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Management Strategy of Slow-Release Nitrogen Fertilizers for Direct-Sown Cotton after Wheat Harvest

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Abstract: The direct-sown cotton after wheat harvest (DSCWH) cropping system has attracted wide attention due to reduced labor inputs compared to transplanting. However, the management strategy of slow-release nitrogen is unclear in such a system. This study aims to investigate the impact of different timings and dosages of slow-release nitrogen fertilizer on the yield, biomass accumulation and distribution, and nitrogen absorption and nitrogen utilization in the DSCWH cropping system. This study was investigated at the experimental farm of Yangzhou University, China in 2020 and 2021, with the short-season cotton variety "Zhongmian 50" used as experimental material. Three dosages of the slow-release nitrogen fertilizer (45 kg·ha^{-1}, 90 kg·ha^{-1}, and 135 kg·ha^{-1}) were applied at two stages of growth (two-leaf and four-leaf). The results showed that applying a 90 kg·ha^{-1} dosage at the two-leaf stage achieved the highest yield, which was increased by 12.6% compared to the no-fertilization control. Applying 90 kg·ha^{-1} of the slow-release nitrogen at the two-leaf stage promoted biomass accumulation, especially in reproductive organs, and this increase in biomass of reproductive organs was attributed to optimum nitrogen accumulation in reproductive organs (80~140 kg·ha^{-1}). In addition, when 90 kg·ha^{-1} was applied at the two-leaf stage, there was a significant enhancement in nitrogen recovery efficiency (NRE), nitrogen agronomic use efficiency (NAE), and nitrogen physiological efficiency (NPE), with increases of 7.2% to 13.0%, 5.7% to 5.8%, and 5.6% to 6.5%, respectively. These results revealed that applying slow-release nitrogen fertilizer with the optimal dosage at the seedling stage could significantly enhance nitrogen use efficiency, nitrogen accumulation and partitioning, and biomass accumulation and distribution, which ultimately resulted in a higher lint yield in DSCWH. Therefore, to optimize yield and NUE, 90 kg·ha^{-1} slow-release nitrogen applied at the two-leaf stage would be recommended in the direct-sown cotton after wheat harvest cropping system.

Keywords: short-season cotton; controlled-release fertilizer; yield; nitrogen use efficiency; biomass

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1. Introduction

Cotton is vital as an economic crop in the world, and the Yangtze River basin is a major cotton production area in China [1,2]. Traditionally, the seedling transplanting planting pattern has been the preferred method of cotton cultivation in the Yangtze River basin to overcome the overlap between the growth seasons of cotton and wheat [3]. However, this technique has faced challenges recently due to the aging of rural labors and rapid urbanization causing increased labor costs [3–5]. In contrast, DSCWH presents a simplified, more efficient alternative to overcome the labor-intensive problem of transplanting [6–8]. Therefore, the DSCWH planting pattern has experienced significant growth in the cotton-growing regions in recent years [9,10].

Effective fertilizer management is crucial in achieving high-quality and high-yield cotton crops, as it significantly influences nutrient absorption and utilization [11–13]. Traditional planting methods typically employ a base application and multiple top-dressings

to achieve a higher cotton yield [5,14]. However, this approach leads to overfertilization [15], contributing to nonpoint source pollution [16–18]. Also, traditional fertilization is labor-intensive and time-consuming and incurs mechanical damage to cotton fruits during top-dressing, thus reducing the yield and economic benefits [5,19]. Moreover, the nitrogen fertilizer utilization rate in agricultural production during different seasons is only 30–35%, which is more than 10% lower than that in developed countries [20]. Many studies have shown that slow-release fertilizers have emerged as a novel fertilizer, offering slow-release characteristics and high fertilizer utilization rates, and reducing both the amount of fertilizer and the frequency of fertilization [21–23]. With an appropriate reduction in the slow-release nitrogen fertilizer application rate, no decline in cotton yield was observed compared to traditional nitrogen fertilizer [24]. Similarly, Wang et al. reported an increase in yield with slow-release urea compared to traditional urea treatment under the same amount of nitrogen application [25]. Cotton in the fallow rotation required a higher nitrogen dose (130 kg ha^{-1}) than in rotation systems with cover crops (100 kg ha^{-1}) to achieve the highest yields. In contrast, controlled-release urea could decrease the N fertilizer demand by 30% in the fallow [26]. A study by Geng et al. observed enhanced boll number and lint yield, N apparent recovery use efficiency (RUE) and agronomic use efficiency (AUE), fiber length and strength, nitrate reductase and peroxidase activities, and photosynthetic rates (Pn) under polymer-coated urea and sulfur fertilization treatment in cotton [27]. A comprehensive evaluation of controlled-release urea over the past few decades on different crops in China showed that controlled-release urea was a good substitution of split nitrogen urea in decreasing nitrogen loss and increasing economic yield [28].

With the conversion from transplanting to direct seeding in China, knowledge is lacking on the slow-release nitrogen fertilizer application strategy in the system of DSCWH. Moreover, the effects of slow-release nitrogen fertilizer on the yield, nitrogen absorption, and utilization in such a system remain unclear. Therefore, the objective of this research was to determine the optimal application dosage and timing of slow-release nitrogen fertilizer according to yield under the cotton direct seeding after wheat harvest cropping system, and the nitrogen absorption and utilization and biomass accumulation and distribution will be studied to further uncover the mechanism.

2. Materials and Methods

2.1. Experimental Design

The experiment was conducted at the experimental farm of Agriculture College, Yangzhou University (32°24′ N, 119°41′ E) in 2020 and 2021. The soil at the experimental site is a fine, mixed, frigid Typic Endoaquent, classified as sandy loam of the Courval series with the following nutrient composition: total nitrogen content of 12.3 g·kg^{-1}, organic matter content of 19.6 g·kg^{-1}, available nitrogen of 69.1 mg·kg^{-1}, available phosphorus of 35.8 mg·kg^{-1}, and available potassium of 86.22 mg·kg^{-1}. The soil properties were assessed according to Jiao et al. [29].

Seeds were sown directly after the wheat harvest on 13 June 2020 and 7 June 2021 using the short-season cultivar "Zhongmian 50 (CCRI, China)" as experimental material. The slow-release fertilizer employed in the experiment was polyurethane-coated urea (44% nitrogen, supplied by Shandong Damao Ecological Fertilizer Co., LTD, Shandong province, Linyi, China).

The experimental design was a randomized complete block design with eight treatments and three replications. CK1 was the untreated control, with no nitrogen fertilizer applied. The conventional nitrogen fertilizer treatment (CK2) consisted of 180 kg·ha^{-1} nitrogen (in the form of urea), which was applied at 3 days before being sown and the early flowering period, accounting for 40% and 60% of the total application, respectively (Table 1). Superphosphate (14% P_2O_5) and potassium chloride (60% K_2O) were used as phosphorus and potassium fertilizers at 82.5 kg·ha^{-1} and 165 kg·ha^{-1}. (CK2). Application of the slow-release fertilizer consisted of three dosage levels (A1, A2, and A3) representing 45 kg N·ha^{-1} (102.27 kg·ha^{-1} slow-release nitrogen fertilizer), 90 kg N·ha^{-1} (204.55 kg·ha^{-1}

slow-release nitrogen fertilizer), and 135 kg N·ha^{-1} (306.82 kg·ha^{-1} slow-release nitrogen fertilizer), respectively, and two application periods (B1 and B2) at the 2-leaf stage (B1) and 4-leaf stage (B2), respectively.

Table 1. The slow-release nitrogen fertilizer treatments in cotton.

Treatment	Abbreviation	Nitrogen Dosage kg ha^{-1}	Management Strategy/%		
			2-Leaf	4-Leaf	Early Flower
No N fertilizer	CK1	0	0	0	0
Conventional fertilizer	CK2	180	3 days before sown	0	60
Slow-release nitrogen fertilizer	A1B1	45	100	0	0
	A1B2	45	0	100	0
	A2B1	90	100	0	0
	A2B2	90	0	100	0
	A3B1	135	100	0	0
	A3B2	135	0	100	0

Each plot had five rows, and the plot area was 32.4 m^2. The planting density was 140,000 plants·ha^{-1}. A defoliation agent (provided by China Agricultural University) was sprayed at 2250 mL·ha^{-1} on 20 October 2020 and 15 October 2020. Furrow irrigation was used to water plants when necessary during the growing season. Disease prevention and insect and weed control were performed according to the local recommendations.

2.2. Investigation and Measurement

2.2.1. Yield and Component

Yield: The seed cotton yield for each plot was determined by weighing the seed cotton harvested by hand from the center four rows. Seed cotton was ginned for lint yield, and lint percentage was calculated as the ratio of lint weight to seed cotton weight.

The continuous 20 plants in the central two rows in each plot were counted on 20 September, and the total number of bolls on a unit ground area was determined. The open bolls from the 20 plants before frost were harvested, and the boll weight per each boll (moisture $\leq$ 11%) was measured.

2.2.2. Determination of Biomass, Nitrogen Accumulation, and Utilization

The samples of cotton were collected on 30 July, 15 August, 30 August, and 15 September in both years. Five representative plants from the fourth row of each plot were selected to determine biomass. These plants were uprooted and separated into vegetative organs (roots, stems, branches, and leaves) and reproductive organs (bolls and squares) for drying. Dry matter had been weighed and recorded after drying at 80 °C to constant weight. Biomass was determined from the total dry weight of vegetative organs and reproductive organs, respectively.

The total N concentration of the cotton plant was determined by the H_2SO_4-H_2O_2 digestion method of Kjeldahl [30,31]. Nitrogen content was determined as the product of N concentration (on a dry weight basis) and dry weight. The uptake and accumulation were estimated as follows:

Nitrogen accumulation = biomass (dry matter mass) × nitrogen content [31].

Nitrogen recovery efficiency (NRE, %) = (nitrogen absorbed by the above-ground part of the nitrogen application zone-nitrogen absorbed by the above-ground part of the non-nitrogen zone)/nitrogen application amount × 100 [32].

Partial yield of nitrogen fertilizer (NPFP, kg·kg^{-1}) = seed cotton yield/nitrogen application amount [32,33].

Nitrogen fertilizer agronomic use efficiency (NAE, kg·kg^{-1}) = (lint yield in nitrogen applied zone-lint yield in nitrogen-free zone)/nitrogen application amount [34].

The physiological utilization rate of nitrogen fertilizer (NPE, kg·kg^{-1}) = (seed cotton yield in nitrogen-applied zone-seed cotton yield in no-nitrogen zone)/(Nitrogen uptake by plants in nitrogen-treated zone-nitrogen uptake by plants in no-nitrogen zone) [35].

2.3. Data Processing

Analysis of variance (ANOVA) was conducted for each experiment for all the characteristics measured using PROC ANOVA in SAS 9.2 (2010, SAS Institute, Cary, NC, USA). Differences between treatments were tested for significance using Duncan's multiple range tests. The data were summarized and presented by year.

3. Results

3.1. Effects of Dosage and Timing of the Slow-Release Nitrogen Fertilizer on Yield and Yield Components for DSCWH

Significant differences in seed cotton yield and lint yield were observed among the treatments during the two-year experiments (Table 2). Compared to other treatments, treatments A2B1 and A2B2 exhibited a significant increase in seed cotton yield, exceeding the yield of the CK2 treatment by 8.2% and 24.2% in 2020 and by 14.0% and 9.7% in 2021, respectively. Similar results were detected in lint yield. The results suggest that application of the slow-release fertilizer containing 90 kg·ha^{-1} of nitrogen could enhance yield. Compared to the fertilization periods in 2020, treatment B2 (four-leaf stage) application demonstrated a superior yield, while the trend reversed in 2021. These findings suggest that applying slow-release fertilizer with 90 kg·ha^{-1} at the two-leaf or four-leaf stage would be beneficial for achieving a high yield in direct-sown cotton after wheat harvest.

Table 2. Effect of slow-release nitrogen fertilizer management on yield and components in 2020 and 2021.

Year	Treatment	Boll Number /×10^4·ha^{-1}	Boll Weight /g	Seed Cotton Yield /kg·ha^{-1}	Lint Percentage /%	Lint Yield /kg·ha^{-1}
2020	CK1	68.0 ± 3.7 e	3.44 ± 0.1 a	2341.1 ± 5.6 e	33.4 ± 0.2 a	783.6 ± 3.1 e
	CK2	85.6 ± 4.1 bc	3.54 ± 0.2 a	3029.8 ± 7.3 bc	34.1 ± 0.4 a	1034.3 ± 4.2 bc
	A1B1	73.8 ± 2.2 de	3.53 ± 0.1 a	2607.1 ± 4.3 d	34.2 ± 0.3 a	892.7 ± 3.7 d
	A1B2	90.2 ± 2.9 bc	3.55 ± 0.1 a	3196.2 ± 5 bc	34.4 ± 0.5 a	1101.0 ± 4.6 bc
	A2B1	89.4 ± 3.8 cd	3.67 ± 0.3 a	3277.7 ± 8.2 b	34.4 ± 0.2 a	1128.2 ± 4.2 b
	A2B2	102.7 ± 4.1 a	3.66 ± 0.2 a	3764.1 ± 6.5 a	34.3 ± 0.3 a	1292.5 ± 5.1 a
	A3B1	82.1 ± 1.8 bc	3.57 ± 0.3 a	2927.9 ± 8.5 c	34.4 ± 0.4 a	1006.7 ± 4.9 c
	A3B2	93.0 ± 2.3 b	3.64 ± 0.2 a	3388.8 ± 7.9 b	34.2 ± 0.3 a	1159.8 ± 4.3 b
2021	CK1	69.5 ± 1.2 d	3.47 ± 0.1 b	2411.0 ± 4.1 d	33.5 ± 0.2 a	807.2 ± 3.7 d
	CK2	83.8 ± 2.4 b	4.39 ± 0.4 a	3681.5 ± 8.3 bc	34.1 ± 0.6 a	1254.5 ± 5.8 bc
	A1B1	87.5 ± 2.6 b	3.98 ± 0.4 a	3476.6 ± 7.2 bc	33.7 ± 0.3 a	1171.8 ± 4.1 bc
	A1B2	84.7 ± 3.2 bc	3.90 ± 0.2 a	3302.2 ± 5.1 c	33.8 ± 0.2 a	1114.6 ± 4.3 c
	A2B1	100.6 ± 3.5 a	4.17 ± 0.1 a	4198.7 ± 6.9 a	34.2 ± 0.3 a	1434.7 ± 5.5 a
	A2B2	98.8 ± 1.9 a	4.09 ± 0.3 a	4037.8 ± 7.5 a	34.1 ± 0.4 a	1374.9 ± 4.7 a
	A3B1	80.1 ± 3.8 c	4.39 ± 0.3 a	3512.4 ± 5.6 b	34.3 ± 0.3 a	1204.1 ± 5.2 b
	A3B2	78.6 ± 2.7 c	4.34 ± 0.2 a	3411.3 ± 4.7 b	33.7 ± 0.2 a	1149.6 ± 4.2 b

Note: Different lowercase letters within the same column indicate significant differences at the 0.05 probability level.

Further analysis of yield components revealed significant variations in boll number under various treatments, particularly with treatments A2B1 and A2B2 showing notably more bolls than others in 2021. Meanwhile, the various treatments had no significant effect on boll weight and lint percentage. These results suggest that the variation in seed cotton yield and lint yield among different treatments was predominantly related to boll number. Therefore, the boll number should be considered as the primary factor for increasing the yield for DSCWH.

3.2. Effects of Dosage and Timing of the Slow-Release Nitrogen Fertilizer on Biomass Accumulation and Distribution for DSCWH

The biomass of vegetative organs increased with growth season for all treatments. The slow-release nitrogen fertilizer treatments resulted in a higher biomass accumulation of vegetative organs than that of CK1, but treatments A1B1 and A1B2 had a lower vegetative organs biomass than treatment CK2 in the two-year experiments (Figure 1). Compared to CK2, A3B1 exhibited the highest vegetative organs biomass, with the values increased by 113.5% and 20.9%, respectively, in 2020 and 2021, followed by A2B1 and A3B2. Under different nitrogen dosages within the same application timing, treatment A3B1 had the highest vegetative organs biomass, with the values enhanced by 22.4% and 52.0% more than those of treatments A2B1 and A1B1, respectively, on 20 September in 2020. Similar results were observed in 2021. Under different application timings within the same nitrogen dosage for slow-release nitrogen treatments, a higher vegetative organs biomass was detected in treatment B1 than that in treatment B2, with the values enhanced by 43.6% and 4.4% on Sep 20th, respectively, in 2020 and 2021. This study confirmed that the quantity and timing of slow-release fertilizer nitrogen application significantly impacted the biomass of the vegetative organs in the direct-sown cotton after wheat harvest.

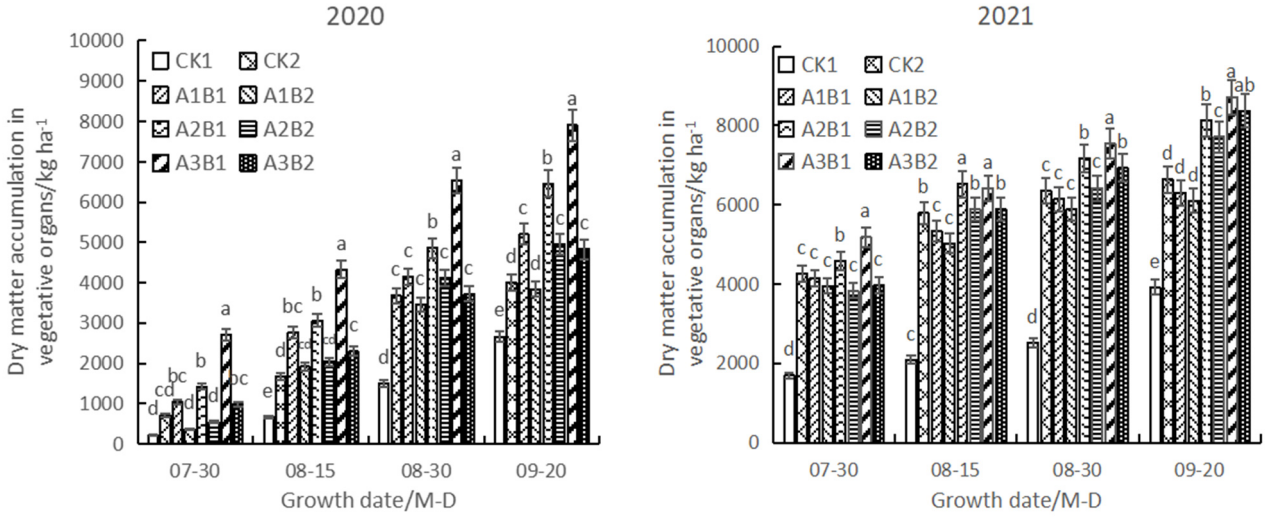


Figure 1. Effect of slow-release nitrogen treatments on biomass accumulation of vegetative organs during 2020–2021 cotton growth seasons. Lowercase letters at the same investigation date indicate significant differences among the treatments at the 0.05 probability level. Error bars represent S.E. of the mean (n = 3).

There was an increase in the biomass accumulation of reproductive organs throughout the growth process, particularly from 30 August to 20 September (Figure 2). Under the same slow-release nitrogen dosage, there was a higher biomass of reproductive organs in treatment B1 than that in treatment B2. Under the same slow-release nitrogen applied period, the highest biomass of reproductive organs was detected with treatment A2, but no significant differences were observed between treatment A2 and CK2 in 2021. Treatments A2B1 and A3B1 in both years of the two-year experiment had the highest biomass at the critical period of effective bolls (20 September), which was 4558.0 and 5001 kg·ha^{-1} and 5965.0 and 5858.0 kg·ha^{-1} in 2020 and 2021, respectively. These results suggest that applying 90 kg·ha^{-1} of the slow-release nitrogen at the two-leaf stage promoted the biomass accumulation of reproductive organs.

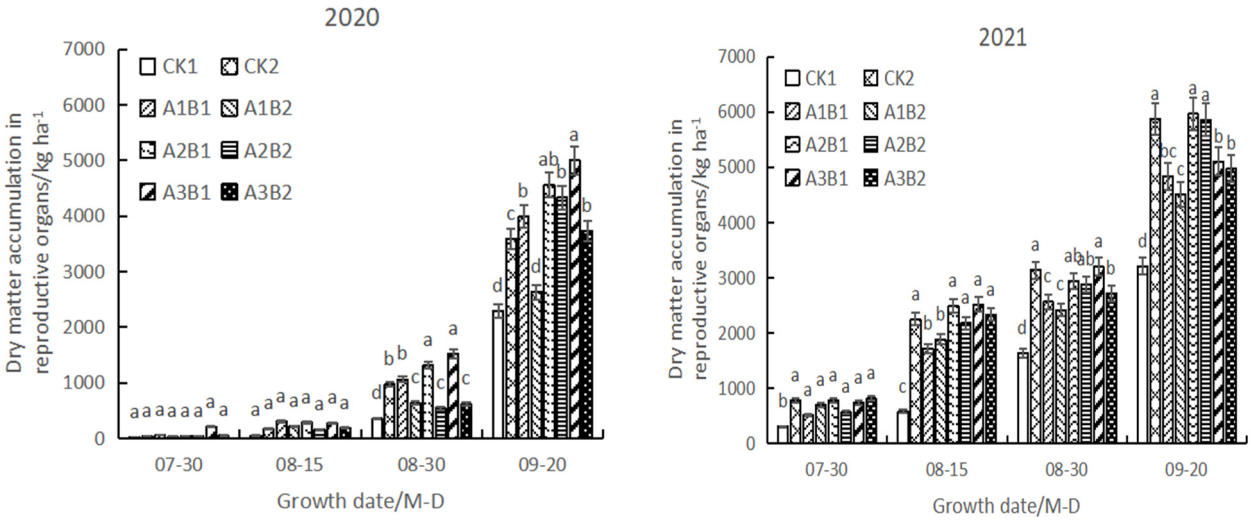


Figure 2. Effect of the slow-release nitrogen treatments on biomass of reproductive organs during 2020–2021 cotton growth seasons. Lowercase letters at the same investigation date indicate significant differences among the treatments at the 0.05 probability level. Error bars represent S.E. of the mean (n = 3).

There were significant differences in total dry matter accumulation among various treatments. During the two-year experiment, under the same dosage of the slow-release nitrogen fertilizer application, treatment B1 had higher dry matter accumulation than that of treatment B2, where the value was increased by 36.2% and 4.1% on 20 September in 2020 and 2021, respectively (Table 3). Under the same fertilization application timing, treatment A2 had higher total dry matter accumulation than that of other treatments. Compared to CK2, treatments A2B1, A2B2, and A3B1 had significantly higher total dry matter accumulation. These findings indicate that applying comparatively high slow-release nitrogen fertilizer promoted total dry matter accumulation in directly sown cotton after wheat harvest, resulting in an increased yield.

Table 3. Effect of slow-release nitrogen fertilizer management on total dry matter accumulation (kg·ha^{-1}) of cotton plant for DSCWH.

Year	Treatment	Growth Date/M-D			
		07-30	08-15	08-30	09-20
2020	CK2	223.5 ± 2.3 d	720.8 ± 5.1 d	1853.7 ± 6.2 e	4954.5 ± 6.4 d
	CK1	733.3 ± 3.6 bc	1840.9 ± 6.7 c	4644.5 ± 4.9 c	7597.1 ± 5.7 bc
	A1B1	1098.2 ± 4.7 b	3064.8 ± 7.2 b	5208.7 ± 5.1 bc	9187.6 ± 7.8 ab
	A1B2	365.8 ± 2.8 cd	2135.0 ± 7.8 bc	4091.5 ± 5.5 d	6469.9 ± 6.4 c
	A2B1	1464.0 ± 5.9 ab	3345.0 ± 5.4 ab	6172.9 ± 7.6 b	11,014.2 ± 8.6 a
	A2B2	559.1 ± 3.9 c	2187.3 ± 5.9 bc	4655.0 ± 6.4 c	9279.6 ± 8.7 ab
	A3B1	2915.0 ± 6.3 a	4597.5 ± 7.9 a	8059.2 ± 8.9 a	12,904.5 ± 10.1 a
	A3B2	1035.0 ± 5.2 b	2481.2 ± 4.6 bc	4336.9 ± 8.2 cd	8566.0 ± 7.2 b
2021	CK2	1989.0 ± 4.8 d	2665.5 ± 4.9 c	4147.0 ± 7.7 c	7130.0 ± 6.8 d
	CK1	5046.5 ± 8.3 ab	8031.0 ± 9.2 ab	9487.5 ± 9.2 ab	12,509.0 ± 9.9 b
	A1B1	4650.5 ± 7.5 b	7052.0 ± 8.1 b	8702.5 ± 8.7 b	11,129.5 ± 9.2 bc
	A1B2	4648.0 ± 6.9 b	6903.5 ± 8.7 b	8296.5 ± 7.8 b	10,599.0 ± 9.7 c
	A2B1	5363.0 ± 7.6 ab	8997.0 ± 8.9 a	10,107.0 ± 9.3 a	14,090.5 ± 10.4 a
	A2B2	4391.0 ± 6.2 bc	8057.5 ± 7.3 ab	9298.0 ± 9.5 ab	13,564.5 ± 10.2 ab
	A3B1	5911.5 ± 8.1 a	8931.5 ± 8.3 a	10,740.5 ± 9.7 a	13,816.0 ± 8.9 a
	A3B2	4782.0 ± 5.5 b	8219.0 ± 7.8 ab	9636.5 ± 9.5 ab	13,333.0 ± 11.6 ab

Note: Different lowercase letters within the same column indicate significant differences at the 0.05 probability level ($p < 0.05$).

3.3. Effects of Dosage and Timing of Slow-Release Nitrogen Fertilizer on Nitrogen Accumulation and Distribution for DSCWH

Throughout the experiment, the nitrogen accumulation of the vegetative organs gradually increased as the growth process progressed (Figure 3). Treatment B1 had higher nitrogen accumulation of the vegetative organs than that of treatment B2 under the same slow-release nitrogen application rate. During the peak boll-setting stage (30 August to 20 September), the nitrogen accumulation was the highest in treatment A2, followed by A3 and A1. By the critical period of effective bolling (20 September), treatments A2B1, A2B2, A3B1, and A3B2 showed a significant increase of 22.6, 22.2, 18.2, and 16.0 kg·ha^{-1}, respectively, compared to CK2 in 2021. Correlation analysis revealed a significant linear positive correlation between nitrogen accumulation and vegetative organs biomass (Figure 4, with correlation coefficients of 0.8627** and 0.9452** in 2020 and 2021, respectively).

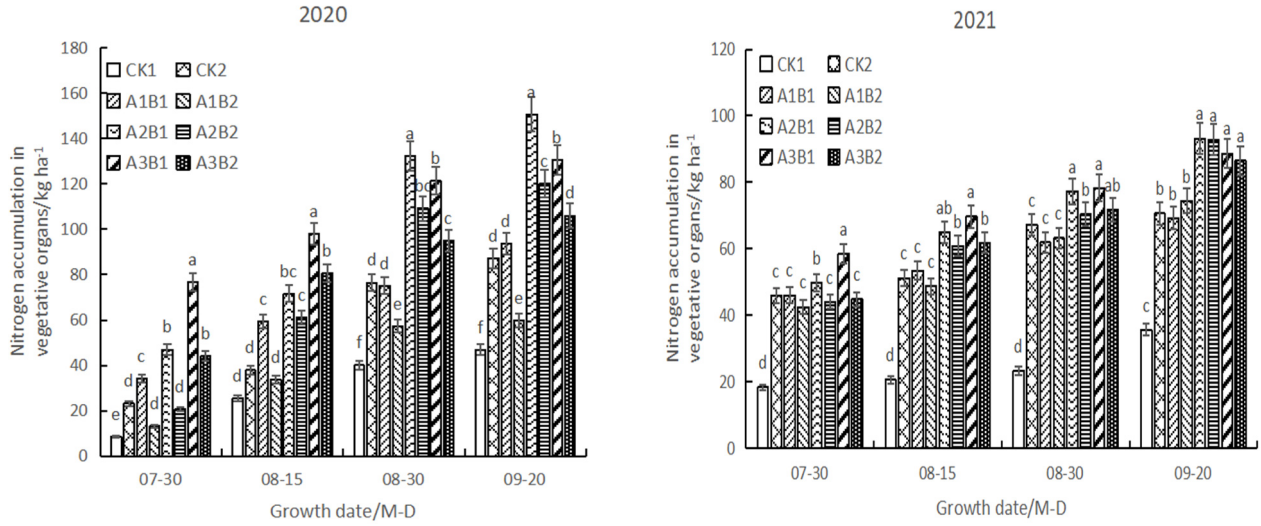


Figure 3. Effect of the slow-release nitrogen treatments on nitrogen accumulation of the vegetative organs for DSCWH. Lowercase letters at the same investigation date indicate significant differences among the treatments at the 0.05 probability level. Error bars represent S.E. of the mean (n = 3).

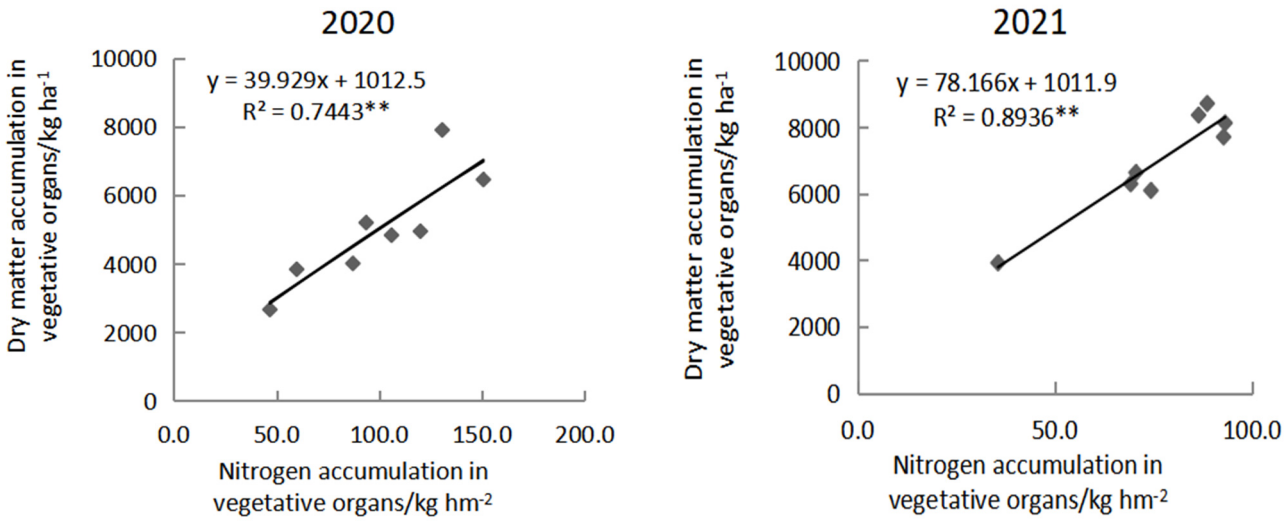


Figure 4. Relationship between biomass and nitrogen accumulation in vegetative organs for DSCWH in 2020 and 2021. y indicates dry matter weight of vegetative organs, x indicates nitrogen accumulation of vegetative organs. ** represent the significance levels of 0.01.

The nitrogen accumulation of reproductive organs showed an initial slow increase, followed by a rapid increase with growth seasons (Figure 5). The nitrogen accumulation

of reproductive organs under all slow-release nitrogen treatments was higher than that of treatment CK2 after 15 August. Under the same dosage of slow-release nitrogen application, nitrogen accumulation of the reproductive organs under treatment B1 was significantly higher than that under treatment B2. Under the same nitrogen-applying period, the highest nitrogen accumulation of reproductive organs was observed under treatment A2, followed by treatment A3, and the lowest was observed under treatment A1. At the critical period of effective boll setting (20 September), treatments A2B1 and A3B1 promoted nitrogen uptake and accumulation in reproductive organs. The results of quadratic regression analysis revealed that the biomass of reproductive organs reached its peak when the nitrogen uptake ranged from 80 to 140 kg·ha^{-1} over the two study years (Figure 6). Therefore, maintaining an optimal nitrogen supply promoted the formation and development of reproductive organs, which can ultimately result in a yield increase.

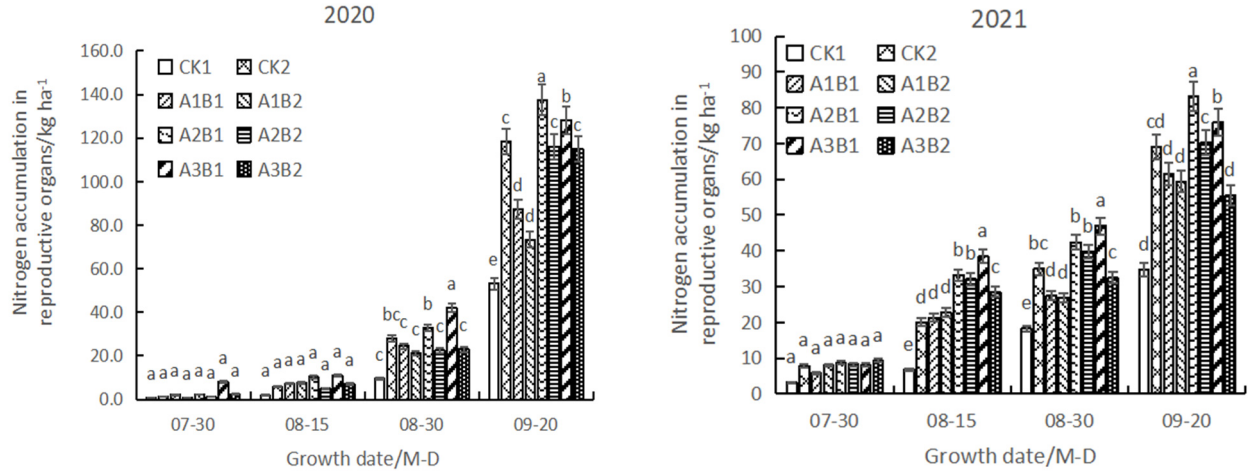


Figure 5. Effect of slow-release nitrogen treatments on nitrogen accumulation in reproductive organs for DSCWH. Lowercase letters at the same investigation date indicate significant differences among the treatments at the 0.05 probability level. Error bars represent S.E. of the mean (n = 3).

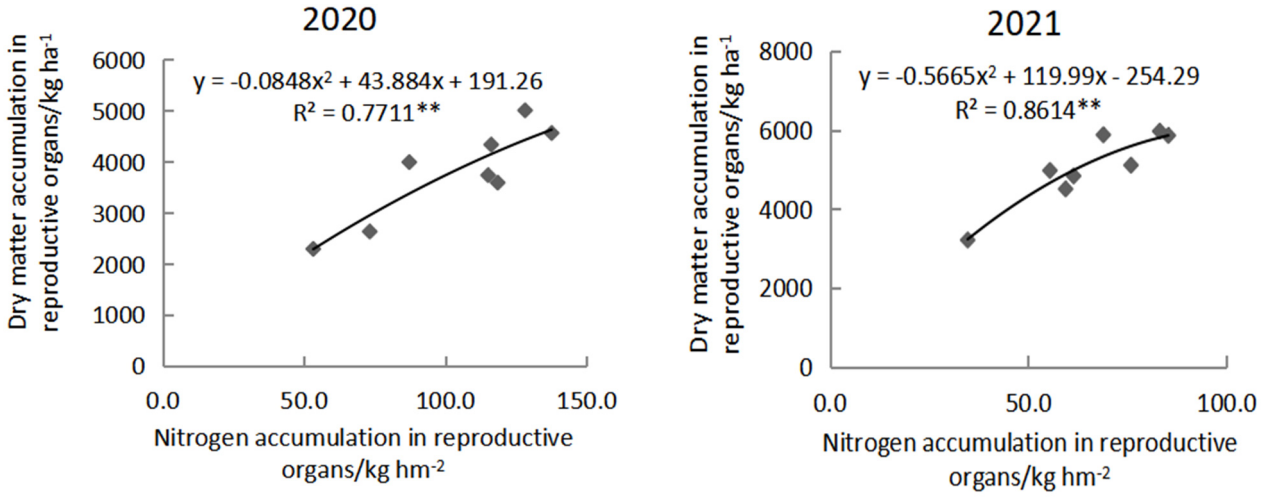


Figure 6. Relationship between nitrogen accumulation and biomass in reproductive organs for DSCWH in 2020 and 2021. y indicates dry matter weight of reproductive organs, x indicates nitrogen accumulation of reproductive organs. ** represent the significance levels of 0.01.

3.4. Effects of Dosage and Timing of Slow-Release Nitrogen Fertilizer on Nitrogen Absorption and Utilization Efficiency for DSCWH

The NRE, NAE, NPFP, and NPE consistently decreased as the slow-release nitrogen application rate increased within the same applied timing (Table 4). The highest NRE,

NAE, NPFP, and NPE were achieved when applying 45 kg·ha^{-1} of slow-release nitrogen. Under the same amount of nitrogen application, higher NRE, NAE, NPFP, and NPE were detected under treatment B1 compared to treatment B2. There were significant differences in nitrogen absorption and utilization rates among the different slow-release nitrogen treatments. In comparison to CK2, treatments A1B1, A1B2, and A2B1 showed significantly higher NRE than CK2, with the values increased by 37%, 30%, and 26%, respectively, but there was no significant difference between treatments A2B2 and CK2, whereas treatments A3B1 and A3B2 were significantly lower than CK2. There were higher NAE, NPFP, and NPE with treatments A1B1, A1B2, A2B1, and A2B1, whereas A3B1 and A3B2 showed significantly lower levels compared to CK2. These results suggest that applying 45–90 kg of slow-release nitrogen per hectare further improved the uptake and utilization of nitrogen for DSCWH.

Table 4. Effect of slow-release nitrogen fertilizer management on nitrogen absorption and utilization of DSCWH.

Year	Treatment	NRE /%	NAE /kg kg^{-1}	NPFP /kg kg^{-1}	NPE /kg kg^{-1}
2020	CK2	48.23 ± 0.8 e	11.26 ± 0.4 de	36.89 ± 1.2 e	6.87 ± 0.6 e
	A1B1	63.67 ± 0.7 a	15.98 ± 0.5 a	69.45 ± 1.6 a	5.45 ± 0.3 f
	A1B2	60.15 ± 1.3 b	13.13 ± 0.3 c	63.67 ± 1.5 b	5.34 ± 0.5 g
	A2B1	57.93 ± 1.1 c	15.25 ± 0.5 b	45.68 ± 0.9 c	13.75 ± 0.7 a
	A2B2	55.95 ± 1 cd	11.82 ± 0.7 cd	42.69 ± 1.3 d	12.67 ± 0.8 b
	A3B1	47.62 ± 0.9 de	10.16 ± 0.9 ef	27.81 ± 0.6 fg	9.86 ± 0.9 c
	A3B2	43.57 ± 0.8 f	8.75 ± 0.7 f	25.76 ± 0.5 h	8.52 ± 0.5 de
2021	CK2	49.27 ± 1.1 de	15.18 ± 0.9 d	42.83 ± 1.1 e	17.13 ± 0.9 d
	A1B1	70.32 ± 1.5 a	23.75 ± 1.1 a	75.25 ± 1.7 a	21.67 ± 1.1 c
	A1B2	66.36 ± 1.3 b	20.21 ± 0.8 b	71.39 ± 1.5 b	19.83 ± 0.8 cd
	A2B1	64.80 ± 1.2 b	20.18 ± 1.2 b	50.13 ± 1.1 c	27.12 ± 1.2 a
	A2B2	60.57 ± 0.9 c	17.97 ± 0.7 c	46.87 ± 0.9 d	25.42 ± 1.1 ab
	A3B1	48.28 ± 0.8 e	10.29 ± 0.6 e	29.86 ± 0.7 fg	12.63 ± 0.4 ef
	A3B2	46.68 ± 0.6 f	8.19 ± 0.8 f	27.38 ± 0.5 g	11.86 ± 0.9 f

Note: different lowercase letters within the same column indicate significant differences at the 0.05 probability level ($p < 0.05$).

4. Discussion

4.1. Single-dose Application at Reduced Nitrogen Rate of Slow-Release Nitrogen Fertilizer at Seedling Stage Increased Yield for DSCWH

Previous studies have indicated that applying a slow-release fertilizer containing 150–375 kg of nitrogen per hectare can enhance the yield and nitrogen utilization rate of transplanted cotton [11,36]. Convention nitrogen fertilizer (urea) with a nitrogen rate of 180 kg ha^{-1} (72 kg ha^{-1} at three-leaf stage and 108 kg ha^{-1} at early flowering stage) was the optimum strategy for nitrogen management [6,9,37]. In our present study, the treatment of 90 kg·ha^{-1} slow-release nitrogen fertilizer at the two-leaf and four-leaf stages exhibited a significant increase in seed cotton yield, exceeding the yield of conventional fertilizer treatment by 8.2% and 24.2% in 2020 and by 14.0% and 9.7% in 2021, respectively. Our results were in agreement with Geng et al. [27], who reported a 5.54–11.17% increase in lint yield by controlled-release urea fertilizer. And, the yield enhancement was mainly related to a 7.03–8.91% increase in boll number, which also agreed with our results. Similarly, the seed cotton yield was increased by 14.81–18.15% by polymer-coated urea and the polymer coating of sulfur-coated urea, and the boll weight was closely associated with the enhance yield [24]. Zhang et al. [28] collected studies on controlled-release urea in recent decades and performed a meta-analysis. This study reported that controlled-release urea and split nitrogen urea increased crop yield by 10.08% and 8.11% compared with all nitrogen urea applied as base fertilizer. This research also concluded that controlled-release urea performed well in most cases, but when the soil available N content (<50 mg kg^{-1}) and the N application rate (<150 kg ha^{-1}) were both low, or the crop was wheat, controlled-release

urea could not substitute for the split nitrogen urea. Compared to urea, few studies paid attention to controlled-release potassium, phosphate, or other microelements. Yang et al. found that the application of 70% polymer-coated potassium chloride together with 50% polymer-coated urea increased cotton yield, fertilizer use efficiency, and fiber quality [38].

For the application timing, under the normal climate in 2021, there was no statistically significant difference in yield between the two-leaf stage and the four-leaf stage. However, the yield at the two-leaf stage was numerically higher and more conducive to early maturity (higher bolling rate and bolling intensity), which was beneficial for concentrated and mechanical harvesting. Therefore, it is preferable to apply slow-release nitrogen fertilizer at the two-leaf stage for light and simplified cotton production.

4.2. Enhanced Nitrogen Absorption and Utilization Efficiency of Slow-Release Nitrogen Fertilizer Promoted Optimum Nitrogen and Biomass Accumulation and Distribution in Reproductive Organ

In the traditional seedling transplanting planting pattern, the NRE is typically 30–35%, which requires multiple applications and large quantities of fertilizer [20,24]. In our present study, the NRE of conventional nitrogen fertilizer management was 48.23–49.27% in DSCWH. However, applying slow-release nitrogen fertilizer in DSCWH further enhanced the nitrogen absorption and utilization efficiency. During the two-year study period, the NRE of the slow-release nitrogen fertilizer varied between 55.95% and 64.80%. Geng et al. also found that the NUE of the polymer sulfur-coated urea was increased by 41.05% and 53.95%, and that of the polymer-coated urea was increased by 34.19% and 34.64% [24]. The apparent recovery use efficiency (RUE) and agronomic use efficiency (AUE) was increased by the polymer-coated urea application [27]. When urea was used as fertilizer one time at early flowering, 90 kg·ha^{-1} N exhibited a higher NUE than 180 kg·ha^{-1} N, which was consistent with our study [9]. Based on studies of past decades on controlled-release fertilizer, Zhang et al. [28] found that controlled-release urea and split nitrogen urea enhanced NUE by 47.55% and 45.21% compared with all-nitrogen urea applied as base fertilizer. These results indicate the substantial improvement in nitrogen absorption and utilization efficiency by the application of slow-release nitrogen fertilizer for DSCWH.

Biomass production is the prerequisite of cotton yield, with the fastest accumulation from first flowering to full bolling stage [5]. In our present study, the highest biomass in the reproductive organ was detected under 90 kg·ha^{-1} slow-release nitrogen fertilizer in the two-leaf stage, and the relationship between biomass in reproductive organs and nitrogen accumulation in reproductive organs demonstrated further that maximum reproductive biomass could be achieved at optimum nitrogen accumulation (80~140 kg·ha^{-1}) in reproductive organs. Previous studies also reported enhanced biomass accumulation with controlled-release urea fertilizer [24]. Therefore, a reduced rate of slow-release nitrogen application at the two-leaf stage can maintain appropriate nitrogen absorption and utilization in reproductive organs, which increases biomass and ultimately promotes the yield increase.

5. Conclusions

In this study, slow-release nitrogen fertilizer with 90 kg·ha^{-1} nitrogen applied at the two-leaf stage exhibited the highest yield, with a 12.6% increase compared to the no-fertilization control. The enhanced yield under slow-release nitrogen fertilizer was a result of improved nitrogen absorption and utilization and biomass accumulation and distribution, as higher biomass accumulation in reproductive organ and higher NRE, NAE, NPFP, and NPE were observed. This fertilization management can provide practical guidance for the light, simplified, and efficient fertilization for DSCWH in the Yangtze River basin. Future studies on this new system should pay more attention to physiological and molecular mechanisms associated with this process. Also, slow-release fertilizer studies currently mainly focus on nitrogen, whereas few studies pay attention to controlled-release potassium, phosphate, or other microelements, and how phosphate, potassium, and other microelements impact the slow-release urea.

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