treatments were set up in a randomized field trial with each treatment repeated three times: (1) CK1: no fertilizer; (2) CK2: 100% inorganic fertilizer; (3) T1: recommended amount of biochar with 100% inorganic fertilizer; (4) T2: recommended amount of organic fertilizer with 80% inorganic fertilizer; (5) T3: recommended amount of organic fertilizer and biochar with 80% inorganic fertilizer; (6) T4: recommended amount of organic fertilizer with 60% inorganic fertilizer; and (7) T5: recommended amount of organic fertilizer and biochar with 60% inorganic fertilizer. The results of this study showed that biochar combined with organic fertilizer can reduce the amount of chemical fertilizer by 40%~20% while ensuring wheat yield. Combining the input and output, 80% inorganic fertilizer with biochar and organic fertilizer (T3) was recommended. Under this fertilization scheme, the wheat yield was 37.32% higher than that of 100% chemical fertilizer (CK2), and the photosynthetic capacity was 54.97% higher at seedling stage. At the tillering stage, the root nitrogen content of T3 was significantly higher than that of T2, T4 and T5, which was 21.44%, 54.63% and 60.16%, respectively. The nitrogen content of T3 was significantly higher than that of other treatments at maturity, and the nitrogen content of T3 was 4.38% higher than that of CK2. At heading stage, the nitrogen allocated to T3 leaves was 4.71% higher than CK2. Overall, the results of this study showed that the combination of biochar and organic fertilizer could effectively reduce the application of chemical fertilizer. The recommended fertilizer regimen was 80% inorganic fertilizer with biochar and organic fertilizer, under this scheme, wheat had stronger photosynthetic capacity and better nutrient absorption and distribution mechanism.

Keywords Biochar, Chemical fertilizer reduction, Wheat, Nutrient absorption, Nutrient distribution

As the most densely populated nation globally, China prioritizes agricultural development[1]. Given the prevailing national circumstances, the advantages derived from ongoing wasteland reclamation fall short of meeting actual demands. Consequently, enhancing crop yield and quality on existing cultivated land becomes imperative[2,3]. Chemical fertilizers have emerged as essential components, ensuring both high and consistent plant yields through their convenient application and rapid efficacy[4]. China's fertilizer requirement is the largest in the world, but the fertilizer utilization rate is less than 30%[5–7]. Problems, such as the misuse of fertilizers limit the crop yield potential. Paradoxically, this not only diminishes the efficacy of fertilization but also leads to soil fertility degradation, reduced crop quality and yield, posing a threat to the sustainable trajectory of agriculture[8,9].

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To solve these problems, it is necessary to reduce the use of fertilizer and improve the efficiency of fertilizer use. Studies have shown that the agricultural sector is currently confronted with a significant crisis stemming from climate change, excessive application of chemical fertilizers and other reasons[10]. Excessive phosphorus (P) along with drained water from farmland in the arid and semiarid watersheds when entering into water bodies brings about serious environmental problems in the aquatic ecosystem[11]. Hence, from the vantage point of ecological environmental preservation and the pursuit of agricultural green development, the adoption of novel soil amendments to enhance crop yield and soil quality stands as a crucial measure for fertilizer reduction. It also represents a focal point in realizing the green and sustainable evolution of agriculture.

Biochar, a carbon-rich solid derived from the high-temperature, anaerobic pyrolysis of biomass, constitutes a novel soil amendment[12]. Its incorporation into soil not only enhances the soil environment and mitigates acidification but also augments the soil's carbon sink capabilities, fostering crop germination[13]. With a substantial specific surface area and high porosity, biochar's loose structure effectively reduces soil bulk density, elevates soil porosity and water content, and accelerates nutrient assimilation by crops, thereby promoting higher biomass production[14]. Field experiments conducted in tea gardens by Jiang demonstrated that at an application rate of 16t/hm^2, biochar significantly increased total soil porosity, field water capacity, and saturated water content[15]. As a conventional substitute for traditional fertilizers, organic fertilizers have demonstrated efficacy in enhancing the physical and chemical attributes of soil, thereby ameliorating fertility and augmenting crop yield and quality[16–18]. Judicious reduction in fertilizer application and the appropriate incorporation of organic fertilizers yield positive outcomes in terms of enhancing crop productivity and ameliorating the ecological quality of soil. With a substantial reserve of approximately 5.7 billion tons of organic fertilizer resources in China, there exists significant untapped potential for application[19]. Tailoring the consumption of organic fertilizer resources to local conditions and adopting agricultural recycling represent mutually beneficial strategies for enhancing the efficiency and quality of agricultural production, as well as fostering a green and sustainable ecological environment. Empirical evidence supports the assertion that the partial substitution of chemical fertilizers with organic counterparts is an effective approach to curbing fertilizer application, improving crop quality, and augmenting income in crop production[20–22]. Studies have shown that Biochar induced the dominant diazotroph community succession and increased Rhizobiales, which contributed to the biological nitrogen fixation activity[23]. Meanwhile, the relative increase in total carbon was favored by increasing biochar rates applied to fine-textured soils with low carbon content in temperate climate regions seen through short-term experiments conducted under controlled conditions[24].

The growth and development of crops entail a complex process wherein nutrient absorption and distribution play pivotal roles. Disparities exist in the capacity of crops to absorb and utilize nutrients under varying environmental conditions, as soil pH, temperature, humidity, and light directly influence nutrient absorption efficiency[25]. Notably, in acidic soils, specific crops may exhibit diminished phosphorus absorption, whereas in alkaline soils, enhanced absorption may be observed[26]. Furthermore, the nutritional requirements of distinct crop organs vary during growth, and crops dynamically adjust these requirements based on growth stages and physiological states[27]. For instance, during early growth stages, crops allocate more nutrients to leaves, promoting photosynthesis and leaf area expansion. Conversely, in later growth stages, crops prioritize nutrient allocation to fruits or seeds to support their development and maturation[28–30]. Soil nutrient content disparities directly impact crop growth and yield. While a nutrient-rich soil prompts increased absorption of that specific nutrient, deficiencies in key nutrients can impede crop growth, leading to suboptimal states. Nutrient imbalances compromise optimal growth, subsequently affecting yield and output quality[31–33]. Significantly, variations in nutrient distribution exert pronounced effects on crop yield and quality. Insufficient critical nutrients at specific growth stages may induce growth stagnation and heightened susceptibility to diseases, ultimately impacting the final yield.

This research endeavors to synergize biochar with organic fertilizer to attain a reduction in fertilizer usage. However, the regulatory mechanisms governing nutrient absorption, distribution, and accumulation in crops under these conditions remain unclear. Consequently, this study centers on the examination of the growth, development, and nutrient dynamics in wheat under reduced fertilizer conditions through the integration of biochar and organic fertilizer. By analyzing wheat agronomic traits, biomass, photosynthetic capacity and final yield, the growth and development of wheat under different nutrient control conditions were comprehensively measured. Meanwhile, nitrogen content and nitrogen accumulation in different parts of wheat were analyzed to explore the changes of nitrogen uptake and utilization under different nutrient control conditions. We previously assumed that (1) Reducing the application amount of fertilizer might reduce the plant height yield and other traits of wheat, (2) The addition of organic fertilizer would weaken the influence of fertilizer reduction on these traits of wheat, and the addition of biochar might bring better performance. But the specific amount of fertilizer reduction and the effect of biochar addition were not clear.

Materials and methods

Experiment design

This research was conducted from October 2021 to May 2022 in the test site of college of agronomy and biotechnology, Southwest University, Chongqing, China. The research area was located at 220 m in altitude, 29°49′32″N in latitude, and 106°26′02″E in longitude. The soil of the experimental site was dryland purple soil with relatively uniform fertility. The main physical and chemical properties of the soil was: soil bulk density 1.21 g·cm^{-3}, pH value 6.47, organic matter content 28.00 g·kg^{-1}, total nitrogen content 1.68 g·kg^{-1}, total phosphorus content 1.46 g·kg^{-1}, total potassium content 34.54 g·kg^{-1}, the alkaline hydrolysable nitrogen 35.23 mg·kg^{-1}, the available phosphorus 18.13 mg·kg^{-1}, and the available potassium 270.23 mg·kg^{-1}.

The field trial was conducted in a randomized block design with 7 treatments and 3 replicates. Each plot was 10 m long and 10 m wide, covers an area of 100 m^2, and each plot was 50 cm apart. The seven treatments were: (1) CK1: no fertilizer; (2) CK2: 100% inorganic fertilizer; (3) T1: recommended amount of biochar with 100% inorganic fertilizer; (4) T2: recommended amount of organic fertilizer with 80% inorganic fertilizer; (5) T3: recommended amount of organic fertilizer and biochar with 80% inorganic fertilizer; (6) T4: recommended amount of organic fertilizer with 60% inorganic fertilizer; and (7) T5: recommended amount of organic fertilizer and biochar with 60% inorganic fertilizer. Urea, calcium superphosphate, and potassium chloride were used as inorganic fertilizers. The biochar used was produced from rice husks through pyrolysis at 400 °C under limited oxygen and was supplied by Nanjing Qinfeng Straw Technology Co., LTD., China. The basic physical and chemical properties of the biochar were as follows: pH 9.90 ± 0.04, total nitrogen 5.76 ± 0.23 g·kg^{-1}, total phosphorus 3.75 g·kg^{-1}, total potassium 21.15 ± 0.17 g·kg^{-1}, CEC 34.49 ± 5.16 cmol·kg^{-1}, and organic carbon 439.01 ± 40.06 g·kg^{-1} (measured in 2021). The organic fertilizer used in the experiment was provided by Beijing Xingpeng Agricultural Development Co., Ltd. The primary component of the organic fertilizer was pig manure, and the main technical parameters were organic matter content > 50%, amino acid + nucleotide > 3%, moisture lower than 18.0%, effective viable count > 50 million/g, Zn + B + Fe + Mn + Mo + Si > 0.1%. Specific fertilizer application rates for each treatment are presented in Table 1.

In early October 2021, biochar and the fertilizer were evenly spread onto the soil surface and immediately tilled into the soil for ridging; a furrow depth of 10–15 cm was opened between the ridges for fertilization prior to sowing. Wheat cv Yumai No.13 was sown by placing two seeds per hole at the middle of the ridges to with 10 cm plant spacing and 10 cm row spacing, and was harvested in May 2022. Wheat cv Yumai No.13 is a semi-winter, multi-spike type, mid-early-maturing variety. All treatments had the same field management and the other management measures were the same as field routine management.

Plant sampling and analysis

Five plants with similar growth were selected for each treatment at seedling stage, tillering stage, elongation stage, heading stage and flowering stage. From 9:00 to 11 on sunny days: The net photosynthetic rate (Photo), transpiration rate (Trmmol), stomatal conductance (Cond) and intercellular carbon dioxide concentration (Ci) of the leaves were measured by a portable photosynthetic apparatus (Li-6400, USA). The chlorophyll content (SPAD) of wheat leaves was determined by SPAD-502, Japan.

At the seedling, tillering, jointing, heading, flowering, and maturity stages, the height and stem diameter of wheat plants were measured. Five plants with similar growth were selected from each treatment, their organs were separated, subjected to 30 min of greening treatment at 105 °C, and then dried at 80 °C until a constant weight was achieved. The dry matter weight of each organ was then recorded. The dry samples of each organ were crushed and boiled by concentrated H_2SO_4-H_2O_2 method. Nitrogen in the boiled solution was determined by Kjeldahl nitrogen determination instrument (KN520), phosphorus by ammonium molybdate colorimetric method (UV-2450) and potassium by flame photometer (PEAA800)[34].

Statistical analysis

SPSS 19.0 software package (IBM, Armonk, USA) was used for statistical analysis. Univariate analysis of variance was used for all data, followed by Tukey's HSD test, $P \leq 0.05$. R software (Version 4.0.0) was employed to perform the following analyses. analyze the relationship between wheat yield components and wheat yield was calculated using principal coordinate analysis (PCoA) in the "vegan" package. Normalize data when analytical assumptions need to be met[35].

Results

Agronomic characters and photosynthetic capacity

By systematically assessing the plant height (Table 2), stem diameter (Table 3), and dry matter weight (Fig. 1) of wheat throughout its entire growth period, the impact of the amalgamation of biochar and organic fertilizer on the growth and development of wheat, particularly in the context of reduced inorganic fertilizer application, could be quantified. The data presented in Table 1 had revealed that the wheat plant height, under various treatments, exhibited no significant variance as anticipated. Notably, during the seedling stage, due to the absence of supplementary fertilizer, the wheat plant height in CK1 had been markedly inferior, registering reductions of 30.65%, 24.43%, 29.22%, 22.27%, 20.31%, and 18.57% in comparison to CK2, T1, T2, T3, T4, and T5, respectively. By the jointing stage, treatments T4 and T5 had exhibited noteworthy distinctions from

Treatment	Application amount (kg/ha)				
	Urea	Calcium superphosphate	Potassium chloride	Organic fertilizer	Biochar
CK1	0	0	0	0	0
CK2	489.1	750	150	0	0
T1	489.1	750	150	0	10,000
T2	391.1	600	120	3000	0
T3	391.1	600	120	3000	10,000
T4	293.5	450	90	3000	0
T5	293.5	450	90	3000	10,000

Table 1. The fertilizer application for each treatment. Urea (N 46%); Calcium superphosphate (P 16%); Potassium chloride (K 12%).

Treatment	Seedling	Tillering	Jointing	Heading	Flowering	Maturity
CK1	17.10 ± 2.21 b	47.93 ± 0.50 ab	78.00 ± 0.7 a	82.33 ± 0.58 a	86.50 ± 0.50 a	81.00 ± 60.8 a
CK2	24.66 ± 0.95 a	49.56 ± 0.85 a	74.66 ± 0.58 a	79.33 ± 3.06 a	85.33 ± 6.11 a	85.00 ± 1.00 a
T1	22.63 ± 1.02 a	51.20 ± 1.55 a	72.66 ± 1.52 ab	81.33 ± 5.51 a	87.66 ± 4.04 a	80.00 ± 3.60 a
T2	24.16 ± 1.44 a	49.97 ± 0.88 a	75.00 ± 3.00 a	81.66 ± 3.79 a	82.66 ± 6.65 a	79.33 ± 3.78 a
T3	22.00 ± 1.57 a	47.10 ± 0.40 ab	71.33 ± 2.89 ab	78.00 ± 9.17 a	86.66 ± 1.52 a	81.33 ± 3.06 a
T4	21.46 ± 0.21 a	48.46 ± 2.20 a	63.33 ± 5.77 b	78.33 ± 1.52 a	77.66 ± 1.15 b	79.33 ± 5.50 a
T5	21.00 ± 2.56 a	46.93 ± 1.36 b	65.00 ± 4.36 b	77.33 ± 2.51 a	81.66 ± 9.45 a	79.33 ± 6.65 a

Table 2. Plant height during the whole growth period of wheat under different treatments (cm). Different lower letters indicate significant differences between processes ($p < 0.05$).

Treatment	Seedling	Tillering	Jointing	Heading	Flowering	Maturity
CK1	1.87 ± 0.10 ab	4.37 ± 0.20 c	5.63 ± 0.24 c	6.06 ± 0.48 a	5.72 ± 0.08 abc	4.42 ± 0.26 a
CK2	1.94 ± 0.03 a	4.58 ± 0.29 bc	9.03 ± 0.17 ab	6.63 ± 0.89 a	5.53 ± 0.41 bc	4.55 ± 0.15 a
T1	2.04 ± 0.09 a	4.88 ± 0.27 abc	11.37 ± 0.11 a	5.78 ± 0.35 a	5.63 ± 0.23 bc	4.42 ± 0.81 a
T2	1.78 ± 0.04 b	5.29 ± 0.16 ab	9.90 ± 1.29 ab	6.63 ± 0.48 a	5.93 ± 0.27 ab	4.52 ± 0.20 a
T3	1.86 ± 0.04 ab	5.05 ± 0.10 abc	9.48 ± 0.68 ab	6.31 ± 0.59 a	6.05 ± 0.23 a	4.61 ± 0.15 a
T4	2.03 ± 0.06 a	5.54 ± 0.56 a	7.85 ± 1.34 bc	5.73 ± 0.16 a	5.62 ± 0.33 bc	4.53 ± 3.00 a
T5	1.97 ± 0.06 a	5.14 ± 0.24 ab	6.11 ± 1.94 c	5.89 ± 0.93 a	5.43 ± 0.15 c	4.12 ± 0.14 b

Table 3. Stem diameter during the whole growth period of wheat under different treatments (mm). Different lower letters indicate significant differences between processes ($p < 0.05$).

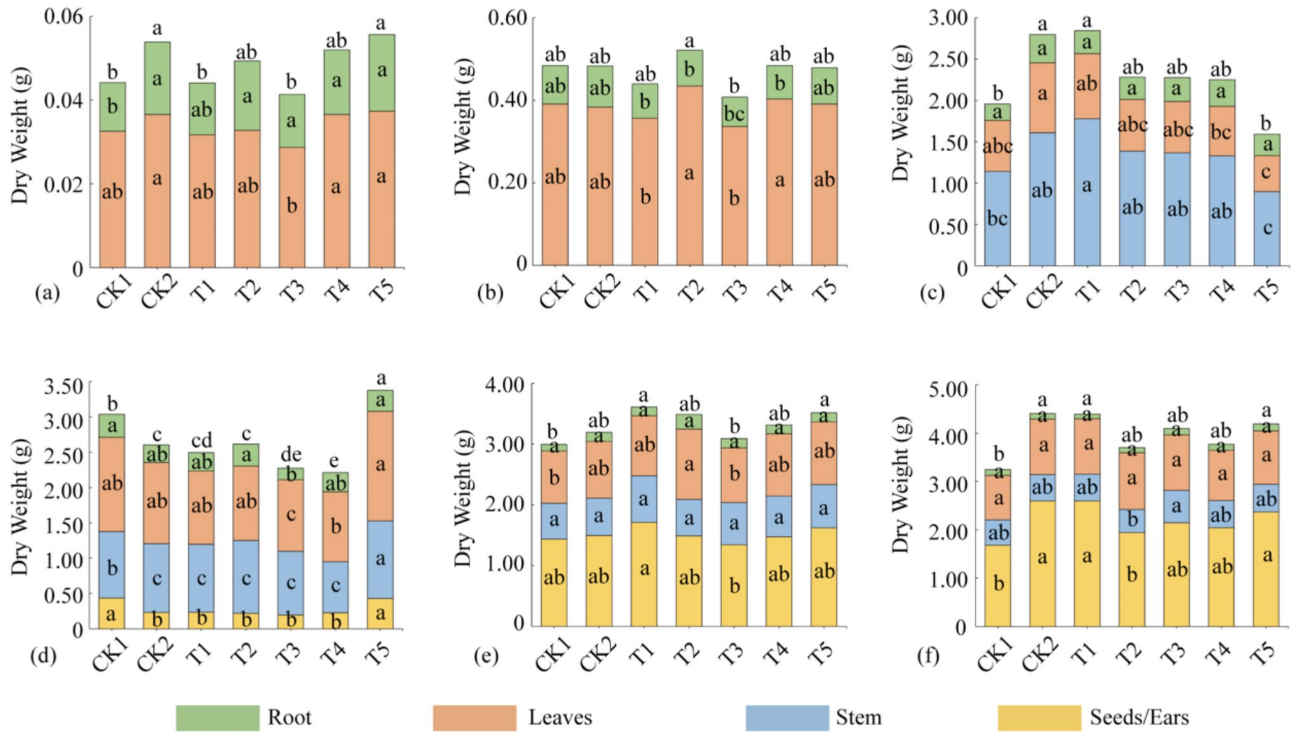

Fig. 1. Wheat biomass during the whole growth period under different treatments (g). (**a**) Seedling stage; (**b**) Tillering stage; (**c**) Jointing stage; (**d**) heading stage; (**e**) flowering stage; (**f**) maturity stage. Different lower letters indicate significant differences between processes ($p < 0.05$).

other treatments ($P < 0.05$). Conversely, at maturity, there had been an absence of significant divergence in plant height across treatments ($P < 0.05$). Regarding stem diameter, the synergistic application of biochar and organic fertilizer had exerted a more pronounced influence on stem thickness during the initial growth and development phases of wheat under reduced inorganic fertilizer conditions. At the seedling stage, the stem diameter of T2 had demonstrated a noteworthy reduction compared to other treatments, with declines of 4.18%, 8.24%, 12.74%, 4.30%, 12.31%, and 9.64% in contrast to CK1, CK2, T1, T3, T4, and T5, respectively. During the tillering stage, the stem diameter of CK1 had been markedly inferior compared to other treatments, registering a 26.77% reduction compared to T4. As the growth progressed to the jointing stage, the disparity in stem diameter between treatments had become more pronounced, with CK1 exhibiting a 93.95% reduction compared to T1. At maturity, the distinctions between treatments had diminished, with only T5 demonstrating significant differences from other treatments, whereas no significant variances had been observed among the remaining treatments.

During the seedling stage, the biomass of CK1, T1, and T3 had exhibited a significant decrease compared to other treatments, though such differences were not statistically significant at the tillering stage. At the jointing stage, the biomass of CK1 and T5 had displayed a significant reduction in comparison to CK2 and T1. Specifically, CK1 had exhibited a 43.05% and 45.35% decrease compared to CK2 and T1, while T5 had registered a substantial decline of 76.02% and 78.85% relative to CK2 and T1. The primary contributing factor to this disparity had been the significant variation in the dry weight of leaves among the different treatments. By maturity, the distinctions in biomass between treatments had been primarily attributed to variations in the dry weight of wheat grains, with the dry weight ranking having been as follows: T1 > CK2 > T5 > T3 > T4 > T2 > CK1.

As evidenced by Table 4, the primary determinants influencing the variations in photosynthetic capacity among different treatments had been disparities in Ci, Trmmol, and SPAD. As the wheat growth had advanced, the disparities in photosynthetic capacity among treatments had gradually intensified. Notably, at the heading stage, the photosynthetic rate of T2 had exceeded that of T3 by 13.14%, and T4 had surpassed T5 by 11.24%. Similarly, during the flowering stage, T2 had exhibited a 24.44% increase over T3, and T4 had demonstrated a 21.13% elevation compared to T5. Concurrently, at the heading stage, the Ci of T1 had reached its peak, surpassing that of T4 by 7.76%. Additionally, the Trmmol of T4 had exceeded that of T1 by 24.35%. Even at the flowering stage, T1 had maintained a higher SPAD, surpassing T5 by 5.64%.

Yield and its constituent factors

Table 5 illustrated the disparities in wheat yield and its components across various treatments. Notably, the inclusion of biochar had significantly augmented yield in comparison to treatments lacking biochar. Specifically, the yield of T1 had surpassed that of CK2 by a substantial 42.65%, and the yield of T3 had exceeded that of T2, resulting in a 27.96% increase. Similarly, T5 had exhibited a higher yield than T4, with an increment of 17.00%. Concurrently, all yield components indicated that treatments incorporating biochar had outperformed those without biochar at the time. Of all the yield components, the variance in grain number per spike had closely mirrored the differences in overall yield and had exhibited the most substantial contribution rate (Fig. 2). The number of grains per spike in T1 had exceeded that in CK2 by 21.67%, while T3 had exhibited a 9.82% increase over T2. Furthermore, the number of grains per spike in T5 had surpassed that of T4, demonstrating a noTable 20.36% elevation.

Nutrient absorption

Table 6 presented the variations in nutrient content across different parts of wheat during its entire growth period. Upon examining the nitrogen content in wheat shoots under diverse treatments, it revealed notable distinctions during the seedling stage. Specifically, the shoot nitrogen content of CK2 had significantly exceeded that of other treatments, whereas T2 and T5 had exhibited markedly lower levels compared to alternative treatments. CK2 had surpassed T2 and T5 by 9.10% and 9.34%, respectively. During the tillering stage, the nitrogen content in the shoots of T4 and T5 had registered a significant reduction relative to other treatments, while the nitrogen content in the roots of T3 had significantly surpassed that of T2, T4, and T5 by 21.44%, 54.63%, and 60.16%, respectively. At the heading stage, no significant disparity had been observed in nitrogen content in the roots under each treatment, but the stems and leaves had displayed a consistent pattern: T2 > T3, T4 > T5. Specifically, the nitrogen content of T2 had exceeded T3 by 17.64%, and the stems of T4 had exhibited a 45.09% increase compared to T5. Upon reaching maturity, the nitrogen content in the seeds of T3 and T5 had significantly surpassed that of other treatments. The T3 seeds had displayed a 6.98% increase over T2, and T5 seeds had surpassed T4 by 5.27%.

As evident from Table 7, the phosphorus content in both the shoots and roots of wheat, subject to various treatments, had exhibited divergent patterns during the seedling stage. Specifically, the shoot phosphorus content of T2 had surpassed that of T3 by 10.53%, and the phosphorus content in the shoots of T4 had exceeded that of T5 by 4.26%. Conversely, the phosphorus content in the roots of T2 had been lower than that of T3, registering a decrease of 11.90%, while the underground portion of T4 had displayed a phosphorus content 11.36% lower than that of T5. Upon reaching the jointing stage, the phosphorus content in T2 leaves had been significantly elevated compared to T3, demonstrating an 18.87% increase. Similarly, the phosphorus content in T4 leaves had exceeded that of T5 by 11.29%. As the heading stage had unfolded, the roots, stems, and leaves of each treatment had exhibited a consistent pattern, specifically T2 > T3, T4 > T5. Notably, the phosphorus content in the roots of T2 had surpassed that of T3 by 32.65%, while the phosphorus content in the roots of T4 had exceeded that of T5 by 37.85%. Furthermore, the phosphorus content in the stems of T2 had exceeded that of T3 by 62.45%, and the phosphorus content in the stems of T4 had been 24.45% higher than that of T5. Additionally, the phosphorus content in T2 leaves had been 43.31% higher than that of T3, and T4 leaves had exhibited an 8.31% increase compared to T5.

Stage	Treatment	Photo $\mu molCO_2\cdot m^{-2}\cdot s^{-1}$	Cond $molH_2O\cdot m^{-2}\cdot s^{-1}$	Ci $molH_2O\cdot m^{-2}\cdot s^{-1}$	Trmmol $mmolH_2O\cdot m^{-2}\cdot s^{-1}$	SPAD
Seedling	CK1	4.85 ± 0.88 c	0.31 ± 0.04 ab	475.30 ± 6.40 a	1.68 ± 0.20 c	38.56 ± 1.62 a
	CK2	5.33 ± 0.26 bc	0.39 ± 0.01 a	477.17 ± 3.36 a	2.18 ± 0.02 abc	41.08 ± 1.64 a
	T1	5.93 ± 0.25 bc	0.38 ± 0.05 a	464.16 ± 4.68 bc	2.22 ± 0.23 ab	41.56 ± 1.10 a
	T2	6.16 ± 0.69 bc	0.34 ± 0.07 a	461.56 ± 5.63 bc	2.18 ± 0.41 abc	41.15 ± 1.14 a
	T3	8.26 ± 0.63 a	0.41 ± 0.08 a	463.16 ± 2.50 bc	2.53 ± 0.47 a	41.66 ± 2.98 a
	T4	6.14 ± 1.22 bc	0.36 ± 0.06 a	468.45 ± 8.95 b	2.39 ± 0.38 a	38.90 ± 1.13 a
	T5	6.55 ± 0.65 b	0.25 ± 0.01 b	456.83 ± 1.87 c	1.75 ± 0.17 bc	38.90 ± 1.62 a
Tillering	CK1	5.37 ± 0.82 a	0.48 ± 0.11 a	463.25 ± 1.40 a	1.21 ± 0.18 c	48.13 ± 0.87 a
	CK2	5.85 ± 0.35 a	0.53 ± 0.08 a	458.96 ± 2.16 a	1.49 ± 0.17 b	47.66 ± 2.07 a
	T1	6.08 ± 0.78 a	0.54 ± 0.06 a	459.70 ± 7.50 a	1.55 ± 0.19 b	45.76 ± 1.44 a
	T2	6.43 ± 1.22 a	0.58 ± 0.07 a	457.63 ± 3.49 a	1.79 ± 0.13 a	47.00 ± 0.50 a
	T3	6.72 ± 0.82 a	0.56 ± 0.09 a	461.05 ± 2.27 a	2.01 ± 0.17 a	47.03 ± 1.59 a
	T4	6.69 ± 1.33 a	0.58 ± 0.09 a	456.78 ± 4.56 a	1.89 ± 0.24 a	48.00 ± 1.56 a
	T5	6.27 ± 0.29 a	0.51 ± 0.09 a	457.47 ± 1.49 a	1.97 ± 0.23 a	47.36 ± 0.93 a
Jointing	CK1	5.14 ± 0.08 a	0.34 ± 0.09 a	449.90 ± 11.03 c	1.00 ± 0.06 b	47.96 ± 1.40 ab
	CK2	5.35 ± 0.18 a	0.36 ± 0.05 a	456.56 ± 4.72 abc	1.08 ± 0.08 b	49.91 ± 1.03 a
	T1	5.29 ± 0.25 a	0.41 ± 0.04 a	465.07 ± 4.53 a	1.31 ± 0.10 a	48.75 ± 0.58 ab
	T2	5.39 ± 0.16 a	0.37 ± 0.04 a	461.75 ± 2.25 ab	1.30 ± 0.09 a	48.05 ± 1.43 ab
	T3	5.25 ± 0.38 a	0.41 ± 0.04 a	460.13 ± 2.79 ab	1.43 ± 0.08 a	48.71 ± 1.72 ab
	T4	4.96 ± 0.26 a	0.37 ± 0.05 a	453.49 ± 4.66 bc	1.32 ± 0.09 a	49.45 ± 1.18 a
	T5	5.23 ± 0.20 a	0.36 ± 0.04 a	453.88 ± 3.48 bc	1.35 ± 0.10 a	47.11 ± 1.20 b
Heading	CK1	12.18 ± 1.31 a	0.45 ± 0.12 a	409.31 ± 12.07 ab	3.38 ± 0.26 c	49.60 ± 0.27 ab
	CK2	12.42 ± 1.86 a	0.44 ± 0.08 a	400.56 ± 9.78 abc	3.55 ± 0.47 c	50.50 ± 2.52 a
	T1	11.44 ± 0.93 a	0.53 ± 0.10 a	413.93 ± 8.25 a	4.64 ± 0.65 b	49.00 ± 0.75 ab
	T2	12.22 ± 1.05 a	0.50 ± 0.10 a	397.42 ± 11.53 bcd	4.83 ± 0.61 b	47.38 ± 2.13 b
	T3	10.8 ± 0.49 a	0.55 ± 0.05 a	405.39 ± 3.23 ab	5.71 ± 0.49 a	50.65 ± 1.52 a
	T4	12.77 ± 1.68 a	0.47 ± 0.10 a	384.10 ± 9.92 d	5.77 ± 0.56 a	50.05 ± 0.58 a
	T5	11.48 ± 1.32 a	0.45 ± 0.04 a	387.22 ± 11.65 cd	6.38 ± 0.16 a	49.31 ± 1.31 ab
flowering	CK1	5.00 ± 1.49 a	0.31 ± 0.08 a	428.70 ± 9.49 a	1.64 ± 0.31 a	53.90 ± 2.16 a
	CK2	4.62 ± 0.76 a	0.26 ± 0.04 ab	422.47 ± 13.08 ab	1.48 ± 0.28 a	54.26 ± 0.51 a
	T1	4.04 ± 0.57 a	0.24 ± 0.12 ab	414.24 ± 15.01 abc	1.38 ± 0.54 a	52.93 ± 0.19 ab
	T2	5.65 ± 0.68 a	0.19 ± 0.05 ab	409.72 ± 12.57 bc	0.96 ± 0.17 b	52.14 ± 0.83 ab
	T3	4.54 ± 1.24 a	0.15 ± 0.02 b	398.27 ± 10.76 bc	0.73 ± 0.12 b	52.81 ± 1.02 ab
	T4	5.33 ± 0.65 a	0.26 ± 0.01 ab	407.01 ± 4.98 c	1.57 ± 0.06 a	51.05 ± 1.00 b
	T5	4.40 ± 0.40 a	0.27 ± 0.01 ab	401.16 ± 12.57 c	1.55 ± 0.25 a	51.55 ± 2.15 b

Table 4. Photosynthetic capacity of wheat during the whole growth period under different treatments. Different lower letters indicate significant differences between processes ($p < 0.05$).

Stage	Spikes per plant	Grains per spike	Thousand grain weight (g)	Yield (kg/hm^2)
CK1	6.43 ± 0.54 c	26.61 ± 0.54 e	20.31 ± 0.23 e	933.96 ± 29.60 d
CK2	7.25 ± 1.09 b	40.65 ± 2.07 c	22.12 ± 0.11 b	1934.96 ± 370.73 b
T1	7.66 ± 0.54 b	49.47 ± 2.61 a	22.96 ± 0.28 a	2760.15 ± 103.98 a
T2	7.24 ± 0.44 b	44.88 ± 2.58 b	20.96 ± 0.18 d	2076.55 ± 221.41 b
T3	7.41 ± 1.34 b	49.25 ± 0.44 a	21.68 ± 0.61 c	2657.2 ± 247.76 a
T4	8.88 ± 0.44 a	33.44 ± 1.34 d	22.18 ± 0.12 b	1705.86 ± 264.11 c
T5	6.85 ± 0.83 c	40.22 ± 1.78 c	22.45 ± 0.11 b	1995.87 ± 198.89 b

Table 5. Yield and yield components of wheat under different treatments. Different lower letters indicate significant differences between processes ($p < 0.05$).

As observed in Table 8, the shoot potassium content and phosphorus content of wheat across diverse treatments had exhibited analogous trends, yet divergent patterns emerged at the seedling stage. Specifically, the potassium content in the shoot of T2 had surpassed that of T3 by 17.25%, with T2 demonstrating a noTable 17.25% elevation over T3. Similarly, the potassium content in the shoot of T4 had exceeded that of T5

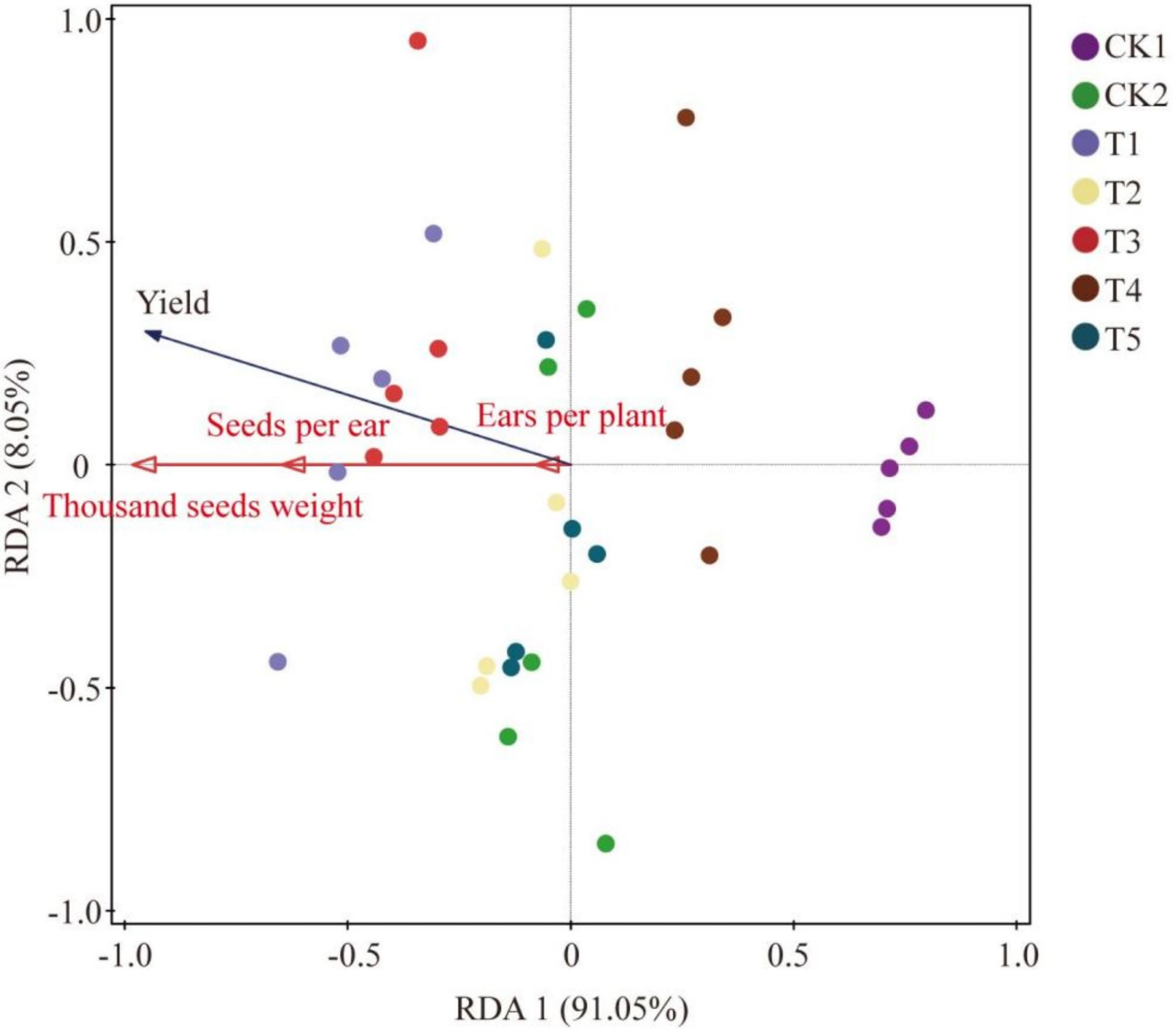

Fig. 2. The PCoA of wheat yield and yield components in different treatments.

by 15.61%, reflecting a 15.61% increase. Conversely, the potassium content in the roots of T2 had been lower than that of T3, registering a 7.21% decrease, while the potassium content in the roots of T4 had been 4.19% lower than that of T5. Advancing to the tillering stage, the disparities between T2 and T3, as well as between T4 and T5, had continued to escalate. Specifically, the potassium content in the roots of T2 had surpassed that of T3 by a substantial 47.19%, and the potassium content in the roots of T4 had exceeded that of T5 by 49.58%.

Nutrient distribution

The depicted figures delineated the nutrient distribution in distinct segments of wheat across varying periods (Figs. 3, 4 and 5). Figure 3 illustrated notable differences in nitrogen distribution among wheat treatments during the seedling stage. CK1, T4, and CK2 had exhibited a higher allocation of nitrogen to the shoot, constituting 82.62–83.41% of the total plant nitrogen. Conversely, other treatments, particularly T2 and T3, had demonstrated lower nitrogen allocation to the shoot, accounting for only 79.50% and 79.13% of the total nitrogen. In tandem, nitrogen allocation to the roots had been significantly higher in T2 and T3 compared to other treatments. By the heading stage, the nitrogen allocated to wheat leaves under T2 and T3 treatments had markedly surpassed that of other treatments, reaching 64.04% and 65.56%. At maturity, the nitrogen content allocated to T2 seeds had been lower than that of T3, exhibiting a 11.70% decrease. Similarly, the nitrogen content allocated to T4 grains had been lower than that of T5, with a reduction of 2.98%. These differences among T2, T3, T4, and T5 had been statistically significant.

Figure 4 had shown that at the tillering stage, the phosphorus assigned to the shoot by T1, T2, and T3 treatments had been significantly higher than that by other treatments, reaching 76.34%, 75.99%, and 76.97%, respectively. CK1, CK2, T4, and T5 had allocated 59.03%, 61.01%, 66.24%, and 58.75% of phosphorus to the

Stage	Parts	CK1	CK2	T1	T2	T3	T4	T5
Seedling	Shoot	2.58 ± 0.02 b	2.65 ± 0.02 a	2.63 ± 0.04 ab	2.43 ± 0.02 c	2.57 ± 0.02 b	2.58 ± 0.02 b	2.43 ± 0.02 c
	Root	1.34 ± 0.02 b	1.18 ± 0.02 d	1.42 ± 0.02 c	1.24 ± 0.02 d	1.54 ± 0.02 a	1.21 ± 0.02 d	1.09 ± 0.08 e
Tillering	Shoot	5.15 ± 0.07 a	5.01 ± 0.32 a	5.08 ± 0.04 a	5.00 ± 0.09 a	4.91 ± 0.15 a	4.60 ± 0.10 b	4.31 ± 0.18 c
	Root	2.19 ± 0.01 b	2.08 ± 0.21 b	2.15 ± 0.02 b	2.35 ± 0.01 b	2.86 ± 0.04 a	1.84 ± 0.22 c	1.78 ± 0.09 c
Jointing	Stem	2.56 ± 0.25 ab	2.45 ± 0.15 b	2.89 ± 0.22 ab	2.86 ± 0.17 ab	2.99 ± 0.18 a	2.98 ± 0.09 a	2.69 ± 0.18 ab
	Leaves	4.63 ± 0.06 ab	4.67 ± 0.05 a	4.48 ± 0.04 bc	4.54 ± 0.09 abc	4.57 ± 0.04 ab	4.58 ± 0.04 ab	4.42 ± 0.04 c
	Root	1.65 ± 0.10 a	1.30 ± 0.12 ab	1.45 ± 0.09 ab	1.22 ± 0.08 b	1.36 ± 0.26 ab	1.48 ± 0.17 ab	1.17 ± 0.05 b
Heading	Stem	1.28 ± 0.02 ab	1.49 ± 0.12 a	1.35 ± 0.01 ab	1.39 ± 0.07 ab	1.18 ± 0.02 bc	1.48 ± 0.03 a	1.02 ± 0.20 c
	Leaves	3.48 ± 0.08 d	3.79 ± 0.05 b	3.67 ± 0.02 c	3.75 ± 0.03 bc	3.57 ± 0.06 d	3.91 ± 0.05 a	3.50 ± 0.01 d
	Ear	1.80 ± 0.21 a	1.88 ± 0.06 a	1.92 ± 0.03 a	1.77 ± 0.15 a	1.86 ± 0.09 a	2.00 ± 0.10 a	1.94 ± 0.13 a
	Root	1.02 ± 0.01 a	0.93 ± 0.07 a	1.01 ± 0.03 a	1.01 ± 0.15 a	0.95 ± 0.22 a	1.07 ± 0.02 a	0.94 ± 0.04 a
Flowering	Stem	0.68 ± 0.02 d	0.88 ± 0.02 a	0.69 ± 0.01 d	0.74 ± 0.04 c	0.80 ± 0.01 b	0.82 ± 0.01 b	0.57 ± 0.01 e
	Leaves	2.70 ± 0.01 cd	3.11 ± 0.25 a	2.73 ± 0.05 bcd	2.94 ± 0.01 abc	2.98 ± 0.03 ab	2.95 ± 0.01 abc	2.58 ± 0.02 d
	Ear	1.84 ± 0.08 b	2.02 ± 0.01 a	1.90 ± 0.02 ab	1.94 ± 0.04 ab	1.92 ± 0.01 ab	2.07 ± 0.07 a	1.93 ± 0.11 b
	Root	0.79 ± 0.03 bc	0.71 ± 0.18 bc	1.12 ± 0.07 a	0.81 ± 0.05 bc	0.91 ± 0.04 b	0.73 ± 0.02 b	0.67 ± 0.08 c
Maturity	Stem	0.63 ± 0.01 a	0.51 ± 0.01 a	0.61 ± 0.01 a	0.79 ± 0.01 a	0.63 ± 0.01 a	0.54 ± 0.01 a	0.79 ± 0.30 a
	Leaves	0.63 ± 0.02 b	0.50 ± 0.01 d	0.57 ± 0.02 bc	0.79 ± 0.02 a	0.61 ± 0.08 b	0.54 ± 0.02 cd	0.76 ± 0.01 a
	Seeds	2.29 ± 0.02 b	2.28 ± 0.03 b	2.28 ± 0.05 b	2.22 ± 0.03 b	2.38 ± 0.04 a	2.25 ± 0.01 b	2.37 ± 0.02 a
	Root	1.25 ± 0.09 ab	0.90 ± 0.11 c	1.18 ± 0.08 c	1.56 ± 0.22 a	1.40 ± 0.13 ab	1.31 ± 0.18 ab	0.78 ± 0.15 c

Table 6. Nitrogen content in different parts of wheat during the whole growth period under different treatments (%). Different lower letters indicate significant differences between processes ($p < 0.05$).

Stage	Parts	CK1	CK2	T1	T2	T3	T4	T5
Seedling	Shoot	0.47 ± 0.01 d	0.43 ± 0.01 e	0.52 ± 0.01 c	0.63 ± 0.01 a	0.57 ± 0.04 b	0.49 ± 0.01 cd	0.47 ± 0.01 d
	Root	0.55 ± 0.09 ab	0.48 ± 0.04 b	0.64 ± 0.02 a	0.42 ± 0.03 b	0.47 ± 0.01 b	0.44 ± 0.07 b	0.49 ± 0.04 b
Tillering	Shoot	0.47 ± 0.01 d	0.53 ± 0.01 bc	0.63 ± 0.05 a	0.51 ± 0.01 cd	0.5 ± 0.01 cd	0.5 ± 0.04 cd	0.55 ± 0.02 b
	Root	0.4 ± 0.01 b	0.41 ± 0.06 b	0.62 ± 0.04 ab	0.63 ± 0.05 ab	0.73 ± 0.01 a	0.66 ± 0.27 ab	0.6 ± 0.11 ab
Jointing	Stem	0.37 ± 0.02 b	0.28 ± 0.03 c	0.42 ± 0.02 b	0.38 ± 0.05 b	0.38 ± 0.01 b	0.37 ± 0.01 b	0.47 ± 0.05 a
	Leaves	0.54 ± 0.02 c	0.56 ± 0.02 c	0.55 ± 0.01 c	0.53 ± 0.01 c	0.63 ± 0.01 b	0.62 ± 0.01 b	0.69 ± 0.01 a
	Root	0.34 ± 0.02 b	0.27 ± 0.03 bc	0.27 ± 0.01 c	0.21 ± 0.01 c	0.34 ± 0.02 b	0.42 ± 0.03 a	0.3 ± 0.07 b
Heading	Stem	0.16 ± 0.01 bc	0.16 ± 0.01 bc	0.13 ± 0.01 c	0.15 ± 0.02 c	0.09 ± 0.02 d	0.22 ± 0.01 a	0.18 ± 0.01 b
	Leaves	0.35 ± 0.02 c	0.45 ± 0.01 bc	0.43 ± 0.07 bc	0.59 ± 0.17 a	0.41 ± 0.01 bc	0.5 ± 0.01 b	0.46 ± 0.01 bc
	Ear	0.47 ± 0.02 b	0.46 ± 0.02 b	0.48 ± 0.01 b	0.53 ± 0.03 a	0.47 ± 0.03 b	0.51 ± 0.02 ab	0.51 ± 0.03 ab
	Root	0.14 ± 0.03 ab	0.12 ± 0.01 bc	0.14 ± 0.01 ab	0.13 ± 0.02 ab	0.1 ± 0.01 c	0.16 ± 0.01 a	0.11 ± 0.01 bc
Flowering	Stem	0.13 ± 0.01 a	0.13 ± 0.01 a	0.14 ± 0.01 a	0.13 ± 0.01 a	0.09 ± 0.05 b	0.07 ± 0.01 b	0.07 ± 0.01 b
	Leaves	0.16 ± 0.01 d	0.26 ± 0.01 b	0.27 ± 0.01 b	0.23 ± 0.01 c	0.29 ± 0.02 a	0.26 ± 0.01 b	0.23 ± 0.01 c
	Ear	0.36 ± 0.01 c	0.38 ± 0.01 bc	0.39 ± 0.01 ab	0.36 ± 0.01 c	0.42 ± 0.02 a	0.41 ± 0.02 a	0.42 ± 0.02 a
	Root	0.18 ± 0.01 b	0.17 ± 0.01 bc	0.2 ± 0.01 a	0.16 ± 0.01 c	0.15 ± 0.01 c	0.16 ± 0.01 c	0.15 ± 0.01 c
Maturity	Stem	0.13 ± 0.01 b	0.13 ± 0.01 b	0.13 ± 0.01 b	0.16 ± 0.01 a	0.13 ± 0.01 b	0.13 ± 0.01 b	0.13 ± 0.01 b
	Leaves	0.11 ± 0.01 c	0.12 ± 0.01 c	0.13 ± 0.01 b	0.15 ± 0.01 a	0.14 ± 0.01 b	0.13 ± 0.01 b	0.15 ± 0.01 a
	Seeds	0.39 ± 0.01 ab	0.39 ± 0.01 ab	0.42 ± 0.01 ab	0.47 ± 0.01 a	0.43 ± 0.01 ab	0.33 ± 0.17 b	0.44 ± 0.01 ab
	Root	0.17 ± 0.01 ab	0.15 ± 0.01 b	0.17 ± 0.01 a	0.16 ± 0.01 ab	0.17 ± 0.01 a	0.15 ± 0.01 ab	0.15 ± 0.01 b

Table 7. Phosphorus content in different parts of wheat during the whole growth period under different treatments (%). Different lower letters indicate significant differences between processes ($p < 0.05$).

shoot, respectively. At maturity, the phosphorus distribution to seeds had mirrored that of nitrogen, with the phosphorus content allocated to T2 seeds being 6.71% lower than T3. Furthermore, the phosphorus content allocated to T4 seeds had been 15.43% lower than that of T5. Simultaneously, the phosphorus allocated to stems by T2 had exceeded that by T3 by 4.89%, and the phosphorus content allocated to T4 stems had been 9.71% higher than that of T5.

Figure 5 illustrated the distribution of potassium in various segments of wheat at different growth stages. Unlike nitrogen and phosphorus, the distribution of potassium in wheat during the seedling stage did not exhibit any significant differences among diverse treatments. However, at the jointing stage, a divergent trend emerged for the four treatments (T2, T3, T4, and T5) when compared to nitrogen and phosphorus. Specifically,

Stage	Parts	CK1	CK2	T1	T2	T3	T4	T5
Seedling	Shoot	4.27 ± 0.5 ab	4.61 ± 0.41 a	4.54 ± 0.51 a	3.72 ± 0.47 ab	3.17 ± 0.42 b	4.23 ± 0.54 ab	3.66 ± 0.41 ab
	Root	1.64 ± 0.35 a	1.61 ± 0.60 a	1.63 ± 0.29 a	1.26 ± 0.26 a	1.35 ± 0.06 a	1.22 ± 0.26 a	1.27 ± 0.14 a
Tillering	Shoot	7.04 ± 0.07 a	7.25 ± 0.43 a	7.45 ± 0.10 a	6.41 ± 0.17 b	5.75 ± 0.38 c	5.60 ± 0.24 c	5.66 ± 0.46 c
	Root	3.12 ± 0.17 b	2.96 ± 0.57 b	1.99 ± 0.25 c	2.74 ± 0.53 b	4.06 ± 0.11 a	2.03 ± 0.12 c	3.04 ± 0.08 b
Jointing	Stem	3.76 ± 0.33 ab	2.40 ± 0.48 b	4.49 ± 0.52 ab	3.98 ± 0.31 ab	4.52 ± 0.84 ab	3.26 ± 0.42 b	5.65 ± 1.89 a
	Leaves	9.14 ± 0.11 c	9.99 ± 0.25 b	10.46 ± 0.23 a	10.25 ± 0.19 a	10.69 ± 0.34 a	10.08 ± 0.16 b	9.33 ± 0.34 c
	Root	5.38 ± 0.56 c	6.13 ± 0.60 bc	6.22 ± 0.18 bc	5.64 ± 0.09 c	6.99 ± 0.65 ab	7.71 ± 0.40 a	5.45 ± 0.87 c
Heading	Stem	0.75 ± 0.19 d	1.23 ± 0.14 b	1.11 ± 0.11 bc	0.90 ± 0.02 cd	0.72 ± 0.01 d	1.87 ± 0.11 a	1.62 ± 0.27 a
	Leaves	5.50 ± 0.10 a	4.04 ± 0.10 b	4.09 ± 0.95 b	4.68 ± 0.06 ab	5.03 ± 0.11 ab	4.73 ± 0.14 ab	4.33 ± 0.02 b
	Ear	1.66 ± 0.86 a	1.48 ± 0.40 a	1.75 ± 0.59 a	2.52 ± 0.08 a	1.63 ± 0.36 a	2.83 ± 0.22 a	2.37 ± 0.42 a
	Root	1.77 ± 0.01 a	1.11 ± 0.28 a	1.53 ± 0.08 a	1.60 ± 0.57 a	1.04 ± 0.11 a	1.37 ± 0.32 a	1.60 ± 0.24 a
Flowering	Stem	0.77 ± 0.16 c	0.88 ± 0.01 bc	0.93 ± 0.08 bc	1.13 ± 0.04 ab	0.63 ± 0.21 c	1.16 ± 0.16 ab	1.36 ± 0.05 a
	Leaves	3.33 ± 0.09 e	4.02 ± 0.31 d	4.47 ± 0.15 c	3.18 ± 0.04 e	4.87 ± 0.26 b	5.53 ± 0.11 a	3.85 ± 0.13 d
	Ear	2.78 ± 0.39 a	3.02 ± 0.01 a	2.62 ± 0.30 a	2.53 ± 0.09 a	2.98 ± 0.14 a	1.95 ± 0.25 b	1.43 ± 0.03 c
	Root	3.89 ± 0.23 b	3.12 ± 0.38 c	4.82 ± 0.88 a	2.80 ± 0.11 c	2.45 ± 0.15 cd	1.89 ± 0.08 d	1.73 ± 0.05 d
Maturity	Stem	7.08 ± 0.98 a	5.97 ± 0.41 a	5.68 ± 0.31 a	5.77 ± 0.58 a	6.18 ± 1.64 a	7.15 ± 2.42 a	4.15 ± 0.69 a
	Leaves	5.08 ± 0.20 a	4.66 ± 0.17 a	4.30 ± 0.64 a	4.83 ± 0.60 a	4.98 ± 0.29 a	4.71 ± 1.07 a	2.68 ± 1.98 a
	Seeds	3.27 ± 0.31 b	2.7 ± 0.25 b	4.12 ± 0.92 ab	4.46 ± 0.50 ab	4.68 ± 0.52 a	3.81 ± 0.39 ab	3.79 ± 0.92 ab
	Root	2.45 ± 0.19 bc	2.29 ± 0.15 bc	2.61 ± 0.25 b	2.49 ± 0.21 bc	3.11 ± 0.11 a	2.23 ± 0.24 bc	1.89 ± 0.46 c

Table 8. Potassium content in different parts of wheat during the whole growth period under different treatments (%). Different lower letters indicate significant differences between processes ($p < 0.05$).

the potassium allocated by T2 to stems was 1.83% lower than that allocated by T3, and the potassium content in the stem of T4 was 10.73% lower than that of T5. Advancing to the flowering stage, the potassium allocated to the ear by T2 had surpassed that by T3 by 5.50%, and the potassium content allocated to the spike of T4 had exceeded that of T5 by 1.31%. By the maturity stage, the potassium allocated by T2 to seeds had been 5.50% lower than that allocated by T3, while the potassium content allocated to T4 seeds had been 1.31% lower than that of T5. Concurrently, the potassium allocated to leaves by T2 had exceeded that by T3 by 7.60%, and the potassium content allocated to T4 leaves had been 6.10% higher than that of T5.

Discussion

Effects of combined application of biochar and organic fertilizer on agronomic traits and photosynthetic capacity of wheat under fertilizer reduction

This study revealed that variations in wheat plant height among treatments were less pronounced than anticipated, diverging from previous research findings where fertilizer reduction significantly reduced plant height[36–38]. The concurrent application of biochar and organic fertilizer mitigated the negative effects of fertilizer reduction on wheat height, suggesting that this combination can counterbalance the stress induced by nutrient deficiencies. However, differences in stem thickness across treatments reflected variations in biochar and organic fertilizer application rates, aligning with prior observations. For instance, under nitrogen-deficient conditions, 51 downregulated genes were identified as inhibitors of chlorophyll synthesis, chloroplast development, light harvesting, and electron transfer in the photosystem, leading to decreases of 32% in SPAD value and 15.2% in photosynthetic rate (Pn), ultimately impairing photosynthesis[39]. In this study, the addition of organic fertilizer effectively alleviated these photosynthetic limitations.

Prior studies have also shown that bio-organic fertilizers enhance plant height, stem diameter, leaf area index, and yield, as demonstrated in Chinese cabbage[40]. Similarly, biochar improves photosynthetic parameters such as photosynthetic rate (Pn), intercellular CO, concentration (Ci), variable fluorescence (Fv), maximum fluorescence (Fm), PSII maximum photochemical efficiency (Fv/Fm), and PSII potential photochemical activity (Fv/Fo) in crops like tomatoes[41]. The combined effects of biochar and organic fertilizer in this study likely improved photosynthetic efficiency, ultimately contributing to increased biomass and wheat yield.

The findings of Miao[42] and Hu[43] corroborate the observed enhancement of stem thickness in rice and Brassica napus L. due to biochar and organic fertilizers, respectively. Biomass, a critical indicator of crop growth, remained consistently high under the T2 treatment, particularly during critical developmental phases, significantly surpassing other treatments. Moreover, the dry weight ratio of leaves under T2 was the highest during these stages, reflecting optimized growth and efficient dry matter distribution. Dry matter allocation to leaves plays a pivotal role in photosynthetic capacity, influencing carbon assimilation and yield[44–47]. The enhanced photosynthesis observed in T2 wheat aligns with these principles, driven by higher biomass accumulation and strategic allocation to photosynthetically active tissues. The results echo studies by Gao[48] and Zhang[49], emphasizing the synergistic benefits of biochar and organic fertilizer in enhancing photosynthesis and crop performance.

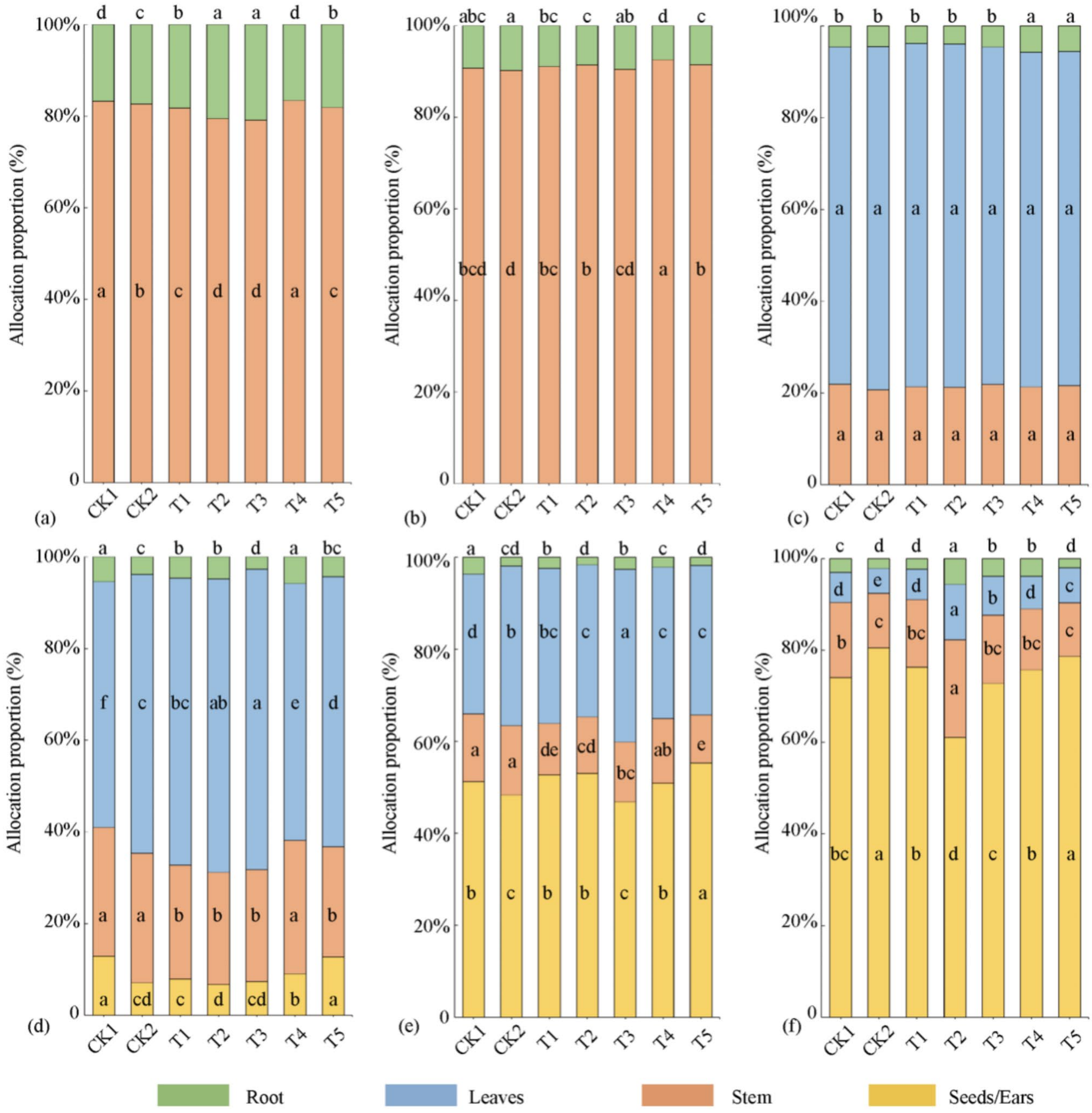

Fig. 3. Nitrogen distribution of wheat at different stages under different treatments (%) (**a**) Seedling stage; (**b**) Tillering stage; (**c**) Jointing stage; (**d**) Heading stage; (**e**) Flowering stage; (**f**) Maturity stage. Different lower letters indicate significant differences between processes ($p < 0.05$).

Effects of combined application of biochar and organic fertilizer on wheat yield and yield components under fertilizer reduction

The integration of biochar and organic fertilizer significantly improved wheat yields in four of five treatments compared to sole reliance on chemical fertilizers. This underscores the potential of biochar and organic fertilizer to compensate for yield losses associated with reduced chemical fertilizer use. Consistent with prior studies, such as those by Qiu[50] and He[51], biochar and organic fertilizers positively influenced wheat yield. Treatments involving biochar consistently achieved higher yields, emphasizing its role in enhancing yield potential, as evidenced by Kumar's findings in sweet peppers[52].

All yield components showed improvement under combined biochar and organic fertilizer treatments, with grain number per spike being the primary contributor to yield enhancement. These results align with Philipp's findings[53] that grain number per spike is a critical determinant of winter wheat yield. The synergistic effects of biochar and organic fertilizer, as demonstrated in this study, affirm their efficacy in promoting yield stability and productivity under reduced fertilizer regimes.

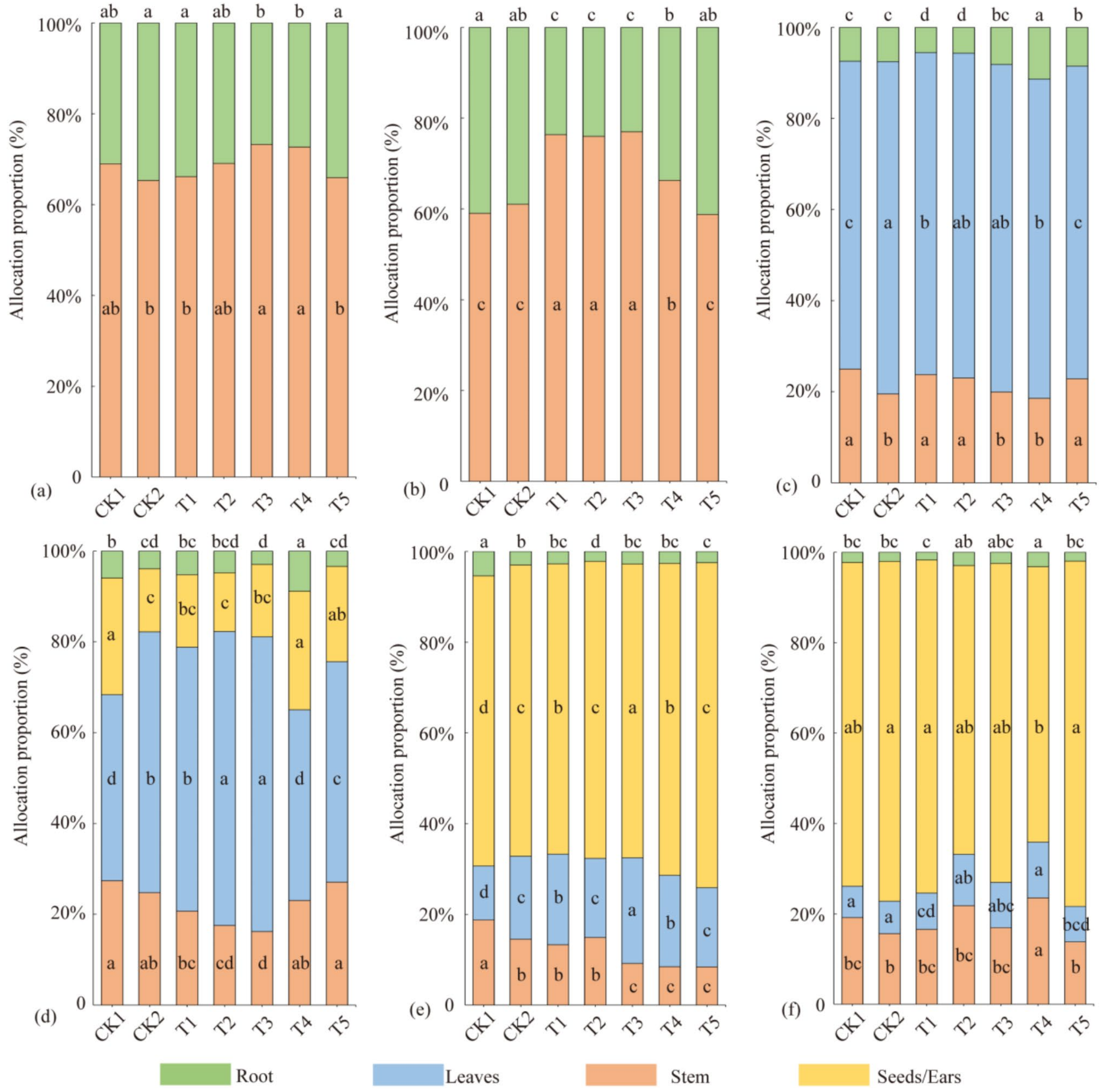

Fig. 4. Phosphorus distribution of wheat at different stages under different treatments (%) (**a**) Seedling stage; (**b**) Tillering stage; (**c**) Jointing stage; (**d**) Heading stage; (**e**) Flowering stage; (**f**) Maturity stage. Different lower letters indicate significant differences between processes ($p < 0.05$).

Effects of combined application of biochar and organic fertilizer on nutrient absorption of wheat under fertilizer reduction

The combined application of biochar and organic fertilizer significantly influenced nitrogen and phosphorus absorption, particularly during the seedling stage under reduced fertilizer conditions. Notable variations in nitrogen content across treatments were observed, consistent with Liu's meta-analysis highlighting increased nitrogen use efficiency and yield in rice with biochar application[54]. Organic fertilizer has been shown to partially replace chemical nitrogen fertilizer while maintaining yield and improving nitrogen efficiency, as reported by Wang[55].

At maturity, biochar-treated grains exhibited significantly higher nitrogen content than other treatments, corroborating Manzoor's findings in cotton[56]. Similarly, biochar application enhanced phosphorus uptake, particularly during the heading stage, aligning with Xu's observations of biochar's role in increasing soil phosphorus availability[57]. Regarding potassium, wheat roots treated with biochar during the seedling stage demonstrated increased potassium content, reflecting improved nutrient availability and root development.

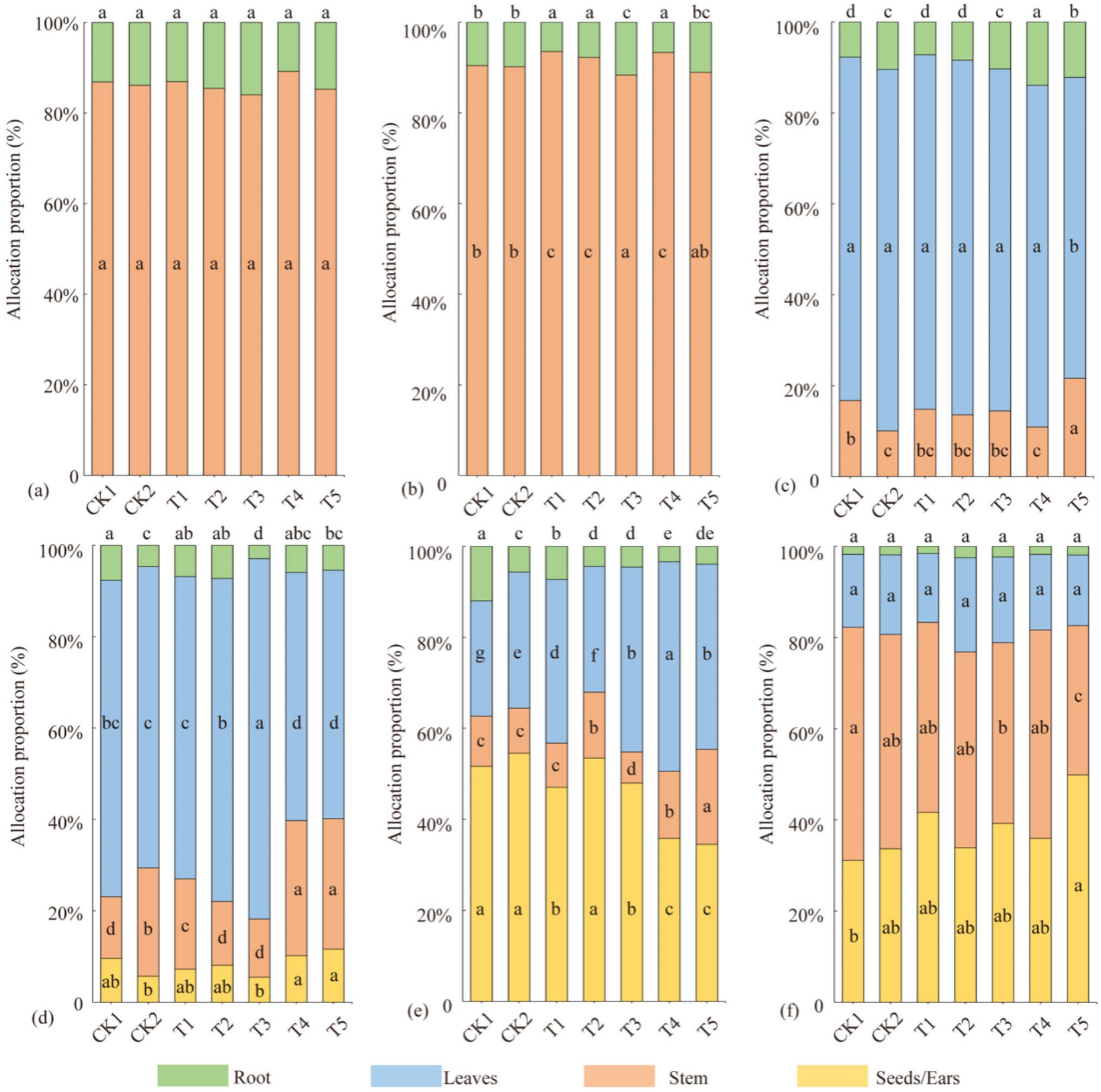

Fig. 5. Potassium distribution of wheat at different stages under different treatments (%) (**a**) Seedling stage; (**b**) Tillering stage; (**c**) Jointing stage; (**d**) Heading stage; (**e**) Flowering stage; (**f**) Maturity stage. Different lower letters indicate significant differences between processes ($p < 0.05$).

These outcomes align with findings by Ren[61] and others, which highlight biocha's role in enhancing root growth and nutrient absorption under stress conditions.

Effects of combined application of biochar and organic fertilizer on nutrient accumulation in wheat under fertilizer reduction

This study provided a detailed analysis of nutrient distribution in wheat under various treatments, revealing distinct patterns of nitrogen allocation. Treatments with biochar showed increased nitrogen allocation to roots, while those without biochar favored shoots. This finding aligns with studies by Su[62] and Urban[63], which demonstrate the effects of nitrogen on root development and photosynthetic efficiency.

Phosphorus accumulation in wheat stems was significantly enhanced under biochar treatments, consistent with Vera-García's research linking phosphorus availability to improved stalk strength and lodging resistance[64]. Additionally, biochar application facilitated higher potassium accumulation in grains, further enhancing plant growth and resilience. These results emphasize the pivotal role of biochar and organic fertilizer in optimizing nutrient distribution and utilization, thereby promoting robust growth and yield under reduced fertilizer regimes.

Conclusion

The combined application of biochar and organic fertilizer presented an avenue for reducing reliance on chemical fertilizers while ensuring wheat yield. An optimal fertilization strategy, constituting 80% chemical fertilizer, could be realized through the judicious integration of biochar and organic fertilizer. The results of this study indicated that biochar and organic fertilizer can enhance the photosynthetic capacity to improve the agronomic characteristics of wheat. At the same time, the application of biochar and organic fertilizer changed the distribution of nutrients in the wheat, and more nitrogen was distributed to the leaves, thus ensuring normal growth and development in the case of fertilizer reduction.

Data availability

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Conceptualization, M.L. and J.S.; methodology, L.Y.; sofware, Z.Z.; validation, S.G.; formal analysis, K.G.; investigation, K.G.; resources, K.G.; data curation, M.L.; writing—original draf preparation, K.G.; writing—review and editing, J.S.; visualization, K.G.; supervision, K.G.; project administration, J.S.; funding acquisition, J.S. All authors have read and agreed to the published version of the manuscript.

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Declarations

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Competing interests

The authors declare no competing interests.

Additional information

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