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# Spatiotemporally Matched Nitrogen Release from a Double Core-Shell Urea Improves Rice Growth

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## Abstract

Photosynthetic efficiency and dry matter accumulation are essential for achieving high rice yields, yet conventional controlled-release fertilizers often fail to synchronize nitrogen (N) supply with crop demand. In this study, we evaluated a novel double core–shell controlled-release urea (DCSCRU) designed to align with the bimodal N uptake pattern of rice. A two-year field experiment was conducted to compare DCSCRU at three application rates (180, 225, and 270 kg N $ha^{-1}$) with conventional urea and conventional controlled-release urea (both at 270 kg N $ha^{-1}$). DCSCRU exhibited a distinct biphasic N release profile, with a rapid initial release peaking at 1.60% $d^{-1}$ on day 10 to meet early vegetative demand, followed by a second peak (1.85% $d^{-1}$ on day 45) supporting reproductive development. Compared with conventional urea, DCSCRU treatments significantly improved photosynthetic efficiency and dry matter accumulation during critical growth stages. The 270 kg N $ha^{-1}$ DCSCRU treatment achieved a grain yield exceeding 11.50 × $10^3$ kg $ha^{-1}$, substantially higher than that of conventional urea. Notably, the 225 kg N $ha^{-1}$ DCSCRU treatment produced a comparable yield (10.90 × $10^3$ kg $ha^{-1}$) to that of the conventional urea treatment (10.83 × $10^3$ kg $ha^{-1}$), indicating the potential to reduce N input by 16.7% without compromising yield. The enhanced physiological performance was attributed to improved N availability and optimized canopy function. These findings highlight DCSCRU as a promising strategy for high-yield, resource-efficient, and environmentally sustainable rice production.

**Keywords:** controlled-release nitrogen fertilizer; rice yield; photosynthetic efficiency; dry matter accumulation; nitrogen use efficiency

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## 1. Introduction

Rice (*Oryza sativa* L.), a staple for nearly half of the global population, is central to global food security [1]. However, its production is increasingly challenged by climate change, shrinking arable land, and rising population pressures [2,3]. In response, improving rice yield through resource-efficient and environmentally sustainable technologies has become a major focus of modern agriculture. The rice production in China exemplifies the resource–environment dilemma. Nitrogen (N) fertilizer input averages 209 kg $ha^{-1}$, approximately 90% higher than the global average [4], yet nitrogen use efficiency (NUE) remains below 35% [5]. Excess N leads to ammonia volatilization, denitrification, and runoff, contributing to greenhouse gas emissions and water eutrophication [6,7]. This "high

input-low efficiency-high pollution" cycle necessitates the adoption of green, high-efficiency fertilization strategies [8].

Among the fertilization strategies, slow- and controlled-release nitrogen fertilizers (SCRFs) have demonstrated potential to synchronize nitrogen supply with crop demand, enhance NUE, and reduce environmental losses [9,10]. Polymer-coated urea (PCU), for example, extends N release from tillering to grain filling, improves chlorophyll retention, and boosts photosynthetic efficiency by 10–15%, resulting in improved yield and grain quality [11–13]. Nitrogen is fundamental for synthesizing chlorophyll, proteins, and nucleic acids, thereby regulating photosynthesis, dry matter accumulation, and grain formation [14,15]. Rice requires 15–20 kg of N to produce one ton of grain [16,17], yet fast-release fertilizers often fail to meet the crop's stage-specific needs. Optimal N supply during vegetative growth promotes canopy establishment, while appropriately timed and precisely measured N application during the reproductive and grain-filling stages is essential to support panicle differentiation without causing excessive vegetative growth that impedes the translocation of assimilates to the grains [17]. Conventional practices, which emphasize heavy basal applications, are poorly aligned with these dynamics.

SCRFs overcome this mismatch by regulating release patterns through physical or biochemical mechanisms, thereby improving synchrony with plant uptake and reducing environmental losses [18]. Compared with urea, SCRFs can raise NUE to 50–70%, cut ammonia volatilization by 30–50%, and enhance flag leaf photosynthesis during grain filling [19–21]. Given that ~90% of rice biomass derives from photosynthesis (60–80% of which occurs post-anthesis) maintaining canopy photosynthetic capacity is essential [22,23]. This is closely tied to leaf area index (LAI), nitrogen distribution, and delayed leaf senescence. Moreover, N availability influences grain filling via effects on carbon metabolism enzymes and assimilate translocation [24,25]. Despite these advancements, key gaps remain. First, the impact of N management during the grain-filling stage on carbon-nitrogen interactions and grain quality is underexplored. Second, the release kinetics of diverse SCRFs require mechanistic evaluation to match rice's dynamic N demands. Third, most field studies emphasize final yield but neglect physiological measurements during critical growth stages. Lastly, results from pot or hydroponic studies often lack validation under complex field conditions.

To address these gaps, we conducted a two-year field experiment in Jiangsu Province, China, using two japonica rice cultivars (*Oryza sativa* L. subsp. *japonica* cv. 'Nanjing 9108' and *Oryza sativa* L. subsp. *japonica* cv. 'Nanjing 9308'). The study aimed to clarify the physiological mechanisms by which double core–shell controlled-release urea (DCSCRU) influences canopy photosynthesis and biomass accumulation. Specifically, we examined (1) how DCSCRU affects light energy utilization efficiency; (2) the role of LAI dynamics in regulating photosynthesis; (3) the contribution of enhanced late-stage panicle formation to yield; and (4) variations in dry matter translocation efficiency and their impact on yield components. These findings aim to support precision nitrogen management, promote innovations in controlled-release fertilizer technology, and contribute to sustainable, low-carbon rice production systems.

## 2. Materials and Methods

### *2.1. Experimental Site*

Field experiments were conducted during the 2023 and 2024 rice-growing seasons in Yangzhou City, Jiangsu Province, China (119°40′ E, 32°34′ N). Meteorological data were obtained from the Xihe Energy Big Data Platform (Tudor Technology Co., Ltd., Nanjing, China). During the experimental periods, the average temperatures were 25.90 °C in 2023 and 26.60 °C in 2024, with total precipitation of 627 mm and 779 mm, respectively

(Figure 1). The experimental soil was classified as sandy loam with the following characteristics: pH 6.52, organic matter 24.80 g $kg^{-1}$, total N 1.49 g $kg^{-1}$, $NO_3^-$-N 17.50 mg $kg^{-1}$, $NH_4^+$-N 1.50 mg $kg^{-1}$, available phosphorus 42.20 mg $kg^{-1}$, and available potassium 71.10 mg $kg^{-1}$.

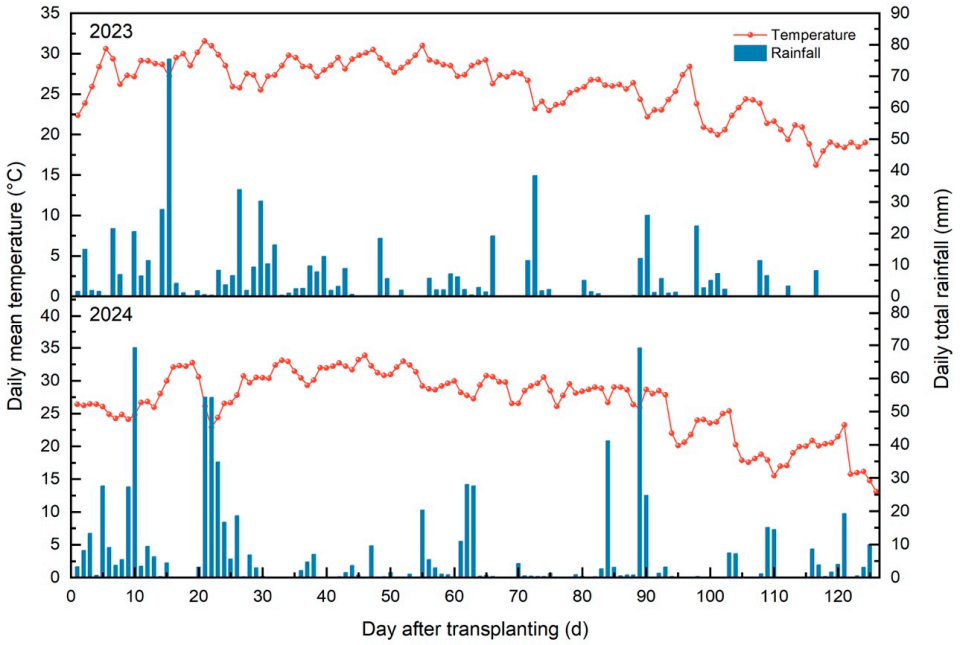



**Figure 1.** Daily rainfall and temperature from transplanting to harvest in 2023 and 2024.

### *2.2. Experimental Materials*

Two late-maturing japonica rice cultivars, 'Nanjing 9108' and 'Nanjing 9308', were used in this study. Both cultivars were developed by the Institute of Grain Crops, Jiangsu Academy of Agricultural Sciences (Nanjing, China) and are characterized by compact plant architecture, high panicle number, strong lodging resistance, and adaptability to the agroecological conditions of central Jiangsu Province. The growth duration of both varieties is approximately 158 days.

Three nitrogen fertilizers were employed: double-core–shell controlled-release urea (DCSCRU, 43.1% N), conventional controlled-release urea (CRU, 43.6% N), and conventional urea (46% N), with the controlled-release types supplied by Maoshi Agricultural Science and Technology Co., Ltd. (Chizhou, China).

### *2.3. Experimental Design*

To evaluate the effects of nitrogen type and rate, six treatments were established in a randomized complete block design with three replicates: (i) CK1, no nitrogen fertilizer; (ii) CK2, conventional urea at 270 kg N $ha^{-1}$; (iii) T1, conventional CRU at 270 kg N $ha^{-1}$; (iv) T2, DCSCRU at 180 kg N $ha^{-1}$; (v) T3, DCSCRU at 225 kg N $ha^{-1}$; and (vi) T4, DCSCRU at 270 kg N $ha^{-1}$. In the CK2 treatment, nitrogen was applied in three splits: 40% before transplanting (as basal fertilizer), 30% at the tillering stage (7 days after transplanting), and 30% at panicle initiation. In contrast, all controlled-release urea treatments were applied entirely as basal fertilizer. In addition to nitrogen, all plots received 135 kg $ha^{-1}$ of $P_2O_5$ (as calcium superphosphate) and 216 kg $ha^{-1}$ of $K_2O$ (as potassium chloride) prior to transplanting.

The size of each plot was 30 $m^2$ (5 m × 6 m). Rice seedlings were raised in plastic nursery trays, subjected to 48 h of dark treatment to promote uniform germination, and then transferred to a moist environment for seedling growth. At 25 days old, seedlings were

manually transplanted on 24 June 2023, and 20 June 2024, at a spacing of 12.5 cm × 25 cm, with four seedlings per hill (the basic agronomic unit for transplanting) [26]. The corresponding harvest dates were 14 October 2023, and 20 October 2024. Standard crop management practices, including irrigation scheduling and pest, disease, and weed control, were conducted according to local agricultural guidelines to ensure optimal growth conditions across all treatments.

### *2.4. Sampling and Measurements*

#### 2.4.1. Yield and Yield Components

At maturity, 30 hills per plot were sampled to assess yield components. All panicles were collected, air-dried, threshed, and cleaned. Total grain number per 30 hills was counted, and grains per spike were calculated. Thousand-grain weight was determined from three replicate samples of 1000 randomly selected filled grains. Grain yield was measured after sun drying and adjusted to a moisture content of 14.5% using a portable moisture meter (PM-8188-A, Kett Electric Laboratory, Tokyo, Japan).

#### 2.4.2. Chlorophyll Content

Three plants were randomly selected per plot, and the upper three fully expanded leaves of each were measured for chlorophyll content using a SPAD-502 Plus handheld meter (Konica Minolta Sensing, Inc. Tokyo, Japan). Chlorophyll content was expressed as SPAD values.

#### 2.4.3. Photosynthetic Efficiency

During heading and grain-filling stages, flag leaf photosynthetic parameters were measured using a portable photosynthesis system (Li-6400, LI-COR, Inc., Lincoln, NE, USA) under natural light. Measurements included net photosynthetic rate ($P_n$), stomatal conductance ($G_s$), intercellular $CO_2$ concentration ($C_i$), and transpiration rate ($T_r$).

#### 2.4.4. Leaf Area Index and Dry Matter Accumulation

At tillering, jointing, heading, and maturity stages, three representative plants per plot were sampled. Leaf area was determined using the length × width method, and LAI was calculated as the ratio of total leaf area to ground area. For dry matter determination, above-ground plant samples were collected at maturity. The samples were first oven-killed at 105 °C for 30 min to deactivate enzymatic activity and then dried at 80 °C to constant weight.

#### 2.4.5. Enzyme Activities of Nitrogen Metabolism

To evaluate nitrogen metabolism, the uppermost fully expanded leaves were collected from three randomly selected plants per plot. The leaf veins were removed, and the samples were immediately frozen in liquid nitrogen, ground into a fine powder, and stored at −80 °C until further enzymatic analysis. Crude enzyme extracts were prepared from 0.10 g of fresh leaf tissue for subsequent assays. Nitrate reductase (NR) activity was determined according to a modified method based on Savidov et al. [27], which involves extraction in buffer, centrifugation, and spectrophotometric measurement of nitrite-N accumulation via sulfanilamide colorimetry. Glutamine synthetase (GS) activity was measured according to Han et al. [28] by quantifying the formation of γ-glutamyl hydroxamate. Meanwhile, glutamate synthase (GOGAT) activity was assessed spectrophotometrically by monitoring NADH oxidation in the presence of glutamine, as described by Liu et al. [29].

2.4.6. Nutrient Release Rate

The nutrient release characteristics of the DCSCRU were determined using the standard water immersion method [30]. The DCSCRU was placed into a permeable inert nylon bag with a pore size $\leq$ 0.15 mm. The bag was then immersed in 200 mL of deionized water and incubated under constant temperature conditions. At predetermined time intervals (0.25 (6 h), 0.75 (18 h), 1, 2, 5, 10, 20, 28, 38, 45, 55, 60, 70, and 80 days), aliquots of the solution were collected, and the nitrogen concentration was determined using the Kjeldahl method [31] with a Kjeltec 8400 system (FOSS, Hillerød, Denmark). After each sampling, an equal volume of fresh pre-tempered extraction solution was replenished to maintain a constant total volume throughout the experiment. The cumulative nutrient release rate was calculated as the percentage of the total nutrient released at each time point relative to the initial nutrient content in the fertilizer. Release curves were plotted based on these values to evaluate the release profiles.

### *2.5. Statistical Analysis*

Data were processed using Microsoft Excel 2023 and analyzed with SPSS 19.0. One-way ANOVA was conducted, and treatment means were compared using the least significant difference (LSD) test at the 0.05 significance level. Figures were generated using Origin 2024.

## 3. Results

### *3.1. Nitrogen Release Characteristics of Double-Core–Shell Controlled-Release Urea*

As shown in Figure 2, the DCSCRU exhibited a biphasic nitrogen release pattern, with two distinct peaks occurring around days 10 and 45 after soil incorporation. The initial peak supported early vegetative growth, while the second, more pronounced peak corresponded to the panicle differentiation stage, providing a sustained nutrient supply that enhanced grain number per panicle and minimized late-stage spikelet abortion. This dual-release profile facilitated nutrient synchronization with crop demand, improved nitrogen accumulation, and ultimately contributed to enhanced panicle formation and grain setting, thereby promoting higher yield potential.

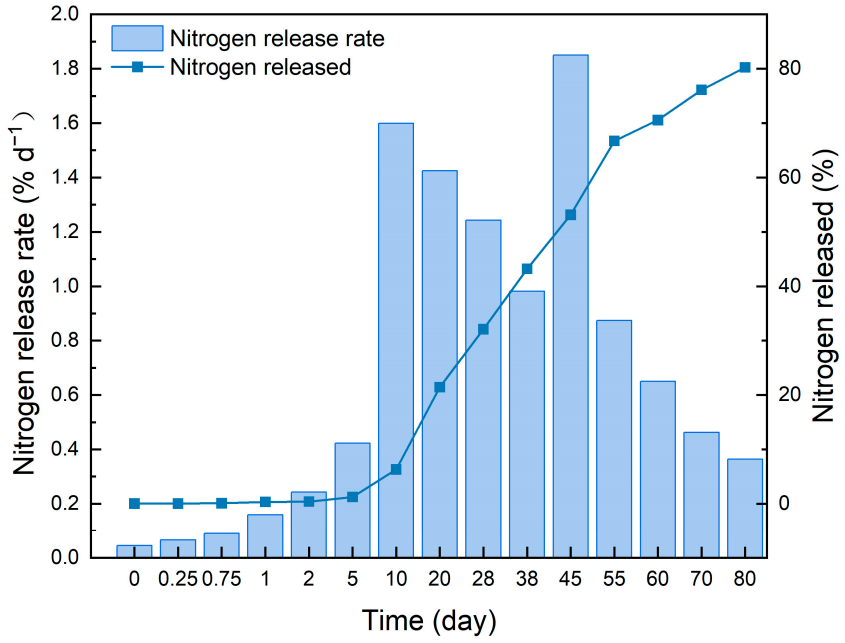



**Figure 2.** Nitrogen release, total nitrogen accumulation and total nitrogen release rate of controlled-release nitrogen fertilizer with double core–shell structure.

### 3.2. Productive Tiller Percentage

Significant differences in productive tiller percentage were observed across treatments and cultivars (Figure 3). In 'Nanjing 9108', the T3 treatment increased the productive tiller percentage by 12.94% relative to CK2, while in 'Nanjing 9308', there was no significant difference between the T4 treatment and the CK2 treatment. These findings suggest that DCSCRU significantly enhances late-stage panicle formation by aligning nitrogen release with critical reproductive growth phases, which is essential for yield improvement.

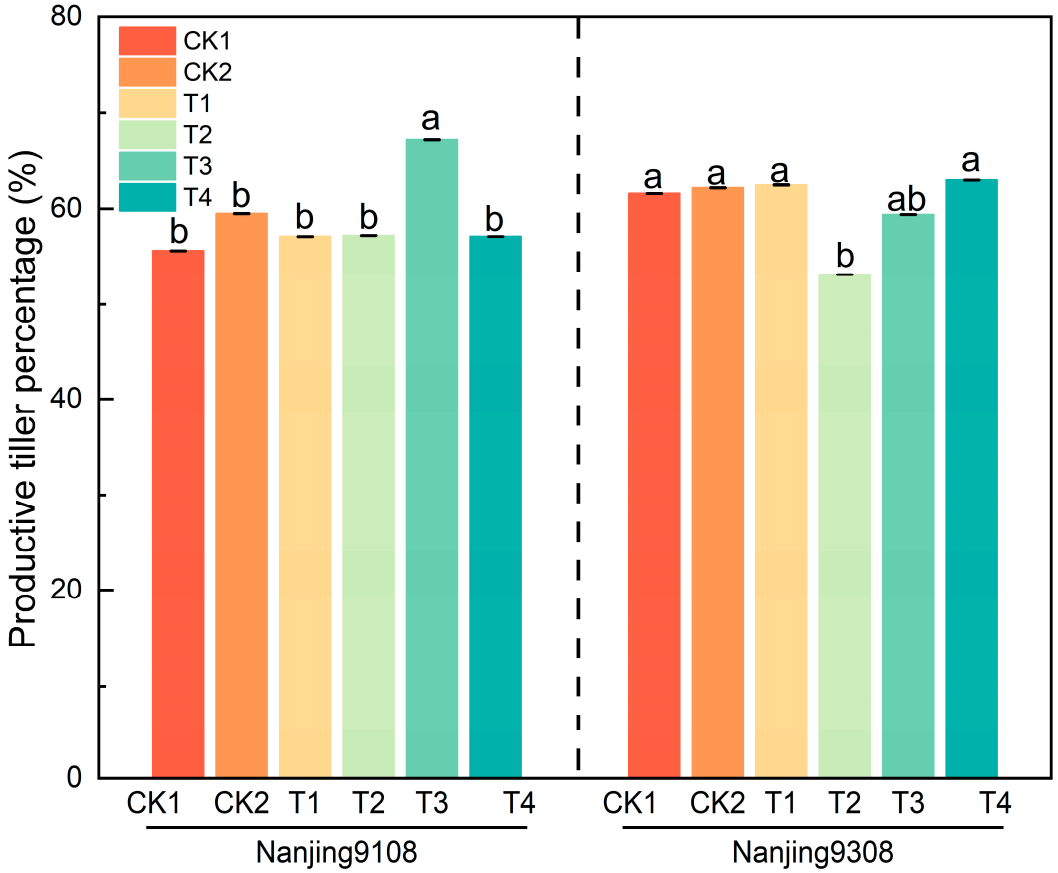



**Figure 3.** Effects of different fertilization treatments on rice productive tiller percentage. Different letters indicate a significant difference among treatments ($p < 0.05$).

### 3.3. Photosynthetic Traits

Chlorophyll content (SPAD values) differed significantly among treatments and cultivars but showed no significant year effect or year × treatment × cultivar interaction. As shown in Table 1, SPAD values declined after August 26, likely due to dilution of nitrogen concentration during the vegetative-to-reproductive transition. During heading and grain filling, DCSCRU treatments (T2–T4) maintained higher SPAD values than conventional and non-fertilized controls, with T4 showing a 16.74–30.88% increase compared to CK2. The sustained SPAD levels in controlled-release treatments indicate delayed leaf senescence and enhanced photosynthetic capacity, supporting higher biomass production.

As shown in Figures 4 and 5, 'Nanjing 9108' exhibited consistently higher transpiration rates throughout the heading stage compared to 'Nanjing 9308', indicating inherent differences in their water use strategies. Both cultivars showed a progressive decline in transpiration rate from early to late heading. However, the distinct absolute values suggest that 'Nanjing 9308' may possess traits conducive to water conservation, potentially leading to higher water-use efficiency under water-limited conditions. Further analysis of Table 1, Figures 4 and 5 reveals that although SPAD values and photosynthetic rates declined after

heading, the rate of decline was slower in DCSCRU treatments, indicating prolonged photosynthetic activity and nutrient supply during grain filling. This enhanced the formation of photoassimilates, contributing to yield stability.

**Table 1.** Effect of different treatments on chlorophyll content in rice.

| Year | Cultivar | Treatment | The First Day of Heading | The 7th Day of Heading | The 14th Day of Heading | The 21st Day of Heading | The 28th Day of Heading | The 35th Day of Heading |
|---|---|---|---|---|---|---|---|---|
| 2023 | 'Nanjing 9108' | CK1 | 38.18 c | 37.14 b | 34.41 b | 35.61 c | 29.37 b | 23.53 b |
| | | CK2 | 39.68 bc | 40.02 ab | 36.62 b | 37.95 bc | 35.97 a | 30.29 a |
| | | T1 | 40.39 bc | 38.07 ab | 40.90 a | 42.65 a | 41.11 a | 34.30 a |
| | | T2 | 43.50 ab | 39.77 ab | 36.87 b | 36.92 c | 36.37 a | 29.04 ab |
| | | T3 | 43.92 ab | 39.80 ab | 40.73 a | 40.38 ab | 37.13 a | 35.13 a |
| | | T4 | 45.99 a | 40.77 a | 40.33 a | 40.33 ab | 41.22 a | 35.36 a |
| | 'Nanjing 9308' | CK1 | 33.46 d | 38.62 a | 32.71 d | 31.11 b | 25.86 b | 17.96 c |
| | | CK2 | 38.41 c | 37.98 a | 37.60 c | 37.11 a | 34.35 a | 26.34 b |
| | | T1 | 38.88 c | 38.48 a | 37.42 c | 39.02 a | 37.95 a | 30.82 ab |
| | | T2 | 42.43 b | 38.34 a | 38.49 bc | 37.49 a | 35.56 a | 29.79 ab |
| | | T3 | 43.87 ab | 40.01 a | 39.33 ab | 40.53 a | 38.27 a | 33.23 a |
| | | T4 | 45.36 a | 41.13 a | 40.05 a | 38.69 a | 39.45 a | 34.41 a |
| 2024 | 'Nanjing 9108' | CK1 | 37.96 b | 36.73 c | 34.39 c | 35.62 d | 30.03 c | 22.98 c |
| | | CK2 | 39.70 b | 39.43 b | 36.44 b | 38.38 c | 37.05 b | 29.83 b |
| | | T1 | 39.92 b | 37.50 c | 41.02 a | 42.66 a | 41.12 a | 34.63 a |
| | | T2 | 44.09 a | 39.04 b | 37.41 b | 36.43 d | 36.71 b | 28.89 b |
| | | T3 | 43.06 a | 39.26 b | 40.96 a | 40.10 b | 36.85 b | 35.72 a |
| | | T4 | 44.22 a | 40.99 a | 40.25 a | 40.23 b | 40.86 a | 35.42 a |
| | 'Nanjing 9308' | CK1 | 33.23 d | 38.27 b | 32.15 d | 30.79 c | 25.41 d | 17.60 e |
| | | CK2 | 38.85 c | 37.61 b | 38.12 bc | 37.55 b | 34.41 c | 26.62 d |
| | | T1 | 38.49 c | 38.45 b | 37.53 c | 38.80 b | 37.18 b | 31.40 b |
| | | T2 | 42.53 b | 37.76 b | 38.53 bc | 37.77 b | 35.61 c | 29.17 c |
| | | T3 | 43.58 b | 38.93 b | 39.53 ab | 40.32 a | 38.32 ab | 32.84 b |
| | | T4 | 45.00 a | 40.82 a | 40.50 a | 38.38 b | 39.23 a | 34.84 a |
| Analysis of variance | | Year (Y) | NS | NS | NS | NS | NS | NS |
| | | Cultivar (C) | ** | NS | ** | ** | ** | ** |
| | | Treatment (T) | ** | ** | ** | ** | ** | ** |
| | | Y × C | NS | NS | NS | NS | NS | NS |
| | | Y × T | NS | NS | NS | NS | NS | NS |
| | | C × T | ** | * | ** | ** | NS | * |
| | | Y × C × T | NS | NS | NS | NS | NS | NS |

Note: Different letters indicate a significant difference among treatments ($p < 0.05$). NS, not significant at the $p < 0.05$ level; *, significant at the $p < 0.05$ level; **, significant at the $p < 0.01$ level.

Fertilizer treatments significantly influenced LAI at each growth stage, with no significant effects of year or interactions. LAI increased during vegetative development and declined thereafter (Table 2). Compared to CK2, the T4 treatment consistently yielded the highest LAI during both the heading and maturity stages, with average increases of 20.16% and 43.86% for 'Nanjing 9108', and 43.38% and 37.26% for 'Nanjing 9108', respectively. The impact of DCSCRU on late-stage LAI became more pronounced with increasing nitrogen dosage, highlighting its role in maintaining canopy structure and photosynthetic efficiency during grain filling.

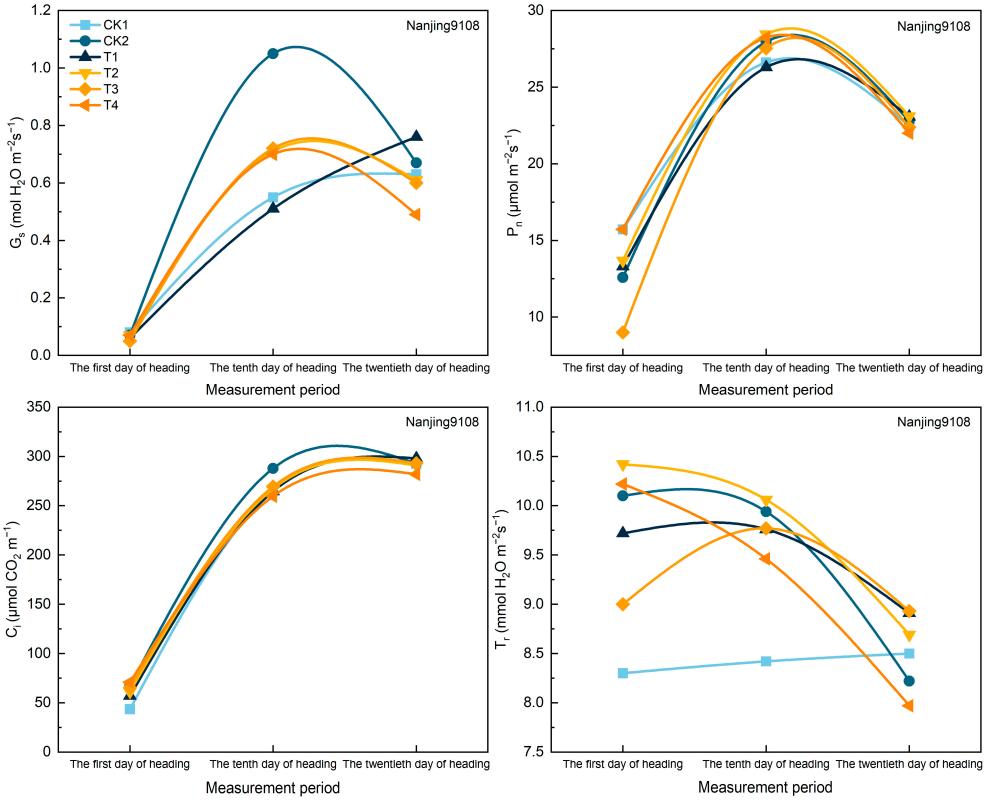



**Figure 4.** Effect of different treatments on photosynthetic rate of 'Nanjing 9108'. $G_s$, stomatal conductance; $P_n$, net photosynthetic rat; $C_i$, intercellular $CO_2$ concentration; $T_r$, transpiration rate.

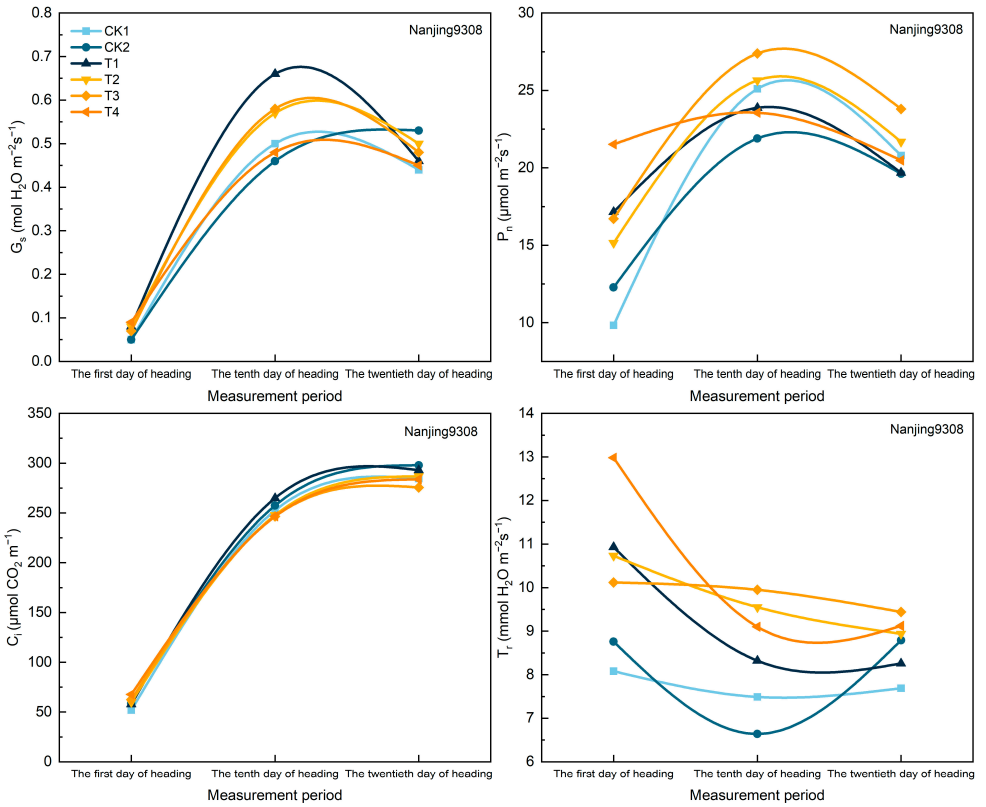



**Figure 5.** Effect of different treatments on photosynthetic rate of 'Nanjing 9308'. $G_s$, stomatal conductance; $P_n$, net photosynthetic rat; $C_i$, intercellular $CO_2$ concentration; $T_r$, transpiration rate.

**Table 2.** Effect of different treatments on leaf area index of rice.

| Year | Cultivar | Treatment | TS | JS | HS | MS |
|---|---|---|---|---|---|---|
| 2023 | ‘Nanjing 9108’ | CK1 | 0.53 b | 1.31 b | 3.87 c | 3.75 c |
| | | CK2 | 1.11 a | 4.92 a | 7.08 ab | 3.85 c |
| | | T1 | 0.81 ab | 4.70 a | 6.40 b | 4.58 bc |
| | | T2 | 0.74 ab | 4.49 a | 7.23 ab | 5.09 abc |
| | | T3 | 0.84 ab | 4.84 a | 7.06 ab | 5.30 ab |
| | | T4 | 0.81 ab | 5.10 a | 8.87 a | 6.01 a |
| | ‘Nanjing 9308’ | CK1 | 0.35 c | 1.65 c | 3.43 c | 3.34 c |
| | | CK2 | 1.15 a | 3.95 b | 5.68 b | 4.53 b |
| | | T1 | 0.76 b | 3.94 b | 7.48 ab | 5.17 ab |
| | | T2 | 0.80 ab | 4.15 ab | 7.35 ab | 4.88 b |
| | | T3 | 0.53 bc | 4.45 ab | 7.53 ab | 5.00 b |
| | | T4 | 0.75 b | 4.99 a | 8.39 a | 6.19 a |
| 2024 | ‘Nanjing 9108’ | CK1 | 0.53 b | 1.29 b | 3.87 d | 3.74 b |
| | | CK2 | 1.33 a | 5.72 a | 7.58 b | 4.87 ab |
| | | T1 | 0.86 ab | 5.19 a | 6.90 c | 5.13 ab |
| | | T2 | 0.72 b | 4.32 a | 7.23 bc | 5.04 ab |
| | | T3 | 0.86 ab | 4.41 a | 7.56 b | 5.36 ab |
| | | T4 | 0.75 ab | 4.61 a | 8.72 a | 6.41 a |
| | ‘Nanjing 9308’ | CK1 | 0.38 c | 1.67 d | 3.45 b | 3.31 d |
| | | CK2 | 1.11 a | 3.71 c | 5.61 ab | 4.41 c |
| | | T1 | 0.79 ab | 3.97 bc | 7.59 a | 5.15 bc |
| | | T2 | 0.68 bc | 4.37 bc | 7.44 a | 5.26 b |
| | | T3 | 0.58 bc | 4.61 ab | 7.69 a | 5.30 b |
| | | T4 | 0.76 abc | 5.29 a | 7.80 a | 6.08 a |
| Analysis of variance | | Year (Y) | NS | NS | NS | NS |
| | | Cultivar (C) | NS | * | NS | NS |
| | | Treatment (T) | ** | ** | ** | ** |
| | | Y × C | NS | NS | NS | NS |
| | | Y × T | NS | NS | NS | NS |
| | | C × T | NS | ** | * | NS |
| | | Y × C × T | NS | NS | NS | NS |

Different letters indicate a significant difference among treatments ($p < 0.05$). NS, not significant at the $p < 0.05$ level; *, significant at the $p < 0.05$ level; **, significant at the $p < 0.01$ level. TS: Tillering stage; JS: Jointing stage; HS: Heading stage; MS: Maturity stage.

### *3.4. Grain Yield and Yield Components*

As shown in Table 3, in 2023, yield differences between CK2 and T4 were not significant, but in 2024, T4 improved yield by 7.60% and 8.53% in ‘Nanjing 9108’ and ‘Nanjing 9308’, respectively. Yield improvements were primarily attributed to increased effective panicle number and grains per panicle, while differences in grain-setting rate and 1000-grain weight were not statistically significant. For example, T4 average increased effective panicle number by 19% and 19.05% in ‘Nanjing 9108’ and ‘Nanjing 9308’, respectively, compared to CK2.

### *3.5. Effects on Rice Dry Matter Accumulation*

As shown in Figure 6, fertilizer treatment had a highly significant effect on dry matter accumulation, while year effects were not significant. For ‘Nanjing 9108’, T4 treatments resulted in significantly higher dry weights at maturity compared to T2 and T3, though no differences were observed from tillering to heading stages. In ‘Nanjing 9308’, T4 also exhibited significantly higher dry matter accumulation from jointing onward, except at the

tillering stage. These results suggest that DCSCRU ensures stable biomass production in late growth stages.

**Table 3.** Effect of different fertilization treatments on rice yield and its components.

| Year | Cultivar | Treatment | Yield | Effective Panicle Density | Grains Per Panicle | 1000-Grain Weight | Grain Filling Percentage |
|---|---|---|---|---|---|---|---|
| | | | ($\times 10^3$ kg ha$^{-1}$) | ($\times 10^4$ ha$^{-1}$) | | (g) | (%) |
| 2023 | 'Nanjing 9108' | CK1 | 7.51 c | 233.08 e | 107.07 c | 27.90 a | 90.59 a |
| | | CK2 | 10.85 ab | 271.15 d | 151.34 b | 25.49 c | 91.61 a |
| | | T1 | 10.78 ab | 285.72 c | 161.24 a | 25.71 c | 89.01 a |
| | | T2 | 10.39 b | 268.54 d | 146.13 b | 27.20 ab | 89.65 a |
| | | T3 | 10.90 ab | 298.79 b | 163.76 a | 26.45 bc | 90.53 a |
| | | T4 | 11.50 a | 326.46 a | 168.36 a | 25.96 bc | 92.30 a |
| | 'Nanjing 9308' | CK1 | 7.47 b | 236.14 f | 103.95 d | 29.94 a | 90.63 a |
| | | CK2 | 10.91 a | 279.98 e | 158.10 bc | 27.00 b | 92.01 a |
| | | T1 | 11.01 a | 317.71 c | 162.31 ab | 28.07 b | 92.14 a |
| | | T2 | 10.51 a | 296.63 d | 150.21 c | 28.43 ab | 91.85 a |
| | | T3 | 11.07 a | 330.08 b | 166.10 ab | 28.32 ab | 91.79 a |
| | | T4 | 11.65 a | 346.67 a | 169.98 a | 27.83 b | 92.51 a |
| 2024 | 'Nanjing 9108' | CK1 | 7.39 d | 212.47 d | 104.96 e | 27.81 a | 90.49 a |
| | | CK2 | 10.79 bc | 266.13 c | 151.25 c | 25.41 b | 91.13 a |
| | | T1 | 10.87 bc | 295.99 b | 161.03 b | 25.66 b | 90.42 a |
| | | T2 | 10.41 c | 268.74 c | 144.83 d | 25.99 b | 90.96 a |
| | | T3 | 11.14 ab | 305.03 a | 161.23 b | 26.39 ab | 91.98 a |
| | | T4 | 11.61 a | 312.96 a | 165.87 a | 25.85 b | 92.57 a |
| | 'Nanjing 9308' | CK1 | 7.43 d | 219.61 d | 101.96 e | 29.76 a | 90.29 b |
| | | CK2 | 10.78 bc | 305.85 c | 156.94 c | 26.92 e | 90.39 b |
| | | T1 | 11.15 abc | 311.29 bc | 163.43 b | 27.77 cd | 90.78 b |
| | | T2 | 10.54 c | 298.77 c | 149.18 d | 28.39 b | 90.68 b |
| | | T3 | 11.37 ab | 325.11 b | 165.13 b | 27.94 bc | 91.38 ab |
| | | T4 | 11.70 a | 349.52 a | 170.27 a | 27.27 de | 92.67 a |
| Analysis of variance | | Year (Y) | NS | NS | NS | NS | NS |
| | | Cultivar (C) | NS | ** | NS | ** | NS |
| | | Treatment (T) | ** | ** | ** | ** | * |
| | | Y × C | NS | NS | NS | NS | NS |
| | | Y × T | NS | ** | NS | NS | NS |
| | | C × T | NS | ** | * | NS | NS |
| | | Y × C × T | NS | ** | NS | NS | NS |

Different letters indicate a significant difference among treatments ($p < 0.05$). NS, not significant at the $p < 0.05$ level; *, significant at the $p < 0.05$ level; **, significant at the $p < 0.01$ level.

The yield performance of different treatments (T1–T4) relative to the control (CK2) in 2023 is shown in Table 4, Figures 7 and 8. Among them, T4 demonstrated the most significant improvement, with yield increases of 5.99% and 6.78%, respectively. In contrast, T3 resulted in more modest gains, corresponding to 0.46% and 1.47%, respectively. These findings support a positive correlation between higher grain percentage and enhanced yield, confirming that the higher the grain percentage, the greater the yield.

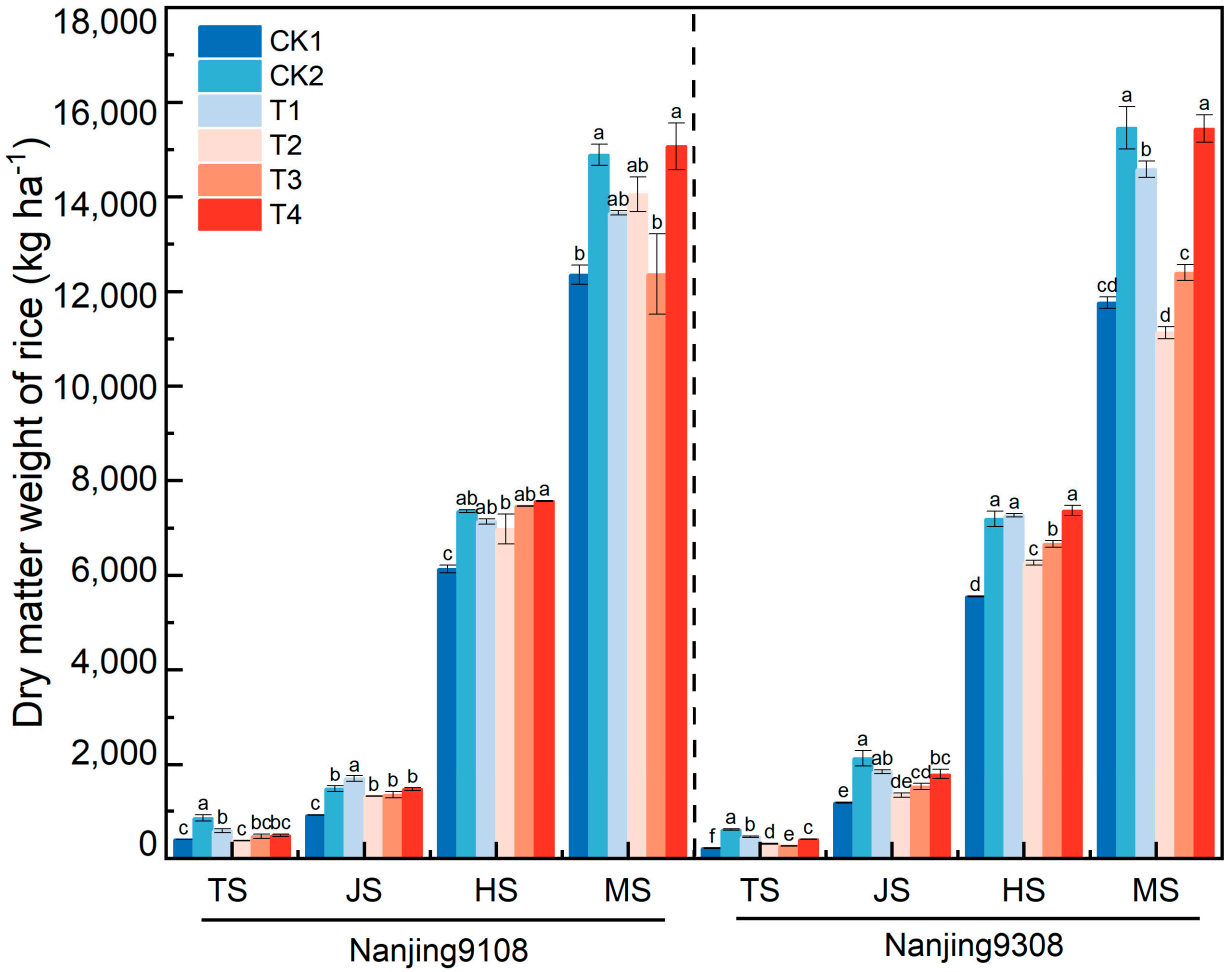



**Figure 6.** Effect of different fertilization treatments on dry matter weight of rice. Different letters indicate a significant difference among treatments ($p < 0.05$). TS: Tillering stage; JS: Jointing stage; HS: Heading stage; MS: Maturity stage.

**Table 4.** Effect of different fertilization treatments on the distribution ratio of rice dry matter weight among different organs.

| Year | Cultivar | Treatment | Stem (%) | Leaf (%) | Grain (%) | Difference in Yield from CK2 ($\times 10^3$ kg ha$^{-1}$) |
|---|---|---|---|---|---|---|
| 2023 | 'Nanjing 9108' | CK1 | 28.75 b | 13.13 a | 58.12 a | - |
| | | CK2 | 30.94 ab | 14.40 a | 54.67 abc | - |
| | | T1 | 36.23 a | 14.77 a | 49.00 c | −0.07 c |
| | | T2 | 33.23 ab | 15.76 a | 51.02 bc | −0.46 d |
| | | T3 | 30.68 ab | 13.25 a | 56.07 ab | 0.05 b |
| | | T4 | 29.69 b | 15.48 a | 54.83 abc | 0.65 a |
| | 'Nanjing 9308' | CK1 | 30.04 a | 10.83 b | 59.13 a | - |
| | | CK2 | 29.43 ab | 13.95 a | 56.62 a | - |
| | | T1 | 29.10 ab | 14.91 a | 55.99 a | 0.1 b |
| | | T2 | 28.30 ab | 12.44 ab | 59.27 a | −0.4 c |
| | | T3 | 27.26 ab | 12.63 ab | 60.11 a | 0.16 b |
| | | T4 | 26.00 b | 13.25 ab | 60.75 a | 0.74 a |

**Table 4.** *Cont.*

| Year | Cultivar | Treatment | Stem (%) | Leaf (%) | Grain (%) | Difference in Yield from CK2 ($\times 10^3$ kg ha$^{-1}$) |
|---|---|---|---|---|---|---|
| 2024 | 'Nanjing 9108' | CK1 | 30.87 ab | 12.95 b | 56.18 a | - |
| | | CK2 | 26.95 b | 23.36 a | 49.69 b | - |
| | | T1 | 35.36 a | 15.60 b | 49.04 b | 0.08 c |
| | | T2 | 32.40 ab | 15.25 b | 52.35 ab | −0.38 d |
| | | T3 | 30.78 ab | 14.30 b | 54.92 ab | 0.35 b |
| | | T4 | 30.92 ab | 14.94 b | 54.14 ab | 0.82 a |
| | 'Nanjing 9308' | CK1 | 30.51 a | 11.14 a | 58.36 a | - |
| | | CK2 | 29.66 a | 13.61 a | 56.73 a | - |
| | | T1 | 29.38 a | 12.97 a | 57.65 a | 0.37 c |
| | | T2 | 28.26 ab | 12.85 a | 58.89 a | −0.24 d |
| | | T3 | 28.55 ab | 12.94 a | 58.51 a | 0.59 b |
| | | T4 | 25.60 b | 13.49 a | 60.91 a | 0.92 a |
| Analysis of variance | | Year (Y) | NS | NS | NS | NS |
| | | Cultivar (C) | ** | ** | ** | ** |
| | | Treatment (T) | ** | ** | ** | ** |
| | | Y × C | NS | NS | NS | NS |
| | | Y × T | NS | NS | NS | NS |
| | | C × T | ** | NS | NS | NS |
| | | Y × C × T | NS | * | NS | NS |

Different letters indicate a significant difference among treatments ($p < 0.05$). -, data excluded from analysis; NS, not significant at the $p < 0.05$ level; *, significant at the $p < 0.05$ level; **, significant at the $p < 0.01$ level.

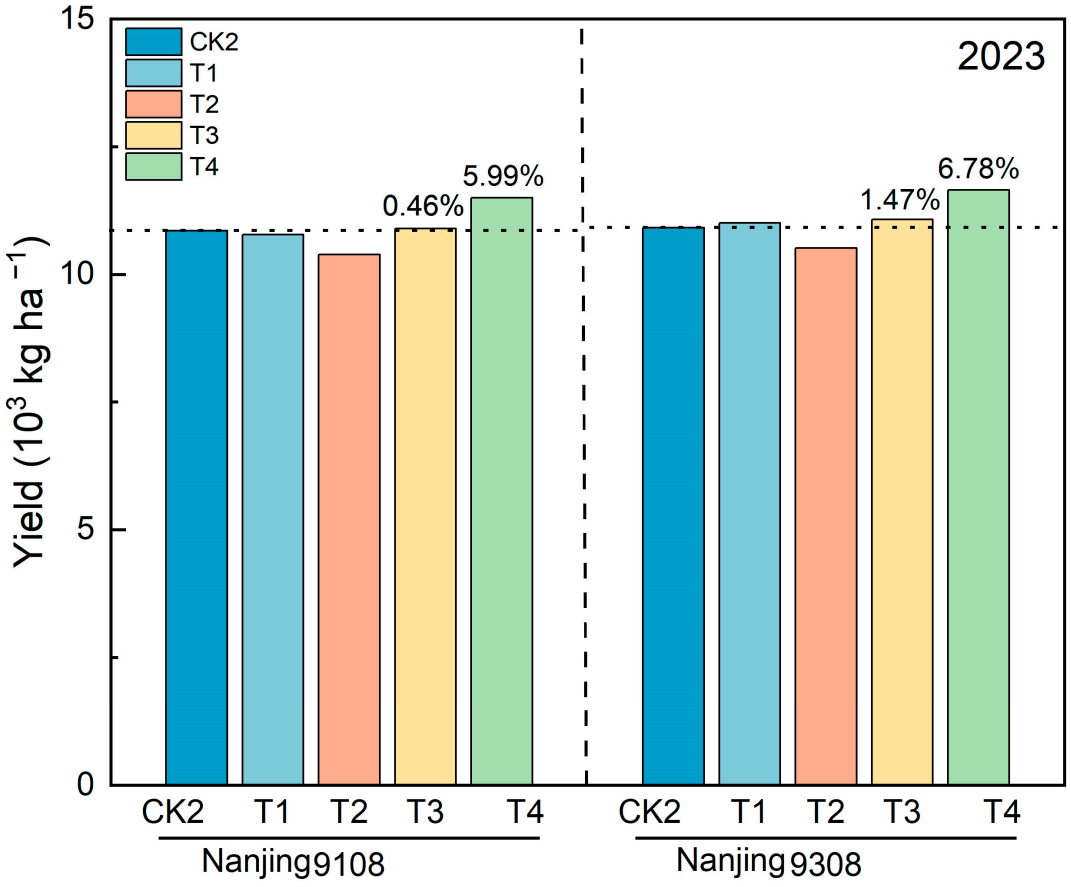



**Figure 7.** Yield differences from CK2 under various treatments in 2023. A dashed line indicates the yield standard for CK2.

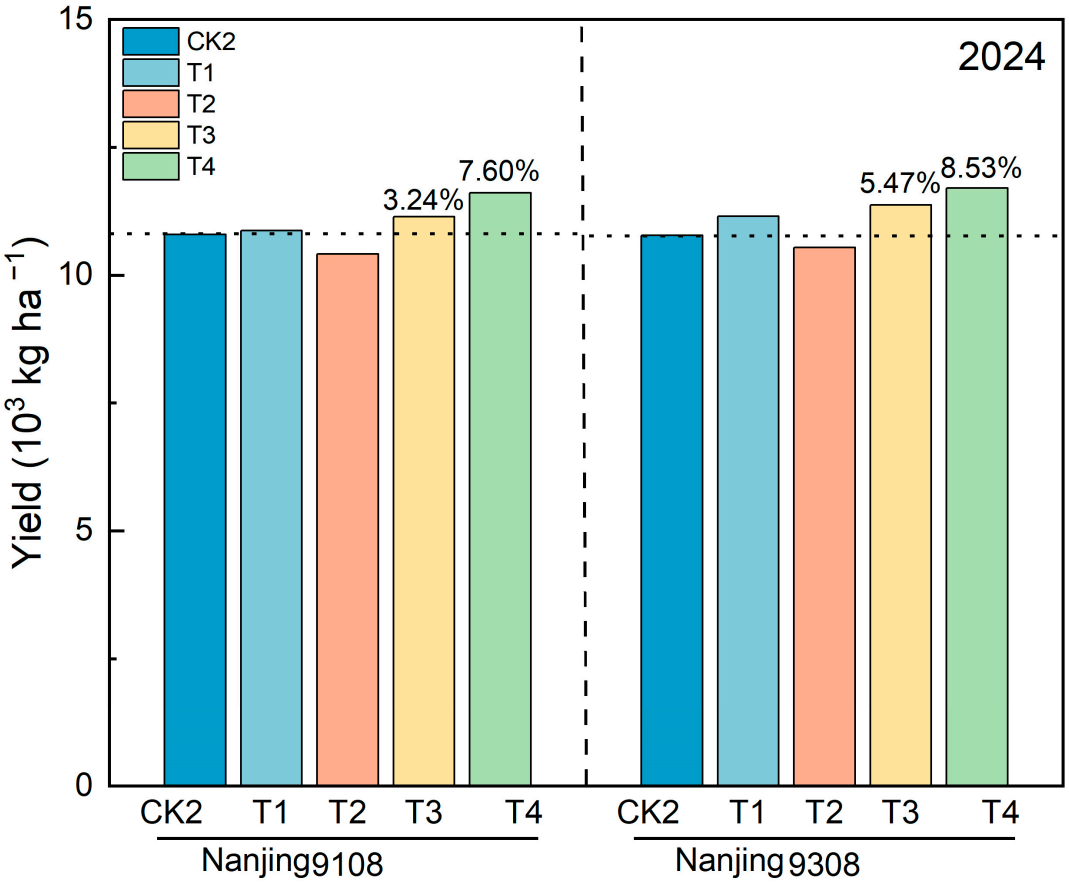



**Figure 8.** Yield differences from CK2 under various treatments in 2024. A dashed line indicates the yield standard for CK2.

A comparison of the yield performance between treatments (T1–T4) and CK2 in 2023 is provided in Table 4 and Figures 7 and 8. Specifically, T4 exhibited the most substantial increase, corresponding to 5.99% and 6.78% improvement. In contrast, T3 resulted in more modest increases of 0.46% and 1.47%, respectively. These results support a positive correlation between higher grain percentage and improved yield, The higher the grain percentage, the higher the yield.

### *3.6. Enzyme Activities Related to Nitrogen Metabolism*

As shown in Table 5, activities of nitrate reductase (NR), glutamine synthetase (GS), and glutamate synthase (GOGAT) were significantly influenced by fertilizer treatment and cultivar, with no significant year effect. DCSCRU treatments (T3 and T4) consistently exhibited higher enzyme activities than CK2. Averaged across two years, T4 increased NR activity by 9.73% and 12.28%, GS activity by 10.84% and 11.29%, and GOGAT activity by 12.7% and 9.28% in 'Nanjing 9108' and 'Nanjing 9308', respectively, highlighting improved nitrogen assimilation efficiency under DCSCRU regimes.

### *3.7. Correlation Analysis of Physiological and Agronomic Traits*

Pearson correlation analysis (Figure 9) revealed that activities of NR, GS, and GOGAT were significantly correlated with heading-stage LAI (LAIH) and dry matter at maturity (DWM), suggesting that enhanced nitrogen metabolism is closely associated with improved canopy function and biomass accumulation. Notably, NR showed strong correlations with GS (r = 0.88) and GOGAT (r = 0.92), indicating efficient conversion of inorganic nitrogen into organic forms. LAIH was also strongly correlated with DWM (r = 0.75) and all three

enzymes (r = 0.89–0.92), confirming that canopy structural optimization plays a central role in translating metabolic efficiency into yield gains.

**Table 5.** Effects of different fertilization treatments on enzyme activities of nitrogen metabolism in rice leaves.

| Year | Cultivar | Treatment | NR μmol $g^{-1}$ FW $h^{-1}$ | GS U $g^{-1}$ | GOGAT U $g^{-1}$ |
|---|---|---|---|---|---|
| 2023 | 'Nanjing 9108' | CK1 | 0.43 d | 0.47 c | 0.24 d |
| | | CK2 | 0.57 b | 0.60 b | 0.31 b |
| | | T1 | 0.53 c | 0.60 b | 0.29 c |
| | | T2 | 0.58 b | 0.62 b | 0.28 c |
| | | T3 | 0.62 a | 0.69 a | 0.29 c |
| | | T4 | 0.63 a | 0.67 a | 0.35 a |
| | 'Nanjing 9308' | CK1 | 0.45 d | 0.47 e | 0.25 e |
| | | CK2 | 0.57 b | 0.62 c | 0.33 ab |
| | | T1 | 0.54 c | 0.60 d | 0.30 cd |
| | | T2 | 0.59 b | 0.67 b | 0.29 d |
| | | T3 | 0.64 a | 0.70 a | 0.31 bc |
| | | T4 | 0.64 a | 0.69 a | 0.35 a |
| 2024 | 'Nanjing 9108' | CK1 | 0.42 d | 0.46 b | 0.24 d |
| | | CK2 | 0.56 b | 0.60 a | 0.32 bc |
| | | T1 | 0.52 c | 0.59 a | 0.30 c |
| | | T2 | 0.57 b | 0.62 a | 0.29 c |
| | | T3 | 0.62 a | 0.70 a | 0.34 ab |
| | | T4 | 0.61 a | 0.66 a | 0.36 a |
| | 'Nanjing 9308' | CK1 | 0.46 d | 0.46 e | 0.25 d |
| | | CK2 | 0.57 b | 0.62 cd | 0.32 bc |
| | | T1 | 0.55 c | 0.59 d | 0.30 c |
| | | T2 | 0.58 b | 0.65 bc | 0.30 c |
| | | T3 | 0.63 a | 0.70 a | 0.34 ab |
| | | T4 | 0.64 a | 0.69 ab | 0.36 a |
| Analysis of variance | | Year (Y) | NS | NS | ** |
| | | Cultivar (C) | ** | ** | ** |
| | | Treatment (T) | ** | ** | ** |
| | | Y × C | * | NS | NS |
| | | Y × T | NS | NS | ** |
| | | C × T | NS | * | NS |
| | | Y × C × T | NS | NS | NS |

Different letters indicate a significant difference among treatments ($p < 0.05$). NS, not significant at the $p < 0.05$ level; *, significant at the $p < 0.05$ level; **, significant at the $p < 0.01$ level.

### *3.8. Pathway Analysis of Yield Determinants*

Path analysis revealed a well-fitted model explaining causal relationships among key physiological and yield-related traits. Heading-stage LAI exhibited the highest direct contribution to yield ($R^2$ = 0.882), followed by 1000-grain weight (0.668). These results underscore the central role of canopy photosynthetic capacity and assimilate accumulation in yield formation. The findings suggest that optimizing nitrogen supply to enhance LAI and grain weight is critical for achieving higher rice yields under controlled-release fertilization strategies.

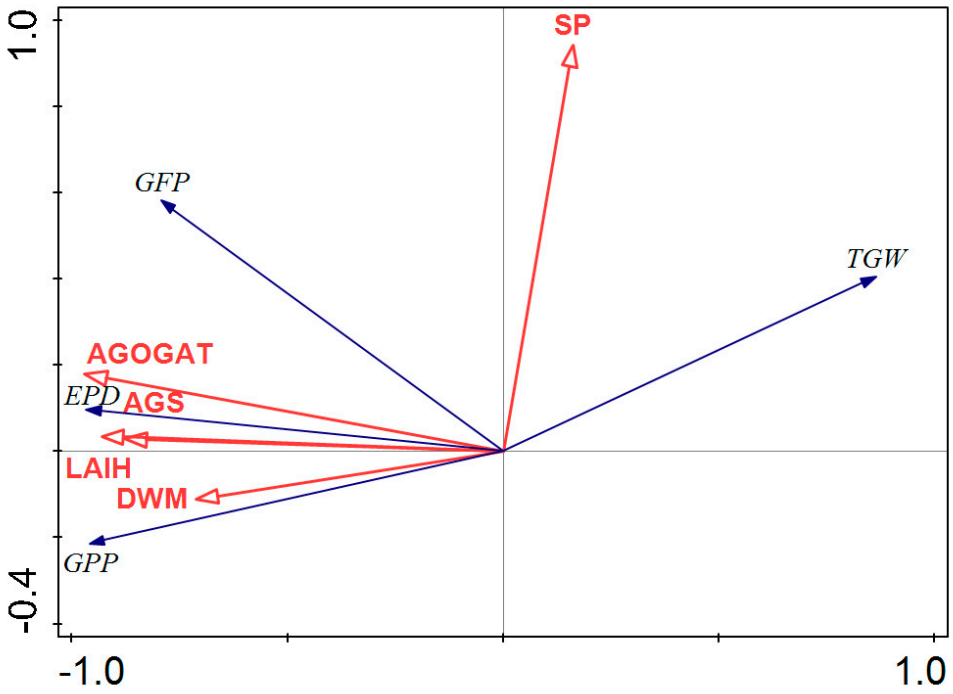



**Figure 9.** Correlation coefficients between rice yield composition and some indexes under 6 nitrogen fertilizer treatments across the two years. TGW, 1000-grain weight; EPD, effective panicle density; GFP, grain filling percentage; GPP, Grains per panicle; AGS, the activity of GS; AGOGAT, the activity of GOGAT; DWM, dry weight at maturity stage; LAIH, Leaf area index at heading stage; SP, Spike as a proportion of dry matter weight. The correlation is positive when the angle between the arrows is acute and negative when the angle between the arrows is larger than 90 degrees. The correlation between two indicators is interpreted by projecting one onto the arrow representing the other: the farther the projection point lies in the direction of the arrow, the stronger the positive correlation; a point near the coordinate origin suggests a near-zero correlation, whereas a projection in the opposite direction indicates a negative correlation.

## 4. Discussion

### *4.1. Effects of the Double Core–Shell Controlled-Release Urea on Rice Photosynthesis and Dry Matter Accumulation*

Nitrogen is a central regulator of rice growth and development, directly influencing photosynthesis, dry matter accumulation, and ultimately grain yield [32,33]. The precise management of nitrogen supply is therefore crucial to optimizing crop productivity and sustainability. Our results demonstrate that the application of double core–shell controlled-release urea (DCSCRU) significantly enhances photosynthetic performance and dry matter accumulation in rice through multiple coordinated mechanisms. Compared with conventional urea and single-layer controlled-release fertilizers, DCSCRU exhibited a more stable and prolonged nitrogen release pattern, enabling a better match between nitrogen availability and crop demand during the critical growth period of rice. This sustained nitrogen supply supported continuous leaf development and delayed leaf senescence, as reflected by higher SPAD values and net photosynthetic rates during the grain-filling stage. Previous studies have similarly shown that extended leaf functionality improves source capacity and grain filling [11,34].

The leaf area index, a key indicator of canopy structure and photosynthetic potential, was significantly increased by DCSCRU, particularly under the T4 treatment. LAI at maturity increased by 50.73% and 39.52% in ‘Nanjing 9108’ and ‘Nanjing 9308’, respectively, compared to conventional urea. This suggests that DCSCRU promotes the formation of a more robust and photosynthetically active canopy, consistent with findings that optimized

canopy architecture contributes to higher photosynthetic efficiency and grain yield [35,36]. In terms of dry matter accumulation, DCSCRU-treated plants exhibited greater biomass production, especially during the latter growth stages. This increase is attributable to enhanced nitrogen-use efficiency and improved coordination between nitrogen metabolism and carbon assimilation pathways. Our results align with previous studies indicating that controlled-release nitrogen fertilizers can significantly increase aboveground biomass by synchronizing nitrogen supply with crop physiological needs [19,37]. The increased proportion of dry matter allocated to reproductive organs further underscores the role of DCSCRU in optimizing source-sink relationships, which is essential for high-yield formation. Overall, DCSCRU both enhanced photosynthetic efficiency and ensured stable dry matter accumulation, providing a physiological basis for improved grain yield. Its slow and regulated nutrient release pattern offers a promising strategy for improving nitrogen management in rice cultivation under resource- and environment-constrained conditions. Furthermore, emerging research demonstrates that advanced biodegradable polymer coatings significantly reduce environmental persistence while maintaining controlled-release efficacy, thereby lowering the risk of microplastic pollution and promoting sustainable and environmentally friendly development [38].

### *4.2. Effects of Double Core–Shell Controlled-Release Urea on Yield and Yield-Related Physiological Traits*

The application of DCSCRU significantly improved grain yield in both japonica rice cultivars tested, with average increases of 6.8% and 7.66% over conventional fertilization. Yield gains were not attributable to a single component but rather to a comprehensive enhancement of key yield determinants, including effective panicle number, grain number per panicle, seed-setting rate, and 1000-grain weight. The effective panicle number is a critical determinant of rice yield and is particularly responsive to nitrogen availability during the tillering stage [39]. DCSCRU, by releasing nitrogen gradually and steadily, facilitated consistent tiller growth and survival. Our findings showed that the T4 treatment increased effective panicle number by 16.42% (‘Nanjing 9108’) and 11.57% (‘Nanjing 9308’), demonstrating the superior capacity of DCSCRU to support high tillering productivity [40].

Productive tiller percentage was also significantly improved under DCSCRU treatments. Compared with CK2, T3 treatment increased productive tiller percentage by 12.94% in 2023. This improvement reflects the role of sustained nitrogen supply in supporting panicle differentiation and reducing degeneration during reproductive development [37]. A well-timed nitrogen supply during the panicle initiation stage enhances spikelet primordia survival and promotes the formation of fertile florets, directly influencing grain number per panicle [14,41]. Moreover, the grain number per panicle and 1000-grain weight also remained stable under DCSCRU treatments. This is consistent with previous findings showing that maintaining high leaf nitrogen content and chlorophyll levels during grain filling enhances photoassimilate production and translocation, leading to improved grain filling and weight [22,23]. Thus, DCSCRU not only improved nitrogen utilization efficiency but also facilitated better coordination between nitrogen supply and physiological processes governing rice yield formation. This study confirms the potential of DCSCRU as an effective tool for synchronizing nutrient availability with crop demand, thereby enhancing multiple physiological traits that contribute to high and stable rice yields.

## 5. Conclusions

This study demonstrated that double core–shell controlled-release urea (DCSCRU) significantly improves rice yield by 6.80–7.66%, primarily through spatiotemporal alignment of nitrogen release with crop demand. Compared with traditional controlled-release

fertilizers, DCSCRU shows the potential to maintain relatively high chlorophyll content and photosynthetic activity, extend the functional period of flag leaves, and promote dry matter accumulation, even under reduced fertilizer application rates and fewer topdressing events. At early stages, its controlled nitrogen release supports canopy formation, while during reproductive stages, it enhances spikelet differentiation, panicle formation rate, and grain filling. Application at 225 kg N $ha^{-1}$ achieved yields comparable to those under conventional split fertilization, while 270 kg N $ha^{-1}$ significantly outperformed it. The coordinated improvement in photosynthesis, nitrogen metabolism, and source–sink balance under DCSCRU provides a theoretical and technical foundation for advancing precision fertilization strategies in rice production, contributing to yield enhancement and agricultural sustainability.

**Author Contributions:** R.F.: Data curation, Formal analysis, Writing—original draft. C.D.: Data curation, Writing—review and editing. T.C.: Writing—review and editing. H.L.: Conceptualization, Software. P.C.: Data curation. N.Z.: Writing—review and editing. Y.Y.: Writing—review and editing, Conceptualization, Funding acquisition, Writing—review and editing. H.Z.: Funding acquisition. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** Data supporting the findings of this study are available within the article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| DCSCRU | Double Core–Shell Controlled-Release Urea |
| N | Nitrogen |
| NUE | Nitrogen Use Efficiency |
| SCRFs | Slow- and Controlled-Release Nitrogen Fertilizers |
| PCU | Polymer-Coated Urea |
| LAI | Leaf Area Index |
| CRU | Controlled-Release Urea |
| NR | Nitrate Reductase |
| GS | Glutamine Synthetase |
| GOGAT | Glutamate Synthase |
| LSD | Least Significant Difference |
| TS | Tillering Stage |
| JS | Jointing Stage |
| HS | Heading Stage |
| MS | Maturity Stage |
| TGW | 1000-grain Weight |
| EPD | Effective Panicle Density |
| GFP | Grain Filling Percentage |
| GPP | Grains Per Panicle |
| ANR | the Activity of NR |
| AGS | the Activity of GS |
| AGOGAT | the Activity of GOGAT |
| DWM | Dry Weight at Maturity Stage |
| LAIH | Leaf Area Index at Heading Stage |
| SP | Spike as a Proportion of Dry Matter Weight |

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