Journal of Cotton Research

RESEARCH

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The efficacy of chemical topping in field-grown cotton is mediated by drip irrigation amount in irrigated agricultural area

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Abstract

Background: Cotton production in China is challenged by high labor input including manual topping (MT). Recently, to replace MT in the Xinjiang cotton region of China, mepiquat chloride (MC) was applied once more than the traditional multiple-application; this was designated as chemical topping (CT), but it is unclear whether the amount of irrigation needs to be adjusted to accommodate CT.

Results: The main plots were assigned to three drip irrigation amounts [300 (I_1), 480 (I_2), and 660 (I_3) mm], and the subplots were assigned to the CT treatments [450 (MC_1), 750 (MC_2), and 1 050 (MC_3) mL·hm^{-2} 25% MC] with MT as a control that was performed after early bloom. The optimum drip irrigation amount for CT was explored based on leaf photosynthesis, chlorophyll fluorescence, biomass accumulation, and yield. There were significant influences of drip irrigation, topping treatments and their interaction on chlorophyll fluorescence characteristics, gas exchange parameters and biomass accumulation characteristics as well as yield. The combination of I_2 and MC_2 (I_2MC_2) performed best. Compared with I_2MT, the net photosynthetic rate (*Pn*), stomatal conductance (*Gs*), transpiration rate (*Tr*), and photochemical quenching coefficient (*qP*) of I_2MC_2 significantly increased by 4.0%~7.2%, 6.8%~17.1%, 5.2%~17.6%, and 4.8%~9.6%, respectively, from the peak flowering to boll opening stages. Moreover, I_2MC_2 showed fast reproductive organ biomass accumulation and the highest seed cotton yield; the latter was 6.6%~12.8% higher than that of I_2MT. Further analysis revealed that a 25% MC emulsion in water (MC_{EW}) application resulted in yield improvement by increasing *Pn*, φPSII, and *qP* to promote biomass accumulation and transport to reproductive organs.

Conclusion: The results showed that the 480 mm drip irrigation combined with 750 mL·hm^{-2} MC increased the rate of dry matter accumulation in reproductive organs by increasing *Pn*, *φ*PSII, and *qP* to improve photosynthetic performance, thus achieving higher yield.

Keywords: Cotton, Irrigation amount, Chemical topping, Photosynthesis, Biomass accumulation

Introduction

Cotton (*Gossypium hirsutum* L.) is an important industrial crop with an indeterminate growth pattern (Chen et al. 2017; Constable and Bange 2015). Excessive vegetative development has been a major factor limiting yield improvement, particularly in ecological zones with a short growth period. Therefore, a series of strategies for controlling excessive vegetative development have been used in cotton production, including the management of fertilizer, irrigation, and plant growth

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regulators (PGRs). Manual topping (artificially removing the apex of cotton plants) is a traditional practice for restricting unnecessary vegetative growth to increase yield and early production (Renou et al. 2011; Dai and Dong 2014). However, manual topping requires considerable labor and time input, which makes it a significant impediment to the full mechanization of cotton production (Bai et al. 2017; Chen et al. 2019; Liang et al. 2020). As a result, people are seeking alternative methods to replace manual topping in China.

Mepiquat chloride (N, N-dimethylpiperidinium chloride, MC) is the most widely used plant growth regulator in cotton, which can inhibit gibberellin biosynthesis (Zhang et al. 2020) and control excessive vegetative development (Ren et al. 2013). It has been reported that MC application at high rates could replace manual topping by inducing short-term oxidative stress at the cotton apex and inhibiting the growth of cotton shoots (Han et al. 2017; An et al. 2018), which was called chemical topping (CT). However, different cultivation practices, particularly variation in soil moisture, may influence the effectiveness of chemical topping. Therefore, it is necessary to consider soil moisture when determining the dosage and timing of MC application. Previous studies have elucidated the effect of irrigation methods (Choudhary et al. 2016; Tang et al. 2005), drip irrigation amount (Singh et al. 2010; Travis et al. 2020), and drip irrigation frequency (Mugabe and Munyanyi 2004) on cotton growth, physiological characteristics, and yield formation. However, when increasing the rate of MC application to replace manual topping, whether traditional irrigation needs to be adjusted is still unclear.

Photosynthate is the material basis for the formation of cotton yield, and moisture is the key factor affecting cotton photosynthesis and yield (Meeks et al. 2019; Shangguan et al. 2000). However, there is a lack of research on the interaction between chemical topping and drip irrigation amount and its effect on the photosynthetic physiology and yield of cotton, which limits the potential of chemical topping techniques to stabilize and increase production. Therefore, this study was conducted to specify the effects of different rates of MC as a topping method by clarifying the effects of a 25% MC emulsion in water (MC_{EW}) and drip irrigation amount on photosynthetic performance and biomass accumulation of cotton and the relationship between them. These results will help to clarify the feasibility of using PGRs to replace manual topping in high-density cotton planting areas and provide a theoretical basis for the simplified cultivation of cotton under mulch drip irrigation conditions.

Materials and methods

Experimental site, cultivar and PGR

The field study was conducted at the Xinjiang Academy of Agricultural and Reclamation Science experimental station (44°19′N, 86°03′E) in Shihezi, Xinjiang Uyghur Autonomous Region, China, from 2013 to 2014. The soil was loam containing 20.1 $g·kg^{-1}$ organic matter, 71.7 $mg·kg^{-1}$ hydrolyzed nitrogen, 0.95 $g·kg^{-1}$ total nitrogen, 274 $mg·kg^{-1}$ available potassium, and 12.1 $mg·kg^{-1}$ available phosphorus. In 2013 and 2014, the conditions during the cotton growing season (from April to October) were 166.5 mm and 128.2 mm, respectively, for total precipitation, 2 142.6 h and 2 163.2 h, respectively, for sunshine duration, 19.6 °C and 19.5 °C, respectively, for average temperature, and 4 007.9 °C and 4 040.1 °C, respectively, for active accumulated temperature (≥10 °C).

Xinluzao 53 (*Gossypium hirsutum* L.), a high-yielding and early-maturity cotton cultivar, was used in the experiment. The cultivar was developed by Xinjiang Academy of Agricultural and Reclamation Science and officially registered and released by the Xinjiang Crop Variety Examination and Approval Committee.

The PGRs selected to replace manual topping was a 25% MC emulsion in water (MC_{EW}), which was jointly developed by the Engineering Research Center of Plant Growth Regulators, Ministry of Education, China Agricultural University and Beijing Agricultural Technology Extension Station.

Experimental design and crop management

A split plot design with three replicates was adopted in this experiment, and the plot area was 45.6 m^2. The main plot treatment was the total drip irrigation amount (I_1, I_2, and I_3 at 300, 480, 660 mm, respectively; I_2 was the conventional drip irrigation amount for high-yield cotton fields in Xinjiang), and the subplot was the MC_{EW} rate (MC_1, MC_2, and MC_3 at 450, 750, 1 050 $mL·hm^{-2}$, respectively, with manual topping, MT, as the control).

Cotton was planted from April 18 to 20 at a density of 26.3×10^4 $plants·hm^{-2}$. Cotton was harvested from October 8 to 12. The row spacing was (66 + 10) cm, and the distance between plants within a row was 10 cm. Six rows of cotton were covered by one plastic film with 205 cm in width and irrigated with three drip irrigation tapes (16 mm diameter) with a discharge rate of 2.1 $L·h^{-1}$.

Drip irrigation was applied 8 times during the cotton growing season, which was started on June 25 to 26, and stopped around August 20. The interval of each drip irrigation was 7~8 days. The first irrigation accounted for 14.1% of the total irrigation amount. Four irrigations were conducted in July, which accounted for 62.5% of the total irrigation amount. The last three irrigations were conducted in August, which accounted for 23.4% of the total irrigation amount. A 25% MC_{EW} was sprayed on July 4 and 5, and manual topping was conducted at the same time.

A total of 300 $kg \cdot hm^{-2}$ nitrogen (N) was applied with irrigation during the entire growth period of cotton, and the application rates of K_2O and P_2O_5 were 51 and 78 $kg \cdot hm^{-2}$, respectively. The source of N fertilizer was urea, and the source of K_2O and P_2O_5 was potassium dihydrogen phosphate. The ratio of N application in June, July, and August was 3:13:4, and the ratio of P and K application during the same period was 5:11:4. To control excessive vegetative growth, 98% MC soluble powder was applied three times on June 24, July 2, and July 9 at doses of 37.5 $g \cdot hm^{-2}$, 30 $g \cdot hm^{-2}$, and 150 $g \cdot hm^{-2}$, respectively. Other field management was conducted according to local practices.

Leaf gas exchange parameters

The net photosynthetic rate (*P*n), stomatal conductance (*G*s), intercellular CO_2 concentration (*C*i), and transpiration rate (*T*r) of the third leaf on the main stem from the terminal were determined using a portable photosynthetic system Li-6400 (Li-COR, Lincoln, NE, USA) at the peak flowering (PF), peak boll (PB), and boll opening (BO) stages. Data were collected from 10:00 to 12:00 on sunny days with photosynthetic photon flux density of 1 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$. In addition, 3~4 representative plants were randomly selected from each plot.

Chlorophyll fluorescence

After measuring the photosynthetic rate, the chlorophyll fluorescence of the same leaf was determined using a MINI-PAM fluorometer. The initial fluorescence (F_0) and maximum fluorescence (*F*m) of the leaves were measured before dawn in the early morning. The maximum photochemical efficiency of photosystem II (*F*v/*F*m) was calculated as $Fv = Fm\text{-}F_0$. The leaves were then light adapted for approximately 15 min for measurements of the photochemical quenching coefficient (*q*P) and nonphotochemical quenching coefficient (NPQ), which were obtained at a photosynthetic photon flux density of 1 200~1 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The actual photochemical efficiency of photosystem II (ϕPSII) was calculated as $\phi PSII = Fv/Fm \times qP$ (Maxwell and Johnson 2000).

Biomass accumulation calculation methods and yield measurements

Four representative cotton plants were randomly selected and uprooted from each plot at the initial flowering, PF, PB, later PB, and BO stages, respectively. The cotton shoots were cut from the cotyledon nodes and divided into vegetative and reproductive organs. The samples were dried at 105 °C for 30 min, and at 80 °C for 48 h to constant weight and then weighed.

A logistic equation was used to describe biomass accumulation (Gao et al. 2021):

$$Y = \frac{K}{1 + ae^{bt}} \quad (1)$$

where t(d) represents the number of days after emergence, Y(g) represents the weight of biomass at time t, K(g) represents the maximum biomass accumulation, and a and b are constants.

From Formula (1) we can obtain:

$$t_0 = -\frac{\ln a}{b}, \quad t_1 = \frac{1}{b}\ln\left(\frac{2+\sqrt{3}}{a}\right),$$
$$t_2 = \frac{1}{b}\ln\left(\frac{2-\sqrt{3}}{a}\right), \quad T = t_2 - t_1 \quad (2)$$

$$V_M = \frac{-bk}{4} \quad (3)$$

$$V_T = \frac{Y_2 - Y_1}{t_2 - t_1} \quad (4)$$

When $t = t_0$, biomass accumulation has reached the maximum speed V_M. T represents the rapid period of biomass accumulation, which starts at t_1 and ends at t_2. V_T is the average growth rate during this period.

The final yield was obtained from a representative sample point (3.33×10^{-4} hm^2) with a length of 1.46 m on the film.

Statistical analysis

All data were processed using Microsoft Excel 2016. The variance analysis and stepwise regression analysis were performed in SPSS 19.0 (SPSS Inc., Chicago, IL, USA). Means were compared with Duncan's multiple range test at a significance level of 5%, and figures were drawn using SigmaPlot 12.5 software. A principal component analysis was performed using Origin 2019 software.

Results

Gas exchange parameters

*P*n showed significant responses to drip irrigation amount at all stages and to MC_{EW} only at the PF stage. A higher drip irrigation amount significantly increased *P*n at all stages. Compared with manual topping, low MC_{EW} (MC_1) significantly increased *P*n at the PF stage (Table 1).

Table 1 Significance (*P*-values) of drip irrigation amounts and MC_{EW} effects and their interactions on gas exchange parameters at different growth stages in 2014

Source of variance	Peak flowering stage				Peak boll stage				Boll opening stage			
	Pn	*Gs*	*Ci*	*Tr*	*Pn*	*Gs*	*Ci*	*Tr*	*Pn*	*Gs*	*Ci*	*Tr*
Drip irrigation (I)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.626	< 0.001	< 0.001	< 0.001	0.390	< 0.001	< 0.001
MC_{EW} rate(MC)	0.003	0.001	0.292	< 0.001	0.166	0.001	0.083	< 0.001	0.060	0.019	< 0.001	0.12
I × MC	0.026	0.060	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.009	< 0.001	< 0.001

MC_{EW} represents a 25% mepiquat chloride emulsion in water; *Pn*, *Gs*, *Ci*, and *Tr* represent the net photosynthetic rate, stomatal conductance, intercellular CO_2 concentration, and transpiration rate, respectively

There was also a significant interaction effect between drip irrigation amount and MC_{EW} on the *P*n at all stages. At the PF stage, the I_3MC_1 treatment showed the highest *P*n, whereas at the PB and BO stages, the *P*n was highest under the I_2MC_2 treatment (Fig. 1).

Drip irrigation amount did not influence *G*s at the PB and BO stages, but the irrigation amounts of 480 and 660 mm increased *G*s at all stages. MC_2 of 480 mm significantly increased *G*s at all stages, and its interaction with drip irrigation was significant at the PB and BO stages (Table 1). The highest *G*s values at the PF, PB and BO stages were found in the treatment combinations of I_2MC_2, I_3MC_3, and I_3MC_3, respectively (Fig. 1).

*C*i was significantly affected by drip irrigation at all stages and by MC_{EW} at the BO stage. The interaction between drip irrigation amount and MC_{EW} rate was also significant at all stages. At the PF and PB stages, I_2 showed the highest *C*i among all three irrigation treatments, whereas at the BO stage, I_3 had the highest *C*i. Compared with manual topping, a high MC_{EW} rate significantly decreased *C*i at the BO stage. The highest *C*i at the PF, PB and BO stages were found in the treatments of I_3MC_3, I_2MC_2, and I_3MC_3, respectively (Table 1; Fig. 1).

Tr was significantly affected by drip irrigation amount and its interaction with MC_{EW} at all stages (Table 1). The *Tr* showed an increasing trend with increasing drip irrigation, the *Tr* of I_2 and I_3 were significantly higher than that of I_1, but there was no significant difference between the I_2 and I_3 treatments. At the PF and BO stages, I_2MC_2 had the highest *Tr*, whereas at the PB stage, I_3MC_3 showed the highest *Tr* among all treatments (Fig. 1).

Chlorophyll fluorescence parameters

Table 2 shows that drip irrigation amount and MC_{EW} rate did not significantly affect F_v/F_m, which ranged from 0.82 to 0.86 across all treatments. However, the F_v/F_m in 2013 was higher than that in 2014 across all stages. The amount of drip irrigation and the MC_{EW} rate significantly affected the ϕPSII of cotton leaves (except for the PF stage in 2014). At the PB and BO stages, the ϕPSII of I_2 and I_3 were significantly higher than that of I_1 (except for the BO period in 2013). A high MC_{EW} (MC_3) significantly decreased ϕPSII at the PF stage in 2013, but no effect was found in 2014. At the PB stage in 2013, MC_3 and MT showed similar ϕPSII, which were significantly higher than those of MC_1 and MC_2. However, MC_3 significantly decreased ϕPSII in the PB stage compared with those of MC_1 and MC_2 in 2014. At the BO stage, the ϕPSII of MC_2 was higher than those of MC_1 and MC_3 in 2013, and in 2014, it was higher than that of MC_1. There was also a significant interaction between the drip irrigation amount and MC_{EW}. The effect of the MC_{EW} on ϕPSII was inconsistent under the different irrigation amount. The ϕPSII of I_1MC_1 was significantly higher than those of I_1MC_2 and I_1MC_3 at the PB and BO stages. Under I_3, the ϕPSII of MC_1 was significantly lower than that of MC_3 (Table 2).

As shown in Table 2, *q*P was significantly affected by drip irrigation amount, MC_{EW} rate and their interaction at all stages. At the PF and PB stages in 2013 and the PF stage in 2014, *q*P showed an increasing trend with increasing irrigation amount. At the BO stage, the *q*P of I_2 was significantly higher than those of I_1 and I_3. MC_{EW} decreased the *q*P at the PF stage in both years. At the PB

(See figure on next page.)

Fig. 1 The effect of the MC_{EW} on cotton gas exchange parameters under different drip irrigation amounts at different growth stages in 2014. MC_{EW} represents a 25% mepiquat chloride emulsion in water; PF, peak flowering stage; PB, peak boll stage; BO, boll opening stage; MT, MC_1, MC_2, and MC_3 represent manual topping as control, 450, 750, and 1 050 mL·hm^{-2} MC_{EW}, respectively. *Pn*, *Gs*, *Ci*, and *Tr* represent the net photosynthetic rate, stomatal conductance, intercellular CO_2 concentration, and transpiration rate, respectively. For each stage, bars with different letters are significantly different at $P < 0.05$

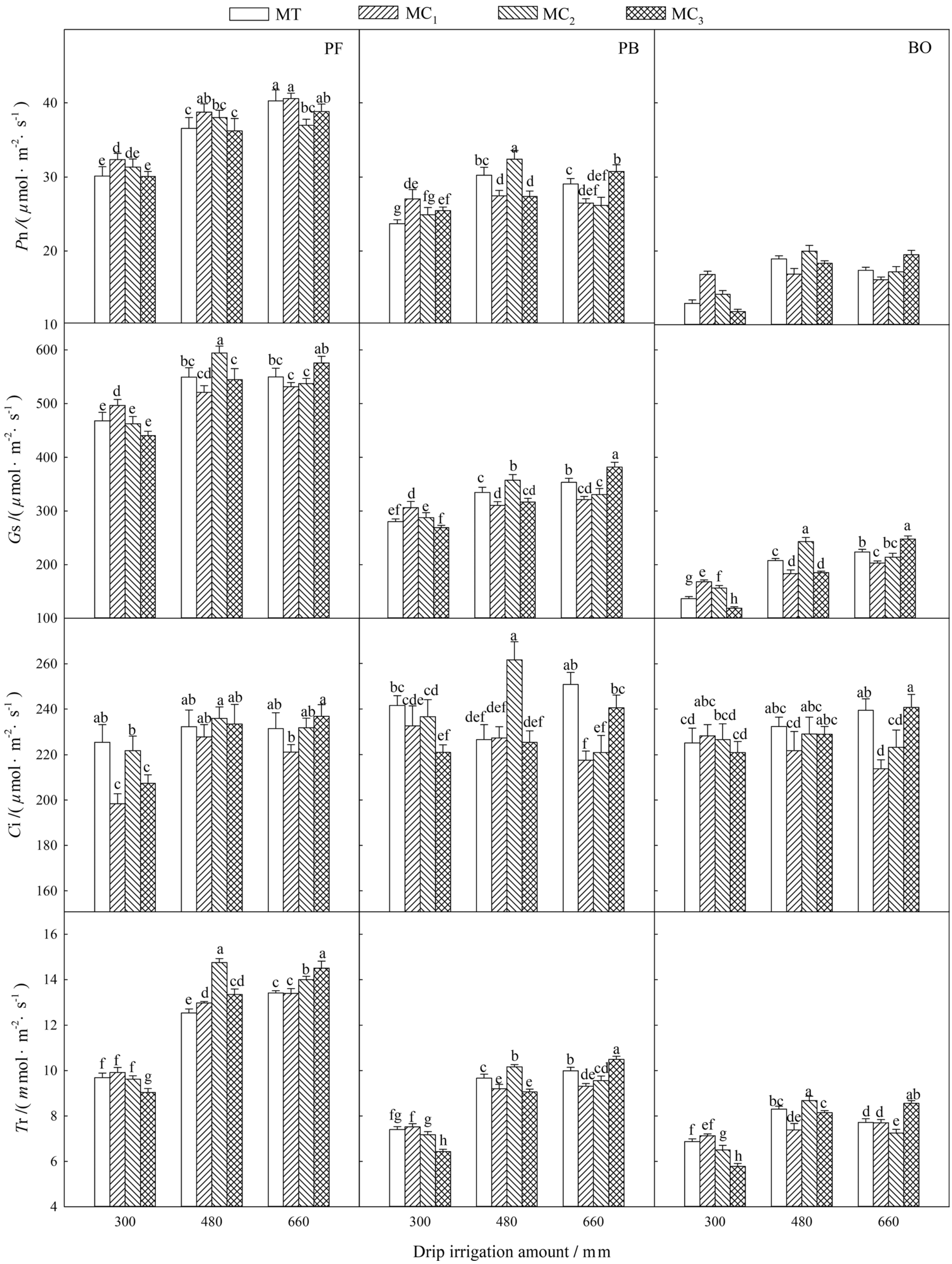

Fig. 1 (See legend on previous page.)

Table 2 Effect of drip irrigation amounts (I) and MC_{EW} rate (MC) on chlorophyll fluorescence parameter during the cotton growing seasons

Year	Treatment combination	Peak flowering stage				Peak boll stage				Boll opening stage			
		F_v/F_m	*φ*PSII	*q*P	NPQ	F_v/F_m	*φ*PSII	*q*P	NPQ	F_v/F_m	*φ*PSII	*q*P	NPQ
2013	I_1MC_1	0.84 ab	0.34 def	0.36 f	0.48 ef	0.86 a	0.40 ef	0.46 de	0.73 d	0.86 a	0.38 a	0.40 b	0.64 f
	I_1MC_2	0.84 ab	0.33 ef	0.34 g	0.63 d	0.86 cd	0.36 gh	0.43 g	0.84 b	0.83 cd	0.35 b	0.38 cd	0.80 cd
	I_1MC_3	0.84 ab	0.31 g	0.31 h	0.69 c	0.85 cd	0.36 h	0.42 g	0.88 a	0.83 d	0.32 d	0.33 f	0.94 a
	I_1MT	0.84 ab	0.33 ef	0.34 g	0.45 ef	0.86 abc	0.38 fg	0.44 f	0.71 d	0.84 bcd	0.35 b	0.37 de	0.82 bc
	I_2MC_1	0.84 ab	0.35 de	0.41 d	0.75 b	0.86 bc	0.41 de	0.47 d	0.77 c	0.84 abc	0.29 e	0.35 f	0.87 b
	I_2MC_2	0.84 ab	0.36 cd	0.43 c	0.68 c	0.86 bc	0.44 bc	0.51 bc	0.67 e	0.85 ab	0.35 b	0.41 a	0.63 f
	I_2MC_3	0.83 b	0.33 f	0.40 e	0.83 a	0.86 ab	0.41 de	0.47 d	0.77 c	0.84 abc	0.32 d	0.39 bc	0.75 de
	I_2MC_T	0.84 ab	0.34 def	0.40 de	0.61 d	0.86 abc	0.43 cd	0.50 c	0.73 d	0.85 ab	0.33 bcd	0.39 b	0.72 e
	I_3MC_1	0.83 ab	0.37 c	0.43 c	0.61 d	0.85 d	0.40 ef	0.47 d	0.79 c	0.84 bcd	0.33 cd	0.34 f	0.98 a
	I_3MC_2	0.86 a	0.37 c	0.44 c	0.60 d	0.86 bc	0.38 fg	0.45 ef	0.82 b	0.85 abc	0.35 b	0.36 de	0.87 b
	I_3MC_3	0.84 ab	0.39 b	0.46 b	0.50 e	0.86 a	0.48 a	0.55 a	0.62 f	0.86 a	0.38 a	0.39 bc	0.70 e
	I_3MT	0.83 ab	0.40 a	0.48 a	0.43 f	0.86 bc	0.45 b	0.52 b	0.61 f	0.85 ab	0.35 bc	0.36 e	0.72 e
2014	I_1MC_1	0.83 ab	0.43 a	0.40 g	0.74 f	0.85 ab	0.42 bc	0.49 cd	0.65 f	0.84 a	0.41 a	0.43 ab	0.85 d
	I_1MC_2	0.82 b	0.40 b	0.37 h	0.84 e	0.84 bcd	0.38 ef	0.44 f	0.76 e	0.84 a	0.36 cd	0.38 e	0.86 d
	I_1MC_3	0.82 b	0.36 cd	0.33 i	0.97 d	0.83 cd	0.33 g	0.39 h	0.82 d	0.82 ab	0.35 d	0.38 e	0.89 d
	I_1MT	0.83 ab	0.40 b	0.36 h	0.76 f	0.84 abc	0.36 f	0.42 g	0.73 e	0.83 ab	0.38 bc	0.40 d	0.88 d
	I_2MC_1	0.83 ab	0.35 de	0.42 ef	1.12 b	0.83 d	0.43 ab	0.53 ab	0.95 c	0.80 c	0.32 f	0.40 cd	1.04 c
	I_2MC_2	0.83 ab	0.37 c	0.46 c	1.05 c	0.83 d	0.44 a	0.53 a	0.96 c	0.82 abc	0.36 cd	0.44 a	0.85 d
	I_2MC_3	0.82 ab	0.35 de	0.43 de	1.27 a	0.84 bcd	0.39 de	0.46 e	1.15 a	0.80 c	0.33 ef	0.42 bcd	1.09 bc
	I_2MT	0.83 ab	0.34 e	0.42 f	1.13 b	0.83 cd	0.42 bc	0.50 c	1.04 b	0.82 abc	0.33 ef	0.40 cd	1.20 a
	I_3MC_1	0.83 ab	0.34 e	0.41 f	0.92 d	0.84 abc	0.37 f	0.43 f	0.95 c	0.81 abc	0.29 g	0.31 f	1.24 a
	I_3MC_2	0.84 a	0.36 cd	0.44 d	0.74 f	0.84 bcd	0.40 cd	0.47 de	0.92 c	0.81 bc	0.35 de	0.38 e	1.12 b
	I_3MC_3	0.85 a	0.40 b	0.48 b	0.85 e	0.86 a	0.44 a	0.52 b	0.81 d	0.84 ab	0.39 ab	0.42 ab	1.10 bc
	I_3MT	0.84 ab	0.41 b	0.49 a	0.75 f	0.86 a	0.42 bc	0.49 cd	0.77 de	0.82 abc	0.38 b	0.42 abc	1.07 bc
	Source of variance												
	Year (Y)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.004	0.499	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Drip irrigation (I)	0.046	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.015	< 0.001	< 0.001	< 0.001
	MC_{EW} rate (MC)	0.497	0.001	< 0.001	< 0.001	0.023	0.126	0.024	< 0.001	0.603	< 0.001	< 0.001	< 0.001
	Y × I	0.092	< 0.001	< 0.001	< 0.001	< 0.001	0.010	< 0.001	< 0.001	< 0.001	0.030	0.071	< 0.001
	Y × MC	0.608	0.286	0.024	< 0.001	0.610	< 0.001	< 0.001	< 0.001	0.725	0.034	< 0.001	< 0.001
	I × MC	0.010	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Y × I × MC	0.710	0.007	< 0.001	0.036	0.344	0.008	< 0.001	< 0.001	0.650	< 0.001	< 0.001	< 0.001

MC_{EW} represents a 25% mepiquat chloride emulsion in water; I_1, I_2, and I_3 represent 300, 480, and 660 mm drip irrigation amounts, respectively; MT, MC_1, MC_2, and MC_3 represent manual topping as control, 450, 750, and 1 050 $mL \cdot hm^{-2}$ MC_{EW}, respectively. *Fv/Fm*, *φ*PSII, *q*P, and NPQ represent the primary light energy conversion efficiency of PSII in the dark, quantum yield of PSII, coefficient of photochemical quenching, and coefficient of nonphotochemical quenching, respectively. For each year, values in one column followed by different letters are significantly different at $P < 0.05$

stage, MC_1 and MC_2 decreased *q*P in 2013 but increased it in 2014. At the BO stage, the *q*P of MC_2 was significantly higher than that of MT in 2013 but lower than that of MT in 2014. *q*P showed a decreasing trend in response to the increase in MC_{EW} rate, under the irrigation of I_1 and MC_1 had the highest *q*P; however, it was lower than that of MC_3 under the irrigation of I_3 (Table 2).

Drip irrigation, MC_{EW} and their interaction significantly affected the NPQ at all stages in 2013 and 2014. At the PF stage, NPQ of I_2 was the highest among the three irrigation treatments in both years, and NPQ showed an increasing trend with the increase in the MC_{EW} application rate at this stage. At the PB stage, NPQ was decreased by the increase in irrigation amount in 2013, whereas in 2014, I_2 had the highest NPQ. Compared with MT, MC_{EW} application significantly increased the NPQ at the PB stage in both years. Under the irrigation of I_1, NPQ showed an increasing trend with the increase in MC_{EW} rate (except for the BO stage in 2014). Under the irrigation of I_3, NPQ was decreased by the increase in MC_{EW} rate (except for the PF stage in 2014) (Table 2).

Table 3 Simulation equations and eigenvalues of cotton aboveground biomass accumulation

Year	Treatment	Regression equation	t_1/d	t_2/d	T/d	Vt/(kg·hm^{-2}·d^{-1})	Vm/ (kg·hm^{-2}·d^{-1})	Tm/d
2013	I_1MC_1	$Y=39\,189.187\,6/(1+465.723\,9e^{-0.071\,1t})$	67.8	104.9	37.0	611.1	697.0	86.4
	I_1MC_2	$Y=37\,721.907\,3/(1+396.890\,0e^{-0.069\,0t})$	67.6	105.8	38.2	570.8	651.0	86.7
	I_1MC_3	$Y=36\,661.550\,0/(1+331.029\,7e^{-0.066\,8t})$	67.2	106.6	39.4	536.6	612.0	86.9
	I_1MT	$Y=38\,922.490\,8/(1+374.496\,2e^{-0.067\,2t})$	68.6	107.8	39.2	573.4	654.0	88.2
	I_2MC_1	$Y=45\,184.819\,9/(1+298.497\,0e^{-0.065\,9t})$	66.5	106.5	40.0	652.5	744.2	86.5
	I_2MC_2	$Y=47\,738.069\,4/(1+422.657\,8e^{-0.069\,1t})$	68.5	106.6	38.1	722.7	824.3	87.5
	I_2MC_3	$Y=43\,412.265\,5/(1+324.714\,3e^{-0.066\,1t})$	67.5	107.4	39.8	629.1	717.6	87.5
	I_2MT	$Y=46\,227.585\,2/(1+412.900\,5e^{-0.068\,6t})$	68.6	107.1	38.4	694.7	792.3	87.9
	I_3MC_1	$Y=44\,426.721\,0/(1+515.977\,7e^{-0.075\,0t})$	65.8	100.9	35.1	730.0	832.6	83.3
	I_3MC_2	$Y=44\,931.277\,7/(1+494.906\,2e^{-0.073\,5t})$	66.5	102.3	35.8	724.2	826.0	84.4
	I_3MC_3	$Y=49\,579.434\,5/(1+401.142\,2e^{-0.069\,0t})$	67.8	106.0	38.2	749.9	855.3	86.9
	I_3MT	$Y=47\,421.597\,2/(1+534.220\,3e^{-0.073\,6t})$	67.5	103.3	35.8	764.6	872.0	85.4
2014	I_1MC_1	$Y=45\,098.242\,0/(1+205.223\,2e^{-0.056\,6t})$	70.8	117.3	46.5	559.7	638.4	94.0
	I_1MC_2	$Y=43\,945.917\,3/(1+184.797\,6e^{-0.054\,8t})$	71.2	119.2	48.0	528.2	602.4	95.2
	I_1MC_3	$Y=40\,262.221\,0/(1+181.066\,8e^{-0.055\,9t})$	69.4	116.6	47.1	493.3	562.7	93.0
	I_1MT	$Y=40\,601.721\,4/(1+319.224\,1e^{-0.063\,9t})$	69.6	110.8	41.2	568.7	648.6	90.2
	I_2MC_1	$Y=45\,367.516\,2/(1+252.860\,6e^{-0.063\,0t})$	67.0	108.8	41.8	626.1	714.1	87.9
	I_2MC_2	$Y=52\,455.878\,5/(1+208.022\,6e^{-0.057\,3t})$	70.1	116.1	45.9	659.3	752.0	93.1
	I_2MC_3	$Y=46\,278.329\,3/(1+193.341\,1e^{-0.058\,2t})$	67.8	113.1	45.2	590.5	673.5	90.4
	I_2MT	$Y=47\,501.021\,6/(1+240.842\,6e^{-0.060\,9t})$	68.5	111.8	43.3	633.6	722.6	90.1
	I_3MC_1	$Y=42\,584.477\,7/(1+327.189\,9e^{-0.070\,0t})$	63.9	101.5	37.6	653.5	745.3	82.7
	I_3MC_2	$Y=43\,548.103\,7/(1+333.394\,7e^{-0.069\,6t})$	64.5	102.3	37.8	664.7	758.1	83.4
	I_3MC_3	$Y=47\,725.614\,0/(1+371.678\,4e^{-0.069\,4t})$	66.3	104.2	37.9	726.4	828.5	85.2
	I_3MT	$Y=45\,494.754\,2/(1+361.552\,5e^{-0.069\,4t})$	65.9	103.9	38.0	692.0	789.2	84.9

I_1, I_2, and I_3 represent 300, 480 and 660, mm drip irrigation amounts, respectively; MT, MC_1, MC_2, and MC_3 represent manual topping as control, 450, 750, and 1 050 mL·hm^{-2} 25% mepiquat chloride emulsion in water, respectively; t_1, fast growth start time; t_2, fast growth end time; T, duration of fast growth period; Vt, average speed of fast growth period; Vm, maximum speed of fast growth period; Tm, occurrence time of maximum speed in fast growth period

Characteristics of cotton biomass accumulation

Cotton plant biomass accumulation increased with the number of days after emergence and followed a sigmoid curve, which was described by the logistic equation $Y=K/(1+ae^{bt})$. With the increase in drip irrigation amount, the fast accumulation period (FAP) of cotton plant biomass started (t_1) and ended (t_2) earlier. A higher irrigation amount resulted in a shorter FAP with a higher average speed (Vt) and maximum speed (Vm). Under the irrigation of I_1, the FAP of MC_1 was the shortest, with the highest Vt and Vm. Under I_2, MC_2 had the highest Vt and Vm, which were 4.0%~4.1% higher than those of MT. Under I_3 irrigation, as the MC_{EW} rate increased, the initiation and termination of FAP were delayed and the FAP was longer. Vt and Vm of MC_3 were also significantly higher than those of MC_1 and MC_2 (Table 3).

With the increase in the drip irrigation amount, the FAP for reproductive organs showed an increasing trend. The Vt and Vm of I_2 were significantly higher than those of I_1 and I_3. Under the irrigation of I_1, both Vt and Vm showed a decreasing trend with increasing MC_{EW}, and there was no significant difference between MC_1 and MT. When the irrigation amount increased to 480 mm, the Vt and Vm of MC_2 were significantly higher than those of MC_1 and MC_3, and they were increased by 5.4%~5.6% compared with MT. Under the irrigation of I_3, no significant difference was found in the FAP start and end times of reproductive organs among the different MC_{EW} rates. Both Vt and Vm were significantly increased with increasing MC_{EW}. Compared with MT, the Vt and Vm of MC_3 were increased by 10.8%~14.9% (Table 4).

Seed cotton yield

The seed cotton yields of I_2 and I_3 were 12.1%~20.9% higher than that of I_1, but there was no significant difference between I_2 and I_3 (Fig. 2; Table 5). There was a significant interaction between the drip irrigation amount and the MC_{EW} rate, and the effect of the MC_{EW} rate on cotton yield was inconsistent under different irrigation amounts. Under 300 mm of irrigation, the seed cotton

Table 4 Simulation equation and eigenvalue of cotton reproductive organs biomass accumulation

Year	Treatment	Regression equation	t_1/d	t_2/d	T/d	Vt/($kg\cdot hm^{-2}\cdot d^{-1}$)	Vm/ ($kg\cdot hm^{-2}\cdot d^{-1}$)	Tm/d
2013	I_1MC_1	$Y=22\ 511.358\ 8/(1+1\ 445.296\ 9e^{-0.074\ 1t})$	80.5	116.0	35.6	365.4	416.8	98.3
	I_1MC_2	$Y=21\ 120.509\ 2/(1+1\ 382.209\ 2e^{-0.073\ 8t})$	80.1	115.8	35.7	341.8	389.9	97.9
	I_1MC_3	$Y=20\ 119.317\ 6/(1+1\ 250.212\ 8e^{-0.072\ 9t})$	79.8	115.9	36.2	321.3	366.5	97.9
	I_1MT	$Y=22\ 050.645\ 7/(1+1\ 534.209\ 9e^{-0.074\ 4t})$	80.9	116.3	35.4	359.7	410.3	98.6
	I_2MC_1	$Y=26\ 395.453\ 4/(1+1\ 068.453\ 1e^{-0.069\ 8t})$	81.0	118.7	37.7	404.1	460.9	99.8
	I_2MC_2	$Y=30\ 172.298\ 6/(1+1\ 231.556\ 7e^{-0.071\ 0t})$	81.6	118.7	37.1	469.8	535.8	100.2
	I_2MC_3	$Y=25\ 556.184\ 8/(1+1\ 175.044\ 6e^{-0.071\ 1t})$	80.9	118.0	37.1	398.1	454.1	99.5
	I_2MT	$Y=28\ 897.582\ 1/(1+1\ 148.916\ 5e^{-0.070\ 4t})$	81.4	118.8	37.4	445.8	508.5	100.1
	I_3MC_1	$Y=24\ 018.515\ 1/(1+783.244\ 8e^{-0.066\ 6t})$	80.3	119.9	39.6	350.4	399.6	100.1
	I_3MC_2	$Y=24\ 950.285\ 5/(1+740.774\ 1e^{-0.065\ 7t})$	80.5	120.6	40.1	359.5	410.0	100.5
	I_3MC_3	$Y=29\ 424.402\ 3/(1+1\ 061.732\ 0e^{-0.069\ 3t})$	81.5	119.6	38.0	447.0	509.8	100.5
	I_3MT	$Y=26\ 181.298\ 3/(1+1\ 081.177\ 4e^{-0.070\ 3t})$	80.6	118.1	37.5	403.5	460.2	99.3
2014	I_1MC_1	$Y=21\ 580.530\ 0/(1+1\ 328.056\ 0e^{-0.074\ 6t})$	78.8	114.1	35.3	352.7	402.3	96.4
	I_1MC_2	$Y=20\ 875.538\ 5/(1+1\ 290.362\ 1e^{-0.073\ 9t})$	79.1	114.7	35.6	338.1	385.7	96.9
	I_1MC_3	$Y=19\ 922.948\ 9/(1+1\ 295.216\ 3e^{-0.074\ 5t})$	78.5	113.8	35.3	325.5	371.2	96.2
	I_1MT	$Y=21\ 268.013\ 3/(1+1\ 540.686\ 6e^{-0.076\ 3t})$	78.9	113.4	34.5	355.8	405.8	96.2
	I_2MC_1	$Y=27\ 738.252\ 6/(1+739.984\ 8e^{-0.064\ 2t})$	82.3	123.3	41.0	390.6	445.5	102.8
	I_2MC_2	$Y=33\ 415.680\ 6/(1+920.665\ 9e^{-0.064\ 7t})$	85.2	125.9	40.7	473.8	540.3	105.5
	I_2MC_3	$Y=30\ 662.918\ 8/(1+662.765\ 5e^{-0.061\ 0t})$	85.0	128.2	43.2	409.7	467.3	106.6
	I_2MT	$Y=32\ 431.538\ 0/(1+736.777\ 2e^{-0.063\ 1t})$	83.8	125.5	41.7	448.6	511.7	104.6
	I_3MC_1	$Y=23\ 028.804\ 6/(1+483.036\ 2e^{-0.061\ 3t})$	79.3	122.3	43.0	309.5	353.0	100.8
	I_3MC_2	$Y=25\ 551.585\ 3/(1+633.041\ 6e^{-0.063\ 0t})$	81.4	123.2	41.8	353.0	402.6	102.3
	I_3MC_3	$Y=31\ 055.285\ 1/(1+666.848\ 2e^{-0.062\ 6t})$	82.9	125.0	42.1	425.8	485.7	103.9
	I_3MT	$Y=26\ 422.088\ 0/(1+652.396\ 0e^{-0.064\ 0t})$	80.7	121.9	41.2	370.6	422.7	101.3

I_1, I_2, and I_3 represent 300, 480, and 660 mm drip irrigation amounts, respectively; MT, MC_1, MC_2, and MC_3 represent manual topping as control, 450, 750, and 1 050 $mL\cdot hm^{-2}$ 25% mepiquat chloride emulsion in water, respectively; t_1, fast growth start time; t_2, fast growth end time; T, duration of fast growth period; Vt, average speed of fast growth period; Vm, maximum speed of fast growth period; Tm, occurrence time of maximum speed in fast growth period

yield showed a decreasing trend with increasing MC_{EW}. Compared with MT, MC_1 significantly increased cotton yield by 6.2%~7.2%. Under I_2 irrigation, the cotton yield of MC_2 was significantly higher than that of MT by 6.57%~12.79%. When 660 mm of irrigation was applied, the seed cotton yield showed an increasing trend with increasing MC_{EW}. MC_3 had the highest cotton yield, which was 6.9%~9.7% higher than that of MT.

Principal components of each index and stepwise regression analysis with yield

A principal component analysis was performed on the 33 parameters measured (Fig. 3), and 4 principal components were selected based on the cumulative contribution rate (data not shown). The results showed that the cumulative contribution rate of the first 4 eigenvalues reached 87.1%, indicating that most of the influence of the 33 parameters can be summarized by the first 4 principal components, and the cumulative contribution rate of the first 2 principal components was 67.5%, which explained most of the variation. PC1 explained 46.3% of the variation, and PC2 explained 21.2% of the variation. The weight coefficients of seed cotton yield, *T*r-PB, *P*n-PF, Vt-AGB, Vm-AGB, *G*s-PB, *T*r-PF, *qP*-PF, *P*n-BO, *G*s-BO, and *G*s-PF were higher for the first principal component. For the second principal component, the load values of *F*v/*F*m-BO, *F*v/*F*m-PB, *F*v/*F*m-PF, *C*i-BO, *C*i-PF, t-ROB, NPQ-BO, NPQ-PB, and NPQ-PF were higher.

A stepwise regression was used to analyze the influence of various indices on seed cotton yield in different periods, and the insignificant indices were eliminated. The regression equation was $Y=-1\ 836.874+4.898X_6-18.671X_{12}+7.467X_{17}-95.419X_{23}+6\ 508.531X_{25}-3\ 056.348X_{29}+1\ 965.299X_{31}-256.165X_{33}$, and Vt-ROB($X_6$), *P*n-PF($X_{12}$), *G*s-BO($X_{17}$), *T*r-BO($X_{23}$), *F*v/*F*m-PB ($X_{25}$), ϕPSII-BO(X_{29}), *q*P-PB(X_{31}), and NPQ-BO(X_{33}) were the indices that significantly influenced seed cotton yield (Y) ($R^2=0.934$). The increase in Vt-ROB, *G*s-BO, *F*v/*F*m-PB, and *q*P-PB increased seed cotton yield, but excessive *T*r-BO, *P*n-PF, ϕPSII-BO, and NPQ-BO were not conducive to high seed cotton yield.

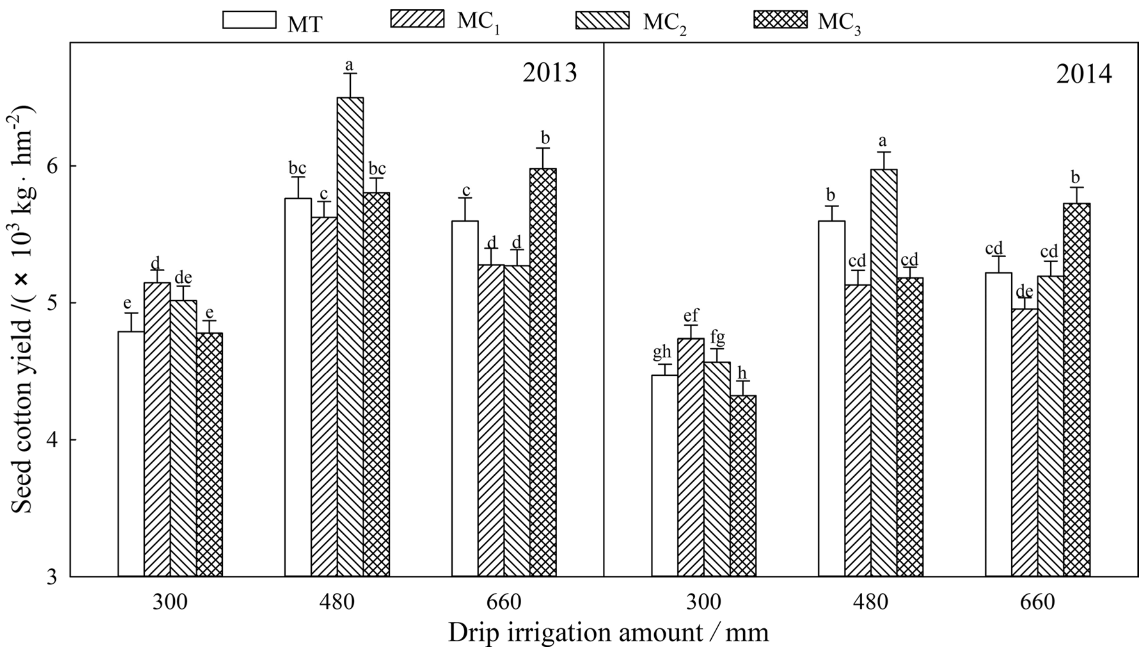

Fig. 2 The effect of MC_{EW} on seed cotton yield under different drip irrigation amounts (Han et al. 2017). MC_{EW} represents a 25% mepiquat chloride emulsion in water; MT, MC_1, MC_2 and MC_3 represent manual topping as control, 450, 750 and 1 050 mL·hm^{-2} MC_{EW}, respectively. For each year, bars with different letters are significantly different at $P < 0.05$

Table 5 Significance (*P*-values) of drip irrigation amount and MC_{EW} rate effects and their interactions on seed cotton yield

Source of variance	Seed cotton yield
Year (Y)	< 0.001
Drip irrigation (I)	< 0.001
MC_{EW} rate (MC)	< 0.001
Y × I	0.066
Y × MC	0.395
I × MC	< 0.001
Y × I × MC	0.162

MC_{EW} represents a 25% mepiquat chloride emulsion in water

Discussion

Manual topping is currently the main obstacle limiting the full mechanization of cotton production in China (Bai et al. 2017). Using PGRs to replace manual topping not only reduces labor costs but also helps to shape a more compact plant, which is conducive to the improvement of photosynthesis (Liang et al. 2020; Stewart et al. 2003). In this study, it was found that the I_1MC_1, I_2MC_2, and I_3MC_3 treatments increased the seed cotton yield compared with I_1MT, I_2MT, and I_3MT, respectively. This result indicated that it was feasible to replace manual topping with MC_{EW} in this arid cotton-growing region, but the application rate needs to be adjusted based on the drip irrigation amount to achieve optimal yield.

Photosynthesis plays an important role in cotton biomass accumulation and yield formation (Zhu et al. 2010; Raines 2011). Irrigation and PGRs have a considerable impact on crop photosynthesis (Yang et al. 2016; Han et al. 2017). Many studies have shown that reasonable water management (Han et al. 2011; Simao et al. 2013) and MC application (Zhao et al. 2000; Gwathmey and Clement 2010; Gao et al. 2019) can increase cotton yield by improving canopy photosynthesis. In the present study, the highest *Pn*, *Tr*, and *Gs* were found in the I_2MC_2 treatment, which could explain why this treatment had the highest yield. Soil moisture facilitates the expansion of cotton leaves for photosynthesis, but excessive vegetative growth is not conducive to increasing yield. Therefore, it is feasible to apply an appropriate MC rate (MC_2) based on moderate irrigation amount (I_2) to achieve synchronous improvement in photosynthetic performance and yield by combining "promotion" and "control" to build a highly light efficient population (Zhao et al. 2011; Stewart et al. 2003).

Chlorophyll fluorescence parameters demonstrates light energy absorption, transmission, dissipation and distribution, which can provide a rapid and minimally invasive measurement of photosynthesis (Baker 2008;

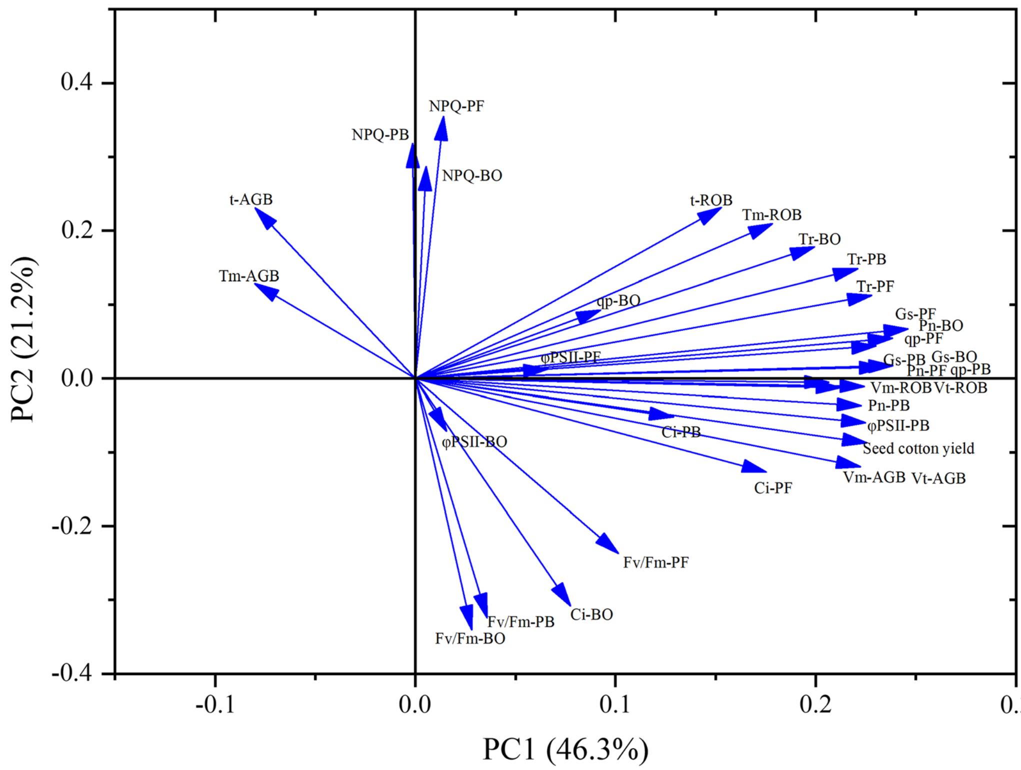

Fig. 3 Principal component analysis of various indices at different growth stages. PF, peak flowering stage; PB, peak boll stage; BO, boll opening stage; AGB, aboveground biomass; ROB, reproductive organ biomass; *Fv/Fm*, *φ*PSII, *qP*, and NPQ represent the primary light energy conversion efficiency of PSII in the dark, quantum yield of PSII, coefficient of photochemical quenching and coefficient of nonphotochemical quenching, respectively. *Pn*, *Gs*, *Ci*, and *Tr* represent the net photosynthetic rate, stomatal conductance, intercellular CO_2 concentration and transpiration rate, respectively. t, Tm, and Vm represent the duration of the fast growth period, occurrence time of maximum speed during the fast growth period and maximum speed of biomass accumulation during the fast growth period, respectively

Krause and Weis 1991). In our study, the *φ*PSII and *q*P of CT were higher than those of the control (manual topping, MT), suggesting that optimizing the application rate of MC_{EW} under different drip irrigation amounts can increase the light utilization. The NPQ of CT under I_3 irrigation was higher than that of MT. These results indicated that MC_{EW} application could improve heat dissipation efficiency to protect photosynthetic organs from damage by excessive light energy (Yi et al. 2016). However, this trend was not obvious under medium or lower irrigation amounts. It was infered that under higher irrigation amount, cotton vegetative growth was stronger, and photosynthetic products could not be transferred in a timely manner, leading to the phenomenon of excess light energy (Pilon et al. 2018).

Biomass is the final product of photosynthesis, and a reasonable distribution of biomass is the key to high yield and high quality of cotton (Yang et al. 2011). In the present study, an increase in irrigation amount accelerated the accumulation of cotton dry matter, whereas MC_{EW} application inhibited the vegetative growth and promoted the transport of photosynthetic products to the reproductive organs, which is consistent with the studies of Zhang et al (2016) and Fernandez et al (1991). It was also found that the biomass accumulation patterns of cotton shoots and reproductive organs were inconsistent under the treatment combinations of irrigation and MC_{EW} application. The Vt and Vm of cotton shoots reached the maximum under the I_3MC_3 and I_3MT treatments, whereas the reproductive organs were maximized by I_2MC_2. This may be related to the inefficient transport of photosynthetic products to reproductive organs under excessive soil moisture conditions (Zhu et al. 2010). Therefore, an intermediate level of drip irrigation combined with appropriate MC_{EW} application (I_2MC_2) coordinated the vegetative and reproductive growth of cotton to the greatest extent, and promoted the transport of photosynthetic products to the reproductive organs.

Yield is the most important index to evaluate cotton growth status (Dai et al. 2014). The principal component analysis showed that too long FAP and too late Tm of vegetative organs were not conducive to high yield. This suggests that adequate reproductive growth is the key to high yield (Shi et al. 2020). The stepwise regression analysis showed that the amount of drip irrigation and the MC_{EW} application rate improved seed cotton yield by increasing the Vt of reproductive organs, the *G*s at the BO stage, and the *F*v/*F*m and *q*P at the PB stage. However, an excessively high *P*n at the PF stage was not conducive to high yield. A possible explanation for this result may be that the reproductive sink of cotton at the PF stage was relatively small, hence excessive photosynthetic products were transported to the vegetative organs (Yang et al. 2016).

Conclusions

The amount of drip irrigation and the MC_{EW} application rate had an interactive effect on photosynthetic characteristics, the biomass accumulation characteristics and the yield of seed cotton. Moisture has a dominant effect, and MC_{EW} plays a regulating effect. Under the conditions of an intermediate level of drip irrigation (480 mm), the application of 750 $mL \cdot hm^{-2}$ MC_{EW} is beneficial, increasing the net photosynthetic rate, enhancing the actual photochemical activity and light energy conversion efficiency of the *PS*II reaction center, promoting the accumulation of cotton dry matter, and increasing the transport of photosynthetic products to the reproductive organs, thus producing higher yield and realizing the replacement of manual topping with chemical topping. If the amount of drip irrigation is increased or decreased, the amount of MC_{EW} must also be changed to achieve the best effect.

Abbreviations

I: Drip irrigation amount; MC: Mepiquat chloride; CT: Chemical topping; MT: Manual topping; PGRs: Plant growth regulators; PF: Peak flowering stage; PB: Peak boll stage; BO: Boll opening stage; *P*n: Net photosynthetic rate; *G*s: Stomatal conductance; *C*i: Intercellular CO_2 concentration; *Tr*: Transpiration rate; *Fv/F*m: Maximum photochemical efficiency; *φ*PSII: Actual photochemical efficiency; *q*P: Photochemical quenching coefficient; NPQ: Non-photochemical quenching coefficient; t_1: Fast growth start time; t_2: Fast growth end time; t: Duration of fast growth period; Vt: Average speed of fast growth period; Vm: Maximum speed of fast growth period; Tm: Occurrence time of maximum speed in fast growth period.

Acknowledgements

Not applicable.

Author contributions

Han HY, Tian XL and Li ZH conceived and designed the experiments; Tian Y and Han HY performed the experiments; Tian Y and Liao BP analyzed the data and wrote the manuscript; Wang FY, Du MW and Tian XL edited and revised the manuscript. All authors read and approved the final manuscript.

Funding

This study was financially supported by the Research Fund for the National Natural Science Foundation of China (31760369), Xinjiang Corps Science and Technology Innovation Talent Program (2020CB014), and Major projects of the eighth Division (2020ZD01).

Availability of data and materials

All relevant data are within this article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All co-authors have consent for submission of manuscript.

Competing interests

The authors have declared that no competing interests exist.

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Received: 13 January 2022 Accepted: 21 April 2022
Published online: 06 May 2022

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