

Topdressing different fertilizers causes differences in root traits, canopy photosynthesis and accumulation of photosynthetic products of wheat

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ABSTRACT

Topdressing is crucial in wheat production, but it remains unclear whether topdressing different fertilizers with the same amount at jointing stage has a significant impact on wheat (*Triticum aestivum* L.), therefore, field experiments with four fertilizer treatments: Ordinary compound fertilizer (F1), wheat-specific compound fertilizer (F2), urea (F3) and no topdressing (CK) were conducted. Compared to F1 and F3, F2 significantly increased root length, root surface area, root volume, root diameter, root tips and root forks. Topdressing urea increased single leaf area of canopy when compared to F1. Compared to CK, F2 and F3 significantly enhanced chlorophyll content, while topdressing urea increased chlorophyll content when compared to F1. The effect of topdressing fertilizer on photosynthetic rate, stomatal conductance, and transpiration rate was consistently F2 > F3 > F1 > CK. The canopy photosynthetically active radiation in F2 was the highest, and in F3 was higher than in F1 (increased by 4.33% ~ 6.72%). Compared to topdressing urea, F1 and F2 improved grain filling rate, while topdressing urea was more beneficial for improving DM accumulation rate of stem and leaf; compared to topdressing F1, F2 improved accumulation rate of photosynthetic products. Topdressing compound fertilizer (F1 and F2) improved yield and harvest index when compared to topdressing urea, compared to F1, F2 increased yield and harvest index by 8.13% and 2.77% in 2025. This study demonstrates that topdressing the same weight of wheat-specific compound fertilizer improved root traits, canopy photosynthesis, yield and harvest index when compared to topdressing ordinary compound fertilizer and urea.

Key words: Canopy photosynthesis, harvest index, photosynthetic rate, root traits, topdressing, *Triticum aestivum*.

INTRODUCTION

Given the fact that wheat (*Triticum aestivum* L.) provides about one-fifth of both calories and proteins to human diet, there is, therefore, a need for enhancing the yield of this crop so as to feed the world's growing population. Fertilization is one of the most important management factors affecting growth and development, and yield of wheat. However, it is well known that wheat use only 30%-45% of the applied fertilizers, while the rest remains unused causing severe environmental pollution (Illescas et al., 2020). Decreasing fertilizer loss and enhancing fertilizer use efficiency are essential not only for high yielding consideration but also for environmental protection. When applied at a low rate, NPK and other nutrients can limit grain yield, whereas excessive fertilizer rate can cause plant lodging, making it difficult to harvest and reduce wheat yield (Galetto et al., 2017). In addition, the development of more productive genotypes requires some adjustments in fertilizer and fertilization to meet adequate demand of nutrients by plants. How to reduce fertilizer application and increase crop yield has become

extremely important, remarkably, previous studies have showed that optimized fertilizer application strategies and use new type of fertilizer (specific compound fertilizer, slow and controlled-release fertilizers) can achieve high yield and high fertilizer utilization rate simultaneously (Hao et al., 2020; Vejan et al., 2021; Hou et al., 2024).

In terms of dividing the fertilizer application, Nyiraneza et al. (2012) not only reported that applying half of the recommended fertilizer rate at planting and the rest at tillering resulted in a high total yield and high grain N uptake, but also indicated that split application of fertilizer could help to synchronize nutrient supply with wheat nutrient demand and reduce nutrient loss. Sui et al. (2013) observed that optimizing fertilizer topdressing strategies increased rice yield by 8.2%-12.6% and N use efficiency (NUE) by 57.14%-138.30% when compared with local farmers' fertilization practices. Fu et al. (2022) found that applying some fertilizer before sowing and some at later growth periods, contributes to synchronize fertilizer supply with crop nutrients demand and reduce fertilizer loss; however, an unsuitable fertilizer application rate and time will usually cause a lack of nutrients in a certain crop growth period. In terms of the type of fertilizer application, Qiong et al. (2021) indicated that prolonged and excessive application of conventional fertilizers not only leads to low fertilizer utilization efficiency and difficulty in increasing crop yield, but also damages soil structure and pollutes environment. Lyu et al. (2021) reported that slow-release fertilizer has been considered as an effective way to decrease fertilizer loss, improve fertilizer use efficiency and crop yield. Yang et al. (2020) observed that compound microbial fertilizer as base fertilizer could not only increase the contents of soil available P and available N but also enhance the grain yield markedly. Several studies also have shown beneficial effects of the use of controlled-release fertilizers and specific compound fertilizers to enhance productivity of crops (Ercoli et al., 2013; Vejan et al., 2021).

Fertilizer has contributed significantly to the increase of wheat yield; however, the rates of yield growth have slowed down in the past 10-20 yr, and even become stagnated in many countries (Grassini et al., 2013; Cao et al., 2016). Applying inappropriate fertilizers is one of the major problems in wheat production, which have caused low nutrients use efficiency and difficulty in enhancing yield. Generally speaking, attaining high yield requires an adequate synchronicity between crop nutrient demand and suitable fertilizer supply (Zhang et al., 2023; Rajicic et al., 2025). Fertilization in wheat production usually uses two fertilizer applications basal-application and topdressing, and integrating topdressing at jointing stage and suitable fertilizer types has critical significance on improving wheat yield. Although topdressing fertilizer can increase yield, the question that topdressing different types of fertilizers with the same weight at jointing stage whether cause significant differences in wheat yield and harvest index has not been well clarified. Therefore, we investigated the effect of topdressing different types of solid fertilizers (with the same weight 300 kg ha⁻¹) at jointing stage on wheat root traits, canopy photosynthesis, accumulation rate of photosynthetic products, yield and harvest index, so as to (i) clarify whether topdressing different fertilizers causes significant difference in yield and their underlying mechanisms; (ii) provide assistance in selecting suitable fertilizer type for topdressing at jointing stage of wheat; and (iii) provide technical and theoretical support for increasing yield with reducing fertilizer input.

MATERIALS AND METHODS

Site description

Field experiments were carried out at the Lime Concretion Black Soil Experimental Station of Anhui Academy of Agricultural Sciences, Huaibei City (33°56' N, 116°54' E; 29.0 m a.s.l.), Anhui province in China from 2023 to 2025. The experimental site is located in the northeast of the country with an annual single maize (*Zea mays* L.)-wheat (*Triticum aestivum* L.) rotation system. The region is classified as a semimoiest and semi-dry warm temperature monsoon climate. The annual mean temperature is 15-16 °C and accumulated temperatures above 10 °C are 4350-4800 °C. Annual mean precipitation is 806 mm. Soil samples (0-20 cm) were collected from the experimental field for analyzing soil physical and chemical properties before wheat sowing and basal fertilizers application. The soil properties at the initial of the experiment were total 0.87 g kg⁻¹ N, 0.58 g kg⁻¹ total P, 102.14 mg kg⁻¹ available N, 8.12 mg kg⁻¹ available P, 95.45 mg kg⁻¹ available K, 17.69 g kg⁻¹ organic matter, and pH 7.5. The soil with relatively low N and P content, medium K and organic matter content.

Experimental design

The field experiment was conducted as a randomized block design with four fertilization models as the treatment variables, four treatments and each treatment was replicated three times. For all plots, 155 kg N ha⁻¹, 60 kg P₂O₅ ha⁻¹ and 55 kg K₂O ha⁻¹ were applied as basal fertilizer before sowing, and four types of solid fertilizers were top-dressed at

jointing stage of wheat. The weight of top-dressed fertilizers were the same (300 kg ha^{-1}), the four types of top-dressed fertilizers were: Ordinary compound fertilizer, $\text{N:P}_2\text{O}_5:\text{K}_2\text{O} = 15\%:15\%:15\%$ (F1); wheat-specific compound fertilizer, $\text{N:P}_2\text{O}_5:\text{K}_2\text{O} = 26\%:10\%:9\%$ (F2); urea, $\text{N} = 46\%$ (F3); and no topdressing (CK). The F1, F2 and F3 are the three most commonly used fertilizers in wheat production in China. The plot size was $10 \text{ m} \times 20 \text{ m}$ with a row space of 20 cm , and the distance between neighboring plots was 40 cm . The local wheat variety Wanken wheat 22 was selected and planted on 14 October 2023 and 2024 with the density $250 \times 10^4 \text{ ha}^{-1}$ for basic seedlings, and was harvested on 3 June of the following year 2024 and 2025.

Sampling and measurements

For root traits, roots were sampled at flowering stage in 2024 and 2025, sampling depth was $0 \sim 40 \text{ cm}$, and sampling width was 20 cm (10 cm on each side of wheat plant). Root samples were kept in an icebox and transported to the laboratory within 2 h of collection, and the root system of the target plant was separated from other roots by carefully extracting roots under running water on a sieve (mesh size 0.2 mm). Root samples were scanned by root image analysis software WinRhizo (Instruments Regent Co., Ville de Québec, Québec, Canada), each treatment was repeated nine times, and root length, root surface area, root volume, root diameter, root forks and root tips per plant were measured.

For leaf area of photosynthetic efficiency, flag leaf, second and third leaves from the top of wheat plants were selected and measured by a portable leaf area meter (LI-3000C, LI-COR, Lincoln, Nebraska, USA). Nine wheat plants were sampled from each treatment at flowering stage in 2024 and 2025, respectively, and the measurements were repeated nine times for each parameter.

Chlorophyll content was measured with a hand-held chlorophyll meter (SPAD-502, Konica Minolta Company, Tokyo, Japan), measuring area was $2 \text{ mm} \times 3 \text{ mm}$; the same parts of flag leaves of the wheat plants were selected and measured at flowering and middle of filling stages in 2024 and 2025, respectively. Nine flag leaves in each treatment were chosen for measurement (each leaf was measured three times).

Photosynthetic characteristics were measured with a portable photosynthesis system (LI-6400, LI-COR) to evaluate leaf photosynthetic rate, stomatal conductance, transpiration rate, and intercellular CO_2 concentration at 09:30-11:30 h local time at the flowering stage in 2024 and 2025. Nine flag leaves of wheat plant in each plot were chosen for the photosynthetic measurements.

Canopy photosynthetically active radiation (PAR) was measured by SunScan Canopy Analysis System (Delta-T Devices, Cambridge, UK) at flowering and middle of filling stages of wheat, and the PAR of the canopy was calculated by the difference value between the PAR of the top (approximately 1.5 m above-ground level) and bottom (transmitted PAR measured at the base of the canopy) of wheat canopy; the measurement time was 09:30-11:30 h and 13:30-15:30 h in 2024 and 2025. The spot measurements were limited to clear days to avoid poor quality of incident PAR (e.g., multiple sources of PAR due to cloud refraction and reflection), which influences the light interception measurements. Nine measurements were taken for the 'top' and 'bottom' canopy position at locations selected randomly in each plot in rapid succession.

Accumulation rate of photosynthetic products was evaluated as: Grain filling rate = DM weight of grain of population (kg)/Number of days during the measurement of two growth periods (d); DM accumulation rate of stem and leaf = DM weight of stem and leaf of population (kg)/Number of days during the measurement of two growth periods (d). To obtain DM weight, 20 wheat plants in each plot were sampled (at jointing stage, booting stage, flowering stage, middle of filling stage and maturity stage) and oven dried at 80°C for 60 h till they reached constant weight.

Harvest index = Grain yield/Total above-ground biomass at physiological maturity.

Data analysis

The experiment was carried out as a randomized block design with four types of topdressing fertilizers as the treatment variable. All data was expressed as means over three replicates. The ANOVA was performed by the general linear model-univariate procedure in SPSS 21.0 software (IBM, Armonk, New York, USA). The ANOVAs were performed with the type of topdressing fertilizer as the main effect, and the tests of population normality and variance equality were also conducted. All treatment means were compared for any significant differences by the Duncan's multiple range tests at the $\alpha = 0.05$ significance level.

RESULTS

Effects of topdressing fertilizer types on root traits

Root length (Table 1), root surface area, root volume, root diameter, root tips and root forks in CK were significantly lower than that in F1, F2 and F3, indicating that topdressing fertilizer at jointing stage significantly improved wheat root traits. Compared to F1 and F3, F2 significantly increased root length, root surface area, root volume, root diameter, root tips, root forks by 9.01%, 7.84%, 5.69%, 7.32%, 2.60%, 9.87% and 15.81%, 16.04%, 11.11%, 11.15%, 6.33%, 15.66 in 2024 and 2025, respectively. Compared to F3, F1 had higher root length, root surface area, root volume, root diameter, root tips and root forks, and the differences in root surface area, root tips, root forks between F1 and F3 were significant.

Table 1. Effects of topdressing fertilizer types on root traits of wheat at flowering stage. Values are means $\pm$ SD ($n = 9$). Means followed by different letters in the same column indicate significant difference ($p < 0.05$). F1: Ordinary compound fertilizer (N:P₂O₅:K₂O = 15%:15%:15%); F2: wheat-specific compound fertilizer (N:P₂O₅:K₂O = 26%:10%:9%); F3: urea (N = 46%); CK: no topdressing.

	Root length cm plant ⁻¹	Root surface area cm ² plant ⁻¹	Root volume cm ³ plant ⁻¹	Root diameter mm plant ⁻¹	Root tips nr	Root forks nr
2024						
F1	126.90 $\pm$ 10.99 ^b	78.30 $\pm$ 5.89 ^b	2.41 $\pm$ 0.12 ^b	0.676 $\pm$ 0.03 ^b	555.71 $\pm$ 12.30 ^b	1009.73 $\pm$ 46.61 ^b
F2	140.70 $\pm$ 7.67 ^a	84.44 $\pm$ 3.25 ^a	2.56 $\pm$ 0.10 ^a	0.731 $\pm$ 0.02 ^a	580.20 $\pm$ 9.96 ^a	1152.26 $\pm$ 45.63 ^a
F3	112.20 $\pm$ 9.19 ^c	70.60 $\pm$ 3.56 ^c	2.30 $\pm$ 0.12 ^b	0.641 $\pm$ 0.04 ^c	518.17 $\pm$ 9.79 ^c	958.58 $\pm$ 23.45 ^c
CK	82.64 $\pm$ 6.26 ^d	55.02 $\pm$ 2.67 ^d	1.97 $\pm$ 0.15 ^c	0.519 $\pm$ 0.02 ^d	420.43 $\pm$ 16.16 ^d	742.29 $\pm$ 17.87 ^d
2025						
F1	124.83 $\pm$ 9.75 ^b	76.94 $\pm$ 3.50 ^b	2.46 $\pm$ 0.14 ^b	0.669 $\pm$ 0.03 ^b	578.33 $\pm$ 11.71 ^b	1042.322 $\pm$ 50.54 ^b
F2	136.08 $\pm$ 9.17 ^a	82.97 $\pm$ 2.17 ^a	2.60 $\pm$ 0.13 ^a	0.718 $\pm$ 0.02 ^a	593.38 $\pm$ 9.21 ^a	1145.178 $\pm$ 52.40 ^a
F3	117.50 $\pm$ 8.28 ^b	71.50 $\pm$ 3.39 ^c	2.34 $\pm$ 0.16 ^c	0.646 $\pm$ 0.03 ^b	558.06 $\pm$ 10.24 ^c	990.1444 $\pm$ 15.24 ^c
CK	86.24 $\pm$ 5.39 ^c	57.00 $\pm$ 2.54 ^d	1.93 $\pm$ 0.15 ^d	0.506 $\pm$ 0.02 ^c	443.34 $\pm$ 15.09 ^d	775.3778 $\pm$ 15.64 ^d

Effects of topdressing fertilizer types on canopy photosynthesis

Leaf area of photosynthetic efficiency. The areas of flag leaf (Figure 1), second leaf, and third leaf from the top in CK were significantly lower than that in F1, F2 and F3. The areas of flag leaf, second leaf, and third leaf from top in F2 were slightly higher than that in F3, but the differences between F2 and F3 were nonsignificant. Compared to F1, F2 significantly increased the area of flag leaf, second and third leaves from top by 11.44%, 9.22%, 9.08% in 2024 and 14.28%, 7.39%, 10.52% in 2025, respectively. In addition, the area of flag leaf, second and third leaves from top in F3 were slightly higher than that in F1, indicating that topdressing the same weight of urea was more beneficial for increasing single leaf area of canopy when compared to ordinary compound fertilizer.

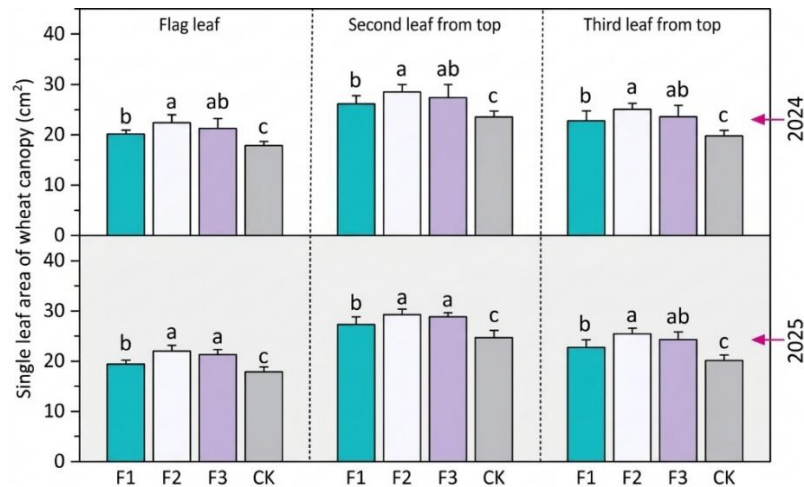


Figure 1. Effects of topdressing fertilizer types on single leaf area of wheat canopy. Values are means $\pm$ SD ($n = 9$). Different letters above columns indicate significant difference by LSD test (ANOVA) at the 5% level. F1: Ordinary compound fertilizer (N:P₂O₅:K₂O = 15%:15%:15%); F2: wheat-specific compound fertilizer (N:P₂O₅:K₂O = 26%:10%:9%); F3: urea (N = 46%); CK: no topdressing.

Chlorophyll content. The chlorophyll content in F2 was slightly higher than that in F3 at flowering stage, while was slightly lower than that in F3 at middle of filling stage, and the differences between F2 and F3 were nonsignificant (Figure 2). The chlorophyll content in CK was the lowest, compared to CK, F2 and F3 significantly increased chlorophyll content. The chlorophyll content in F3 was significantly higher (flowering stage) or slightly higher (middle of filling stage) than that in F1, indicating that topdressing urea (high N content) at jointing stage can increase chlorophyll content when compared to topdressing ordinary compound fertilizer (low N content), even though the ordinary compound fertilizer provided P and K.

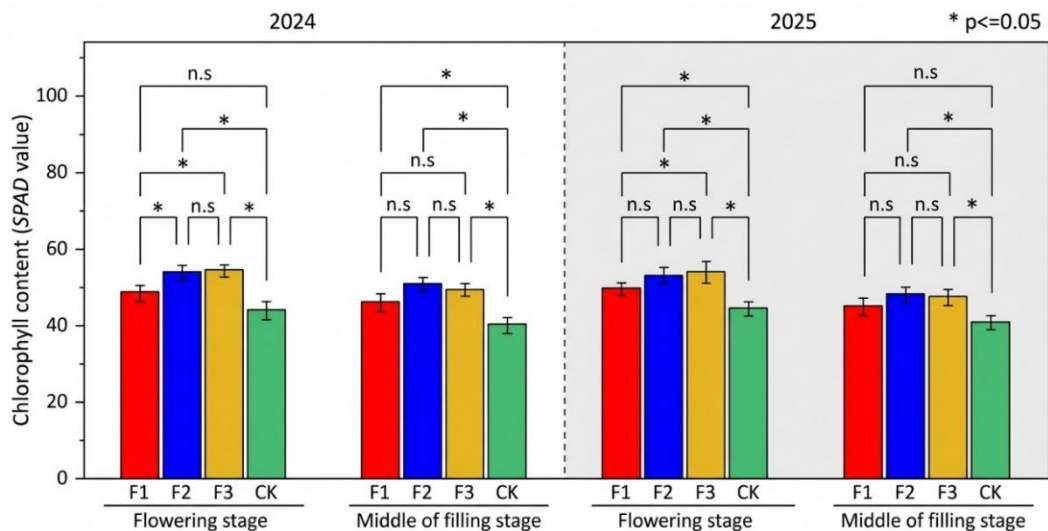


Figure 2. Effects of topdressing fertilizer types on chlorophyll content. Values are means $\pm$ SD ($n = 9$). Different letters above columns indicate significant difference by LSD test (ANOVA) at the 5% level. F1: Ordinary compound fertilizer (N:P₂O₅:K₂O = 15%:15%:15%); F2: wheat-specific compound fertilizer (N:P₂O₅:K₂O = 26%:10%:9%); F3: urea (N = 46%); CK: no topdressing. *Significant ($p < 0.05$); ns: nonsignificant ($p > 0.05$).

Photosynthetic characteristics. The effect of topdressing fertilizer types (Table 2) on photosynthetic rate, stomatal conductance, and transpiration rate was consistently $F2 > F3 > F1 > CK$. The value of intercellular CO_2 concentration was the highest in CK, and the lowest in F2, and the difference between CK and F2 was significant. Compared to CK, F1, F2 and F3 significantly increased photosynthetic rate. The differences in photosynthetic rate, stomatal conductance, transpiration rate and intercellular CO_2 concentration between F1 and F3 were insignificant, indicating that the photosynthetic characteristics does not show obvious differences when topdressing urea or ordinary compound fertilizer at jointing stage.

Table 2. Effects of topdressing fertilizer types on photosynthetic characteristics of flag leaf at flowering stage. Values are means $\pm$ SD ($n = 9$). Means followed by different letters in the same column indicate significant difference ($p < 0.05$). F1: Ordinary compound fertilizer (N:P₂O₅:K₂O = 15%:15%:15%); F2: wheat-specific compound fertilizer (N:P₂O₅:K₂O = 26%:10%:9%); F3: urea (N = 46%); CK: no topdressing.

	Photosynthetic rate	Stomatal conductance	Transpiration rate	Intercellular CO_2 concentration
	$\mu\text{mol m}^{-2} \text{s}^{-1}$	$\text{mol m}^{-2} \text{s}^{-1}$	$\text{mmol m}^{-2} \text{s}^{-1}$	$\mu\text{mol mol}^{-1}$
2024				
F1	15.63 ± 0.92^b	0.475 ± 0.03^{ab}	3.91 ± 0.37^a	386.74 ± 19.46^{ab}
F2	17.80 ± 1.05^a	0.516 ± 0.03^a	4.15 ± 0.27^a	321.51 ± 33.27^c
F3	15.78 ± 1.20^b	0.479 ± 0.11^{ab}	3.98 ± 0.26^a	382.08 ± 38.73^b
CK	14.00 ± 1.38^c	0.419 ± 0.03^b	3.46 ± 0.29^b	413.40 ± 19.06^a
2025				
F1	16.50 ± 1.55^a	0.497 ± 0.04^a	3.88 ± 0.40^b	375.14 ± 32.91^b
F2	17.71 ± 1.74^a	0.541 ± 0.09^a	4.36 ± 0.23^a	327.68 ± 21.89^c
F3	16.55 ± 1.47^a	0.503 ± 0.04^a	3.92 ± 0.29^b	377.23 ± 28.60^b
CK	14.70 ± 1.10^b	0.422 ± 0.02^b	3.09 ± 0.18^c	426.73 ± 28.14^a

Canopy photosynthetically active radiation. The canopy (Figure 3) PAR in CK was significantly lower than that in F1, F2, and F3. Compared to F1 and F3, F2 significantly increased canopy PAR, indicating that topdressing wheat-specific compound fertilizer was beneficial for improving canopy PAR when compared to topdressing ordinary compound fertilizer and urea. Compared to F1, F3 significantly increased canopy PAR by 4.33% and 4.41% at flowering and middle of filling stages in 2024, and significantly increased by 6.72% and 4.63% in 2025, respectively.

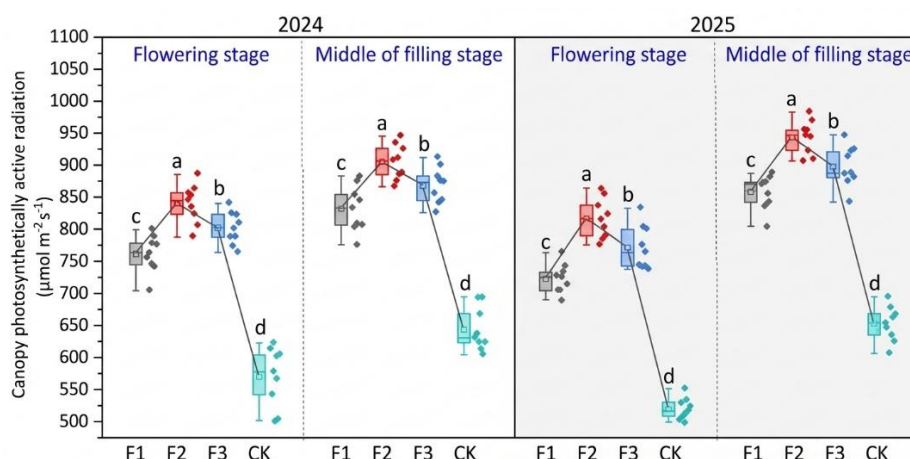


Figure 3. Effects of topdressing fertilizer types on canopy photosynthetically active radiation of wheat. Values are means $\pm$ SD ($n = 9$). Different letters above columns indicate significant difference by LSD test (ANOVA) at the 5% level. F1: Ordinary compound fertilizer (N:P₂O₅:K₂O = 15%:15%:15%); F2: wheat-specific compound fertilizer (N:P₂O₅:K₂O = 26%:10%:9%); F3: urea (N = 46%); CK: no topdressing.

Effects of topdressing fertilizer types on accumulation rate of photosynthetic products

The grain filling rate (Figure 4) from flowering stage to middle of filling stage, and from middle of filling stage to maturity stage were consistently $F2 > F1 > F3$, while DM accumulation rate of stem and leaf from jointing stage to booting stage, and from booting stage to flowering stage were consistently $F3 > F2 > F1$. Indicating that topdressing compound fertilizer was more beneficial for improving grain filling rate, while topdressing urea was more beneficial for improving DM accumulation rate of stem and leaf. Compared to $F1$, $F2$ increased grain filling rate and significantly increased DM accumulation rate of stem and leaf.

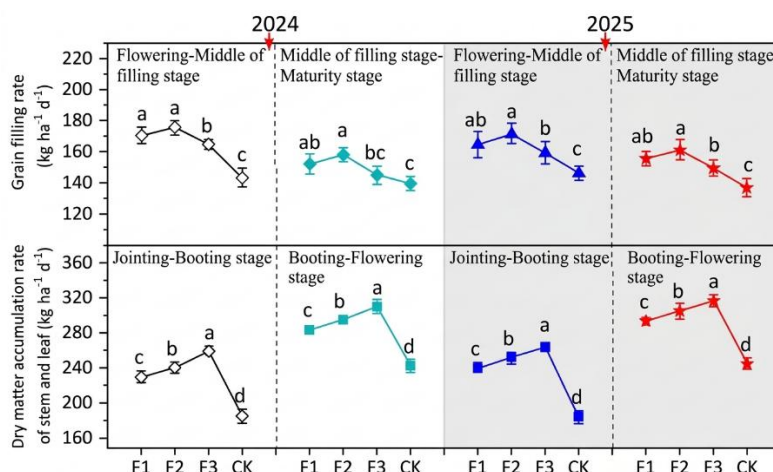


Figure 4. Effects of topdressing fertilizer types on accumulation rate of photosynthetic products. Values are means $\pm$ SD ($n = 6$). Different letters indicate significant difference by LSD test (ANOVA) at the 5% level. F1: Ordinary compound fertilizer ($N:P_2O_5:K_2O = 15\%:15\%:15\%$); F2: wheat-specific compound fertilizer ($N:P_2O_5:K_2O = 26\%:10\%:9\%$); F3: urea ($N = 46\%$); CK: no topdressing.

Effects of topdressing fertilizer types on yield and harvest index

The yield in CK was significantly lower than that in $F1$, $F2$ and $F3$ (Figure 5). Compared to $F1$, $F2$ significantly increased yield by 7.26% and 8.13% in 2024 and 2025, and increased harvest index by 4.05% and 2.77% in 2024 and 2025 respectively. Compared to $F3$, $F1$ and $F2$ significantly increased yield and harvest index, indicating that topdressing compound fertilizer at jointing stage was beneficial for improving yield and harvest index when compared to topdressing urea. Compared to CK, $F3$ significantly increased yield, while the difference in harvest index between CK and $F3$ was nonsignificant, indicating that topdressing urea was beneficial for improving yield, but it was not beneficial for improving harvest index when compared to no topdressing. The yield and harvest index in $F2$ were the highest.

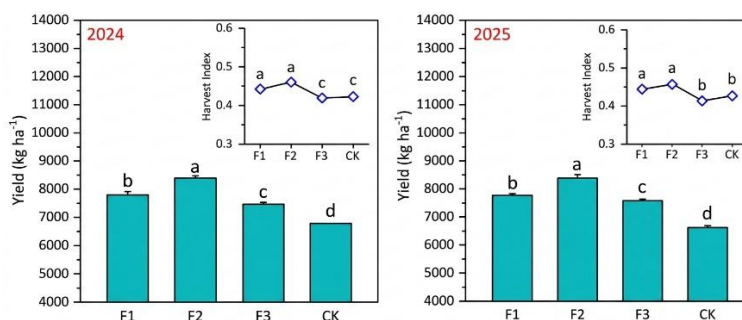


Figure 5. Effects of topdressing fertilizer types on yield and harvest index. Values are means $\pm$ SD ($n = 3$). Different letters above columns indicate significant difference by LSD test (ANOVA) at the 5% level. F1: Ordinary compound fertilizer ($N:P_2O_5:K_2O = 15\%:15\%:15\%$); F2: wheat-specific compound fertilizer ($N:P_2O_5:K_2O = 26\%:10\%:9\%$); F3: urea ($N = 46\%$); CK: no topdressing.

DISCUSSION

Crop root traits are strongly influenced by a wide range of abiotic factors, fertilizer usually affects the nutrient status in the soil, which in turn affects growth, development, and morphology of plant roots. Lopez et al. (2023) observed that crop grown on nutrient-rich soil patches enhanced number and length of fine lateral roots, thus positively affecting the overall specific root length. Wen et al. (2016) observed that the treatment of combined applications of N and P fertilizers with manure had the best effects on improving root growth and development. He et al. (2024) indicated that combining base to topdressing ratio and layered application of fertilizer stimulated root growth, optimized root spatial distribution and delayed root senescence. In this study, we found that topdressing fertilizer at jointing stage significantly improved wheat root traits when compared to no topdressing (CK); compared to ordinary compound fertilizer (F1) and urea (F3), topdressing wheat-specific compound fertilizer (F2) significantly enhanced root length, root surface area, root volume, root diameter, root tips and root forks, and topdressing ordinary compound fertilizer was more conducive to improving root traits than topdressing urea. Compared to topdressing ordinary compound fertilizer, the potential mechanisms for topdressing wheat-specific compound fertilizer can improve root traits mainly due to wheat-specific compound fertilizer has higher N content (under the same weight of solid fertilizer), and suitable or sufficient N supply is extremely important for the growth of wheat roots (Chen et al., 2021a); in addition, wheat-specific compound fertilizer may better balance the N, P and K demand of wheat roots and plants. Compared to topdressing urea, topdressing ordinary compound fertilizer can improve root traits mainly due to P and K are equally important for the growth of wheat roots (Liu, 2021), and excessive N supply with lack of P, K (urea) is not conducive to root growth (Ordóñez et al., 2021; Chen et al., 2021a).

Crop growth is closely related to photosynthesis, which is influenced by fertilizer application and the nutrient status of the plant, expressed at canopy level as leaf area, chlorophyll content, photosynthetic rate and photosynthetically active radiation (PAR). Ahmad et al. (2012) indicated that fertilizer split application as a top dressing along with a basal dose at sowing to C₃ winter cereals in saline soils may be adopted as an alternate strategy to enhance radiation-use efficiency by increasing fertilizer use efficiency. Yousefi et al. (2020) found that applying new (biological) fertilizers obviously increased the maximum leaf area index and radiation-use efficiency of crop when compared with the control. Chen et al. (2021b) also observed that different fertilizer types and dosages could cause significant differences in the photosynthetic effects of crop leaves. In this study, we found that topdressing urea increased single leaf area, chlorophyll content, photosynthetic rate and PAR of canopy when compared to ordinary compound fertilizer; compared to topdressing ordinary compound fertilizer and urea, topdressing wheat-specific compound fertilizer increased the single leaf area of canopy, chlorophyll content (at flowering stage), photosynthetic rate and canopy PAR, while the chlorophyll content in F2 was slightly lower than that in F3 at middle of filling stage. Topdressing urea could improve wheat canopy photosynthesis when compared to topdressing ordinary compound fertilizer (under the same weight), the main reason may be that urea provides more N sources for canopy photosynthesis, and N as a macro-element plays a vital role in photosynthesis (Mu and Chen, 2021), and the soil itself contains a certain amount of P and K; topdressing wheat-specific compound fertilizer could improve canopy photosynthesis when compared to topdressing ordinary compound fertilizer and urea, the reason mainly due to wheat-specific compound fertilizer not only provides suitable or sufficient N but also a certain amount of P and K, which can better meet the demand of N, P and K for canopy photosynthesis.

To date, large amounts of fertilizers have been applied to farmlands to obtain higher crop yields, exploring how the yield respond to fertilizer types and fertilizer application methods would be beneficial for reducing fertilizer application and improving yield (Zhai et al., 2022). Vejan et al. (2021) indicated that the application of slow-release compound fertilizer has been a gamechanger as an environmentally sustainable pathway to enhance crop yields by paving desired phase of plant growth via a direct or indirect mechanism. Liu et al. (2019) and Zhang et al. (2023) also reported that by dividing fertilizer into basal and topdressing applications (topdressing can reduce fertilizer loss caused by limited nutrient absorption capacity of crop in early stage), the source-sink relationship could be regulated, further improving crop yields, increasing fertilizer uptake rate and reducing fertilizer input. In this study we found that topdressing compound fertilizer (F1 and F2) improved grain filling rate, yield and harvest index when compared to topdressing urea, while topdressing urea was more beneficial for improving DM accumulation rate of stem and leaf. The reason may be that the coordination of N, P, and K nutrients (topdressing compound fertilizer) is more conducive to improving grain filling rate and promoting the

transfer of photosynthetic products to grains (Moe et al., 2019; Pleskachiov et al., 2022), thereby increasing yield and harvest index; however, excessive N input (topdressing urea) without P and K would lead to the demand for P and K is difficult to meet in the later stages of wheat growth, and more photosynthetic products transport to leaves and stems, thereby decreasing grain yield and harvest index. In addition, compared to topdressing ordinary compound fertilizer (low N content), wheat-specific compound fertilizer (suitable or sufficient N content) improved accumulation rate of photosynthetic products, yield and harvest index, even though F1 had higher P and K content than F2. The reason may be that although the base fertilizer contains suitable amount of N, N absorption and utilization capacity during wheat seedling stage is relatively low, resulting in large losses of N, therefore, sufficient N supplementation is still needed for topdressing to meet the growth and development needs of wheat in the middle and later stages.

CONCLUSIONS

Our study showed that compared with topdressing the same weight of urea, topdressing ordinary compound fertilizer improved root traits, grain filling rate, yield and harvest index, while decreased single leaf area of canopy, chlorophyll content, photosynthetic rate, canopy photosynthetically active radiation, DM accumulation rate of stem and leaf. Proving that topdressing excessive N without P and K (urea) could improve canopy photosynthesis and the accumulation of photosynthetic products in stems and leaves, but it was not conducive to improving root traits and the transfer of photosynthetic products to grains, thereby reducing yield and harvest index. Revealing that topdressing sufficient N with suitable P and K (wheat-specific compound fertilizer) was more beneficial for improving root traits, canopy photosynthesis, grain filling rate, yield and harvest index when compared with topdressing urea (excessive N without P and K) or less N with sufficient P and K (ordinary compound fertilizer). Therefore, in wheat topdressing strategies, it is necessary to ensure topdressing wheat-specific compound fertilizer (under the same weight condition), rather than urea and ordinary compound fertilizer.

Author contributions

Conceptualization: X.Z., S.D., H.C. Methodology: X.Z., Z.Z., Y.S., Y.Q. Formal analysis: Z.Z., Y.S., S.D., H.C. Investigation: X.Z., Z.Z., Y.S., Y.Q. Data curation: Y.Q. Writing-original draft: X.Z. Writing-review & editing: H.C. Supervision: Z.Z., Y.S. Funding acquisition: H.C. All co-authors reviewed the final version and approved the manuscript before submission.

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References

- Ahmad, S., Ali, H., Ismail, M., Shahzad, M.I., Nadeem, M., Anjum, M.A., et al. 2012. Radiation and nitrogen use efficiencies of C3 winter cereals to nitrogen split application. *Pakistan Journal of Botany* 44:139-149.
- Cao, Q., Miao, Y., Shen, J., Yu, W., Yuan, F., Cheng, S., et al. 2016. Improving in-season estimation of rice yield potential and responsiveness to topdressing nitrogen application with crop circle active crop canopy sensor. *Precision Agriculture* 17:136-154. doi:10.1007/s11119-015-9412-y.
- Chen, Y., Fan, P., Mo, Z., Kong, L., Tian, H., Duan, M., et al. 2021a. Deep placement of nitrogen fertilizer affects grain yield, nitrogen recovery efficiency, and root characteristics in direct-seeded rice in South China. *Journal of Plant Growth Regulation* 40:379-387. doi:10.1007/s00344-020-10107-2.
- Chen, J., Guo, Z., Chen, H., Yang, X., Geng, J. 2021b. Effects of different potassium fertilizer types and dosages on cotton yield, soil available potassium and leaf photosynthesis. *Archives of Agronomy and Soil Science* 67(2):275-287. doi:10.1080/03650340.2020.1723005.
- Ercoli, L., Masoni, A., Pampana, S., Mariotti, M., Arduini, I. 2013. As durum wheat productivity is affected by nitrogen fertilization management in Central Italy. *European Journal of Agronomy* 44:38-45. doi:10.1016/j.eja.2012.08.005.
- Fu, X., Wang, J., Peng, Z., Yang, X., Zhang, S. 2022. Late topdressing can sustain wheat grain yield under straw mulching in the Loess Plateau of China. *Agronomy Journal* 114(6):3487-3497. doi:10.1002/agj2.21200.
- Galetto, S.L., Bini, A.R., Haliski, A., Scharr, D.A., Borszowski, P.R., Caires, E.F. 2017. Nitrogen fertilization in top dressing for wheat crop in succession to soybean under a no-till system. *Bragantia* 76:282-291. doi:10.1590/1678-4499.095.
- Grassini, P., Eskridge, K.M., Cassman, K.G. 2013. Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications* 4:2918-2928. doi:10.1038/ncomms3918.

- Hao, T., Zhu, Q., Zeng, M., Shen, J., Shi, X., Liu, X., et al. 2020. Impacts of nitrogen fertilizer type and application rate on soil acidification rate under a wheat-maize double crop system. *Journal of Environmental Management* 270:110888. doi:10.1016/j.jenvman.2020.110888.
- He, Z., Dang, X., Lin, X., Gao, G., Liu, Y., Ma, F. 2024. Combining base to topdressing ratio and layered application of phosphorus fertilizer enhanced cotton yield by regulating root distribution and activity. *Soil and Tillage Research* 241:106111. doi:10.1016/j.still.2024.106111.
- Hou, P., Hu, C., Yu, J., Gao, Q., Zhou, M., Gao, L., et al. 2024. Increasing topdressing ratio of nitrogen fertilizer improves grain yield and nitrogen use efficiency of winter wheat under winter and spring night-warming. *Journal of Soil Science and Plant Nutrition* 24(2):3459-3473. doi:10.1007/s42729-024-01767-0.
- Illescas, M., Rubio, M.B., Hernández-Ruiz, V., Morán-Díez, M.E., Martínez de Alba, A.E., Nicolás, C., et al. 2020. Effect of inorganic N topdressing and *Trichoderma harzianum* seed-inoculation on crop yield and the shaping of root microbial communities of wheat plants cultivated under high basal N fertilization. *Frontiers in Plant Science* 11:575861. doi:10.3389/fpls.2020.575861.
- Liu, D. 2021. Root developmental responses to phosphorus nutrition. *Journal of Integrative Plant Biology* 63(6):1065-1090. doi:10.1111/jipb.13090.
- Liu, Z., Gao, F., Liu, Y., Yang, J., Zhen, X., Li, X., et al. 2019. Timing and splitting of nitrogen fertilizer supply to increase crop yield and efficiency of nitrogen utilization in a wheat-peanut relay intercropping system in China. *The Crop Journal* 7(1):101-112. doi:10.1016/j.cj.2018.08.006.
- Lopez, G., Ahmadi, S.H., Amelung, W., Athmann, M., Ewert, F., Gaiser, T., et al. 2023. Nutrient deficiency effects on root architecture and root-to-shoot ratio in arable crops. *Frontiers in Plant Science* 13:1067498. doi:10.3389/fpls.2022.1067498.
- Lyu, T., Shen, J., Ma, J., Ma, P., Yang, Z., Dai, Z., et al. 2021. Hybrid rice yield response to potted-seedling machine transplanting and slow-release nitrogen fertilizer application combined with urea topdressing. *The Crop Journal* 9(4):915-923. doi:10.1016/j.cj.2020.08.013.
- Moe, K., Htwe, A.Z., Thu, T.T.P., Kajihara, Y., Yamakawa, T. 2019. Effects on NPK status, growth, dry matter and yield of rice (*Oryza sativa*) by organic fertilizers applied in field condition. *Agriculture* 9(5):109. doi:10.3390/agriculture9050109.
- Mu, X., Chen, Y. 2021. The physiological response of photosynthesis to nitrogen deficiency. *Plant Physiology and Biochemistry* 158:76-82. doi:10.1016/j.plaphy.2020.11.019.
- Nyiraneza, J., Cambouris, A.N., Ziadi, N., Tremblay, N., Nolin, M.C. 2012. Spring wheat yield and quality related to soil texture and nitrogen fertilization. *Agronomy Journal* 104(3):589-599. doi:10.2134/agronj2011.0342.
- Ordóñez, R.A., Castellano, M.J., Danalatos, G.N., Wright, E.E., Hatfield, J.L., Burras, L., et al. 2021. Insufficient and excessive N fertilizer input reduces maize root mass across soil types. *Field Crops Research* 267:108142. doi:10.1016/j.fcr.2021.108142.
- Pleskachiov, Y., Voronov, S., Kurbanov, S., Saquee, F.S., Zargar, M. 2022. Application of new-generation growth regulators and topdressing nitrogen fertilizers increases improver winter wheat yield and grain quality in South Russia. *Agriculture* 12(9):1310. doi:10.3390/agriculture12091310.
- Qiong, W.U., Wang, Y.H., Ding, Y.F., Tao, W.K., Shen, G.A.O., Li, Q.X., et al. 2021. Effects of different types of slow-and controlled-release fertilizers on rice yield. *Journal of Integrative Agriculture* 20(6):1503-1514. doi:10.1016/s2095-3119(20)63406-2.
- Rajcic, V., Terzic, D., Sevic, B., Ugrinovic, M., Tupajic, I., Lukovic, K., et al. 2025. Sustainable wheat production system under the influence of different fertilizers and climatic conditions. *Chilean Journal of Agricultural Research* 85:529-538. doi:10.4067/S0718-58392025000400529.
- Sui, B., Feng, X., Tian, G., Hu, X., Shen, Q., Guo, S. 2013. Optimizing nitrogen supply increases rice yield and nitrogen use efficiency by regulating yield formation factors. *Field Crops Research* 150:99-107. doi:10.1016/j.fcr.2013.06.012.
- Vejan, P., Khadiran, T., Abdullah, R., Ahmad, N. 2021. Controlled release fertilizer: A review on developments, applications and potential in agriculture. *Journal of Controlled Release* 339:321-334. doi:10.1016/j.jconrel.2021.10.003.
- Wen, Z., Shen, J., Blackwell, M., Li, H., Zhao, B., Yuan, H. 2016. Combined applications of nitrogen and phosphorus fertilizers with manure increase maize yield and nutrient uptake via stimulating root growth in a long-term experiment. *Pedosphere* 26(1):62-73. doi:10.1016/S1002-0160(15)60023-6.
- Yang, W., Gong, T., Wang, J., Li, G., Liu, Y., Zhen, J., et al. 2020. Effects of compound microbial fertilizer on soil characteristics and yield of wheat (*Triticum aestivum* L.) *Journal of Soil Science and Plant Nutrition* 20:2740-2748. doi:10.1007/s42729-020-00340-9.
- Yousefi, A., Mirzaeitarposhti, R., Nabati, J., Soufizadeh, S. 2020. Evaluation radiation use efficiency and growth indicators on two mung bean (*Vigna radiata* L.) genotypes under the influence of biological fertilizers. *Journal of Plant Nutrition* 44(8):1095-1106. doi:10.1080/01904167.2020.1862204.
- Zhai, L., Wang, Z., Zhai, Y., Zhang, L., Zheng, M., Yao, H., et al. 2022. Partial substitution of chemical fertilizer by organic fertilizer benefits grain yield, water use efficiency, and economic return of summer maize. *Soil and Tillage Research* 217:105287. doi:10.1016/j.still.2021.105287.
- Zhang, X., Xu, Y., Du, S., Qiao, Y., Cao, C., Chen, H. 2023. Optimized N application improves N absorption, population dynamics, and ear fruiting traits of wheat. *Frontiers in Plant Science* 14:1199168. doi:10.3389/fpls.2023.1199168.