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Effect of Chloride Salicylic Acid Ionic Liquids on Cotton Topping and High-Temperature Resistance

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Abstract: Chemical topping involves using plant growth regulators to facilitate the rapid transition of cotton into reproductive growth, similar to manual topping (MT), thereby enhancing cotton yield. Despite its benefits, high-temperature stress following cotton topping often reduces cotton yield. Therefore, developing an effective formula capable of not only inhibiting cotton top growth but also alleviating high-temperature stress is of critical importance. In this study, chlormequat chloride salicylic acid ionic liquids (CSILs) were synthesized via the acid–base neutralization of salicylic acid (SA) and 2-chloro-N,N,N-trimethyl ethanaminium hydroxide, obtained from the reaction between potassium hydroxide and chlormequat chloride (CCC). The resulting CSILs were characterized using various techniques, including nuclear magnetic resonance (NMR), Fourier transformation infrared spectroscopy (FTIR), and ultraviolet-visible light (UV-vis) spectroscopy. The characterization results confirmed the successful synthesis of CSILs as a novel water-soluble cotton-topping agent. Notably, compared with CCC treatment, CSILs at the same concentration exhibited a more sustainable and stable inhibition effect on cotton tip growth, resulting in an 11% increase in cotton yield. These findings suggest that CSILs have a greater potential for use in cotton chemical topping compared with CCC. Furthermore, compared with MT, the MDA content of cotton leaves treated with CSILs was reduced, and the activities of POD and SOD were increased under high-temperature stress. Moreover, these effects became more pronounced with an increasing CSIL concentration, highlighting the positive impact of CSILs in alleviating high-temperature stress on cotton. Notably, no significant difference in cotton yield was observed between the CSIL treatment at 120 g AI ha^{-1} and the MT treatment. Thus, this study underscores the significant potential of CSILs in both cotton topping and enhancing resistance to high-temperature stress.

Keywords: chlormequat chloride; salicylic acid; cotton; chemical topping; ionic liquid high-temperature stress

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1. Introduction

Cotton topping has become a key step in cotton cultivation and management, which can harmonize nutrient distribution and inhibit cotton apical dominance [1]. Various methods of cotton topping are prevalent, primarily categorized as traditional manual topping (MT), mechanical topping, and chemical topping. MT, despite its precision, simplicity, and farmer-friendly approach, is gradually being phased out due to inefficiencies such as low precision, prolonged duration, labor intensiveness, and a tendency for omissions [2,3]. Though mechanical topping can increase operational efficiency, it often lacks precision and may lead to erroneous or excessive topping, causing physical harm to the cotton plants and elevating the risk of disease, making it unsuitable for widespread implementation in cotton fields [4].

Zhao et al. [5] and Dong et al. [6] found that chemical topping with mepiquat chloride and flumetralin was effective in controlling apical growth, resulting in a compact plant, reduced plant width, increased boll weight, improved ventilation and light transmission in the lower and middle parts of the canopy, and reduced bud and boll loss, with yields comparable to those of manual topping; there was no significant effect on fiber quality. Yang et al. [7] researched mepiquat chloride compounding and flumetralin compounding, and found that the chemical topping agents were also found to increase the leaf area and chlorophyll content, which is beneficial to the overall photosynthetic efficiency and promotes dry matter accumulation, resulting in increased yields. Wang et al. [8] found that the use of chlormequat chloride could regulate cotton growth, significantly reduce cotton plant height, increase cotton fluffing, and promote cotton yield, as well as increase the number of bells per plant in cotton and improve the pre-frost flower rate of the crop, thus further improving pre-frost lint yield and fiber quality.

Chemical topping involves using plant growth regulators, including chlormequat chloride (CCC), mepiquat chloride, and flumetralin to suppress cotton apex dominance, harmonize nutrient distribution, and curtail the growth of unproductive branches and leaves. Chemical topping stands out as an effective approach with high efficiency, positive outcomes, and no physical harm to the cotton plants. Chemical topping methods are progressively replacing MT with the expansion of cotton operations and the escalating shortage of labor [9–11].

In recent years, escalating global temperatures have led to high-temperature weather (daily high temperature $\geq$ 35 °C) approximately 3–7 days after the topping of cotton in Xinjiang. This high-temperature stress has significantly impacted the quality of the cotton boll setting, resulting in reduced cotton yield and compromised quality [12–15]. At present, no chemical capping agent can effectively alleviate the problem of high-temperature stress. Therefore, it is of great significance to explore chemical topping agents with high-temperature resistance. Extensive research has demonstrated that the external application of salicylic acid (SA) can regulate intracellular active antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD), and malondialdehyde (MDA). This regulation enhances the cotton plant's resilience to high-temperature stress, thus reducing the shedding of cotton buds and bolls [16–21]. However, the poor solubility of SA in water has hindered its effective absorption in foliage spray treatment. Therefore, there is an urgent need to develop a novel and effective dosing form.

Ionic liquids (ILs) refer to ionic compounds in a liquid state, characterized as molten salts entirely composed of cations, which exhibit fluid properties at or below 100 °C [22,23]. The unique characteristics of ILs, including high thermal stability, slow-release properties, negligible vapor pressure, and extensive solubility, have led to their multidisciplinary applications [24–26]. Notably, ILs can be tailored to exhibit specific properties by selecting an appropriate combination of cations and anions [27,28]. Consequently, ionic liquids are also recognized as green solvents and multifunctional materials [27]. In this study, chlormequat chloride salicylic acid ionic liquids (CSILs) based on CCC were synthesized, utilizing SA as the anionic framework. These CSILs were subsequently applied in cotton production to address the challenges associated with artificial topping and high-temperature stress in the cotton cultivation process in Xinjiang.

2. Materials and Methods

2.1. Materials

Chlormequat chloride ($\geq$98%) was purchased from Tianjin Hiens Biochemical Technology Co., Ltd. (Tianjin, China). Potassium hydroxide was purchased from Tianjin Zhiyuan Chemical Reagent Co., Ltd. (Tianjin, China). Salicylic acid and absolute ethanol were purchased from Tianjin Beilian Fine Chemicals Development Co., (Tianjin, China).

2.2. Preparation of CSILs

In a 250 mL three-necked flask, approximately 16.1 g (0.1 mol) of 98% chlormequat chloride and 5.6 g (0.1 mol) of potassium hydroxide were dissolved in 80 g of anhydrous ethanol. The resulting mixture was stirred at room temperature until the white crystalline potassium chloride precipitate in the reaction system ceased to increase. The precipitate was filtered out, following which 14.1 g (0.1 mol) of 98% salicylic acid was added and stirred for 2 h at room temperature. The ethanol was subsequently removed via spin evaporation, resulting in a solution containing 47% of the active ingredient chlormequat chloride, with a pH value of 6.4.

2.3. Characterization of CSILs

The synthesized CSILs were analyzed. The nuclear magnetic resonance (^{1}H NMR) hydrogen spectrum data were measured using German-Bruker-Avance III HD 500MHz and the solvent was deuterated methanol. The fourier transform infrared spectroscopy (FTIR) data was measured using Japanese-Shimadzu-IRTracer 100 with wavelengths between 400–4000 cm^{-1}, The ultraviolet-visible spectroscopy (UV-vis) data were measured using Japan-Shimadzu-UV-3600 plus with a wavelength between 200 and 800 nm, and the surface tension was measured using the China-Shanghai Zhongchen-JK99C fully automatic tensiometer.

2.4. Overview of the Study Site

The experiment spanned the duration of 2 years, from 2022 to 2023. The designated test site was situated within the Alar Cotton Reclamation Area in Xinjiang, precisely positioned at 40°23′ N and 81°17′ E. The soil composition of the test field was loamy, with cotton being the previous crop. The cultivated layer exhibited an organic matter content of 17.9 g kg^{-1}, alkaline decomposed nitrogen at 26.7 mg kg^{-1}, fast-acting phosphorus at 24.6 mg kg^{-1}, and fast-acting potassium at 188.0 mg kg^{-1}. The selected test species was Xinluzhong 75, a widely cultivated cotton variety in Xinjiang, China. The cotton seeds were sown at a density of 210,000 plants per hectare on 15 April 2022, and 11 April 2023. The plots were irrigated 11 and 10 times in 2022 and 2023, respectively, with a water consumption of 350 m^3 ha^{-1} each time. Fertilization was carried out with 450 and 420 kg ha^{-1} N (urea), 198 and 184.8 kg ha^{-1} P_2O_5, and 252 and 235.2 kg ha^{-1} K_2O in 2022 and 2023, respectively. In two years, along with cotton topping, three chemical controls were performed using mepiquat chloride, at the seedling, bud, and full bud stages of cotton, respectively. Other field management practices remained consistent with those employed in the extensive local cotton plantations.

2.5. Experimental Design

High-temperature conditions (with the daily high temperatures reaching or exceeding 35 °C) were observed 3 to 7 days after the implementation of the topping treatment. The cotton plants were at the early bloom stage on 3 July 2022, and 8 July 2023. Each treatment was allocated to specific experimental areas measuring 3 m in width and 11 m in length. The CSILs were applied at varying doses (60, 90, and 120 g AI ha^{-1} of CCC) via foliar spraying onto the cotton leaves. The experimental setup was compared with treatments involving 120 g AI ha^{-1} of CCC and MT. Each treatment group was replicated three times for accurate data analysis. The application method is a foliar spray, and no surfactant was added to the solution. Changes in temperature and humidity after cotton topping in the Alaer Reclamation area shown in Table 1.

Table 1. Changes in temperature and humidity after cotton topping in the Alaer Reclamation area.

Year	Date	Daily High Temperature (°C)	Average Relative Humidity (%)
2022	7.3	32	35
	7.4	35	41
	7.5	37	34
	7.6	37	33
	7.7	34	32
	7.8	33	40
	7.9	34	46
	7.10	30	35
	7.11	35	47
	7.12	34	47
	7.13	33	50
	7.14	35	48
	7.15	35	64
	7.16	34	54
	7.17	36	49
2023	7.8	36	58
	7.9	35	45
	7.10	36	48
	7.11	36	46
	7.12	37	44
	7.13	35	38
	7.14	36	47
	7.15	37	39
	7.16	40	40
	7.17	39	35
	7.18	38	29
	7.19	38	40
	7.20	38	33
	7.21	36	38
	7.22	37	40

2.6. Sampling and Determination

2.6.1. Plant Architecture Characteristics

During the experiment, the height of the cotton plant was measured at 10, 20, and 30 days after treatment (DAT). The rate of increase in the cotton plant height was calculated using Equation (1). Additionally, the cotton plants were photographed during the harvest to observe the plant type and the number of bolls atop the cotton plants.

The formula for the increasing rate of cotton height was calculated, as seen in Equation (1):

$$\text{The increasing rate of cotton height } = \frac{H_{T2} - H_{T1}}{H_{T1}} \times 100\% \tag{1}$$

where H_{T2} and H_{T1} represented the cotton heights at different DATs.

2.6.2. Determination of Antioxidant Enzyme Activity in Cotton

The activity of superoxide dismutase (SOD), peroxidase (POD), and the malondialdehyde (MDA) content in the third leaf basal of the cotton was measured at 3, 5, 7, and 9 days after treatment (DAT). The MDA content was determined using the thiobarbituric acid method, SOD activity was measured using the nitrogen blue tetrazolium photochemical reduction method, and POD activity was determined using the guaiacol colorimetric method [29].

2.6.3. Yield Components and Cotton Fiber Quality

Within each plot, the number of plants and bolls was assessed within an area of 6.67 square meters. At the boll opening stage, the plant density and boll count per plant were calculated. Fifteen plants demonstrating 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 three replicates for each measurement. Additionally, a 150 g lint sample was chosen from each section and assigned a unique identifier for the subsequent assessment of cotton fiber quality. All the sampled bolls used in measuring fiber quality were tested using high-capacity instruments from the Cotton Inspection and Testing Center in Alar, China.

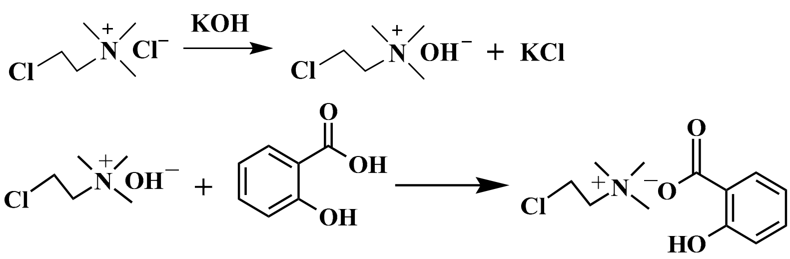
2.7. Data Analysis

The average cotton height growth rate and antioxidant enzyme activity were calculated on an annual basis, and the data from both years were then averaged for further analysis. Data processing and statistical analysis were conducted using Microsoft Office Excel2013. Graphs were generated using Origin 2018. IBM SPSS data processing system 22 was used for a single-factor (ANOVA) test analysis of the data. The significance of differences was determined using the least-significant difference (LSD) method, with the significance level set at 0.05.

3. Results

3.1. Preparation of CSILs

CSILs were produced via the acid–base neutralization of SA and 2-chloro-N,N,N-trimethylethanaminium chloride hydroxide in solvent solutions containing ethanol. The synthetic pathway of CSILs used in this study is illustrated (Scheme 1).



Scheme 1. Synthetic routes of CSILs.

3.2. Characterization of CSILs

We performed ^{1}H NMR, FTIR, and UV-vis tests to determine whether the CSILs were successfully prepared (Figure 1). The ^{1}H NMR spectra of CCC, SA, and CSILs are depicted in Figure 1A. The chemical shifts of hydrogen atoms in CCC were found at 4.14, 3.90, and 3.33 ppm, respectively, with a corresponding integral area ratio of 0.93:0.96:4.12. The chemical shifts of the H atoms in SA were mainly distributed in the range of 6–8 ppm. The chemical shifts of the H atoms in CSILs were mainly distributed in the range of 3–8 ppm, and the displacement range contained the displacement range of the H atoms in CCC and SA. CCC. ^{1}H NMR (500 MHz, D2O) δ 4.11 (d, J = 6.5 Hz, 1H), 3.88 (q, J = 6.2 Hz, 1H), 3.31 (d, J = 4.9 Hz, 5H). SA. ^{1}H NMR (500 MHz, MeOD) δ 7.82 (dd, J = 7.9, 1.8 Hz, 1H), 7.40 (ddd, J = 8.7, 7.2, 1.8 Hz, 1H), 6.88 (dd, J = 8.4, 1.2 Hz, 1H), 6.86–6.79 (m, 1H). CSILs. ^{1}H NMR (500 MHz, MeOD) δ 7.80 (dd, J = 7.9, 1.8 Hz, 2H), 7.41 (ddd, J = 8.8, 7.2, 1.8 Hz, 2H), 6.94–6.80 (m, 4H), 6.59 (ddt, J = 15.2, 8.2, 3.5 Hz, 1H), 5.82–5.73 (m, 1H), 5.49 (dtd, J = 8.2, 5.6, 4.1 Hz, 1H), 4.02 (tt, J = 6.6, 1.5 Hz, 1H), 3.80 (t, J = 6.7 Hz, 1H), 3.56 (q, J = 7.1 Hz, 3H), 3.31 (s, 11H). 3.23 (s, 4H), 1.13 (t, J = 7.0 Hz, 4H).

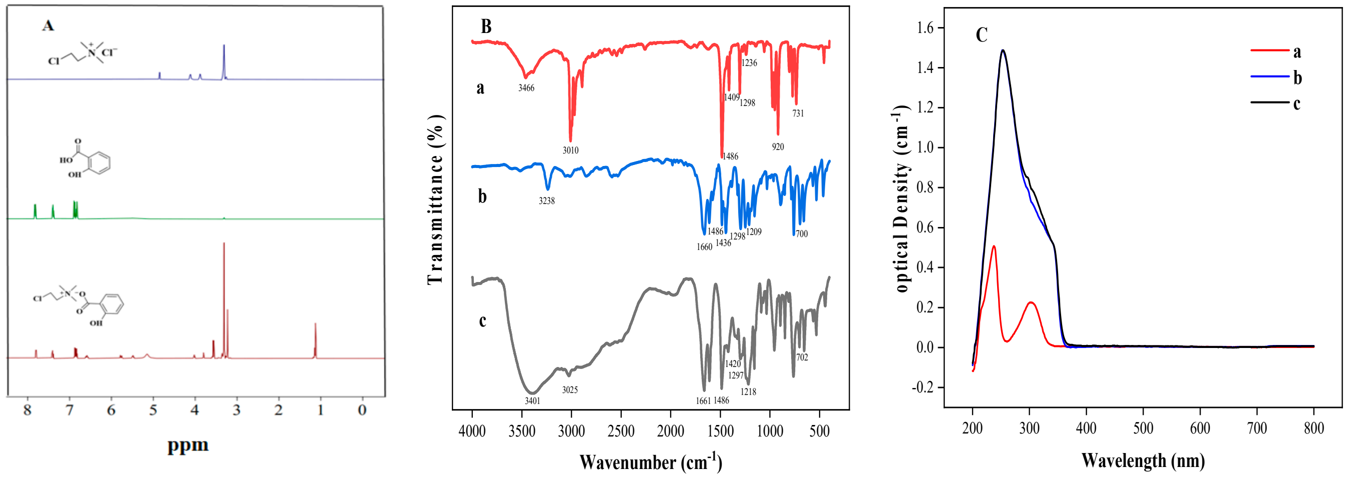


Figure 1. (**A**) ^{1}H NMR spectra; (**B**) FTIR spectroscopy; and (**C**) UV-vis absorbance spectra of (a) CCC; (b) SA; and (c) CSILs. Note: CSILs means chlormequat chloride salicylic acid ionic liquids. CCC means chlormequat chloride. SA means salicylic acid.

The FTIR spectrum of CCC, SA, and CSILs is illustrated in Figure 1B. The results reveal that CSILs exhibit an absorption peak at 3401 cm^{-1}, indicating the presence of a certain amount of H_2O, characteristic of the -OH hydroxyl group. The emergence of this peak could be attributed to the hygroscopic nature of the reactants. The characteristic absorption peak of the stretching vibration of the hydrocarbon bond in the methyl and methylene groups was observed at 3025 cm^{-1}. Additionally, the C=O group was associated with absorption peaks at 1661 cm^{-1} and 1297 cm^{-1}. The C=O bond at 1661 cm^{-1} is a characteristic absorption peak formed via the acid–base neutralization reaction of CCC and SA, the C=C group at 1486 cm^{-1} and 1420 cm^{-1}, C-N at 1218 cm^{-1}, and the C-Cl bond at 702 cm^{-1}. The characteristic IR absorption peaks of CSILs closely resembled those of the two reactants.

The measured compounds were individually dissolved in methanol to yield a solution with a concentration of 200 mg/L for UV-vis analysis. The UV-vis absorption spectra of CCC, SA, and CSILs are presented in Figure 1C. The results illustrate strong absorption peaks for CCC at 236 and 301 nm, and a prominent absorption peak for SA at 252 nm. The strong absorption peak of CSILs was at 256 nm, indicating the presence of a benzene ring consistent with SA. The absorption peak of CSILs at 301 nm is blueshifted because the benzene ring affects the C=O conjugation. Therefore, the absorption peak is shielded. Therefore, based on the data from ^{1}H NMR, FTIR, and UV-vis absorption spectra, the CSILs derived from CCC and SA were successfully prepared.

3.3. Solubility and Surface Tension of CSILs

The solubility and surface test were performed to determine whether CSILs can improve the effective utilization of CCC and SA (Table 2). While 0.1 g of SA posed challenges in dissolving in 3 mL of water, both CCC and CSILs demonstrated favorable solubility in water. The surface tension of the CSIL solution measured at 38.19 mN/m was notably lower than the CCC and SA solutions. This reduction in surface tension can be attributed to the bonding of CSILs with SA and CCC via ionic bonds, disrupting the equilibrium of their structures and transitioning the pre-reaction solids into a liquid state. Consequently, the surface tension decreases, indicating an improved effective utilization rate of the CSILs based on CCC, utilizing SA as the anionic skeleton.

Table 2. Water solubility and surface tension of CSILs.

Treatment	Water Solubility	Surface Tension (mN/m)
CCC	+	70.30 ± 0.02 a
SA	−	64.44 ± 0.02 b
CSILs	+	38.19 ± 0.02 c

Note: The symbol "+" signifies that 0.1 g of the sample is fully dissolved in 1 mL of water, indicating good solubility; the symbol "−" indicates that 0.1 g of the sample does not dissolve in 3 mL of water, implying poor solubility. CSILs means chlormequat chloride salicylic acid ionic liquids. CCC means chlormequat chloride. SA means salicylic acid. Different lowercase letters indicate significant differences at the 5% level between different treatments.

3.4. Effect of CSILs on Cotton Plant Height

The inhibition rate of cotton plant growth serves as a fundamental indicator for evaluating the effectiveness of cotton topping. The growth rate of cotton plant height on different days with various topping agents is displayed in Figure 2. Notably, the increase in plant height was considerably greater with CSILs and CCC treatments than MT. This suggests that the growth of cotton plants could not be entirely suppressed with chemical topping agents between the 1st and 10th day after treatment (DAT) (Figure 2A). Moreover, the growth rates of cotton plants treated with CSILs exhibited a sustained gradual decline, while those treated with CCC experienced a resurgence between the 21st and 30th DAT. This observation implies that the inhibitory effect of the CSIL treatment lasted longer than that of CCC (Figure 2B,C)). It is important to note that the plant height growth rate of the CSILs at a dosage of 60 g AI ha^{-1} was significantly higher than that of the other treatments from the 1st to the 30th DAT (Figure 2D). This suggests that the 60 g AI ha^{-1} CSILs at this level were insufficient to effectively control the cotton plant's top growth.

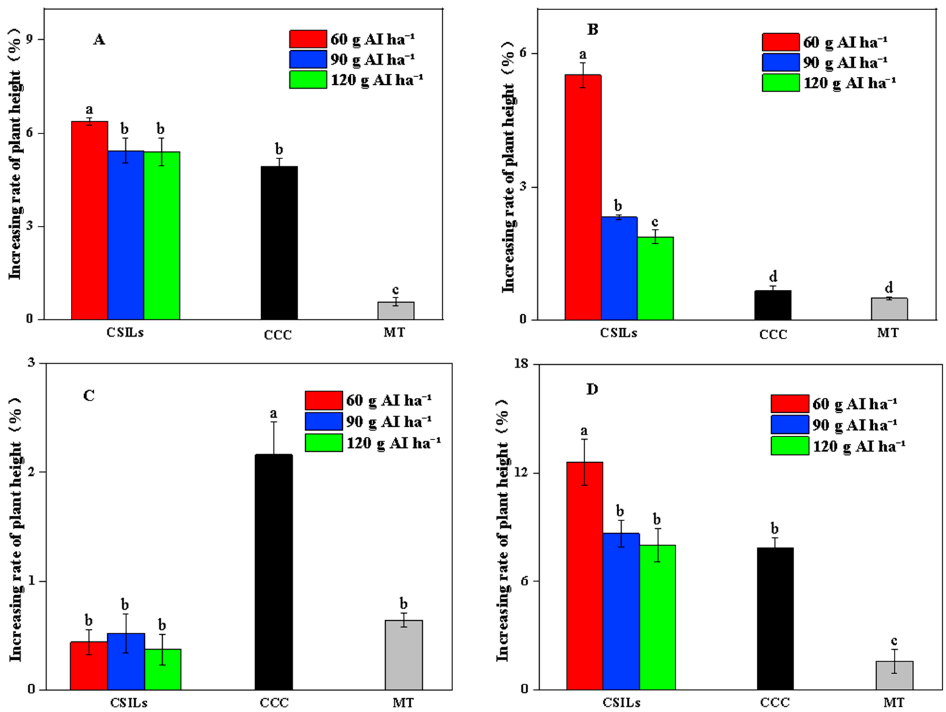


Figure 2. The increasing rates of cotton heights at different days after treatments (DAT) (**A**) from 1st to 10th DAT; (**B**) from 11th to 20th DAT; (**C**) from 21st to 30th; and (**D**) from 1st to 30th DAT. Note: CSILs means chlormequat chloride salicylic acid ionic liquids. CCC means chlormequat chloride. MT means manual topping. Different lowercase letters indicate significant differences at the 5% level between different treatments.

3.5. Effect of CSILs on Antioxidant Enzyme Activity in Cotton

High-temperature stress can result in the excessive accumulation of reactive oxygen species (ROS) in cotton, leading to cell membrane damage. The levels of superoxide dismutase (SOD), peroxidase (POD), and malondialdehyde (MDA) in cotton undergo rapid changes to counter the presence of ROS. The MDA content in cotton from various treatment areas displayed an increasing trend under high-temperature stress. However, the MDA content in cotton treated with 120 g AI ha^{-1} CSILs was significantly lower than that in the cotton treated with MT and CCC during the same period. This suggests that the degree of lipid peroxidation of the cell membrane in cotton treated with CSILs was lower under high-temperature stress (Figure 3A). The SOD activity in cotton treated with 120 g AI ha^{-1} CSILs was significantly higher than that in cotton treated with MT and CCC during the same period under high-temperature stress. This indicates that cotton treated with CSILs exhibited a stronger antioxidant capacity, efficiently eliminating harmful oxygen free radicals produced in the cells (Figure 3B). POD activity in cotton from different treatment areas initially displayed an increasing trend and then decreased under high-temperature stress. Cotton treated with 120 g AI ha^{-1} CSILs exhibited significantly higher POD activity than that treated with MT and CCC during the same period under high-temperature stress. This suggests that cotton treated with CSILs could effectively remove harmful oxygen free radicals produced in the cells (Figure 3C). In summary, the results indicate that CSILs were effective in mitigating the negative effects of high temperatures by modulating SOD, POD, and MDA levels in cotton over a short period; among the three concentrations, the higher the concentration of CSILs, the stronger the antioxidant capacity, and 120 g AI ha^{-1} CSILs work the best.

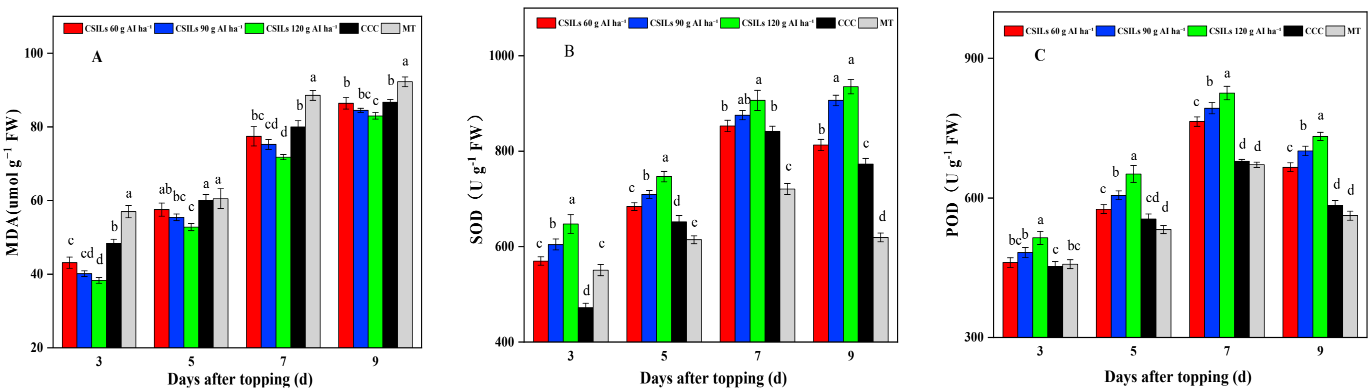


Figure 3. Effects of (**A**) MDA, (**B**) SOD, and (**C**) POD on cotton with different treatments. Note: CSILs means chlormequat chloride salicylic acid ionic liquids. CCC means chlormequat chloride. MT means manual topping. Different lowercase letters indicate significant differences at the 5% level between different treatments. R^2 = 0.98 at 3d, R^2 = 0.996 at 5d, R^2 = 0.999 at 7d, R^2 = 0.999 at 9d for MDA content; R^2 = 0.996 at 3d, R2 = 0.989 at 5d, R^2 = 0.992 at 7d, R^2 = 0.914 at 9d for SOD activity; R^2 = 0.989 at 3d, R^2 = 0.986 at 5d, R^2 = 0.999 at 7d, R^2 = 0.999 at 9d for POD activity at different concentrations of CSILs, indicating good linearity.

3.6. Effects of CSILs on Cotton Canopy Structure

To determine the effect of CSILs on cotton plant type, the length of the top fruiting branches of cotton was measured, and a picture of the cotton plant type was taken (Figure 4 and Table 3). The cotton plant width following MT treatment was the greatest, followed by CCC treatment, while the width was the smallest after treatment with 120 g AI ha^{-1} CSILs. Among the various topping treatments, the length of the first to the fourth fruit branches of 120 g AI ha^{-1} CSIL treatment was significantly lower than that of the CCC and MT treatment (Table 3). The 120 g AI ha^{-1} CSIL treatment resulted in the most compact shape for the cotton plants, particularly evident in the increased density in the upper layers of the cotton plants. This observation suggests that the application of CSILs contributed to a more compact shape of the cotton plants, promoting better ventilation and fostering favorable conditions for the growth of cotton bolls.

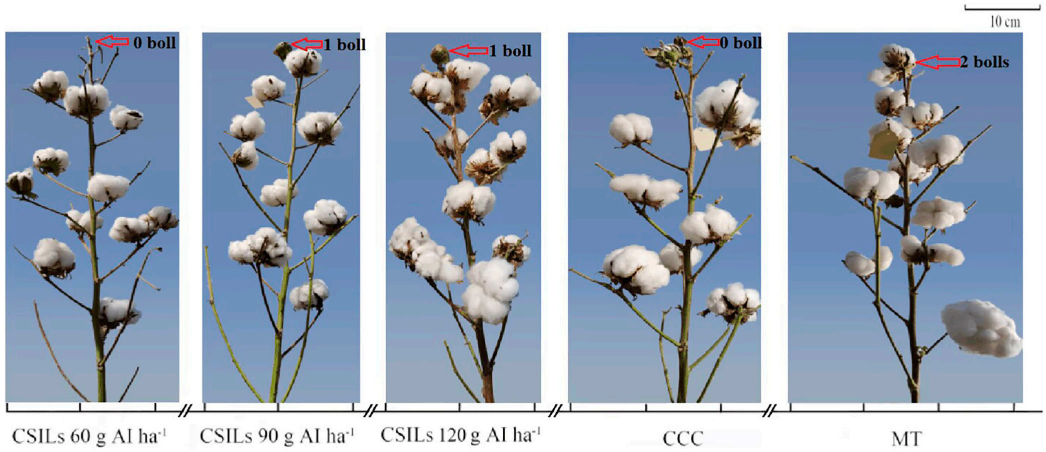


Figure 4. Potential plots of cotton plants after different treatments. Note: CSILs means chlormequat chloride salicylic acid ionic liquids. CCC means chlormequat chloride. MT means manual topping.

Table 3. Length of four lateral branches from the top to the bottom at cotton harvest for different treatments.

Year	Treatment	Length of the Inverted Fruit Branch (cm)	Length of the Second Fruit Branch (cm)	Length of the Inverted Third Fruit Branch (cm)	Length of the Inverted Four Fruit Branch (cm)
2022	CSILs 60 g AI ha^{-1}	6.10 ± 0.53 ^{b}	6.80 ± 0.52 ^{c}	9.10 ± 0.36 ^{c}	10.50 ± 0.70 ^{bc}
	CSILs 90 g AI ha^{-1}	3.17 ± 0.58 ^{c}	6.07 ± 0.55 ^{c}	7.30 ± 0.37 ^{d}	9.77 ± 0.56 ^{c}
	CSILs 120 g AI ha^{-1}	2.40 ± 0.36 ^{c}	4.20 ± 0.36 ^{d}	6.13 ± 0.41 ^{e}	8.27 ± 0.68 ^{d}
	CCC	7.87 ± 0.70 ^{a}	9.10 ± 0.36 ^{b}	11.47 ± 0.65 ^{b}	10.77 ± 0.65 ^{ab}
	MT	8.83 ± 0.65 ^{a}	10.83 ± 1.15 ^{a}	12.73 ± 0.80 ^{a}	11.57 ± 0.50 ^{a}
2023	CSILs 60 g AI ha^{-1}	6.22 ± 0.46 ^{b}	6.78 ± 0.43 ^{c}	9.41 ± 0.44 ^{c}	10.64 ± 0.81 ^{bc}
	CSILs 90 g AI ha^{-1}	3.28 ± 0.39 ^{c}	6.15 ± 0.44 ^{c}	7.74 ± 0.64 ^{d}	9.47 ± 0.60 ^{c}
	CSILs 120 g AI ha^{-1}	2.38 ± 0.25 ^{c}	4.05 ± 0.28 ^{d}	6.08 ± 0.33 ^{e}	8.35 ± 0.63 ^{d}
	CCC	8.08 ± 0.79 ^{a}	9.46 ± 0.45 ^{b}	11.88 ± 0.85 ^{b}	11.08 ± 0.91 ^{ab}
	MT	8.97 ± 0.86 ^{a}	11.23 ± 0.88 ^{a}	12.95 ± 0.92 ^{a}	11.95 ± 0.84 ^{a}

Note: CSILs means chlormequat chloride salicylic acid ionic liquids. CCC means chlormequat chloride. MT means manual topping. Different lowercase letters indicate significant differences at the 5% level between different treatments.

3.7. Effect of CSILs on Cotton Yield

To determine whether CSILs had a positive effect on cotton seed cotton yield, cotton yield measurements were conducted. The yield of cotton under different topping treatments in 2022 and 2023 is illustrated in Figure 5. The cotton yield following treatment with 120 g AI ha^{-1} CSILs was notably higher than that following treatment with CCC and 60 g AI ha^{-1} CSILs. Furthermore, no significant differences were observed between the yield from the 120 g AI ha^{-1} CSIL treatment and the MT and 90 g AI ha^{-1} CSIL treatments. In 2022, the application of 120 g AI ha^{-1} CSILs led to a yield increase of 11% and 1.9% compared to the CCC and MT treatments, respectively. Similarly, in 2023, the application of 120 g AI ha^{-1} CSILs resulted in an 8.9% increase in cotton yield compared to the CCC treatment. The difference in the growth rate of cotton production by CSILs over two years may be due to weather reasons in the early stage of cotton or the problems of artificial and mechanical damage. The yields were significantly higher than CCC in both years, similar to manual topping, which does not affect the overall trend. These results highlight the substantial positive impact of a high concentration of CSILs on enhancing cotton yield.

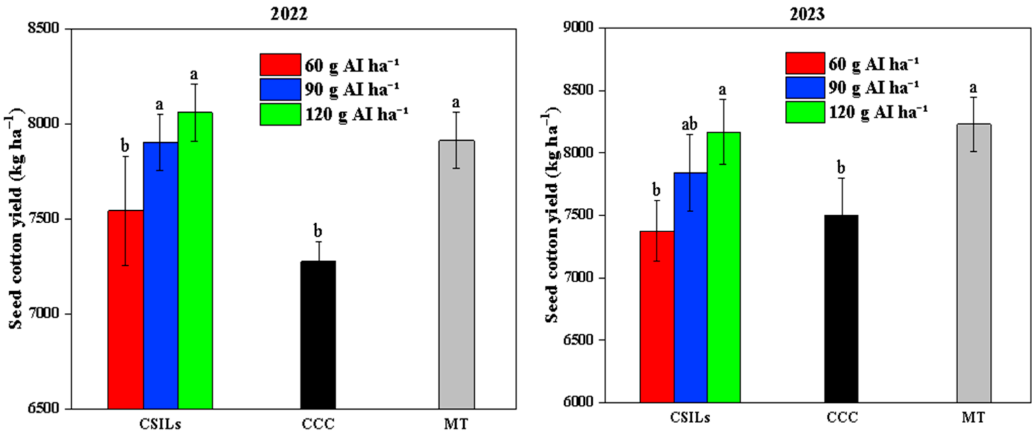


Figure 5. Effect on the yield of seed cotton after treatments in 2022 and 2023. Note: CSILs means chlormequat chloride salicylic acid ionic liquids. CCC means chlormequat chloride. MT means manual topping. Different lowercase letters indicate significant differences at the 5% level between different treatments.

3.8. Effect of CSILs on Cotton Fiber Quality

Cotton upper half mean length, uniformity index, micronaire value, fiber strength, and elongation were noted to determine whether CSILs positively affect cotton fiber quality (Table 4). The upper half mean length, uniformity index, and micronaire value of cotton treated with CSILs had no significant difference compared to those treated with CCC and MT. The fiber strengths in cotton treated with 120 g AI ha^{-1} CSILs were 34.45 cN/tex and 35.84 cN/tex in two years; these values were notably higher than those obtained from the same concentration of CCC. Moreover, the values were also higher than those observed in the MT treatment, although the difference was not statistically significant. The results showed that 120 g AI ha^{-1} CSILs had a positive effect on cotton fiber strength.

Table 4. Cotton fiber quality of different treatments.

Year	Treatment	Upper Half Mean Length (mm)	Uniformity Index (%)	Micronaire	Fiber Strength (cN/tex)	Elongation (%)
2022	CSILs 60 g AI ha^{-1}	29.57 ± 0.49 ^{a}	85.7 ± 1.28 ^{a}	4.92 ± 0.44 ^{a}	32.61 ± 0.26 ^{b}	8.17 ± 0.35 ^{ab}
	CSILs 90 g AI ha^{-1}	30.1 ± 1.28 ^{a}	86.03 ± 0.61 ^{a}	4.87 ± 0.33 ^{a}	34.25 ± 1.22 ^{a}	8.5 ± 0.17 ^{a}
	CSILs 120 g AI ha^{-1}	29.58 ± 1.42 ^{a}	85.43 ± 0.67 ^{a}	5.06 ± 0.26 ^{a}	34.45 ± 1.08 ^{a}	8.3 ± 0.15 ^{ab}
	CCC	30.1 ± 0.83 ^{a}	85.67 ± 1.39 ^{a}	4.71 ± 0.34 ^{a}	30.70 ± 0.72 ^{c}	8.05 ± 0.08 ^{b}
	MT	30.75 ± 1.25 ^{a}	86.37 ± 0.15 ^{a}	4.67 ± 0.37 ^{a}	31.55 ± 0.78 ^{bc}	8.37 ± 0.06 ^{ab}
2023	CSILs 60 g AI ha^{-1}	30.12 ± 0.65 ^{a}	86.78 ± 1.53 ^{a}	4.85 ± 0.13 ^{a}	33.79 ± 0.66 ^{ab}	8.23 ± 0.42 ^{b}
	CSILs 90 g AI ha^{-1}	31.23 ± 1.13 ^{a}	87.55 ± 1.87 ^{a}	4.97 ± 0.14 ^{a}	35.27 ± 1.20 ^{a}	8.65 ± 0.30 ^{a}
	CSILs 120 g AI ha^{-1}	31.08 ± 0.96 ^{a}	88.48 ± 1.94 ^{a}	5.12 ± 0.03 ^{a}	35.84 ± 1.99 ^{a}	8.54 ± 0.25 ^{ab}
	CCC	31.22 ± 1.39 ^{a}	86.58 ± 1.23 ^{a}	4.79 ± 0.24 ^{a}	31.77 ± 1.57 ^{b}	8.21 ± 0.20 ^{b}
	MT	31.88 ± 0.86 ^{a}	88.12 ± 3.05 ^{a}	4.63 ± 0.17 ^{a}	32.78 ± 1.88 ^{ab}	8.47 ± 0.24 ^{ab}

Note: CSILs means chlormequat chloride salicylic acid ionic liquids. CCC means chlormequat chloride. MT means manual topping. Different lowercase letters indicate significant differences at the 5% level between different treatments.

4. Discussion

Chemical topping can effectively reduce plant height, decrease the number of fruit branches, and promote upright leaves and thicker stems, resulting in a more compact cotton plant structure. However, the duration of the chemical effect is often limited [5,30,31]. The period from the 1st to the 10th day after cotton topping in southern Xinjiang is crucial for the growth of the lower fruit branch, followed by the 11th to the 20th day for the middle fruit branch, and the 21st to the 30th day for the rapid growth of the upper fruit branch and cotton boll.

In the present study, it was observed that from the 21st to the 30th day after cotton topping, the plant height growth rate of the 120 g AI ha^{-1} CSIL treatment was significantly lower than that of the CCC application treatment group. This finding suggested that CSILs exhibited long-lasting activity on cotton plants, effectively promoting the transition from vegetative growth to reproductive growth, thereby increasing the ratio of harvested bolls. Consequently, the reduced plant height growth rate of 120 g AI ha^{-1} CSILs during the 21st to the 30th day was conducive to the formation of cotton bolls, leading to increased yield.

In regions of southern Xinjiang, high-temperature stress often occurs a few days after cotton topping, posing risks such as cotton boll shedding. Different studies have shown that cotton shows higher antioxidant enzyme activity in response to high-temperature stress, and high-temperature stress reduces fiber strength [32]. Various studies have demonstrated that exogenously applied salicylic acid (SA) can regulate intracellular active antioxidant enzymes SOD and POD, thereby enhancing plant tolerance to environmental stresses, including high-temperature stress, reducing cotton bud and boll shedding and favoring yield formation [16–21].

MDA content in cotton from various treatment areas displayed an increasing trend under high-temperature stress. POD activity in the cotton from different treatment areas initially displayed an increasing trend and then decreased under high-temperature stress. The MDA content of cotton treated with all concentrations of CSILs appeared to be lower than that of the CCC and MT treatments on different days; 120 g AI ha^{-1} CSILs had the lowest MDA content, significantly lower than that of CCC and MT. Similarly, the SOD and POD activities in all three CSIL groups were higher than those in the groups treated with CCC and MT on different days after application; 120 g AI ha^{-1} CSILs had the highest SOD and POD activities, which were significantly higher than CCC and MT. These results collectively indicated that the three different concentrations of CSILs effectively mitigated the adverse effects of high temperature by enhancing the cotton's ability to eliminate reactive oxygen species (ROS); among the three concentrations, the higher the concentration of the CSILs, the stronger the antioxidant capacity, therefore 120 g AI ha^{-1} CSILs work the best, reducing cotton boll shedding and increasing the output and maximum fiber strength. Abiotic stress is usually pleiotropic, affecting biomass allocation and reproductive output (yield) during drought, which is a stress usually associated with heat when current climatic conditions change [33,34]. The combination of heat stress and drought can also significantly reduce boll retention, boll weight, and seed cotton yield [35,36]. However, there is basically no drought stress at the cotton topping stage under drip irrigation in the southern border, and this aspect has not been studied. This paper cannot account for this either, but this aspect will be examined in subsequent trials.

In field crop production, adopting chemical regulations to shape the ideal plant architecture can potentially lead to a breakthrough in crop yield levels. Plant architecture represents a critical factor influencing crop yield, with an optimal structure ensuring the coordinated enhancement of both yield and quality [37–41]. Shortening the length of the fruit branches of cotton is conducive to nutrient absorption [42].

In this study, CSIL-treated cotton displayed a more compact plant type, facilitating mechanical cotton picking. The upper fruit branch length of cotton treated with 120 g AI ha^{-1} CSILs was the shortest, which was the best for nutrient absorption. The 120 g AI ha^{-1} CSIL treatment resulted in the most bolls in the upper layer of cotton plants, akin to the effect of manual topping. The 120 g AI ha^{-1} CSIL treatment was conducive to enhancing cotton fiber strength. This suggested that applying CSILs reduced the shedding of buds and bolls at the top of the cotton, increased fiber strength, and significantly impacted high-temperature resistance. The yield of cotton following the application of 120 g AI ha^{-1} CSILs increased by 11% and 1.9% compared to both CCC and MT treatments in 2022, and by 8.9% compared to the CCC treatment in 2023. This reduces bud and boll shedding by enhancing cotton's ability to withstand reactive oxygen species (ROS) to increase yields and enhance cotton fiber strength. These findings were consistent with the results reported by Barros [21] and Sarwar [43] et al. Among the different test dosage forms, the treatment of 120 g AI ha^{-1} CSILs was the most effective for cotton topping.

5. Conclusions

In this study, CSILs based on 2-chloro-N,N,N-trimethylethanaminium hydroxide and SA derivatives were synthesized using the acid–base neutralization method. These CSILs exhibited excellent water solubility and reduced surface tension. This can improve the effective utilization rate of CCC and SA in foliar spray. Field-based biological activity tests demonstrated no significant difference in plant height growth rate between CSILs and CCC at a single dose from the 1st to the 30th day after topping. However, CSILs displayed prolonged activity on cotton plants, with a sustained release effect. This sustained effect rendered CSILs capable of effectively mitigating the negative impact of high-temperature stress. It achieved this by enhancing the cotton plants' ability to counteract reactive oxygen species (ROS), subsequently reducing cotton boll shedding and ultimately increasing cotton yield. Furthermore, the cotton yield post application of 120 g AI ha^{-1} CSILs was superior to that obtained from CCC treatments. No significant difference in cotton yield was observed between the CSILs treatment at 120 g AI ha^{-1} and the MT treatment. Additionally, applying CSILs led to a more compact cotton plant structure than the CCC and MT treatments. It is worth noting that compared with CCC treatment, 120 g AI ha^{-1} CSILs improved cotton fiber strength. In conclusion, CSILs offer the cotton capping capability of CCC and the high-temperature resistance of SA with longer lasting efficacy, with 120 g AI ha^{-1} CSILs being the most favorable for cotton growth and development. Ultimately, this study highlights the significant application potential of CSILs in cotton topping and enhancing high-temperature stress resistance.

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Abbreviations

CCC	chlormequat chloride
CSILs	chlormequat chloride salicylic acid ionic liquids
MT	manual topping
SA	salicylic acid

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