agronomy

MDPI

Article

The Effect of New Nano-Released 1,1-Dimethyl-Piperidinium Chloride (DPC) Drip Application on Cotton Agronomic Traits

Shanwei Lou [1,2], Mingwei Du [1], Fei Gao [3], Xiaoli Tian [1], Pengzhong Zhang [2], Jie Li [2] and Liusheng Duan [1,4,*]

[1] College of Agronomy and Biotechnology, China Agricultural University, Beijing 100193, China
[2] China National Cotton R&D Center, Urumqi 830091, China
[3] Institute of Agricultural Environment and Sustainable Development, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[4] College of Plant Science and Technology, Beijing University of Agriculture, Beijing 102206, China
* Correspondence: duanlsh@cau.edu.cn; Tel.: +86-010-80799000

Abstract: The use of 1,1-dimethyl-piperidinium chloride (DPC) in Xinjiang is one of the necessary measures for regulating cotton populations and optimizing canopy structure. However, mechanical spraying involves operation and energy consumption, which can alternatively be achieved via drip application. In the present study, to investigate the effect of drip application, two types of hydrophobic nano-released DPCs were used to regulate plant type at different dosages. DPC dripingation reduced plant height by more than 10 cm and plant width by more than 4 cm, and the effect improved with increasing concentration and times. The main effect of height control was at the 6th–10th nodes of the main stem, and the effect of width control was observed at the 1st and 2nd nodes of the fruit branch. The SPAD value was higher than that in the control group during the initial stages. An irregular downward trend was observed in the subsequent stages. The proline content was higher than that of the control and increased with higher concentrations of DPC. There was no significant difference in the soil DPC content at the different sites. The DPC content decreased by more than 30% at the seventh day after dripping, and the content was 2–4 $\mu g \cdot g^{-1}$ in each treatment. At 15 days after application, the soil DPC was lower than 1 $\mu g \cdot g^{-1}$ in all treatments. The number of harvested plants was more than 150,000 plants$\cdot hm^{-2}$, and the number of bolls per plant increased at least by one, compared with the control. The final yield of seed cotton increased by at least 300 kg$\cdot hm^{-2}$, with a maximum increase of 1672.01 kg$\cdot hm^{-2}$. Considering the different types of DPCs, nano-released types worked better than the conventional type in terms of plant height, plant width, degradation in soil and boll formation. Nano-released DPC can play an even better role than conventional DPC in chemical regulation with drip irrigation.

Keywords: cotton; nano-DPC; drip application; shaping

check for updates

Citation: Lou, S.; Du, M.; Gao, F.; Tian, X.; Zhang, P.; Li, J.; Duan, L. The Effect of New Nano-Released 1,1-Dimethyl-Piperidinium Chloride (DPC) Drip Application on Cotton Agronomic Traits. *Agronomy* **2023**, *13*, 1543. https://doi.org/10.3390/agronomy13061543

Academic Editor: Petronia Carillo

Received: 4 April 2023
Revised: 15 May 2023
Accepted: 29 May 2023
Published: 2 June 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

DPC is a plant growth regulator that appears to antagonize gibberellin. Cotton has unlimited growth habits, requiring complex pruning and plant type regulation in production. Regulating plant shape and canopy structure is an important measure for the "short-dense-early" cotton planting model, in which DPC was the most widely used regulator [1]. DPC is absorbed by the leaves and roots of the plant and transmitted to the whole plant. DPC can guarantee cotton dwarfing for dense planting by inhibiting the growth of the main stem, fruit branch internode elongation and terminal bud, and can achieve the purpose of shaping and simplifying pruning [2,3]. Since the mid-1980s, DPC was widely accepted by farmers because of its stable effect, safety, low price, and so on. At present, DPC is sprayed at least 5–6 times with a machine during the whole growth. Mechanical operation can cause plant damage, lodging, and indirect spreading of pests and diseases. Furthermore, machine spraying is also energy intensive, and increases management costs

by RMB 30–50 [4]. Therefore, it is necessary to explore a more concise, convenient and energy-saving application mode for DPC. Drip irrigation is a mature technology which has covered more than 90% of cotton fields in Xinjiang, and has successfully realized the integration of water and fertilizer [5]. In recent years, according to the actual needs of production, researchers put forward the integrated technology of water, fertilizer and pesticide, in which the fertilizer and pesticide in solution with irrigation water are evenly and accurately transported to the root soil of crops through the irrigation system, and the crops are supplied quantitatively, regularly and proportionally according to the demand of the whole crop growth cycle [6,7]. The goal of saving water, fertilizer, pesticide and labor will be achieved with this technology, which has been explored and applied in disease and pest control [8–12]. Application by either dripping or spraying with DPC have the effect on reshaping of plant type. However, DPC could be easily adsorbed by the soil; migration and infiltration rarely occur, which posed certain difficulties for drip application of DPC [5]. In recent years, an agrochemical nano drug delivery system was constructed with nano materials and technology [13–15], which could enhance the hydrophobicity of DPC by optimizing slow release, and adjust the releasing curve in combination with irrigation mode to make the release dose, time and space of DPC more acceptable. However, little relevant research was reported. In this paper, in order to study the effect of dripping nano-released DPC on the regulation of cotton growth and development instead of conventional DPC, the effects of different dropping concentrations and times on cagronomic traits were studied by using two new types of hydrophobic nano DPC with a combination of drip irrigation system. The results will provide useful information for the field drip application of DPC aimed at simplifying the chemical regulation of cotton.

2. Materials and Methods

2.1. Materials

This study was conducted at Wudui Farm, Daquan Township, Shawan City, Xinjiang from 2020 to 2022. The previous crop of the test plot was cotton. Experimental soil was loam with organic matter 11.80 $g \cdot kg^{-1}$, alkali hydrolyzable nitrogen 52.91 $mg \cdot kg^{-1}$, available phosphorus 19.4 $mg \cdot kg^{-1}$, available potassium 227 $mg \cdot kg^{-1}$. The pH of 0–20 cm top soil was 8.26 before cotton planting.

The cotton variety was Youmian F015-5. The two kinds of tested nano sustained-release DPC were hydrophobic microspheres and hydrophobic supramolecular complexes, which were treated with alcohol-soluble corn protein and supramolecular composite intercalated nanomaterials (also hydrotalcite, chemical composition general formula $[M^{2+}{}_{1-x}M^{3+}{}_{x}(OH)_2]^{x+}\ (A^{n-})_{x/n} \cdot mH_2O$), respectively.

2.2. Methods

According to the schematic diagram of experimental workflow of this study, a random block experiment was designed to study the effect of drip application in 2020 (Table 1). Each treatment was repeated three times with an area of 40 m^2 for each plot. Two types of DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes were labeled as C1, C2, respectively. Three concentrations (L, M, H) were set with conventional DPC and blank water as the references (S1 and CK), respectively. The dosages of low (L), medium (M) and high (H) concentrations were 30 $g \cdot hm^{-2}$, 60 $g \cdot hm^{-2}$ and 90 $g \cdot hm^{-2}$, respectively, according to the former study [1]. All DPCs were applied with water irrigation on June 16, and chemical regulation was not carried out at later stage. The seeds were sowed in plots with 6 rows for each film, in which row space was 66 + 10 cm, and the plant space was 9–10 cm. Other cultivation measures such as intervillage and topping refer to the requirements of general high-yield fields.

Table 1. Design of experiment.

Year	Treatments		Dosage for the First Dripping (g·hm^{-2})	Dosage for the Second Dripping (g·hm^{-2})
2020	C1	L	30	-
		M	60	-
		H	90	-
	C2	L	30	-
		M	60	-
		H	90	-
	S1	L	30	-
		M	60	-
		H	90	-
	CK		-	-
2021	C1	L	30	60
		H	60	120
	C2	L	30	60
		H	60	120
	S2	L	30	60
		H	60	120
	CK		-	-
2022	C1		90	-
	C2		90	-
	S3		90	-

Note: C1 and C2 mean DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S1, S2 and S3 mean commercially available conventional DPC in 2020, 2021 and 2022, respectively. CK means the blank water. L, M and H mean dosages of low, medium and high concentrations, respectively.

In 2021, a random block design was also adopted to optimize the concentration and times of DPC application. Two kinds of slow-release DPC (C1, C2) were set with two concentrations (L and H), with commercially available conventional DPC and blank water as the references (S2 and CK), respectively. DPC was applied twice, on June 4 and 28. For the first application, the concentrations of low (L) and high (H) concentration were 30 and 60 g·hm^{-2}, respectively. For the second dripping, the concentrations of low (L) and high (H) concentration were 60 and 120 g·hm^{-2}, respectively. Based on the results of the two previous years, the absorption path after drip application was further studied in a randomized block experiment in 2022. Two types of (C1, C2) slow-release DPC were applied on June 6 at the concentration of 90 g·hm^{-2}, and commercially available conventional DPC was set as control (S3).

2.3. Measurements

2.3.1. Agronomic Traits

Six plants were selected to investigate the agronomic traits for each plot. Plant height, stem diameter, number of true leaves, number of fruit branches, height of initial node and length of internode of main stem were recorded 5 times every 6–9 days after the application of the DPC. All the agronomic traits were measured again before harvest.

2.3.2. Plant Width

The maximum lateral distance between leaves of fruit or vegetative branches was defined as plant width, which was measured for the first time at the first application of DPC, and then 5 times every 5–8 days after dripping.

2.3.3. Chlorophyll and Proline Concentration

The chlorophyll concentration (SPAD value) of the fourth leaf was measured every 5–10 days after the application of DPC. On the 7th day after the application of DPC, the concentration of proline of the fourth leaf was also measured using the method of acid pyrotrione color [16]. The absorbance was determined with colorimetry at a wavelength of 520 nm.

2.3.4. DPC in Soil and Plant

On the 3rd, 7th and 15th days after dripping of DPC, the residual DPC and water in soil samples was determined, and the DPC of plants was also measured at the same time. Soil samples were taken longitudinally in three gradients from the surface layer (0–10 cm), the middle layer (10–20 cm) and the bottom layer (20–30 cm), and transversely at two sites (5 cm and 15 cm from the drip line).

2.3.5. Yield and Components

The number of plants and bolls were measured within 6.67 m^2 for each plot, and the plant density and boll number per plant were calculated at the boll-opening stage. Ten plants with the same growth trend were selected to sample 15 bolls from the upper, middle and lower bolls, respectively. The boll weight and lint percentage were measured to estimate the yield of each plot.

2.4. Data Analysis

All the data were organized with Microsoft Office 2016 software. SPSS 19.0 software was used for two factor analysis of variance, and a new complex range method was used for multiple comparisons of the mean values between different treatments.

3. Results

3.1. Regulation of Plant Height by Different Types of DPC

The main role of DPC is to control plant height. All treatments were significantly different from the control, except for S1L treatment at low concentrations in 2020 (Figure 1A). The differences between treatments and the CK in plant height were greater than 4 cm, with a maximum of 16.1 cm. Plant height decreased with increasing concentrations; however, the difference was not significant. Among the different treatments, C1 showed the best effect. The plant height of medium and high concentrations of C1M and C1H was 72.7 cm and 71.1 cm, respectively, which was significantly different from that of S1. In 2021, the difference in plant height between each treatment and the control was also significant, with a difference of more than 10 cm, and the effects of the two nano-released DPC drip treatments were better than that of conventional DPC treatments. Plant height under S2H treatment was 57 cm, which was the lowest of all treatments. There was no difference between different concentrations with same type of DPC, and the difference in plant height was less than 10 cm and 5.5 cm, respectively; however, the difference between the low concentration (C2L and S2L) and high concentration (C1H) treatments was significant, with a maximum difference of 12.2 cm (Figure 1B). In 2022, there were no significant differences between the treatments with different types of DPC. The difference in plant height between the different treatments was only 3.1 cm. The C1 treatment with a single application of DPC had the best effect, with a plant height of 69.9 cm (Figure 1C). All treatments with drip DPC application effectively controlled plant height (Figure 2).

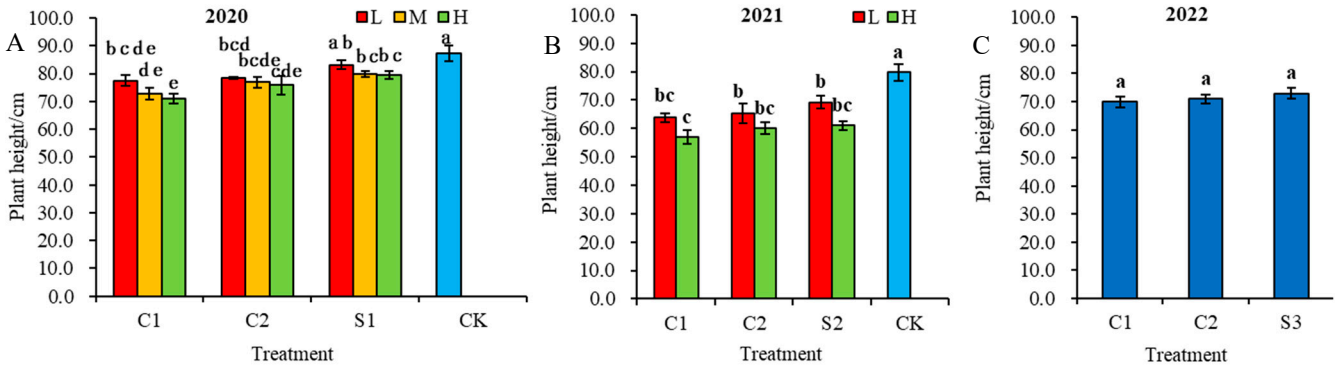


Figure 1. Plant height with different DPC. Note: (**A**–**C**) mean the plant height of different treatments in 2020, 2021 and 2022, respectively. C1 and C2 mean DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S1, S2 and S3 mean commercially available conventional DPC in 2020, 2021 and 2022, respectively. CK means the blank water. L, M and H mean dosages of low, medium and high concentrations, respectively. Different lowercase letters indicate significant differences at the 5% levels between different treatments.



Figure 2. Individuals and population treated with different types of DPC in 2022. Note: C1 and C2 represent DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S3 represents commercially available conventional DPC in 2022.

3.2. Regulation of Internode Length of the Main Stem by Different Types of DPC

The effect of DPC on plant height was mainly reflected in the internode length of the main stem. In 2020, compared with the control, the length of the 6th to 10th internodes was significantly shorter in all treatments (Figure 3). The largest difference was 1.9 cm in the eighth internode in S1L treatment, followed by 1.6 cm in the seventh internode in C2H treatment. The total length between the 6th and 10th nodes from C1L to S1H treatment was 4.0 cm, 3.7 cm, 2.9 cm, 3.1 cm, 4.9 cm, 3.8 cm, 3.6 cm, 4.4 cm and 3.9 cm shorter than that of the control, respectively.

In 2022, all DPC treatments were applied in the period of internode elongation at the sixth to seventh nodes, so the internode length of the first to fifth nodes under each treatment changed to <2 cm, the length tended to be fixed and the impact was limited (Table 2). These results are consistent with those for 2020. However, the length of the internode gradually decreased by 3 cm from the sixth node. The internode length of nodes 6–9 was shortest under C1 treatment and longest under S3 treatment. The length difference between the eighth node of the C1 and S3 treatments was the largest, up to 2.7 cm (Table 2).

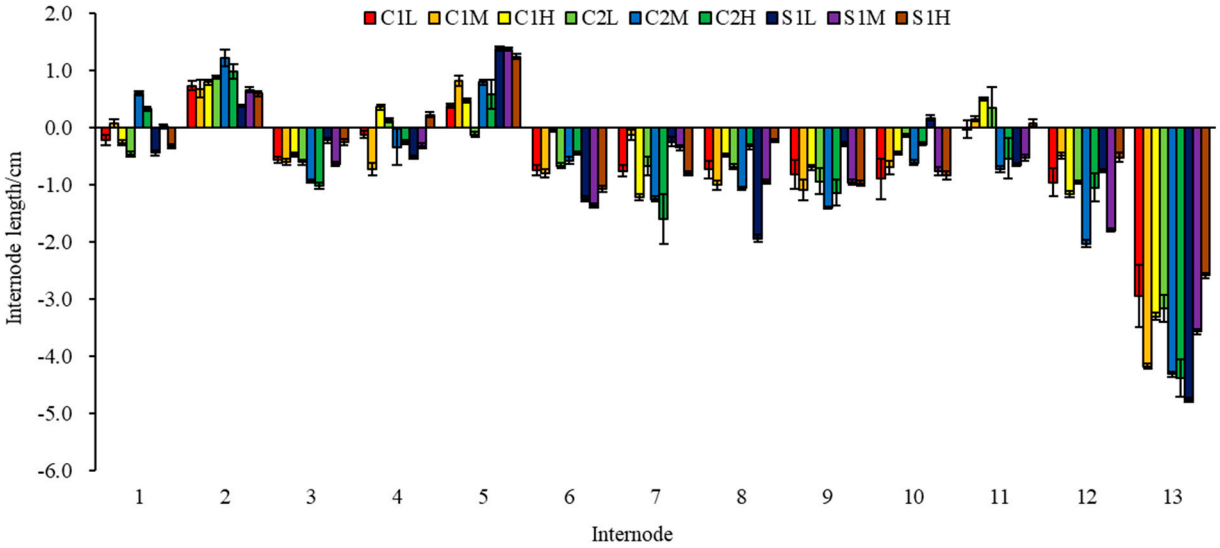


Figure 3. Difference between the internode length of each treatment and the corresponding internode length of the control in 2020. Note: C1 and C2 mean DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S1 means commercially available conventional DPC in 2020. L, M and H mean dosages of low, medium and high concentrations, respectively.

Table 2. Changes in internode length of each treatment in 2022.

Treatment	Date (M–D)	Internode (cm)												
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
C1	6–3	3.2	3.0	3.9	3.4	4.6	2.9	2.0						
	6–10	3.4	3.3	4.2	3.6	4.7	4.4	4.6	3.5	2.3				
	6–15	3.5	3.8	4.4	3.9	4.9	4.5	5.1	5.4	6.4	3.4	2.6	2.1	
	6–20	3.6	4.0	4.7	4.2	4.9	4.9	5.4	5.5	6.6	6.8	5.1	3.2	2.6
	6–25	3.7	4.4	5.2	4.8	5.1	4.9	6.2	5.5	6.8	7.2	7.3	6.3	3.0
	7–9	3.7 a	4.6 a	5.3 a	5.2 a	5.2 a	5.7 a	5.8 a	6.2 a	7.1 a	7.5 a	7.6 a	6.7 a	6.8 a
C2	6–3	3.3	2.3	4.2	3.7	3.9	2.8	3.5						
	6–10	3.5	2.5	4.4	3.9	4.5	3.9	5.1	4.0	3.5	2.6			
	6–15	3.5	2.8	4.5	4.0	5.4	4.0	5.5	5.0	5.5	3.1	1.8		
	6–20	3.7	3.4	4.5	4.6	5.5	4.9	5.6	5.2	7.2	7.3	6.5	3.8	2.3
	6–25	3.9	3.8	4.7	4.8	5.6	5.0	5.7	6.5	7.5	7.5	7.3	5.4	4.4
	7–9	4.1 a	3.9 a	4.8 a	5.0 a	5.8 a	5.6 a	5.8 a	7.0 a	7.5 a	7.7 a	7.6 a	6.5 a	6.0 a
S3	6–3	3.7	3.0	4.6	3.9	3.8	2.9	2.1						
	6–10	3.9	3.5	4.9	4.2	4.4	4.9	4.8	3.0	2.4	2.1			
	6–15	4.0	3.8	5.1	4.4	4.5	5.1	6.3	5.9	5.2	4.7	4.8	2.1	
	6–20	4.0	4.3	5.2	4.7	4.9	5.6	6.6	6.2	5.4	5.7	6.4	3.9	2.1
	6–25	4.2	4.6	5.3	5.1	5.1	6.5	6.8	8.5	8.3	5.7	6.9	4.7	3.5
	7-9	4.3 a	4.9 a	5.3 a	5.6 a	5.1 a	7.1 a	6.8 a	8.9 a	8.0 a	8.0 a	7.2 a	6.9 a	5.7 a

Note: C1 and C2 mean DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S3 means commercially available conventional DPC in 2022. CK means the blank water. Different lowercase letters indicate significant differences at the 5% levels between different treatments.

3.3. Plant width Regulation by Different Types of DPC

Chemical regulation can be used to shape compact plants. The effect of C1H treatment with high concentration was the best, and the plant width was 38.3 cm and 33.3 cm in 2020 and 2021, respectively (Figure 4A,B). There was no significant difference between the treatments at the same concentration. Apart from C2 in 2020, the plant widths of the other treatments with low and high concentrations showed significant differences, with an average difference of more than 4.0 cm. Compared with the control, the plant width was significantly reduced in high concentration treatments, and it decreased by 2 cm and 4.0 cm in 2020 and 2021, respectively (Figure 4A,B). There was no significant differences between the low concentration and control treatments. Plant width decreased

under medium concentration treatments, but the difference was not statistically significant. In 2022, the plant width under C1 treatment was the smallest, and there was no significant difference between any of the treatments (Figure 4C).

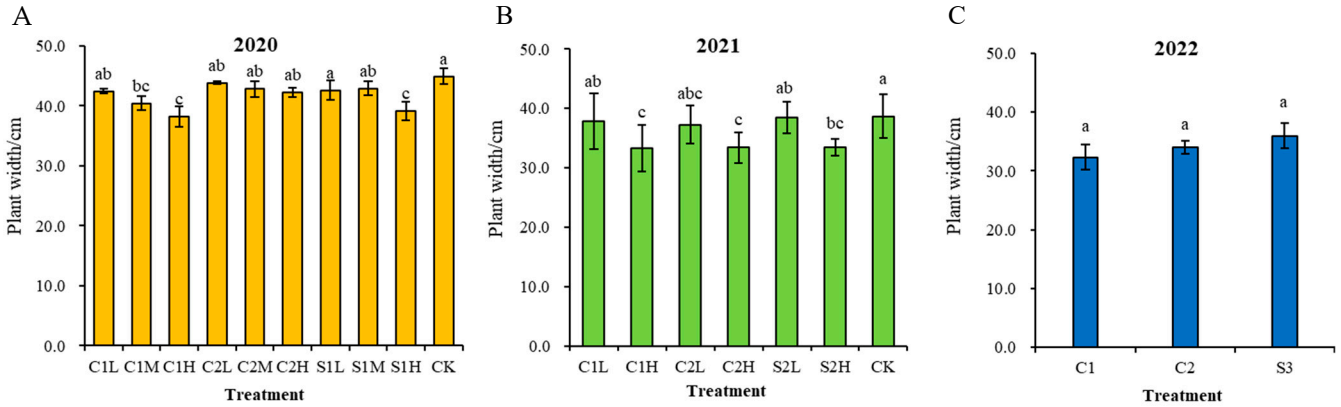


Figure 4. Plant width of cotton under different treatments from 2020 to 2022. Note: (**A**–**C**) mean the plant width of different treatments in 2020, 2021 and 2022, respectively. C1 and C2 mean DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S1, S2 and S3 mean commercially available conventional DPC in 2020, 2021 and 2022, respectively. CK means the blank water. L, M and H mean dosages of low, medium and high concentrations, respectively. Different lowercase letters indicate significant differences at the 5% levels between different treatments.

3.4. Effect of Different DPC Types on Agronomic Traits

Compared with the control, agronomic traits, such as stem diameter, height of the first node of the fruit branch, and length of the first and second nodes of the fourth fruit branch showed a downward trend under each drip application of different forms of DPC, but there were no significant differences in the three years of the experiment (Table 3). Stem diameter was between 10.00 and 11.50 mm. The height of the initial nodes of fruit branches was mostly between 24.0 and 25.0 cm. Compared with the control, the length of the first and second nodes of the fourth fruit branch were reduced by 4.0 cm and 1.8 cm at most, respectively. Significant differences were detected in the numbers of true leaves and fruit branches of the main stem in 2020. C1L, C1H, C2L, S1H were significantly different to in the number of true leaves on the main stem. There was a significant difference in the number of fruit branches between C1L and the control.

Table 3. Effects of each treatment on agronomic characters of cotton.

Year	Treatment	Stem Diameter (mm)	No. of Main Stem Leaves	No. of Fruit Branches	Height of First Fruit Branch (cm)	Length of the First Internode of the Fourth Fruit Branch (cm)	Length of the Second Internode of the Fourth Fruit Branch (cm)
2020	C1L	10.22 a	13.6 b	7.1 b	24.2 a	13.3 a	8.5 a
	C1M	10.86 a	14.0 ab	7.4 ab	24.4 a	13.1 a	8.7 a
	C1H	11.04 a	13.7 b	7.6 ab	26.1 a	13.8 a	9.5 a
	C2L	10.15 a	13.4 b	7.3 ab	25.2 a	14.4 a	9.0 a
	C2M	10.66 a	13.7 ab	7.4 ab	25.9 a	13.2 a	8.0 a
	C2H	10.52 a	13.9 ab	7.3 ab	24.8 a	13.7 a	8.5 a
	S1L	10.77 a	14.0 ab	7.7 ab	24.4 a	12.6 a	8.0 a
	S1M	10.65 a	13.8 ab	7.4 ab	25.3 a	11.4 a	9.7 a
	S1H	10.55 a	13.7 b	7.2 ab	25.2 a	12.0 a	7.9 a
	CK	11.00 a	14.3 a	7.8 a	26.3 a	15.4 a	9.7 a

Table 3. *Cont.*

Year	Treatment	Stem Diameter (mm)	No. of Main Stem Leaves	No. of Fruit Branches	Height of First Fruit Branch (cm)	Length of the First Internode of the Fourth Fruit Branch (cm)	Length of the Second Internode of the Fourth Fruit Branch (cm)
2021	C1L	-	13.8 a	7.9 a	25.5 a	14.7 a	9.7 a
	C1H	-	13.0 a	6.9 a	26.6 a	13.4 a	9.1 a
	C2L	-	13.6 a	7.8 a	22.7 a	14.5 a	8.9 a
	C2H	-	13.8 a	8.0 a	21.8 a	12.6 a	8.4 a
	S2L	-	12.9 a	8.2 a	26.9 a	13.6 a	9.7 a
	S2H	-	12.8 a	7.1 a	22.0 a	12.6 a	8.4 a
	CK	-	13.7 a	8.3 a	26.7 a	15.1 a	10.1 a
2022	C1	11.00 a	14.3 a	8.3 a	-	-	-
	C2	11.91 a	14.4 a	8.6 a	-	-	-
	S3	11.31 a	13.8 a	7.7 a	-	-	-

Note: C1 and C2 mean DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S1, S2 and S3 mean commercially available conventional DPC in 2020, 2021 and 2022, respectively. CK means the blank water. L, M and H mean dosages of low, medium and high concentrations, respectively. Different lowercase letters indicate significant differences at the 5% levels between different treatments.

3.5. Effect of Different Types of DPC on SPAD and Proline Leaf Content

In 2020 and 2022, the SPAD values of the last four leaves from the top showed a downward trend under all treatments from the first ten days of June (Figures 5 and 6). In 2020, the SPAD value of the control remained low, whereas the SPAD values under each treatment remained between 55 and 59. From 19 to 28 June, the SPAD value under each treatment tended to increase with concentration, and C2H treatment exhibited the highest value; however, the trend was not obvious in the later period (Figure 5A). In 2022, the SPAD value of the S treatment was always low for the three types of DPC, while that of C1 remained high. The difference between the two values reached a maximum of 7.2 on 15 June, and then decreased (Figure 5B). In 2020, the proline content under different types of DPC treatments was higher than that of the control, and proline content tended to increase with increasing concentration. C1H, C2M and C2H were significantly different from the control, with a maximum difference of 2.59 ug·g^{-1} (Figure 6A). However, there were no significant differences between the different treatments in 2022 (Figure 6B).

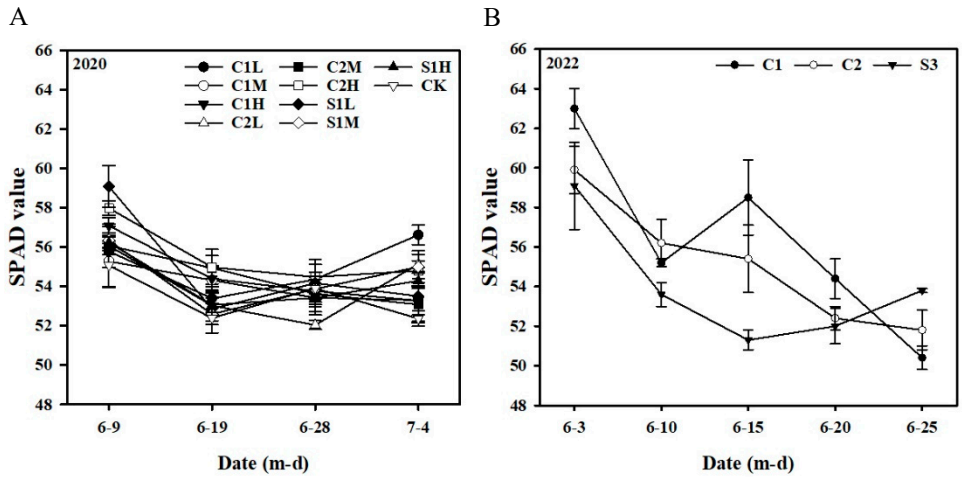


Figure 5. SPAD value of the last four leaves of cotton in each treatment. Note: (**A**,**B**) mean the SPAD value of different treatments in 2020 and 2022, respectively. C1 and C2 mean DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S1 and S3 mean commercially available conventional DPC in 2020 and 2022, respectively. CK means the blank water. L, M and H mean dosages of low, medium and high concentrations, respectively.

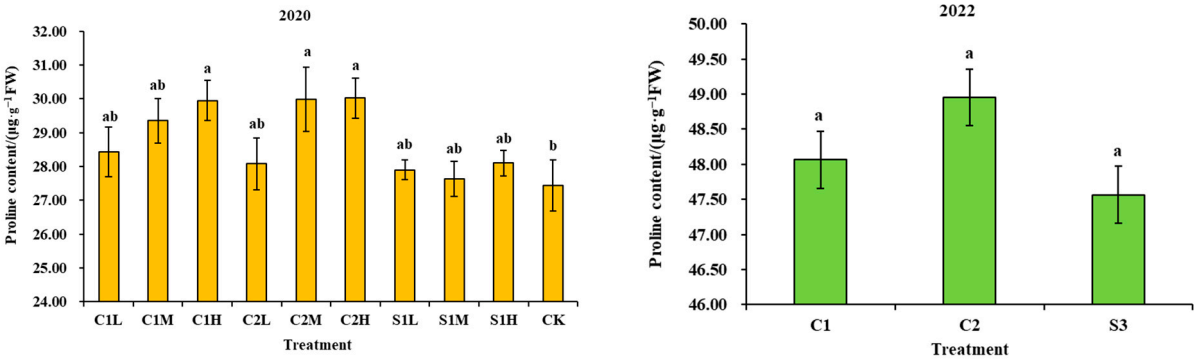


Figure 6. Proline of cotton under various treatments. Note: (**A**,**B**) mean the proline of different treatments in 2020 and 2022, respectively. C1 and C2 mean DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S1 and S3 mean commercially available conventional DPC in 2020 and 2022, respectively. CK means the blank water. L, M and H mean dosages of low, medium and high concentrations, respectively. Different lowercase letters indicate significant differences at the 5% levels between different treatments.

3.6. Adsorption and Transfer of Different Types of DPC in Soil and Plants

The soil DPC was very low after three days of drip application, and the content at different sites and depths was about 3–6.00 $\mu g \cdot g^{-1}$ (Figure 7). There was no significant difference in the content of different types of DPC at the same site and depth seven days after drip application, and there was no significant difference in DPC at the horizontal 5 cm and 15 cm sites. The DPC at the 15 cm site was slightly higher, and the maximum average difference under C2 treatment was 0.87 $\mu g \cdot g^{-1}$. The DPC decreased by approximately 30% within 3–7 days of drip application. The soil content under each treatment decreased significantly, reaching <1.00 $\mu g \cdot g^{-1}$ after 15 days of drip application. The DPC under S3 treatment was the lowest at both horizontal sites, and the minimum was only 0.25 $\mu g \cdot g^{-1}$. Although there were differences among different depth treatments, there was no apparent trend. During the test period, plant DPC was 150–200 $\mu g \cdot g^{-1}$, about 50 times higher than that in soil (Figure 8).

3.7. Effect of Different Types of DPC on Cotton Yield

Based on the analysis of cotton yield and its constituent factors, it was found that the yield and number of bolls per plant could be increased by applying DPC in dripingation. Compared with the control, the number of bolls per plant increased by 0.4–1.5 in under DPC treatment. The highest number of bolls per plant under C2L was 7.3 and 6.0 in 2020 and 2021, respectively. The increase in single-boll weight was not significant. In 2020 and 2021, the highest values were 5.33 g and 5.27 g under S1H and C1H treatments, respectively. In 2020, the yield of the control was 5582.82 $kg \cdot hm^{-2}$, which was 16.03% lower than that under C1H treatment, which had the highest yield, and 15.13% lower than that under C2H treatment. The yield of each treatment showed an increasing trend with increasing DPC concentration. In 2021, the control yield was 5566.28 $kg \cdot hm^{-2}$, 19.08% lower than that under C2L treatment, which had the highest yield, and 6.06% lower than that under S2H treatment. In 2022, the number of bolls per plant, weight per boll, and yield under slow-release treatment were higher than those under normal treatment; however, the differences were not significant.

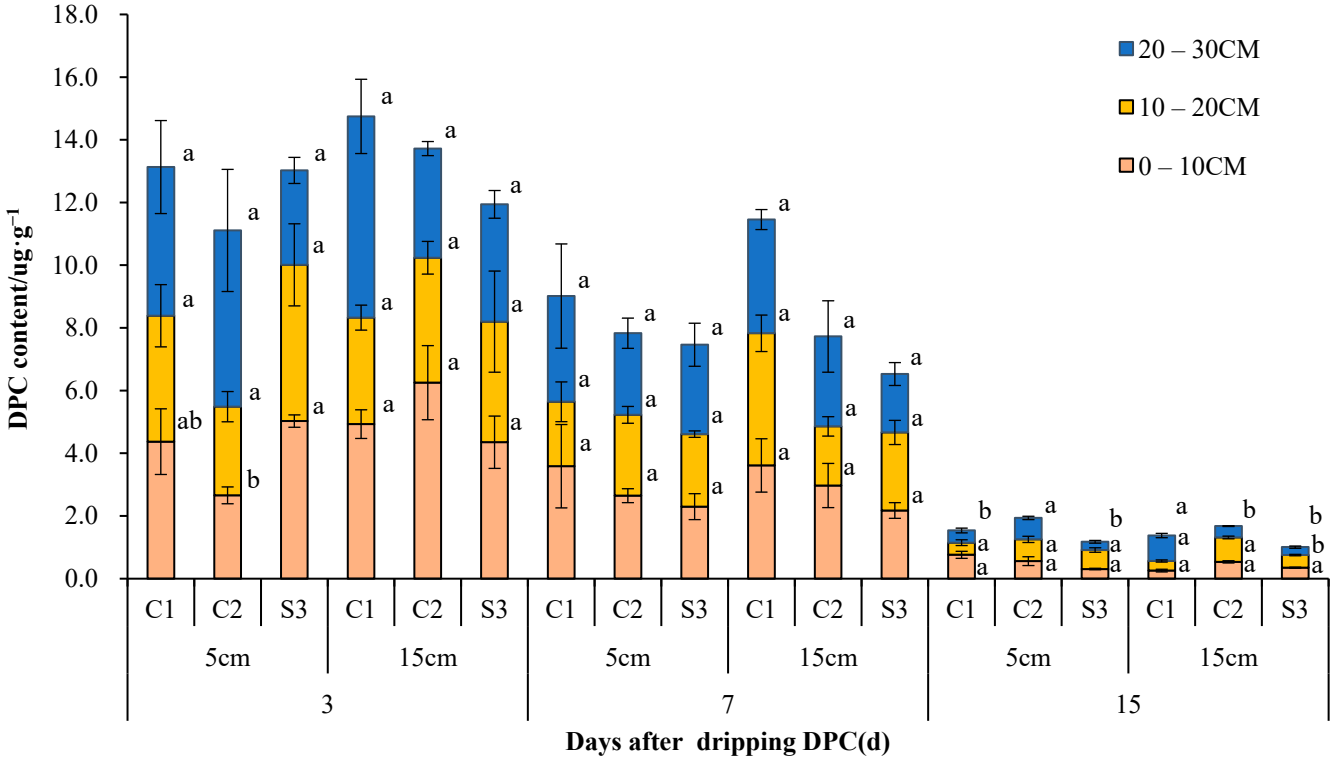


Figure 7. DPC at different sites and depth in soil under different treatments. Note: C1 and C2 mean DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S1 and S3 mean commercially available conventional DPC in 2020 and 2022, respectively. Different lowercase letters indicate significant differences at the 5% levels between different treatments.

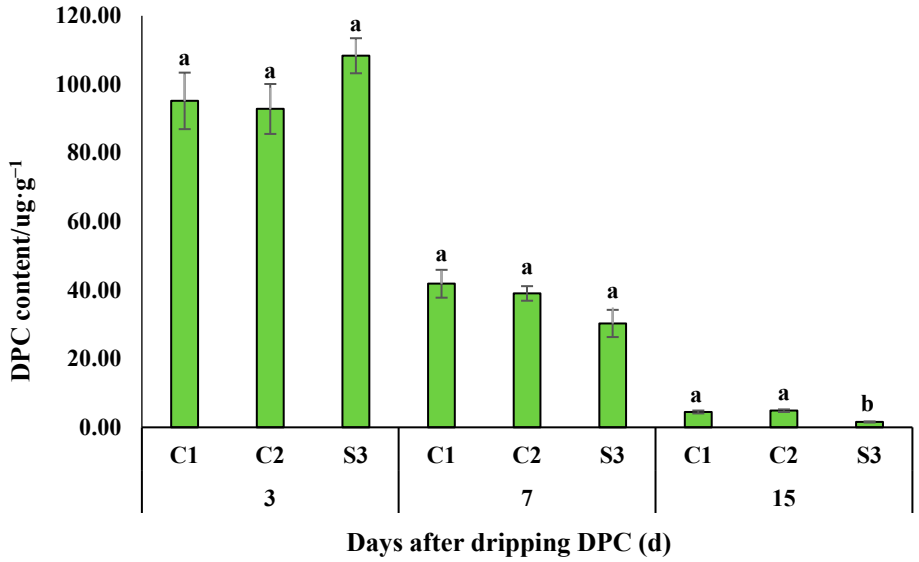


Figure 8. DPC in plants at different stages after dripping. Note: C1 and C2 mean DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S3 means commercially available conventional DPC in 2022. Different lowercase letters indicate significant differences at the 5% levels between different treatments.

4. Discussion

4.1. DPC Application Mode

DPC application is very common, and has become necessary for cotton production in Xinjiang. At present, DPC is mainly applied via foliar spraying 5–6 times during the growth period [17,18]. To adapt to the mechanized light and simple mode, more than 90% of cotton fields have integrated water and fertilizer treatments into the dripping system. Drip application of DPC could further promote this integration and reduce the cost of cotton planting. Zhang [19] found that DPC drip application significantly reduced the plant height and internode length of the main cotton stem in a concentration-dependent manner. Therefore, the drip application method is feasible. Our previous experiment also showed that seedling height could be controlled by applying DPC after sowing [20]. However, researchers have also reported problems, such as the necessary large concentration of DPC and the difficulty in determining the best time for drip application. However, with the rapid development of nanotechnology, the application of nanomaterials could achieve slow release and reduce DPC adsorption by hydrophobic interaction [21]. Simultaneously, the promotion and application of "dry seeding and wet drainage" technology could also achieve chemical control of DPC drip application in the early stages of cotton development, and reduce the number of spraying operations by 1–2 [1]. In addition, the low price, low toxicity and minimal harm to the soil of DPC ensures its feasibility with drip application. The present results showed that drip application of DPC was easy to operate, and was effective for regulation of plant.

4.2. Effect of DPC on the Agronomic Traits

DPC was used to reshape the plant structure by regulating cotton plant height and width, thereby improving the canopy structure. Researchers have found that DPC could regulate the daily growth of the main stem in a concentration-dependent manner [22,23]. Synergistic DPC can reduce plant height, reduce the number of fruit branches, and make the leaves upright and the stem thick, making the cotton plant more compact [24–26]. All of the above conclusions were drawn under spraying conditions. This experiment used drip application to explore the regulatory effect on the plant height, key main stem node position affecting plant height and plant width. Plant height and width could also be controlled via drip application of DPC. Plant height and width were reduced by 10 cm and >4 cm, respectively. This effect improved with increasing concentration and frequency (Figure 1). Nodes 6–10 are the main stem nodes for height control. The first and second nodes of the fruit branches are the main nodes for width control (Figure 3 and Table 2). In actual production, some fruit branches do not have a second node owing to a variety of characteristics; therefore, the second node has a significant impact on plant width.

4.3. DPC Residue in Soil

DPC is a degradable and safe pesticide with little environmental impact. According to the Test Guidelines for Environmental Safety Assessment of Chemical Pesticides, the maximum allowable residue standard of DPC formulated in the United States is 1 ppm. DPC can be easily adsorbed by soil, which reduces its migration and percolation. Li found that the half-life of DPC in soil was 8.2 days, the disappearance rate was >98% after 15 days of application and the minimum detectable concentration was 0.28 ppm [27]. Soil temperature and humidity significantly affected DPC degradation. The average DPC degradation rate in the soil was 3.0–3.5%·d^{-1} when the temperature was 25 °C and the humidity was 60–70% of the saturated water capacity. The half-life was approximately 8 days, and the time required for 95% degradation was 30–35 days. Tian found that part of the DPC was absorbed by the seed embryo, and another part diffused into the soil and was absorbed by the seedling root system [28]. In our study, the DPC in the soil was determined after drip application. The difference between DPC at different locations was small and irregular, indicating that DPC decreased by more than 30% after seven days of water diffusion (Figure 7). The DPC was between 2 and 4 μg·g^{-1}. Although slow-release and

increased DPC dosages were used, its soil content under each treatment was significantly reduced to <1.00 $\mu g \cdot g^{-1}$ after 15 days, which complied with the safety standards (Figure 5).

4.4. Effect of DPC on Cotton Yield

Single plant and population structure under the control of DPC is conducive to "short and dense" planting, improving canopy structure, promoting vegetative growth transformation to reproductive growth, improving dry matter accumulation and increasing yield [29]. Peng and Xu demonstrated that an appropriate amount of DPC could maintain good ventilation and light transmittance in the middle of a cotton field, increase the number of bolls per plant and increase the weight of the bolls per plant [30,31]. Luo also studied the effects of DPC on the canopy structure and cotton yield characteristics at different densities and found that DPC could increase the leaf inclination angle, shape a more compact plant type and improve the canopy structure [32]. DPC could shorten the bud emergence time of fruit nodes by 0.4–2.9 days in different parts of the fruit [33]. The present experiment proved that the yield increased with irrigation application of DPC, and the key factor was to control and realize the population advantage of high density. The density was increased to more than 150,000 plants$\cdot hm^{-2}$ under DPC regulation, followed by optimization of the canopy to facilitate boll formation. The number of bolls per plant increased by more than one compared with the control, and the final yield increased by 6–19%. Among the different test dosage forms, treatment with nano-released DPC consistently achieved a higher yield than that of conventional DPC (Table 4).

Table 4. Effects of different treatments on cotton yield and components.

Year	Treatment	The Harvest Plant of Land /Plant $\times 10^4 \cdot hm^{-2}$	Boll No. per Plant	Boll Weight /g	Seed Cotton Yield /kg$\cdot hm^{-2}$	Percentage of Increasing/%
2020	C1L	18.05	6.2	5.27	5912.58	5.91
	C1M	18.30	6.5	5.30	6256.77	12.07
	C1H	18.45	6.7	5.27	6478.00	16.03
	C2L	16.40	7.3	5.31	6414.22	14.89
	C2M	17.00	7.0	5.31	6334.77	13.47
	C2H	17.80	6.8	5.32	6427.22	15.13
	S1L	16.80	7.0	5.28	6264.16	12.20
	S1M	17.00	6.7	5.28	5991.56	7.32
	S1H	18.30	6.2	5.33	5986.91	7.24
	CK	18.15	5.8	5.27	5582.82	-
2021	C1L	21.20	6.0	5.21	6622.88	18.98
	C1H	21.50	5.7	5.27	6420.62	15.35
	C2L	21.80	6.0	5.23	6628.54	19.08
	C2H	22.40	5.0	5.20	6021.99	8.19
	S2L	20.70	5.5	5.22	5942.97	6.77
	S2H	20.45	5.3	5.20	5903.41	6.06
	CK	21.45	5.0	5.19	5566.28	-
2022	C1	15.65	7.8	5.47	6706.91	4.47
	C2	17.00	7.4	5.48	6885.15	7.25
	S3	15.95	7.4	5.44	6419.76	-

Note: C1 and C2 mean DPC treated with hydrophobic microspheres and hydrophobic supramolecular complexes, respectively. S1 and S3 mean commercially available conventional DPC in 2020 and 2022, respectively. CK means the blank water. L, M and H mean dosages of low, medium and high concentrations, respectively.

5. Conclusions

With the results of 3 years of experiment, adopting the drip application method with DPC could meet the requirements of chemical control with little effort, and be integrated with application of water fertilizer and medicine, and not harm the soil environment. Compared with the control, drip application of DPC reduced the cotton plant's height by more than 10 cm, reduced the plant width by more than 4 cm, increased at least one boll

per plant and improved the yield by more than 300 kg·hm^{-2}. DPC residue in soil was less than 1.00 μg·g^{-1}. The effect of nano-released DPC was greater than that of common DPC in regulating plant height, plant width, boll formation and yield increasing. However, due to limitations in the application time with drip irrigation, the duration of the chemical effect was still not long enough, resulting in unsignificant differences from ordinary DPC and unclear advantages.

With the continuous progress of planting and nano-release technology, drip application of DPC with water will be more accurate and effective with spray assistance.

Author Contributions: Investigation, S.L., M.D. and F.G.; Data analysis, S.L. and F.G., Validation, S.L. and P.Z.; Methodology, J.L.; Writing—original draft, S.L. and X.T.; Conceptualization, S.L., M.D. and P.Z.; Writing—review and editing, S.L. and M.D.; Funding acquisition, L.D. and S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Youth Scientific Research Foundation of Xinjiang Academy of Agricultural Sciences (xjnkq-2021008), Autonomous Cultivation Project of Xinjiang Academy of Agricultural Sciences (nkyzztd-002).

Data Availability Statement: Data will be made available on reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lou, S.W.; Dong, H.Z.; Tian, X.L.; Tian, L.W. The "short, dense and early" cultivation of cotton in Xinjiang: History, current situation and prospect. *Sci. Agric. Sin.* **2021**, *54*, 720–732.
2. Zhao, S.Q.; Zhang, H.C.; Yan, Z.H.; Li, W.; Dai, B.S.; Huang, X.L. Overview of research on the application of DPC in cotton production in China. *Cotton Sci.* **2018**, *40*, 7–11. [CrossRef]
3. Rademacher, W. Growth retardants: Effects on gibberellin biosynthesis and other metabolic pathways. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* **2000**, *51*, 501–531. [CrossRef] [PubMed]
4. Zhou, C.J.; Tian, X.L.; Li, S.L.; Yun, Y.L. Effect of slow release DPC coating on agronomic and economic characters of cotton. *China Cotton.* **2004**, *31*, 14–16.
5. Zhang, T.; Wang, M.F.; Zhao, Q. Effects of DPC and nitrogen fertilizer through drip irrigation on growth and yield in cotton. *Acta Agric. Sin.* **2022**, *48*, 396–409. [CrossRef]
6. Wu, X.Q.; Zhao, Q.; Tian, L.W.; Li, J.Y.; Ma, C.M.; Tian, Y.Q. Effect of three top topping (capping) methods on plant type and dry matter accumulation of cotton in southern Xinjiang. *Acta Agric. Boreali-Occident. Sin.* **2021**, *30*, 1797–1803.
7. Li, Y.; Wang, F.; Sun, J.S.; Liu, H.; Yang, J.Q.; Xian, F.; Su, H. Coupling effect of water and nitrogen on mechanically harvested cotton with drip irrigation under plastic film in arid area of western Inner Mongolia, China. *Chin. J. Appl. Ecol.* **2016**, *27*, 845–854.
8. Lu, N.; Shi, L.; Liu, H.Y.; Si, A.J.; Li, Q.S.; Zhang, G.L.; Chen, Y. Effects of biological agent dripping on cotton *Verticillium* wilt and rhizosphere soil microorganism. *Chin. J. Appl. Ecol.* **2019**, *30*, 602–614.
9. Luo, Y.N.; Du, J.; Li, J.H.; Yan, Y.J.; Zhao, S.F. Control efficacy of bacillus subtilis S37 and S44 against cotton *Verticillium* wilt by under-mulch-drip irrigation. *Plant Prot.* **2011**, *37*, 174–176.
10. Lou, S.W.; Wang, D.G.; Zhang, P.Z.; Lu, X.Y.; Bian, Y.; Zhang, X.D.; Ma, T.F.; Zhang, H.J. The study of *Bacillus subtilis* with water application to control of cotton *Verticillium* wilt. *China Cotton.* **2015**, *42*, 25–28.
11. Luo, J.J.; Liu, X.L.; Li, K.M.; Luo, M.; Maidiniyeti, M.; Tunishaguli, A.; Guan, J.Z.; Ma, J.J. Effects of microbial agent inoculations on controlling *Fusarium oxysporum* and *Verticillium dahliae* in cotton fields of continuous cropping. *Acta Agric. Boreali-Occident Sin.* **2015**, *24*, 136–143.
12. Zhang, Y.L.; Zhou, J.H.; Wang, L.; Wang, Z.; Feng, H.Z.; Huang, Q. Effects of drone and drip irrigation on cotton aphid and its natural enemies. *China Cotton.* **2018**, *45*, 26–29.
13. Wang, N.; Tian, X.L.; Duan, L.S.; Yan, G.T.; Huang, Q.; Li, Z.H. Metabolism of reactive oxygen species involved in increasing root vigor of cotton seedlings by soaking seeds with mepiquat chloride. *Acta Agric. Sin.* **2014**, *40*, 1220–1226. [CrossRef]
14. Scott, N.R.; Chen, H.; Cui, H. Nanotechnology applications and implications of agrochemicals toward sustainable agriculture and food systems. *J. Agric. Food. Chem.* **2018**, *66*, 6451–6456. [CrossRef] [PubMed]
15. Gomollón-Bel, F. Ten chemical innovations that will change our world: IUPAC identifies emerging technologies in chemistry with potential to make our planet more sustainable. *Chem. Inter.* **2019**, *41*, 12–17. [CrossRef]
16. Zeng, Z.J. Regulation of Exogenous Proline on Cotton Growth under Boron Stress. Master's thesis, Huazhong Agricultural University, Wuhan, China, 2022.
17. Li, P.M.; He, Z.P.; Li, Z.H. Overview and progress of the application of DPC chemical control technology in cotton. *Crops* **1991**, *2*, 1–3.
18. Zhang, C.; Yu, Q.Q.; Ma, X.L.; Lu, X.F.; Geng, J.B.; Yu, W.Y.; Zhao, W.; Li, C.H. Advances in the application of mepiquat chloride to the growth and yield of cotton. *Anhui Agric. Sci.* **2020**, *48*, 11–13.

19. Zhang, T.; Zhao, Q.; Li, G.W. Research progress on effect of DPC on growth and development of cotton. *Jiangsu Agric. Sci.* **2021**, *49*, 14–18.
20. Lou, S.W.; Gao, F.; Wang, C.; Tian, X.L.; Du, M.W.; Duan, L.S. Screening of different dropping formulations about mepiquat chloride and their effects on cotton growth and development. *Acta Agric. Sin.* **2023**, *49*, 552–560.
21. Zhao, X.; Cui, H.; Wang, Y.; Sun, C.; Cui, B.; Zeng, Z. Development strategies and prospects of nano-based smart pesticide formulation. *J. Agric. Food. Chem.* **2018**, *66*, 6504–6512. [CrossRef]
22. Xu, M.; Jin, L.L.; Li, S.T.; Li, R.C.; Wang, Z.S. Effect of chemical regulation on different cotton varieties. *Cotton Sci.* **2013**, *35*, 27–32.
23. Li, L.; Tian, C.Y.; Lv, Z.Z.; Huang, Z.W. Influence of DPC on the growth of cotton stem in seedling stage. *Agric. Res. Arid Areas* **2003**, *4*, 26–30.
24. Han, H.Y.; Du, M.W.; Wang, F.Y.; Chen, B.; Tian, X.L. Effects of DPC+ Application dose on agronomic and economic traits of cotton in northern Xinjiang. *Southwest China J. Agric. Sci.* **2019**, *32*, 327–330.
25. Liu, C.; Zhang, J.S.; Wei, X.; Xu, X.X. Effects of mepiquat chloride on physiological indicators of leaf function and characteristics of yield of hybrid cotton in south Xinjiang. *Cotton Sci.* **2014**, *26*, 122–129.
26. Zhao, Q.; Zhou, C.J.; Zhang, J.S.; Li, S.L.; Yun, Y.L.; Tian, X.L. Effect of chemical detopping on the canopy and yield of cotton (*Gossypium hirsutum* L) in south Xinjiang. *Cotton Sci.* **2011**, *23*, 329–333.
27. Li, B.T.; Jiang, S.R. Study on residue and dynamics of meperidine in cotton field soil. *Agrochemicals* **1994**, *4*, 40–41.
28. Tian, X.L.; Xie, X.Y.; Zhou, C.J.; Yang, P.Z.; Wang, B.M.; Duan, L.S.; Li, S.L.; Hui, Y.L.; He, Z.P.; Li, Z.H. Factors affecting the degradation of mepiquat chloride in soil. *J. Agro-Environ. Sci.* **2008**, *5*, 1726–1731.
29. Tian, X.L.; Xie, X.Y.; Zhou, C.J.; Li, S.L.; Yang, P.Z.; Duan, L.S.; Li, Z.H.; Hui, Y.L. Slow release characteristics of mepiquat chloride from starch matrices coated cotton seed. *Sci. Agric. Sin.* **2008**, *10*, 3042–3051.
30. Peng, Z.Y.; Shen, Y.Y.; Duan, S.J.; Wu, Y.F.; Li, Z.R.; Guo, R.S.; Zhang, J.S. Effect of chemical regulation on canopy structure and yield of cotton with different nitrogen amounts. *J. Agric. Sci. Tech.* **2022**, *24*, 177–186.
31. Xu, L.H.; Yang, C.Q.; Li, G.F.; Yang, D.Y. Effects of exogenous hormones on boll setting and fiber quality of high quality cotton. *Cotton Sci.* **2006**, *5*, 294–298.
32. Luo, H.H.; Zhao, R.H.; Han, C.L.; Zhang, W.F. Effects of growth regulators (DPC) on canopy architecture and yield characteristics of cotton under different planting densities. *Cotton Sci.* **2011**, *23*, 334–340.
33. Liao, B.P.; Ren, X.M.; Du, M.W.; Egrinya, E.A.; Xu, Y.D.; Tian, X.L.; Li, Z.H. Study on promoting the development of yield organs of cotton by systematic and chemical control of ketamine. In Proceedings of the 19th Annual Academic Conference of the Crop Science Society of China, Wuhan, China, 8–11 November 2020; p. 321.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.