

Article

Octahedral Paclobutrazol–Zinc Complex for Enhanced Chemical Topping Efficacy in Mechanized Cotton Production: A Two-Year Field Evaluation in Xinjiang

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Abstract

Topping is an essential step in cotton cultivation in Xinjiang, China, which can effectively increase the number of bolls per plant and optimize the yield and quality. Paclobutrazol, as a common chemical topping agent for cotton, faces challenges such as unstable topping effect and limited leaf surface absorption during application. In this study, paclobutrazol was used as the ligand and a zinc complex was synthesized by the thermosolvent method to replace paclobutrazol and improve the topping effect on cotton. The structure of the complex was characterized using FTIR, UV-vis, TG, and XRD analyses. The results confirmed that each zinc ion coordinated with four nitrogen atoms from the triazole rings of paclobutrazol and two oxygen atoms from nitrate ions, forming an octahedral geometry. Surface tension measurement and analysis revealed that the complex had a surface tension reduction of 12.75 mN/m compared to paclobutrazol, thereby enhancing the surface activity of the complex in water systems and improving its absorption efficiency on plant leaves. Two-year field trials indicated that the foliar application of the complex at a dosage of 120 g·hm^{−2} in inhibiting cotton plant height was more stable to that of paclobutrazol or mepiquat chloride. It also shortened the length of fruiting branches, making the shape of cotton plants compact, thereby indirectly improving the ventilation and light penetration of the cotton field and the convenience of mechanical harvesting. Yield data showed that, compared with artificial topping, the complex at a dosage of 120 g·hm^{−2} treatment increased cotton yield by approximately 4.6%. Therefore, the paclobutrazol–zinc complex is a promising alternative to manual topping and have great application potential in future mechanized cotton production.

Keywords: *Gossypium hirsutum*; zinc–paclobutrazol complex; octahedral coordination; chemical topping agents; cotton growth regulation



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1. Introduction

Xinjiang is the largest production base of high-quality cotton in China, accounting for more than 80% of the country's total cotton planting area and over 90% of its total output [1]. The high-quality development of Xinjiang's cotton industry holds strategic importance for regional economic stability and social progress. With continuously rising labor costs,

promoting simplified cultivation techniques and achieving full mechanization have become essential for the sustainable development of the cotton industry in Xinjiang [2–4]. Currently, mechanical harvesting has been largely achieved in cotton production across the region; however, key agronomic practices still depend on traditional artificial topping [5]. Artificial topping presents several notable drawbacks: it requires significant physical labor, incurs high costs, and is susceptible to missed or incorrect topping, which compromises topping quality [6]. As a result, artificial topping has become a major constraint on the advancement of cotton production in Xinjiang. Chemical topping, by contrast, offers cost savings and improved labor efficiency, and is increasingly replacing artificial methods [7–9]. Most chemical topping agents currently used are primarily composed of mepiquat chloride, flumetralin, and paclobutrazol. However, these agents often exhibit unstable topping effects and may cause the premature shedding of cotton terminal buds and bolls [10]. Therefore, the development of a stable and efficient chemical topping agent is of great importance for advancing simplified and mechanized cotton cultivation.

Paclobutrazol, a triazole-based plant growth regulator, can inhibit cell division and elongation at the apical meristems of cotton plants, and is commonly employed in chemical topping treatments [11]. However, due to its limited foliar absorption, its efficacy through foliar spray application is significantly compromised. As a result, it is frequently applied via seed dressing, soil drenching, or drip irrigation, which may lead to residual pollution in agricultural soils. Recent studies have demonstrated that triazole metal complexes represent a promising approach for enhancing the biological activity of triazole-derived compounds while simultaneously reducing their environmental toxicity [12–14].

Coordination chemistry holds broad application prospects in modern science, particularly due to the sustained-release characteristics and the high stability of metal complexes in pesticide formulations, which offer significant potential for development [15–20]. However, zinc ions have good biocompatibility and relatively low environmental toxicity. Compared with the corresponding transition metals, zinc complexes often exhibit stronger growth-regulating effects and drug efficacy [21–24]. Therefore, it is feasible to explore the coordination of existing pesticides with zinc ions.

In this study, a zinc–paclobutrazol complex was synthesized and its application in cotton chemical topping was further evaluated through field experiments. The objective was to provide enhanced technical support for the mechanization of cotton production and the sustainable development of agriculture in Xinjiang, while offering both a theoretical foundation and practical solutions to overcome the key technical challenges in simplified cotton cultivation in the region.

2. Materials and Methods

2.1. Synthesis of Paclobutrazol–Zinc Complexes

Paclobutrazol (0.588 g, 2.0 mmol) was placed into a round-bottomed flask and dissolve it in 12 mL of ethanol. $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (0.121 g, 0.5 mmol) was dissolved in 7 mL of ethanol. Zinc nitrate solution was added dropwise to the paclobutrazol solution under continuous stirring for 4 h. A colorless solution was formed. Following vacuum filtration and allowing the solution to stand undisturbed for 6 days, colorless crystals were obtained [20].

2.2. Characterization of Paclobutrazol–Zinc Complexes

The paclobutrazol–zinc complex was analyzed. Fourier Transform Infrared Spectroscopy (FTIR) data were collected using a Shimadzu IRTracer 100 spectrometer from Japan, within the wavelength range of 400–4000 cm^{-1} , employing potassium bromide pellets, and ultraviolet-visible spectroscopy (UV-Vis) data were collected using a Shimadzu UV-3600 Plus spectrophotometer from Japan, within the wavelength range of 200–800 nm,

in pure sample pellet diffuse reflectance mode. Thermogravimetric analysis (TG) tests were performed using an alumina crucible in a thermogravimetric analyzer (Switzerland-METTLER TOLEDO-TGA/DSC 3+) under a constant nitrogen flow, across a temperature range of 30–600 °C, at a heating rate of 10 K/min, the crystal structure of single crystal was measured by X-ray single-crystal diffractometer (Japan-Rigaku-XtaLAB Synergy-R/S).

The surface tension was measured using a fully automatic tensiometer (Zhongchen JK 99 C, Shanghai, China). The value reported is the average of three repeated measurements. Prior to each experiment, calibration and verification were performed using distilled water. All experiments were conducted at 25 Celsius with a measurement resolution of less than 0.05 millinewton per meter (mN/m).

2.3. General Situation of the Test Site

The trial lasted for two years from 2022 to 2023. The test site was located in the 12th Company of the 10th Regiment of Alar, Xinjiang ($40^{\circ} 23' N$, $81^{\circ} 17' E$). The soil composition of the experimental field was loam and the previous crop was cotton. The content of organic matter in cultivated layer was $17.9 \text{ g}\cdot\text{kg}^{-1}$, the content of basic decomposition nitrogen was $26.7 \text{ mg}\cdot\text{kg}^{-1}$, the content of available phosphorus was $24.6 \text{ mg}\cdot\text{kg}^{-1}$, and the content of available potassium was $188.0 \text{ mg}\cdot\text{kg}^{-1}$. The climatic conditions of the test area are presented in Figure 1.

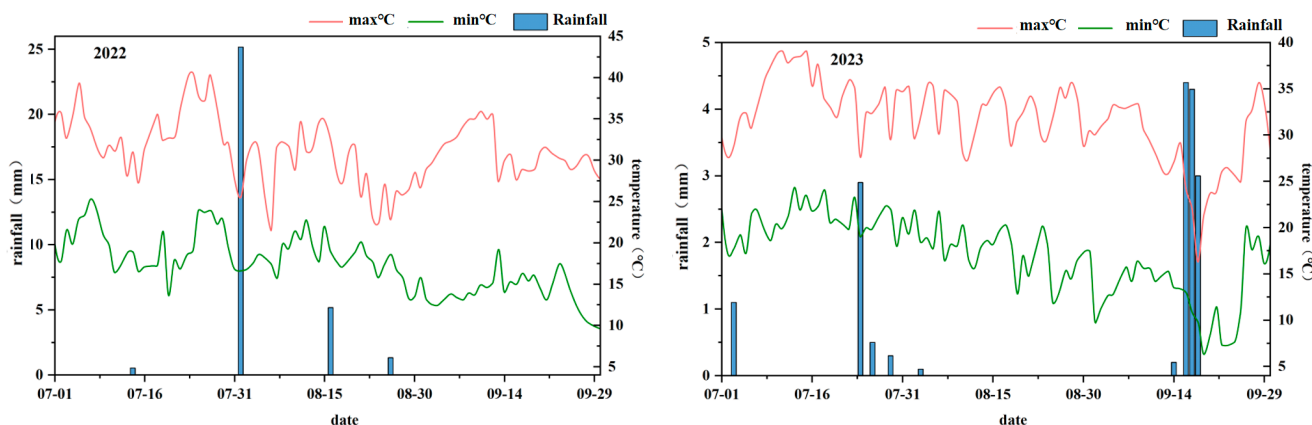


Figure 1. Temperature and precipitation after the peak of the test area in 2022 and 2023.

2.4. Experimental Design

Xinjiang cotton variety Tahe No. 2 was selected as the test variety. The seeds were sown on 15 April 2022 and 11 April 2023, in accordance with the wide rows are spaced at 66 cm, the narrow rows at 10 cm, and the plant spacing is maintained at 10.5 cm, using the ultra-wide 1-membrane 6-row mode, and the theoretical number of plants was $210,000 \text{ plants}\cdot\text{hm}^{-2}$. In 2022 and 2023, 11 and 10 drip irrigation times and $350 \text{ m}^3\cdot\text{hm}^{-2}$ water consumption per time during the whole growth period, respectively. The water droplets were applied with $450 \text{ kg}\cdot\text{hm}^{-2}$ and $420 \text{ kg}\cdot\text{hm}^{-2}$ urea, $200 \text{ kg}\cdot\text{hm}^{-2}$ and $185 \text{ kg}\cdot\text{hm}^{-2}$ P_2O_5 , and $250 \text{ kg}\cdot\text{hm}^{-2}$ and $240 \text{ kg}\cdot\text{hm}^{-2}$ K_2O . In addition to cotton topping, chemical control was carried out three times over two years using mepiquat chloride at the seedling, budding, and blooming stages of cotton. With the exception of chemical capping instead of manual topping, all other field management methods are consistent with those used in the extensive cotton fields in the area. Capped tests will be conducted on 3 July 2022 and 8 July 2023, respectively. A randomized block design was used for the capping test.

Paclobutrazol–zinc complex capping treatment: paclobutrazol–zinc complex at three concentrations, $75 \text{ g}\cdot\text{hm}^{-2}$, $120 \text{ g}\cdot\text{hm}^{-2}$, and $165 \text{ g}\cdot\text{hm}^{-2}$, was used as the controls with $120 \text{ g}\cdot\text{hm}^{-2}$ paclobutrazol, $180 \text{ g}\cdot\text{hm}^{-2}$ mepiquat chloride, artificial topping and water.

Each cell was 10 m long, 2.25 m wide, and had an area of 22.5 m², repeated three times. Foliar spraying was conducted using a backpack sprayer equipped with a fan-shaped nozzle (Model 11003) at a spray rate of 1.2 L/min.

2.5. Measurement Items and Methods

2.5.1. Determination of Agronomic Traits

Ten representative plants were selected from each community and tagged. Plant height was measured on the day of topping and every seven days thereafter. At the beginning of October, the beginning node, the height of the beginning node, the diameter of the stem, the length of the upper fruit branch and the number of fruit branches were measured. Plant height increase = $H_{T2} - H_{T1}$, where H_{T1} and H_{T2} , respectively, represent the cotton plant heights of the last survey and this survey.

2.5.2. Determination of Cotton Yield and Cotton Fiber Quality

In each community, the number of plants and bolls within an area of 6.67 square meters was evaluated, and the number of bolls per plant calculated during the boll opening stage. Fifteen plants with similar growth patterns were selected, and 40 bolls were sampled from the upper, middle, and lower sections of each plant. The weight of the bolls and the lint percentage were recorded to estimate the yield of each plot, with 3 replicates for each measurement. Additionally, a 150 g sample of lint was selected from each section and assigned a unique identifier before being evaluated for fiber quality. All samples for fiber quality measurement were evaluated by high-capacity instruments at the Alar Cotton Inspection and Testing Center.

2.6. Data Analysis

Excel 2016 was utilized for data processing and statistical analysis. Comprehensive data analysis and processing were conducted using IBM SPSS Statistics 26 software. Crystal structure elucidation and refinement were performed with Olex2 1.5 and Diamond 4.6 software, respectively. Origin 2018 was used for drawing. Significance of differences was determined by the Least Significant Difference (LSD) method, with a significance level set at 0.05.

3. Results

3.1. Preparation of the Paclobutrazol–Zinc Complex

The synthesis of the paclobutrazol–zinc complex was achieved through the acid–base neutralization of paclobutrazol and zinc nitrate hexahydrate in an ethanol-containing solvent solution. The synthetic pathway of the pleiotropic azole–zinc complex in this study is shown in Figure 2.

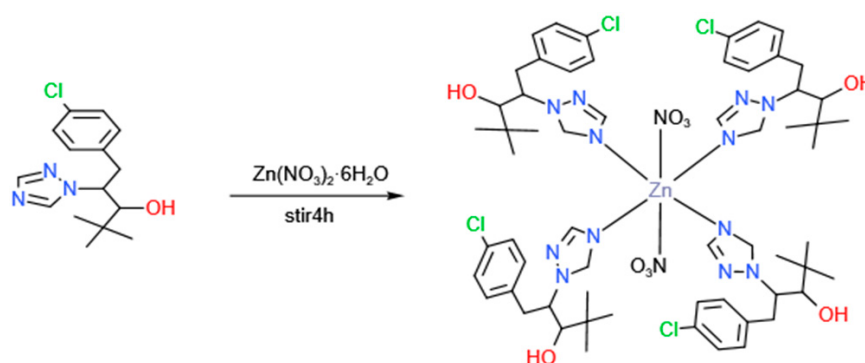


Figure 2. Synthesis pathway of paclobutrazol–zinc complexes.

3.2. Characterization of Paclobutrazol–Zinc Complexes

Infrared spectroscopy (FTIR), ultraviolet-visible spectroscopy (UV-Vis), and thermogravimetric (TG) analyses were performed on the zinc–paclobutrazol complex. The FTIR spectrum is presented in Figure 3a. The zinc complex of paclobutrazol exhibits a characteristic N–H absorption peak at 3415 cm^{-1} . Compared to the N–H absorption peak of pure paclobutrazol, this peak shows a shift in wavenumber and a reduction in intensity, indicating that the N–H group in paclobutrazol is involved in coordination. Furthermore, the nitrate N=O absorption peak appears in the spectra of both the zinc paclobutrazol complex and hexahydrate zinc nitrate at 1389 cm^{-1} and 1364 cm^{-1} , respectively, suggesting that nitrate ions participate in the coordination structure and confirming the successful synthesis of the complex. This observation aligns with the findings reported by Ren Guoyu [20].

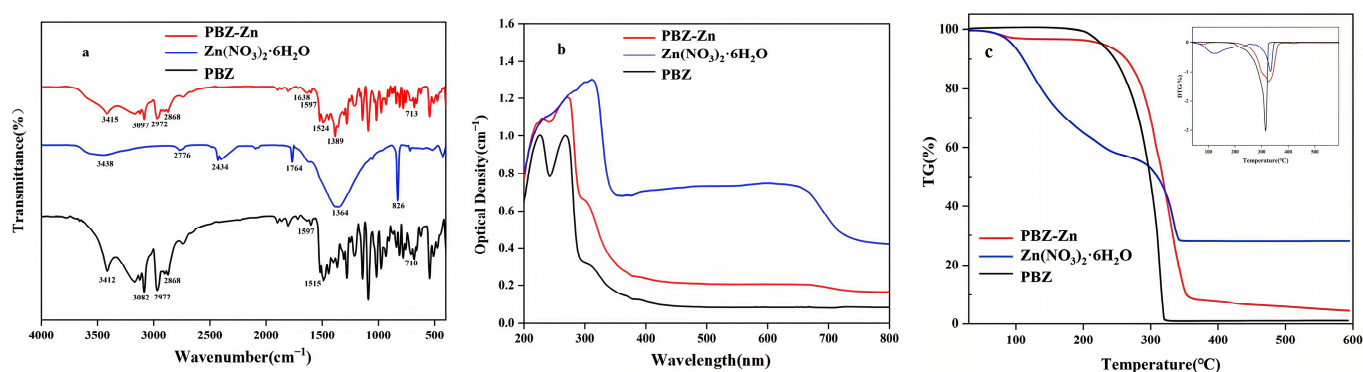


Figure 3. (a) IR spectrum; (b) UV-visible absorption spectra; (c) thermogravimetric (TG) analysis.

Figure 3b presents the ultraviolet-visible spectroscopy (UV-Vis) data of the zinc–paclobutrazol complex. The results reveal that paclobutrazol exhibited strong absorption peaks at 225 nm and 266 nm, whereas the zinc complex showed a prominent absorption peak at 271 nm. This spectral shift was accompanied by an increase in absorption intensity, indicating that the nitrogen atom of the triazole ring coordinates with the zinc ion, thereby influencing the conjugated system. The zinc nitrate hexahydrate displayed a strong absorption peak at 312 nm. According to theoretical expectations, zinc nitrate hexahydrate typically does not exhibit strong absorption in the ultraviolet region, suggesting that this peak is likely caused by water molecules. Notably, no absorption peak above 300 nm was observed for the zinc–paclobutrazol complex, which indicates that paclobutrazol has coordinated with the zinc ions rather than being solvated by water molecules.

Figure 3c presents the thermogravimetric (TG) data of the zinc–paclobutrazol complex. The results demonstrate that the weight loss ratio of the zinc–paclobutrazol complex during the first weight loss stage was lower than that of zinc nitrate, indicating partial replacement of water molecules by paclobutrazol. In the second weight loss stage, paclobutrazol undergoes thermal decomposition. The onset temperature of this decomposition step for the zinc paclobutrazol complex is higher than that of pure paclobutrazol. The zinc–paclobutrazol complex began to lose weight at 235 °C, reached 90% weight loss at 358 °C, and exhibited the maximum weight loss rate of 1.32%/min at 327 °C. In comparison, pure paclobutrazol started to decompose at 205 °C, achieved 99% weight loss at 323 °C, and showed a maximum weight loss rate of 3.02%/min at 312 °C. These findings suggest that the zinc–paclobutrazol complex exhibits enhanced thermal stability compared to paclobutrazol.

3.3. Single-Crystal Structure Analysis of the Paclobutrazol–Zinc Complex

Figure 4A illustrates the molecular coordination of the paclobutrazol zinc complex, revealing that the complex exhibits a symmetric structure with a central Zn ion at the symmetry center. The coordination number of Zn is 6, involving coordination with four N atoms from the triazole rings of the ligands and two O atoms from nitrate ions, thus forming a single crystal of octahedral structure. Figure 4B depicts the molecular packing of the paclobutrazol zinc complex. The results show that the intermolecular interactions are mediated by van der Waals forces, resulting in a three-dimensional spatial arrangement. The molecular packing is orderly. The structure refinement parameters and crystal data are listed in Table 1.

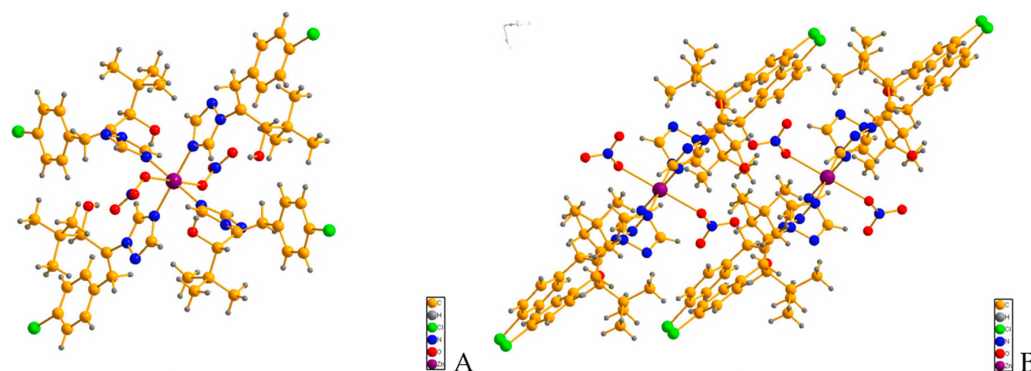


Figure 4. Molecular coordination diagram (A) and molecular packing diagram of the paclobutrazol–zinc complex (B).

Table 1. Structure refinement parameters and crystal data for the paclobutrazol–zinc complex.

Empirical formula	C ₆₀ H ₈₀ C ₁₄ N ₁₄ O ₁₀ Zn
Formula weight	1364.55
Temperature/K	293(2)
Crystal system	triclinic
Space group	P-1
a/Å	8.7372(2)
b/Å	13.4110(4)
c/Å	15.4425(4)
α/°	87.873(2)
β/°	80.689(2)
γ/°	71.387(2)
Volume/Å ³	1692.03(8)
Z	1
ρ _{calc} /cm ³	1.339
μ/mm ^{−1}	2.492
F(000)	716.0
Crystal size/mm ³	0.2 × 0.12 × 0.1
Radiation	Cu Kα (λ = 1.54184)
Index ranges	−7 ≤ h ≤ 10, −15 ≤ k ≤ 15, −18 ≤ l ≤ 18
Reflections collected	19267
Data/restraints/parameters	5929/65/411
Goodness-of-fit on F ²	1.083
Final R indexes [I ≥ 2σ (I)]	R1 = 0.0638, wR2 = 0.1820
Final R indexes [all data]	R1 = 0.0775, wR2 = 0.1954
Largest diff. peak/hole/e Å ^{−3}	0.62/−0.55

3.4. Analysis of the Surface Tension of the Paclobutrazol–Zinc Complex

Through surface tension tests, as shown in Table 2, the surface tension of the paclobutrazol–zinc complex was lower than that of paclobutrazol alone, indicating that the paclobutrazol–zinc complex is more conducive to the absorption by cotton leaves.

Table 2. Surface tension (25 °C) of the paclobutrazol–zinc complex.

Treatment	Surface Tension (mN/m)
Paclobutrazol	70.08 ± 0.02
Paclobutrazol–zinc complex	57.33 ± 0.01

3.5. Effects of the Paclobutrazol–Zinc Complex on Cotton Plant Height

It can be seen from Figure 5 that in 2022 and 2023, 0–7 days after topping, the cotton plant height growth of each treatment was at the maximum, and then the cotton plant height growth of the three concentrations of the paclobutrazol–zinc complex and artificial topping treatment shows a trend of continuous decline. However, the growth rate of cotton plant height treated with paclobutrazol and mepiquat chloride showed a trend of decrease-rise-decrease, and showed a rebound at 14–21 days after treatment. These results indicated that the inhibition effect of the paclobutrazol–zinc complex on cotton plant height was more stable than that of paclobutrazol and mepiquat chloride.

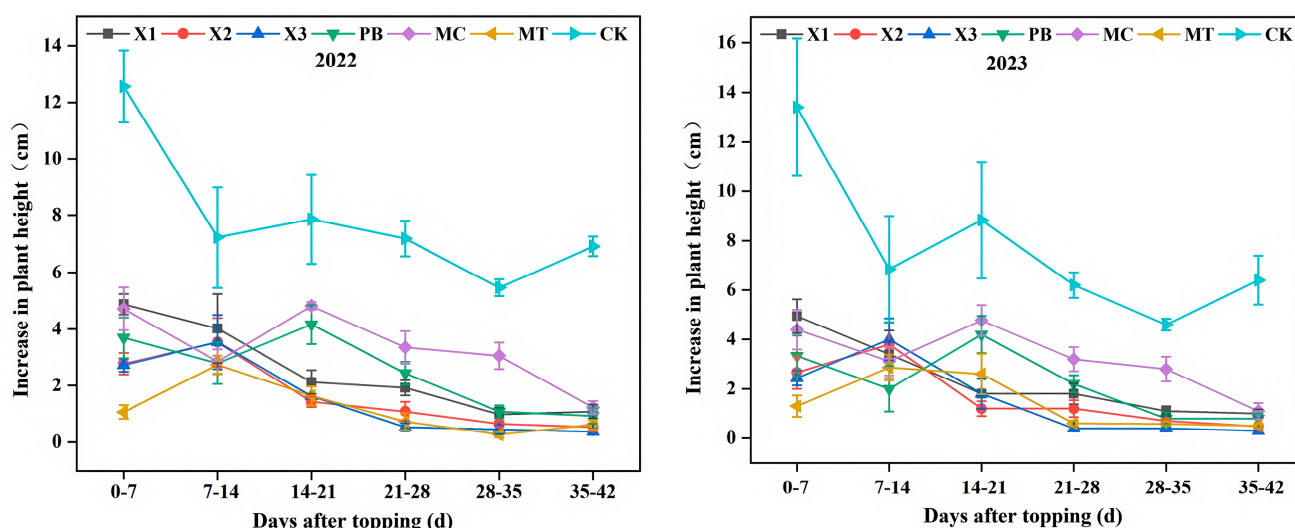


Figure 5. Effect of the paclobutrazol–zinc complex on cotton plant height growth. Note: X1, X2, X3 are three concentrations of paclobutrazol–zinc complexes; MT is artificial topping; PB is paclobutrazol; MC mepiquat chloride.

3.6. Effects of Paclobutrazol–Zinc Complexes on Cotton Fruit Branch Length

To determine the effect of the paclobutrazol–zinc complex on cotton plant type, the length of the top fruiting branches of cotton was measured. As can be seen from Table 3, from the point of view of the length of one fruit branch, 120 g·hm^{−2} treatment of the complex had the best effect among the three concentrations of the complex in two years. Over the two-year period, the length of fallen fruit branches treated with the complex 120 g·hm^{−2} decreased by 64% and 65%, respectively, compared to artificial topping, which was significantly lower than the artificial topping treatment. From the perspective of the length of inverted two-fruit branches, the complex 120 g·hm^{−2} showed significantly shorter lengths than paclobutrazol, mepiquat chloride, and artificial topping treatments. In 2022, compared with paclobutrazol, mepiquat chloride and artificial topping, the reductions were 30.3%, 18.6%, and 54%, respectively; in 2023, the reductions were 31.1%, 21.1%, and 54.2%.

Regarding trichotoma fruiting branches, in 2022, the length of these branches in cotton treated with the complex $120 \text{ g} \cdot \text{hm}^{-2}$ decreased by 11.7%, 18.8%, and 41% compared with paclobutrazol, mepiquat chloride, and artificial topping, respectively; in 2023, the decreases were 11.9%, 18.9%, and 39.5%. For inverted four-fruit branches, the length of those treated with the complex $120 \text{ g} \cdot \text{hm}^{-2}$ was significantly shorter than that of mepiquat chloride and artificial topping. In 2022, the reductions were 15.9% and 22.9%, respectively; in 2023, they were 18.4% and 24.6%. In summary, complex $120 \text{ g} \cdot \text{hm}^{-2}$ treatment can effectively reduce the length of one to four fruit branches of cotton, make the cotton plant more compact and more conducive to nutrient absorption.

Table 3. Effect of paclobutrazol–zinc complexes on the length of the first to the fourth fruiting branches of cotton.

Year	Treatment	Dose ($\text{g} \cdot \text{hm}^{-2}$)	Length of the Inverted First Fruit Branch (cm)	Length of the Inverted Second Fruit Branch (cm)	Length of the Inverted Third Fruit Branch (cm)	Length of the Inverted Fourth Fruit Branch (cm)
2022	Paclobutrazol–zinc complex	75	$4.87 \pm 0.96 \text{ b}$	$7.31 \pm 0.73 \text{ b}$	$9.34 \pm 0.65 \text{ b}$	$11.69 \pm 0.59 \text{ a}$
		120	$3.17 \pm 0.99 \text{ bc}$	$4.56 \pm 0.48 \text{ e}$	$7.32 \pm 0.69 \text{ d}$	$9.64 \pm 0.53 \text{ b}$
		165	$3.04 \pm 0.79 \text{ c}$	$4.79 \pm 0.67 \text{ de}$	$8.68 \pm 0.37 \text{ bc}$	$10.09 \pm 0.93 \text{ b}$
	Paclobutrazol	120	$4.03 \pm 1.03 \text{ bc}$	$6.54 \pm 0.75 \text{ bc}$	$8.29 \pm 0.55 \text{ c}$	$10.09 \pm 0.69 \text{ b}$
	Mepiquat chloride	180	$4.01 \pm 1.12 \text{ bc}$	$5.60 \pm 0.79 \text{ cd}$	$9.01 \pm 0.72 \text{ bc}$	$11.46 \pm 0.82 \text{ a}$
	Artificial topping	/	$8.79 \pm 1.86 \text{ a}$	$9.90 \pm 1.07 \text{ a}$	$12.40 \pm 0.84 \text{ a}$	$12.50 \pm 0.74 \text{ a}$
2023	Water	/	$4.12 \pm 0.64 \text{ bc}$	$5.29 \pm 0.30 \text{ de}$	$8.91 \pm 0.38 \text{ bc}$	$11.69 \pm 0.97 \text{ a}$
	Paclobutrazol–zinc complex	75	$4.94 \pm 1.07 \text{ b}$	$6.90 \pm 0.62 \text{ b}$	$8.68 \pm 0.66 \text{ b}$	$11.12 \pm 0.75 \text{ ab}$
		120	$3.08 \pm 0.79 \text{ c}$	$4.34 \pm 0.51 \text{ e}$	$7.17 \pm 0.65 \text{ c}$	$9.30 \pm 1.05 \text{ c}$
		165	$3.22 \pm 0.94 \text{ bc}$	$4.72 \pm 0.65 \text{ de}$	$8.26 \pm 0.75 \text{ bc}$	$9.90 \pm 0.85 \text{ bc}$
	Paclobutrazol	120	$4.10 \pm 0.96 \text{ bc}$	$6.30 \pm 0.73 \text{ bc}$	$8.14 \pm 0.69 \text{ bc}$	$9.83 \pm 0.58 \text{ c}$
	Mepiquat chloride	180	$4.08 \pm 1.01 \text{ bc}$	$5.50 \pm 0.56 \text{ cd}$	$8.84 \pm 0.65 \text{ b}$	$11.40 \pm 0.62 \text{ ab}$
	Artificial topping	/	$8.91 \pm 1.78 \text{ a}$	$9.43 \pm 1.19 \text{ a}$	$11.86 \pm 1.10 \text{ a}$	$12.34 \pm 0.95 \text{ a}$
	Water	/	$4.18 \pm 0.66 \text{ bc}$	$5.20 \pm 0.42 \text{ cde}$	$8.92 \pm 0.79 \text{ b}$	$11.26 \pm 0.35 \text{ a}$

Note: the value is the mean $\pm$ standard error, different lowercase letters indicate that the difference is significant at the 0.05 level.

3.7. Effects of the Paclobutrazol–Zinc Complex on Main Agronomic Traits of Cotton

It can be seen from Table 4 that among the three concentrations of the paclobutrazol–zinc complex, complex $120 \text{ g} \cdot \text{hm}^{-2}$ treatment has the best effect. Compared with the height of the first pitch, the height of the first pitch of cotton treated by complex $120 \text{ g} \cdot \text{hm}^{-2}$ is significantly lower than that of other treatments in the past two years, which is 21.20 cm in 2022 and 21.66 cm in 2023. Machine-picking cotton requires the height of the first pitch of cotton fruit branches to be about 20 cm, indicating that complex $120 \text{ g} \cdot \text{hm}^{-2}$ treatment is more conducive to machine-picking cotton. From the comparison of main stem internode length, the length of main stem internode of cotton treated by complex $120 \text{ g} \cdot \text{hm}^{-2}$ was significantly less than that treated by clear water and complex $75 \text{ g} \cdot \text{hm}^{-2}$ in two years. From the comparison of the number of fruit branches in cotton, complex $120 \text{ g} \cdot \text{hm}^{-2}$ treatment was superior to artificial topping treatment in two years, and complex $120 \text{ g} \cdot \text{hm}^{-2}$ treatment had no significant effect on cotton stem size. The results showed that complex $120 \text{ g} \cdot \text{hm}^{-2}$ treatment could effectively reduce the height of the first node, increase the number of fruit branches, and shorten the length of internode of the main stem of cotton.

Table 4. Effects of paclobutrazol–zinc complexes on the main agronomic traits of cotton.

Year	Treatment	Dose (g·hm ^{−2})	The Height of the First Fruit (cm)	Length Between Main Stem Nodes (cm)	Number of Fruit Branches (number)	Stem Diameter (mm)
2022	Paclobutrazol–zinc complex	75	23.83 ± 1.29 b	7.09 ± 1.07 a	10.20 ± 0.84 b	11.62 ± 1.69 b
		120	21.20 ± 1.22 c	5.98 ± 0.64 b	11.60 ± 0.55 a	12.68 ± 1.16 ab
		165	23.74 ± 1.55 b	5.98 ± 0.65 b	11.00 ± 0.89 ab	12.89 ± 1.54 ab
	Paclobutrazol	120	26.65 ± 1.42 a	6.36 ± 0.57 ab	11.20 ± 0.45 ab	12.72 ± 1.19 ab
	Mepiquat chloride	180	26.17 ± 1.61 a	6.22 ± 0.91 ab	11.20 ± 0.45 ab	12.00 ± 1.00 b
	Artificial topping	/	27.26 ± 1.42 a	6.71 ± 0.61 ab	10.14 ± 0.76 b	14.21 ± 1.12 a
2023	Water	/	27.95 ± 1.19 a	7.20 ± 0.66 a	11.20 ± 0.84 ab	11.60 ± 1.35 b
	Paclobutrazol–zinc complex	75	24.10 ± 1.34 c	6.80 ± 0.71 a	10.40 ± 0.14 ab	11.58 ± 0.55 b
		120	21.66 ± 1.48 d	5.73 ± 0.58 b	11.40 ± 0.55 a	12.69 ± 1.00 ab
		165	24.08 ± 1.07 c	5.79 ± 0.59 b	11.12 ± 1.47 a	13.09 ± 1.12 ab
	Paclobutrazol	120	27.20 ± 1.04 ab	6.41 ± 0.37 ab	11.40 ± 1.14 a	12.93 ± 1.75 ab
	Mepiquat chloride	180	26.50 ± 1.41 b	6.38 ± 0.55 ab	11.40 ± 0.55 a	12.14 ± 1.12 b
	Artificial topping	/	27.71 ± 1.58 ab	6.40 ± 0.58 ab	9.71 ± 0.65 b	14.51 ± 1.69 a
	Water	/	28.34 ± 1.18 a	7.15 ± 0.77 a	11.60 ± 0.89 a	11.80 ± 0.84 b

Note: the value is the mean ± standard error, different lowercase letters indicate that the difference is significant at the 0.05 level.

3.8. Effects of the Paclobutrazol–Zinc Complex on Cotton Yield

In order to determine whether the paclobutrazol–zinc complex has a positive effect on cotton seed cotton yield, cotton yield and its constituent factors were determined. The cotton yield under different topping treatments in 2022 and 2023 is shown in Table 5. From the perspective of the number of bolls per cotton plant, over the two-year period, the treatment with the complex 120 g·hm^{−2} resulted in a higher number of bolls compared to other treatments, indicating that this treatment positively influenced boll formation and contributed to increased cotton yield. In terms of cotton seed cotton yield, complex 120 g·hm^{−2} treatment had the highest cotton seed cotton yield of 8944.79 kg·hm^{−2} and 9098.28 kg·hm^{−2}, respectively, which was significantly higher than all other treatments, indicating that complex 120 g·hm^{−2} treatment could significantly increase cotton yield. From the point of view of cotton clothing, in 2022, complex 120 g·hm^{−2} treatment is significantly higher than clear water treatment. In terms of cotton lint production, in 2022, complex 120 g·hm^{−2}'s cotton lint production increased by 4.5% compared to artificial topping, 29.6% compared to paclobutrazol, and 24.8% compared to mepiquat chloride. In 2023, cotton yield of the complex by 120 g·hm^{−2} treatment increased by 4.7% compared to artificial topping, 31% compared to paclobutrazol, and 21.8% compared to mepiquat chloride, and complex 120 g·hm^{−2} treatment cotton lint production was significantly higher than all other treatments.

In summary, complex 120 g·hm^{−2} treatment can significantly increase the number of bolls per plant of cotton, thereby increasing the yield. Both seed cotton yield and lint yield are significantly greater than artificial topping treatment. Therefore, complex 120 g·hm^{−2} treatment can replace manual topping and has the effect of increasing production.

Table 5. Effects of paclobutrazol–zinc complexes on cotton yield and yield components.

Year	Treatment	Dose (g·hm ^{−2})	Number of Bolls Per Plant (number)	Boll Weight (g)	Seed Cotton Yield (kg·hm ^{−2})	Ginning Outturn (%)	Lint Cotton Yield (kg·hm ^{−2})
2022	Paclobutrazol–zinc complex	75	6.46 ± 0.23 c	6.23 ± 0.53 a	7244.24 ± 171.14 c	41.86 ± 0.63 ab	3032.44 ± 71.64 cd
		120	7.61 ± 0.17 a	6.53 ± 0.17 a	8944.79 ± 109.69 a	43.15 ± 0.36 a	3859.68 ± 47.33 a
		165	6.23 ± 0.18 c	6.43 ± 0.49 a	7210.60 ± 148.51 c	41.56 ± 0.9 ab	2996.72 ± 61.72 c
	Paclobutrazol	120	6.40 ± 0.17 c	6.18 ± 0.85 a	7119.36 ± 122.94 c	41.83 ± 1.17 ab	2978.03 ± 51.42 cd
	Mepiquat chloride	180	6.56 ± 0.21 bc	6.25 ± 0.19 a	7380.00 ± 107.85 c	41.92 ± 1.06 ab	3093.70 ± 45.21 c
	Artificial topping	/	6.98 ± 0.20 b	6.73 ± 0.45 a	8455.57 ± 183.36 b	43.68 ± 0.89 a	3693.39 ± 80.09 b
	Water	/	5.24 ± 0.24 d	6.11 ± 0.29 a	5762.95 ± 89.49 d	40.86 ± 1.17 b	2354.74 ± 36.57 e
2023	Paclobutrazol–zinc complex	75	6.95 ± 0.38 bc	6.07 ± 0.60 a	7592.32 ± 129.97 c	42.08 ± 0.49 a	3194.60 ± 54.69 c
		120	7.96 ± 0.42 a	6.47 ± 0.54 a	9098.28 ± 127.25 a	42.15 ± 0.43 a	3834.63 ± 53.63 a
		165	6.56 ± 0.32 c	6.35 ± 0.45 a	7634.60 ± 152.44 c	41.23 ± 1.04 a	3147.75 ± 57.85 c
	Paclobutrazol	120	6.67 ± 0.33 c	5.94 ± 0.26 a	7124.04 ± 153.27 d	41.09 ± 1.33 a	2927.50 ± 62.98 d
	Mepiquat chloride	180	6.97 ± 0.20 bc	6.13 ± 0.23 a	7685.35 ± 161.65 c	40.97 ± 1.29 a	3148.94 ± 66.23 c
	Artificial topping	/	7.32 ± 0.23 b	6.52 ± 0.58 a	8596.02 ± 132.99 b	42.59 ± 0.60 a	3660.76 ± 56.64 b
	Water	/	5.57 ± 0.35 d	5.99 ± 0.29 a	6006.88 ± 159.94 e	41.58 ± 1.07 a	2497.66 ± 66.50 e

Note: the value is the mean ± standard error, different lowercase letters indicate that the difference is significant at the 0.05 level.

3.9. Effects of the Paclobutrazol–Zinc Complex on Cotton Fiber Quality

As can be seen from Table 6, there is no significant difference in the average length and uniformity of the top half of each treatment. In two years, the specific breaking strength of cotton treated with complex 120 g·hm^{−2} increased by 8.7% and 7.8%, respectively, compared with the mepiquat chloride treatment. The cotton micronation value treated by complex 120 g·hm^{−2} increased by 15.9% and 16%, respectively, compared with clear water. These results indicate that complex 120 g·hm^{−2} treatment can increase the micronron value and specific breaking strength of cotton, and can effectively improve cotton fiber quality.

Table 6. Effect of paclobutrazol–zinc complexes on cotton fiber quality.

Year	Treatment	Dose (g·hm ^{−2})	Upper Half Mean Length (mm)	Uniformity Index (%)	Fiber Strength (cN/tex)	Micronaire
2022	Paclobutrazol–zinc complex	75	31.38 ± 1.27 a	84.67 ± 0.64 a	28.31 ± 1.83 ab	4.53 ± 0.27 ab
		120	31.98 ± 1.45 a	85.67 ± 0.40 a	29.24 ± 1.24 a	4.60 ± 0.41 a
		165	31.65 ± 1.31 a	85.67 ± 0.60 a	28.83 ± 1.28 ab	4.30 ± 0.25 ab
	paclobutrazol	120	31.41 ± 0.79 a	85.13 ± 0.80 a	28.66 ± 1.55 ab	4.59 ± 0.32 a
	mepiquat chloride	180	31.13 ± 1.47 a	84.57 ± 0.65 a	26.90 ± 1.19 b	4.41 ± 0.57 ab
	artificial topping	/	31.44 ± 0.57 a	85.13 ± 0.93 a	27.25 ± 1.12 ab	4.19 ± 0.28 ab
	clear water	/	31.32 ± 1.14 a	84.83 ± 0.40 a	28.16 ± 0.90 ab	3.97 ± 0.24 b
2023	Paclobutrazol–zinc complex	75	30.70 ± 0.79 a	84.87 ± 0.23 a	30.66 ± 1.58 ab	4.90 ± 0.29 ab
		120	31.28 ± 0.23 a	86.10 ± 0.56 a	31.49 ± 1.45 a	4.99 ± 0.44 a
		165	30.97 ± 0.56 a	85.90 ± 0.79 a	31.22 ± 1.45 ab	4.65 ± 0.27 ab
	paclobutrazol	120	30.74 ± 0.92 a	85.27 ± 1.04 a	31.04 ± 0.97 ab	4.97 ± 0.35 a
	mepiquat chloride	180	30.41 ± 0.90 a	84.70 ± 1.05 a	29.20 ± 0.31 b	4.78 ± 0.61 ab
	artificial topping	/	30.78 ± 1.04 a	84.60 ± 1.25 a	29.51 ± 1.21 ab	4.54 ± 0.30 ab
	clear water	/	31.25 ± 0.15 a	85.33 ± 1.51 a	30.50 ± 0.62 ab	4.30 ± 0.26 b

Note: the value is the mean ± standard error, different lowercase letters indicate that the difference is significant at the 0.05 level.

4. Discussion

Cotton topping has become an essential practice in cotton cultivation and management. It helps coordinate nutrient distribution and suppress apical dominance [25]. In field crop production, chemical capping is used to shape an ideal plant architecture, which can lead to a breakthrough in yield potential. Plant architecture is a critical factor influencing crop yield, and optimizing it ensures a balance between yield and quality [26–30]. Shortening the length of cotton fruit branches facilitates more efficient nutrient uptake [31]. Zhao et al. [32]

demonstrated that chemical capping can significantly reduce plant height, decrease the number of fruit branches, promote upright leaf orientation and stem thickening, resulting in a more compact plant structure. Fagerström et al. [33] proved that the addition of surfactants can markedly reduce the surface tension of spray solutions, thereby expanding the absorption area and increasing the spread of the liquid on wheat leaves by threefold. This indicates that reducing surface tension enhances foliar absorption. Li et al. [34] found that nano-SiO₂/lignin carriers loaded with surfactants provide dual functions of foliar adhesion and controlled penetration. This nanocomposite system extended the retention time of pesticides on cotton leaves by 6 h and increased the absorption rate by 50%.

The duration of the chemical effect of chemical topping agents is generally limited [35,36]. Coordination chemistry in pesticides offers sustained release properties, as the complex structure formed through coordination is more stable than that of free ligands. In this experimental study, it was found that foliar application of the synthesized paclobutrazol–zinc complex achieved the best performance at concentration 120 g·hm^{−2}. The growth rate of cotton plant height treated with the paclobutrazol–zinc complex exhibited a continuous downward trend without any rebound effect, indicating that its efficacy was more lasting and stable. The paclobutrazol–zinc complex can promote a more compact plant architecture, which facilitates nutrient absorption. This structural improvement also supports mechanical harvesting and advances the mechanization of cotton production. Compared to paclobutrazol and piperone used in previous studies, the paclobutrazol–zinc complex demonstrated superior performance. Its outstanding effects on agronomic traits suggest that the complex is most beneficial for optimizing cotton plant structure and possesses a certain degree of persistence.

Qi et al. [37–42] demonstrated that the application of chemical capping agents could significantly enhance cotton plant height, the number of fruit nodes, fruit branches, bolls per plant, individual boll weight, and lint percentage. This not only promotes the growth and development of cotton but also has a significant positive impact on yield. Wu et al. [26] found that different capping agents exert varying effects on individual boll weight. Each chemical capping agent can effectively increase the yield of both seed cotton and lint cotton compared to the control group; however, the difference is not statistically significant when compared with manual capping. In this experiment, the paclobutrazol–zinc complex at concentration 120 g·hm^{−2} significantly increased the number of bolls per plant. The yields of both seed cotton and lint cotton were significantly higher than those of all other treatments. This effect surpasses that of paclobutrazol and mepiquat chloride used in previous studies, indicating that the paclobutrazol–zinc complex can effectively increase the number of bolls per plant and thereby achieve a higher yield.

Zhu et al. [43] found in their study on cotton yield and quality using different chemical capping agents that there were no significant differences in macron value, average upper half length, uniformity, or breaking strength between chemically capped and manually capped cotton. Arekhi et al. [44] demonstrated that the combined application of paclobutrazol and root promoters could effectively improve cotton fiber quality. In this experiment, the breaking specific strength of cotton treated with the paclobutrazol zinc complex at 120 g·hm^{−2} was significantly higher than that of mepiquat chloride-treated cotton, and the macron value was significantly greater than that of water-treated cotton. These results indicate that the effect of the paclobutrazol–zinc complex at 120 g·hm^{−2} is superior to that of mepiquat chloride used in previous studies.

5. Conclusions

In this study, paclobutrazol was combined with zinc nitrate hexahydrate to successfully synthesize an octahedral paclobutrazol–zinc complex. The resulting complex exhibited

a reduced surface tension, which facilitates more efficient plant absorption during foliar application. Field trials demonstrated that the paclobutrazol–zinc complex achieved superior topping effects compared to paclobutrazol alone, mepiquat chloride, manual topping, and the water control. Plant height data revealed a more stable growth regulation effect of the paclobutrazol–zinc complex, effectively addressing the instability and rebound commonly observed in chemical topping of Xinjiang cotton. Among the tested concentrations, 120 g·hm^{−2} of the complex proved most effective in optimizing plant architecture by promoting a compact structure conducive to nutrient uptake and mechanical harvesting. In addition, the complex significantly improved both cotton yield and fiber quality. Therefore, constructing a paclobutrazol–zinc complex based on the enhanced and sustained release properties of metal complexes offers a promising strategy for overcoming the limitations of conventional chemical topping agents. These findings highlight the considerable potential of the paclobutrazol–zinc complex for practical application in cotton production.

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Abbreviations

The following abbreviations are used in this manuscript:

X1	complex 75 g·hm ^{−2}
X2	complex 120 g·hm ^{−2}
X3	complex 165 g·hm ^{−2}
PB	paclobutrazol 120 g·hm ^{−2}
MC	mepiquat chloride 180 g·hm ^{−2}
MT	artificial topping
CK	clear water

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