Ren H *et al.* (2025)
Notulae Botanicae Horti Agrobotanici Cluj-Napoca
Volume 53, Issue 3, Article number 1414538
DOI:10.15835/nbha53314538
Research Article

Effects of drip application of different concentrations of CO_2 solution on canopy gas exchange, growth, yield, and quality of cotton

Hong REN, Mi YANG, Yiru MA, Zilong ZHANG, Lucheng LIANG, Duoer MA, Yan WU, Ze ZHANG*, Jiangli WANG*

*Shihezi University, College of Agriculture, The Key Laboratory of Oasis Eco-Agriculture, Xinjiang Production and Construction Group, Shihezi 832003, China; renhong@stu.shzu.edu.cn; 20232312204@stu.shzu.edu.cn; mayiru@stu.shzu.edu.cn; zhangzilong@stu.shzu.edu.cn; llc_126@stu.shzu.edu.cn; 20232112017@stu.shzu.edu.cn; 15709420614@163.com; zhangze1227@shzu.edu.cn (*corresponding author); wangjiangli@shzu.edu.cn (*corresponding author)*

Abstract

Changes in atmospheric CO_2 concentration strongly affect the photosynthetic performance of C_3 plants. Cotton (*Gossypium hirsutum* L.), a major global cash crop, provides a suitable model to study CO_2 fertilization effects. While moderate CO_2 enrichment can promote growth and yield, the optimal regime for field-scale application remains unclear. In this study conducted in Xinjiang, China, CO_2 gas was dissolved in irrigation water at four concentrations (0.04, 0.08, 0.12, 0.16 $kg{\cdot}m^{-3}$) and applied via a drip irrigation system. The effects on canopy CO_2 distribution, plant physiological responses, yield, and fibre quality were assessed. Drip-applied CO_2 solutions increased canopy CO_2 concentration by gradually releasing CO_2 from the soil, which in turn enhanced plant growth indicators (SPAD, AGB, LAI, plant height). Growth promotion followed a dose–response trend, with effects rising at lower concentrations and declining at higher levels. Yield analysis showed that lint yield increased by 1.9% and 8.4% under 0.04 and 0.08 $kg{\cdot}m^{-3}$ treatments, respectively, compared with the control ($p < 0.05$). In contrast, 0.12 and 0.16 $kg{\cdot}m^{-3}$ treatments reduced yield by 13.4% and 5.4%, respectively ($p < 0.05$). Fibre quality indicators remained within the optimal range across all treatments. Overall, 0.08 $kg{\cdot}m^{-3}$ was identified as the most effective concentration, producing the highest yield while maintaining fibre quality. These findings provide a scientific basis for the field application of CO_2-enriched irrigation, offering a promising approach to enhance cotton productivity and the ecological sustainability of farmland systems.

Keywords: cotton (*Gossypium hirsutum* L.); canopy gas exchange; CO_2 fertilization; drip irrigation; economic benefits; sustainable agriculture; yield and fibre quality

Received: 11 Apr 2025. Received in revised form: 30 Aug 2025. Accepted: 05 Sep 2025. Published online: 17 Sep 2025.
From Volume 49, Issue 1, 2021, Notulae Botanicae Horti Agrobotanici Cluj-Napoca journal uses article numbers in place of the traditional method of continuous pagination through the volume. The journal will continue to appear quarterly, as before, with four annual numbers.

Introduction

Cotton, an important cash crop, is widely planted around the world (Jans *et al.*, 2021). China is one of the world's largest cotton producers, and the cotton production of Xinjiang province accounts for 91% and 20% of China's and the world's total cotton production, respectively. Thus, Xinjiang's cotton industry significantly influences the global cotton market (National Bureau of Statistics of China, 2023; China Cotton Association, 2024). The arid Xinjiang has high cotton yield and quality owing to the abundant solar and thermal resources, high-density planting, and drip irrigation combined with film mulching technology (Dai and Dong, 2014; Zuo *et al.*, 2024). Especially, the drip fertigation under film mulching integrates water and fertilizers, enabling the full absorption and utilization of water and fertilizers by crops (Feng *et al.*, 2024). However, the high plant density leads to fierce competition for nutrients and light among plants (Chen *et al.*, 2019; Zuo *et al.*, 2023). Although high water and fertilizer input has brought stably high yields, it has also greatly increased the production costs (Dai *et al.*, 2015). Therefore, based on Xinjiang's superior solar and thermal resources, improving the photosynthetic productivity of the cotton canopy by optimizing field managements has been widely regarded as a main strategy to increase cotton yields (Brodrick *et al.*, 2013; Bailey-Serres *et al.*, 2019; Araus *et al.*, 2021).

Carbon dioxide is one of the substrates for plant photosynthesis. Its concentration changes affect the photosynthetic rate of plants (Stitt, 1991; Drake *et al.*, 1997; Kaiser *et al.*, 2015). The atmospheric CO_2 concentration is insufficient for C3 crops to reach their CO_2 saturation points. Therefore, an increase in environmental CO_2 concentration may enhance the photosynthesis of C3 crops, stimulating growth, development, and yield formation (Lawlor and Mitchell, 1991; Makino and Mae, 1999). However, the environmental CO_2 concentration is not positively correlated with crop productivity. The promoting effect of CO_2 on plant growth requires CO_2 concentration to be within a certain range (Engineer *et al.*, 2016; Tom-Dery *et al.*, 2018). Insufficient CO_2 can not induce an obviously positive effect, and excessive CO_2 may cause stress in crops, causing adverse effects on agricultural production. Therefore, determining the optimal amounts of CO_2 for application is very necessary for various regions.

Previous studies on the effects of environmental CO_2 concentration on crop growth and yield commonly used experimental platforms such as closed growth chambers, open-top chambers (OTC), and free-air CO_2 enrichment (FACE) (Xu *et al.*, 2015). Besides, most experiments were conducted in controlled environments. However, crop productivity is not entirely controlled by single environmental factors. Temperature, humidity, water supply, solar radiation, wind speed, as well as soil factors all affect crop productivity under field conditions and interact with CO_2 enrichment effects (Chiba and Terao, 2015; Sun *et al.*, 2017). Therefore, previous experimental results of the impact of increased CO_2 concentration on crops largely depend on the specific conditions and may not be applicable to the field environments (Dabros *et al.*, 2010). At the same time, there are no recommended CO_2 concentration ranges suitable for field environments (Miglietta *et al.*, 2001). Therefore, the response of crops to CO_2-related management measures still needs to be tested under field conditions.

In this study, under drip fertigation and film mulching, an optimized CO_2 regime that is suitable for field cotton production in Xinjiang, China was established. The main research objectives were to analyze (i) the impact of drip application of different concentrations of CO_2 solutions on the spatial distribution of CO_2 in cotton canopy, (ii) the response of cotton morphological, yield, and quality indicators to drip application of CO_2 solutions, and (iii) the optimal CO_2 concentration for cotton planting based on the yield. This study will provide a scientific basis for appropriate CO_2 application in cotton production under field conditions, and also provide an effective and promising way to enhance the carbon sequestration and ecological benefits of agricultural ecosystems.

Materials and Methods

Experimental area

The experimental area was located at the Agricultural Research Institute of Xinjiang Tianye Group in Shihezi City, Xinjiang, China (86°01'23"E, 44°21'13"N). The region was arid, with an annual average precipitation of 125.0 - 207.7 mm, a frost free period of 168 – 171 days, an annual average sunshine hours of 2300 - 2700, and an active accumulated temperature (⩾ 10 °C) of 3570 - 3729 °C. The soil texture was sandy loam. The physicochemical properties of the surface soil (0 - 20 cm) were as follows: The pH was 8.52, the electrical conductivity was 870.07 $\mu s\cdot cm^{-1}$, the alkaline hydrolyzed nitrogen content was 74.08 $mg\cdot kg^{-1}$, the available phosphorus content was 9.81 $mg\cdot kg^{-1}$, the available potassium content was 135.12 $mg\cdot kg^{-1}$, the organic matter content was 14.41 $g\cdot kg^{-1}$, and the inorganic carbon content was 21.07 $g\cdot kg^{-1}$. The test area and related setup are shown in Figure 1.

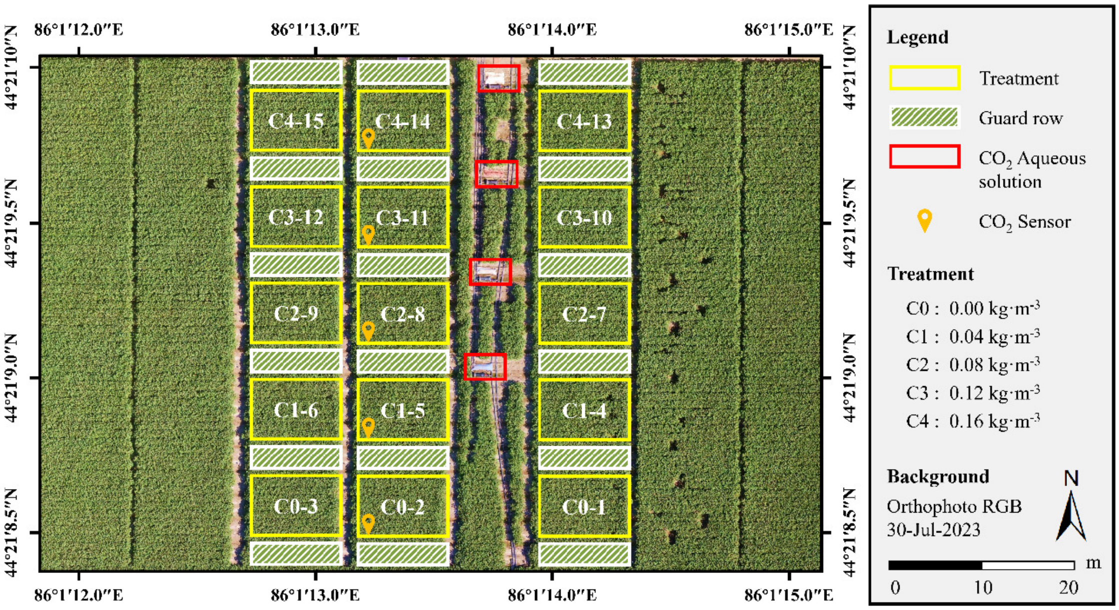

Figure 1. Experimental design

Experimental design

The effects of drip application of different concentrations of CO_2 solutions on crop growth and yield in the field under film mulching was explored. The physiological parameters, morphological indexes (relative chlorophyll content (SPAD), leaf area index (LAI), shoot biomass (AGB), and plant height), yield, and quality of cotton plants were measured during the whole growth period in the field under the condition of sufficient water supply (the field capacity was maintained at 70% - 75% to exclude the influence of water stress).

The cotton variety H219 (Xinjiang Bamian Seed Industry Co., Ltd., China), with a compact plant type, thick stems, less hairy, medium leaf size, and green leaf colour, was used in this experiment. Seeds were sown on April 21, 2023. Six cotton rows were irrigated by three drip tapes and mulched by one film. The row spacing was 10 cm + 66 cm + 10 cm, and the plant spacing was 10 cm. The planting area was 0.393 hectares. From June 20, 2023, when cotton entered the budding stage, drip application of CO_2 solutions through the drip irrigation system was carried out on all plots every seven days (ten times in total). The specific irrigation dates, the growth stages of cotton, and the important management events are detailed in Table 1.

Table 1. Field management details

Irrigation	**Date (2023)**	**Growth stage**	**Management event**
-	21 April	-	Sowing
-	13 May	Seedling stage	-
-	30 May	-	-
1st irrigation (T1)	20 June	Budding stage	-
2nd irrigation (T2)	27 June	-	-
-	01 July	-	-
3rd irrigation (T3)	04 July	-	-
-	10 July	Flowering stage	-
4th irrigation (T4)	11 July	-	-
-	13 July	-	Topping
5th irrigation (T5)	18 July	Peak flowering stage	-
6th irrigation (T6)	25 July	Peak bolling stage	-
7th irrigation (T7)	01 August	-	-
8th irrigation (T8)	08 August	-	-
9th irrigation (T9)	15 August	-	-
10th irrigation (T10)	22 August	-	-
-	23 August	Boll-opening stage	-
-	24 October	-	Harvesting

*Notes: The growth stages of cotton are judged based on 50% of the plants in the field reaching a certain standard

A total of five concentrations of CO_2 solutions were designed (Figure 1), i.e., C0 (0.00 $kg·m^{-3}$), C1 (0.04 $kg·m^{-3}$), C2 (0.08 $kg·m^{-3}$), C3 (0.12 $kg·m^{-3}$), and C4 (0.16 $kg·m^{-3}$). Each treatment had three plots, and there were a total of 15 plots. The width of the plot was 6.95 m, and the length was 10 m. The plot spacing was 2.5 m. To prepare property-stable and concentration-controllable CO_2 solutions in the field, a CO_2 solution generator was designed, installed, and debugged based on the principle of differential pressure method (Figure 2). The device was designed using the pressure relationship between the gas at the steel cylinder outlet and the irrigation water. When the irrigation water passed through the main tank of the device at a certain flow rate, the fast flow rate of the water reduced the pressure of the main tank, and the CO_2 gas from the aeration device inside the main tank was fully and uniformly dissolved in the water with the movement of water, realizing concentration control. Based on multiple equipment debugging, it was concluded that the device had a good CO_2 dissolution performance and was suitable for field irrigation under the conditions of water flow rate of 5 m^3/h, water pressure of 1 bar, and air pressure of 0.85 bar.

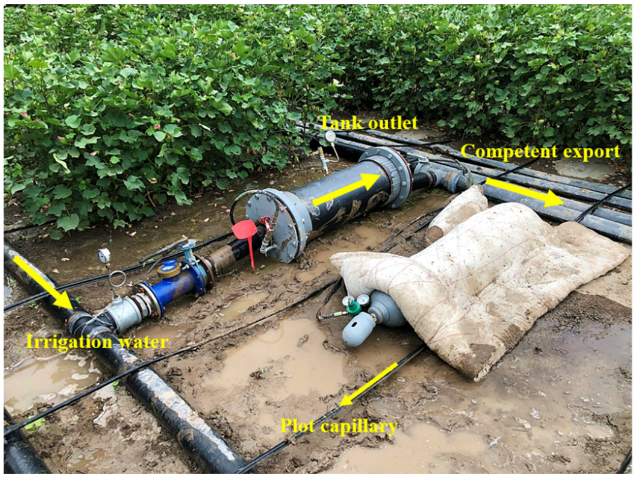

Figure 2. Field CO_2 solution generator

During each irrigation, the CO_2 dissolution was characterized by measuring the pH of water at different positions in the drip irrigation system. If the pH of water of each position decreased compared with that of the original irrigation water and could stabilize within a certain range, the CO_2 dissolution was valid. Figure 3 shows the water pH change of each position in the drip irrigation system under ten irrigation rounds. Other field management measures were carried out in accordance with those in the local farmlands.

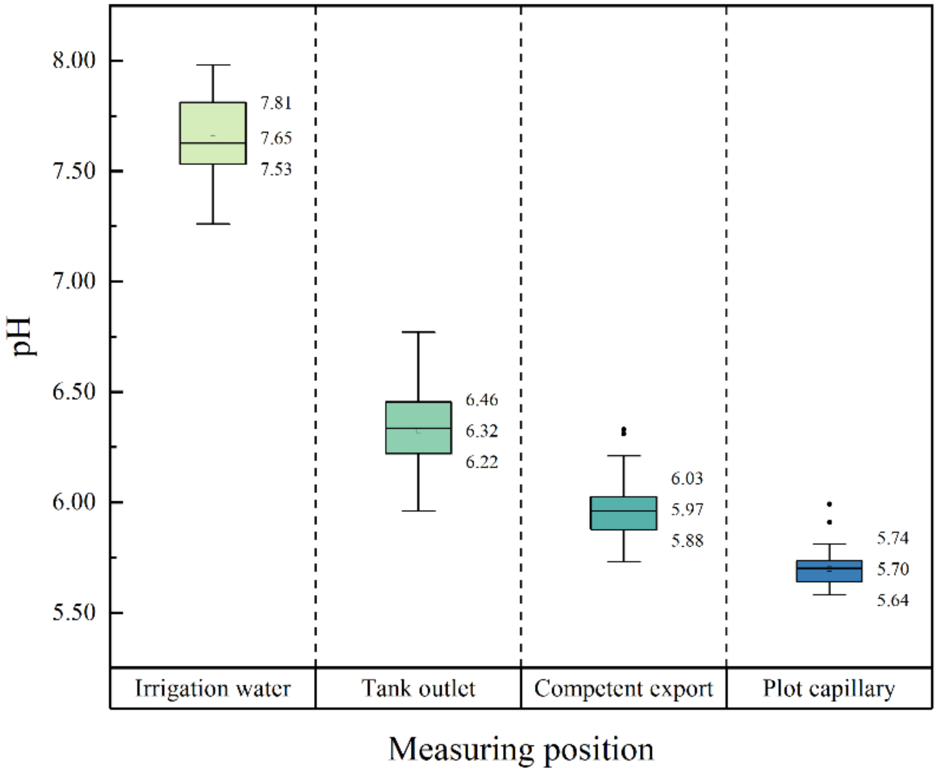

Figure 3. Water pH changes at various positions of the CO_2 increase system under ten irrigation rounds

Monitoring of CO_2 concentrations at different heights of the canopy

The CO_2 concentration of cotton canopy at different heights was measured in real time by RS-BYH-CO_2-M CO_2 meteorological multi-element sensor (Shandong Renke Measurement and Control Technology Co., Ltd., China), with a CO_2 concentration range of 0 - 1500 ppm and a resolution of 1 ppm. In the experiment, a CO_2 concentration monitoring point was set up for each treatment, and the heights included 20, 40, 60, 80, 100, and 150 cm in each monitoring point. The sampling interval was 30 min. The CO_2 concentration during six rounds of CO_2 solution application was monitored (T5, T6, T7, T8, T9, T10; July 18, 2023 - August 28, 2023) (Figure 4). According to the characteristics of cotton respiration and photosynthesis, combined with the environmental and geographical factors of the experimental area, the monitoring data of the period of 11:00 - 18:00 were processed and analyzed. The sliding mean filtering was used to detect the outliers in all data. The points greater than five times the standard deviation of the measured data were marked as outliers and eliminated, and data interpolation was completed by linear interpolation method.

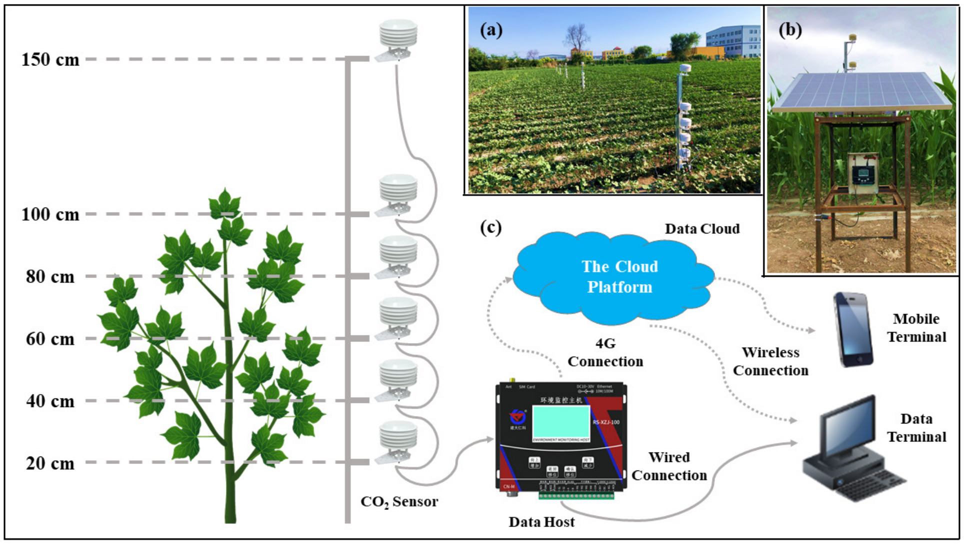

Figure 4. Carbon dioxide concentration at different heights of cotton canopy in the field (a) Layout of CO_2 sensors; (b) Carbon dioxide monitoring host; (c) The CO_2 concentration monitoring system (including CO_2 sensors, a monitoring host, a cloud platform for data storage, a computer, and a mobile phone for data display)

Collection of growth parameters of cotton plants

The growth parameters selected for this study were relative chlorophyll content (SPAD), leaf area index (LAI), shoot biomass (AGB), and plant height. The SPAD of cotton plants was measured by SPAD-502Plus Chlorophyll Meter (Konica Minolta, Japan). The LAI of cotton fields was measured by LAI-2200C Plant Canopy Analyzer (LI-COR Environmental, United States). The measurement range of biomass and plant height was from the cotyledon node of cotton plant to the top of the main stem, which is the natural growth point. Through the monitoring and analysis of these parameters, the effects of different concentrations of CO_2 solutions on the growth and development of cotton were explored. Data collection was performed on all cotton plants from the budding stage (20 June, 2023). Based on the irrigation interval (7 days), on the 6th day after each drip application of CO_2 solutions, three cotton plants were selected from each plot, and the shoots were used for measurements. Data were collected ten times in total (26 June, 3 July, 10 July, 17 July, 24 July, 31 July, 7 August, 14 August, 21 August, and 28 August).

Determination of cotton yield and quality

At the harvest stage, the quadrats of 1.0 m × 2.2 m were randomly selected in each plot to measure the yield indices, including single boll weight, boll density, and lint yield. After that, 10 g of lint samples collected in each plot were used to determine the cotton quality indices, including lint percent, fibre length, fibre strength, and micronaire value (n = 3).

$$LY = BW \times 10^{-3} \times BD \times 10^{5} \times LP \times CF \tag{1}$$

Where LY is the lint yield ($kg{\cdot}ha^{-1}$), BW is the boll weight (g), BD is the boll density ($boll{\cdot}m^{-2}$), LP is the lint percent (%), CF is the correction factor (0.9).

Statistical analysis

Data analysis was completed in SPSS 26.0, and one-way analysis of variance was used to evaluate the significance of differences in cotton growth (SPAD, LAI, AGB, plant height), yield (single-boll weight, boll density, lint yield), and quality indicators (lint percent, fibre length, fibre strength, and micronaire value) between different CO_2 solution treatments ($p < 0.05$). If there was a significant difference between the treatments, multiple comparisons were then performed by the Duncan's test, and the significance of the differences was expressed by letters a, b, c, and d. Data visualization was completed in Origin 2023. The dynamic changes of cotton growth indicators were displayed through the bar charts, with the error bar representing the mean ± standard deviation (Mean ± SD).

Results

Effect of drip application of CO_2 solutions on the spatial distribution characteristics of CO_2 concentration in cotton canopy

The CO_2 concentration in the cotton canopy was significantly increased after drip application of CO_2 solutions. The canopy CO_2 concentration did not change significantly on the day of drip application of CO_2 solutions. From the 2nd to the 4th day, the canopy CO_2 concentration increased greatly, and reached the peak on the 4th day. From the 5th to the 7th day, the CO_2 concentration at each height of the canopy gradually decreased, and finally reached to the value under normal atmospheric conditions (Figure 5).

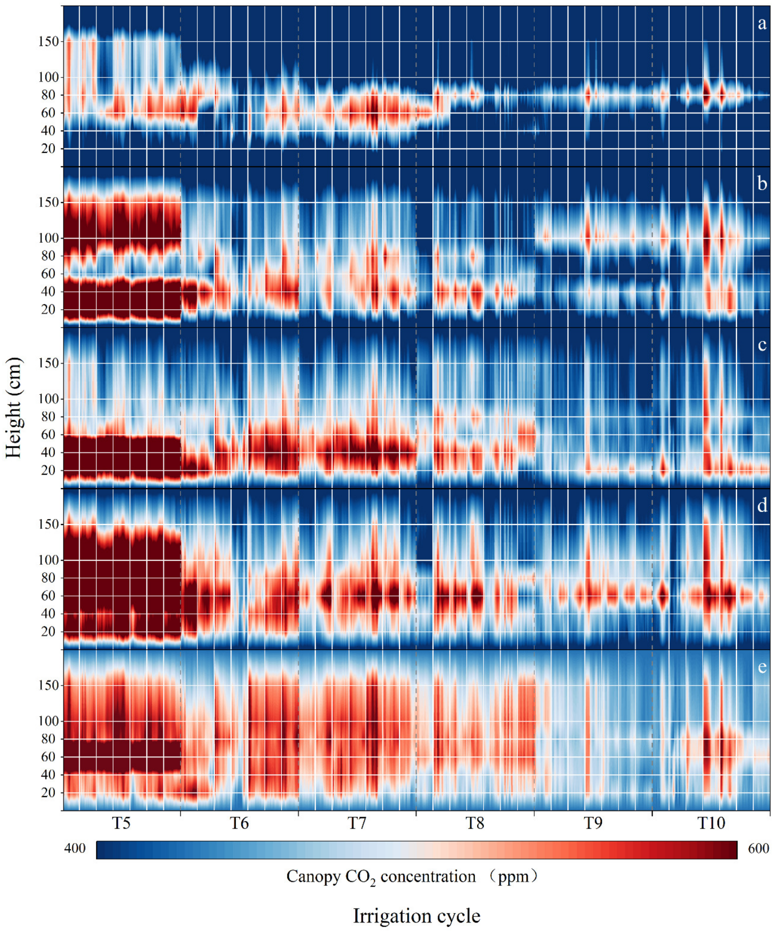

Figure 5. Distribution of CO_2 concentration in cotton canopy under different concentrations of CO_2 solution treatment in the 5th - 10th rounds. (a) C0, 0.00 kg·m^{-3} CO_2 solution treatment; (b) C1, 0.04 kg·m^{-3} CO_2 solution treatment; (c) C2, 0.08 kg·m^{-3} CO_2 solution treatment; (d) C3, 0.12 kg·m^{-3} CO_2 solution treatment; (e) C4, 0.16 kg·m^{-3} CO_2 solution treatment

Drip application of different concentrations of CO_2 solutions did not significantly affect the peak concentration of CO_2 gas in the cotton canopy. The peak CO_2 concentration under drip application of CO_2 solutions was 168 - 184 ppm higher than that in the normal atmospheric conditions (400 ppm). However, the vertical distribution of CO_2 and the uniformity of CO_2 distribution changed significantly with the increase of the concentration of CO_2 solution. The CO_2 was concentrated in the height of 50 - 70 cm in the canopy under conventional irrigation (C0), while the C4 treatment showed a higher CO_2 concentration in the height of 20 - 150 cm compared with other treatments, and had a more uniform CO_2 distribution.

Effect of drip application of CO_2 solutions on the growth and development of cotton

Relative chlorophyll content (SPAD)

For all treatments, the SPAD values of the top four leaves on the main stem of plants gradually increased over time, and decreased after reaching the maximum value (Figure 6). The SPAD value of the C0, C1, C2, C3, and C4 treatments reached the maximum at T9, T9, T8, T10, and T8, respectively. The difference between the CO_2 solution treatments gradually increased since T2. The SPAD value of the C0 treatment was the largest, and the difference was significant between the CO_2 solution treatments ($p < 0.05$), that is, the drip application of CO_2 solutions led to significantly lower SPAD values of the top four leaves on main stem of cotton compared with the control.

It is worth noting that there was no significant difference between the CO_2 solution treatments at T1. The drip application of CO_2 solutions did not immediately change the SPAD value of the top four leaves, but caused a significant difference between the treatments after T2, that is, the CO_2 increase had a lag effect on cotton leaf SPAD values.

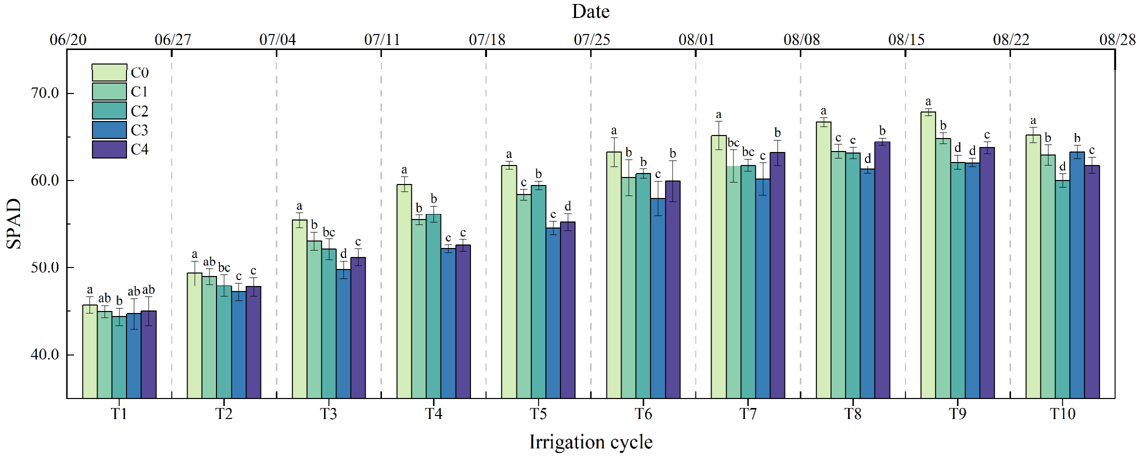

Figure 6. Effects of different concentrations of CO_2 solutions on the SPAD of the top four leaves on the main stem of cotton. All data are mean ± SD (n = 9). Different lowercase letter indicate significant difference between treatments (Duncan test, $p < 0.05$)

Leaf area index (LAI)

The CO_2 solution treatments led to higher LAI values of cotton compared with that of the control. The LAI increased and then decreased with the increase of CO_2 concentration, peaking at C3 (Figure 7). With the growth of cotton, the LAI of the CO_2 solution treatments reached the maximum value at T7, and the LAI of the C3 treatment was 34.28% higher than that of the C0 treatment at T7 ($p < 0.05$). It should be noted that there was also a lagging effect, that is, significant differences in the LAI between the CO_2 solution treatments and the control were observed since T4.

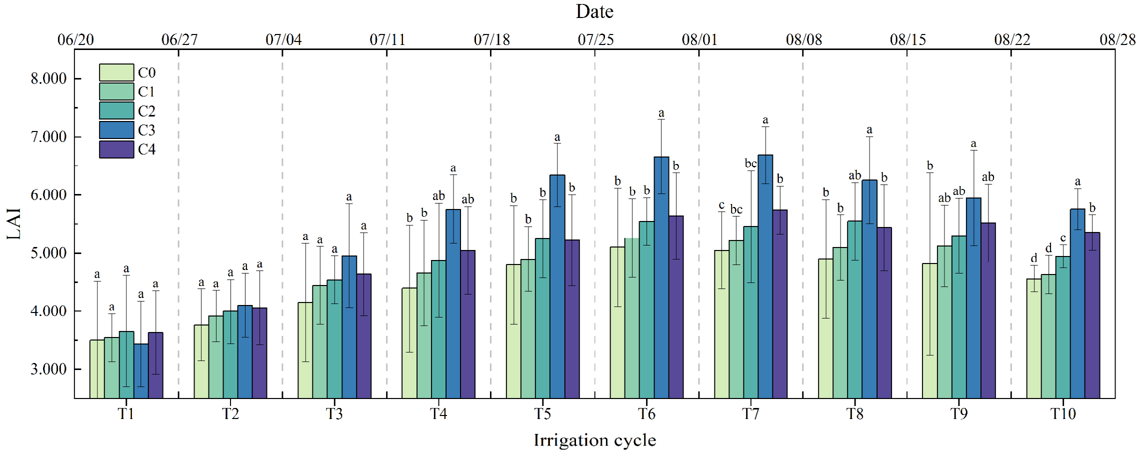

Figure 7. Effects of different concentrations of CO_2 solutions on the LAI of cotton. All data are mean ± SD (n = 9). Different lowercase letter indicate significant difference between treatments (Duncan test, $p < 0.05$)

Shoot biomass (AGB)

The ten rounds of drip application of CO_2 solutions led to higher AGBs of cotton compared with the control (Figure 8). However, there was no difference in AGB between the C0 and CO_2 solution treatments at T1 and T2 ($p > 0.05$). Besides, the CO_2 solution treatments except for C3 also had no difference in the AGB from the C0 treatment at T3 ($p > 0.05$). From T4 to T10, the CO_2 solution treatments had difference from the C0 treatment ($p < 0.05$). Different concentrations of CO_2 solutions had different impacts on the AGB accumulation. From T4 when the C0 treatment was significantly different from the CO_2 solution treatments in the AGB ($p < 0.05$), the C3 treatment had the strongest impact on the AGB, i.e., the AGB was 58.37% - 91.61% higher than that of C0 (Figure 8). Besides, the C2 treatment had the weakest effect on the AGB, with the AGB 18.64% - 34.88% higher than that of C0.

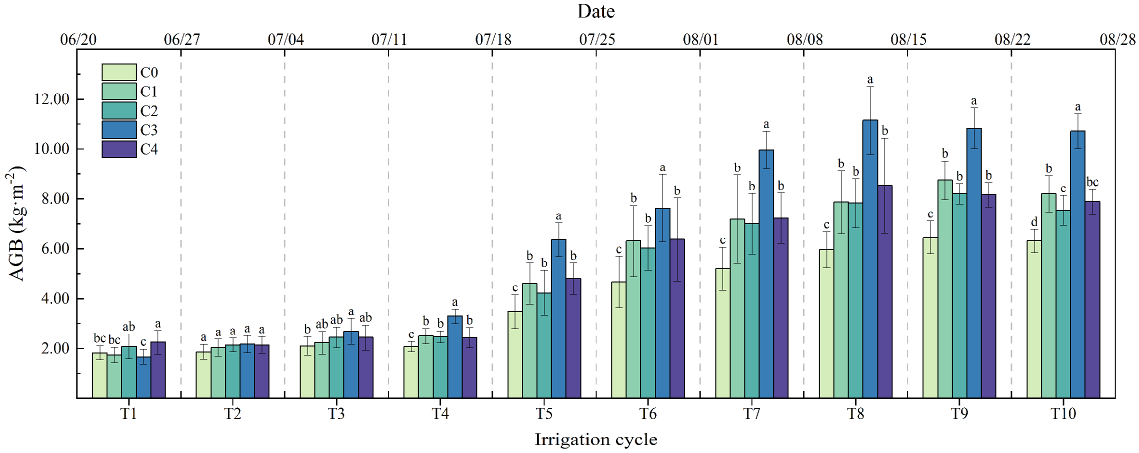

Figure 8. Effects of different concentrations of CO_2 solutions on the AGB of cotton. All data are mean ± SD (n = 9). Different lowercase letter indicate significant difference between treatments (Duncan test, $p < 0.05$)

Plant height

Drip application of CO_2 solutions led to higher plant heights of cotton compared with the control (Figure 9). At T1 and T2, there was no difference in plant height among C0, C1, C2, C3, and C4 treatments

($p > 0.05$). From T3 to T5, the plant height difference between the CO_2 solution treatments and the C0 treatment occurred and gradually expanded. From T6 to T10, the plant height of all treatments stabilized due to topping. At T10, the average plant height of the C0, C1, C2, C3, and C4 treatment was 85.0, 89.8, 94.6, 109.5, and 91.7 cm, respectively. Therefore, the impacts of different concentrations of CO_2 solutions on plant height were different, and the C3 treatment had the strongest effect on cotton height growth, with the plant height 28.82% ($p < 0.05$) higher than that of C0.

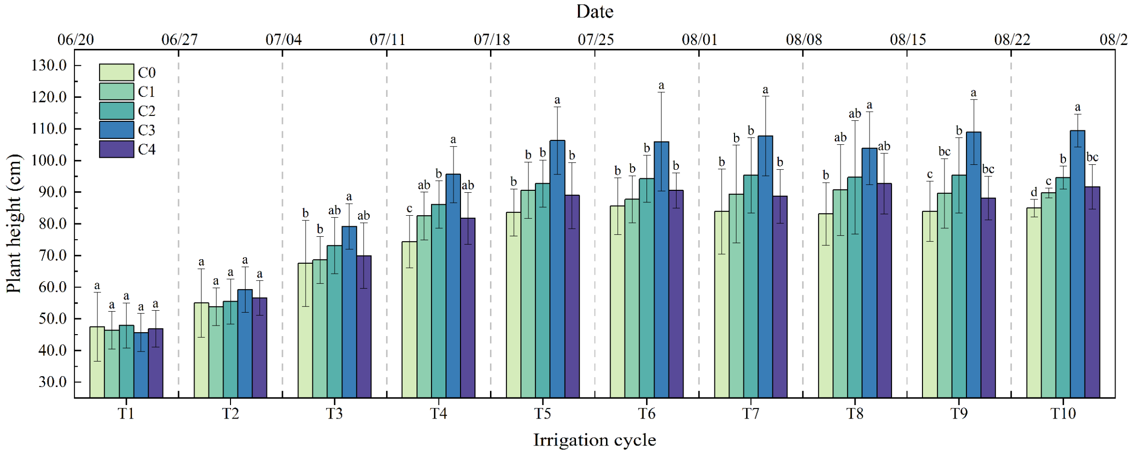

Figure 9. Effects of different concentrations of CO_2 solutions on plant height of cotton. All data are mean ± SD (n = 9). Different lowercase letter indicate significant difference between treatments (Duncan test, $p < 0.05$)

Effects of drip application of CO_2 solutions on yield and quality of cotton

Yield

There were difference in the lint yield between treatments ($p < 0.05$) (Table 2). The lint yield of cotton of the C1 and C2 treatments was 1.9% and 8.4% higher than that of C0, respectively ($p < 0.05$), but the lint yield of the C3 and C4 treatments was 13.4% and 5.4% lower than that of C0, respectively ($p < 0.05$). That is, the lint yield of the C2 treatment was the highest, while that of the C3 treatment was the lowest.

Table 2. Effects of drip application of different concentrations of CO_2 solutions on cotton yield components

Treatment	**Boll weight (g)**	**Boll density ($boll \cdot m^{-2}$)**	**Lint yield ($kg \cdot ha^{-1}$)**
C0	4.2 ± 0.4 a	133.9 ± 2.0 bc	2565 ± 46 c
C1	4.1 ± 0.6 b	140.0 ± 3.7 b	2614 ± 93 b
C2	3.9 ± 0.3 c	153.6 ± 3.5 a	2782 ± 46 a
C3	4.0 ± 0.4 bc	126.1 ± 5.9 c	2221 ± 79 e
C4	4.3 ± 0.3 a	125.5 ± 2.3 c	2427 ± 40 d

*Notes: C0, 0.00 $kg \cdot m^{-3}$ CO_2 solution; C1, 0.04 $kg \cdot m^{-3}$ CO_2 solution; C2, 0.08 $kg \cdot m^{-3}$ CO_2 solution; C3, 0.12 $kg \cdot m^{-3}$ CO_2 solution; C4, 0.16 $kg \cdot m^{-3}$ CO_2 solution. All data are mean ± SE (n = 3). Different lowercase letter indicate significant difference between treatments ($p < 0.05$)

In addition, CO_2 solution treatments also had an impact on the boll density of cotton. The boll density of cotton of the C1 and C2 treatments was 4.5% and 14.7% higher than that of C0, respectively ($p < 0.05$), but the boll density of the C3 and C4 treatments was 5.9% and 6.3% lower than that of C0, respectively ($p < 0.05$). On the whole, the boll density increased first and then decreased with the increase of the CO_2 concentration, and reached the maximum value at C2.

The impact of CO_2 solution treatments on the single boll weight of cotton was opposite to that on boll density. The average single boll weight decreased first and then increased with the increase of the concentration of the CO_2 solution. The minimum value was observed at C2, which was 7.1% lower than that of C0 ($p < 0.05$). The single boll weight of the C4 treatment was the largest, but there was no difference between the C4 and C0 treatment ($p > 0.05$).

Overall, the C1 and C2 treatments had lower single boll weight but higher boll number compared with the control, allowing higher yield. Although the C3 and C4 treatments had higher single boll weight, they also had lower boll density, leading to lower yield compared with the control. Under the experimental conditions in this study, the C2 treatment had the strongest yield-improvement effect.

Quality

There was no difference in fibre length and fibre strength between different treatments ($p > 0.05$) (Table 3). At the same time, there was little difference in the micronaire values between different treatments, and all of them remained in the range of 3.5 – 3.9. The lint percent of the C1 and C2 treatments was 0.75% and 2.23% higher than that of C0, respectively, but the lint percent of the C3 and C4 treatments was 1.67% and 0.36% lower than that of C0, respectively. The effects of all CO_2 solution treatments on the lint percent was weak, and the lint percent remained at 45.0 ± 1.3% in all treatments. The CO_2 solution treatments except for C2 had no difference in lint percent compared with the C0 treatment ($p > 0.05$).

Table 3. Effects of drip application of different concentrations of CO_2 solutions on cotton quality indicators

Treatment	Lint percent (%)	Fiber length (mm)	Fiber strength ($cN\cdot tex^{-1}$)	Micronaire value
C0	45.1 ± 0.3 bc	31.0 ± 0.2 b	29.6 ± 0.7 a	3.5 ± 0.2 b
C1	45.4 ± 0.3 ab	31.2 ± 0.3 ab	29.7 ± 0.5 a	3.6 ± 0.1 ab
C2	46.1 ± 0.2 a	31.3 ± 0.3 ab	30.6 ± 0.7 a	3.5 ± 0.1 b
C3	44.3 ± 0.3 c	32.0 ± 0.2 a	31.3 ± 0.4 a	3.6 ± 0.1 ab
C4	44.9 ± 0.3 bc	31.8 ± 0.3 ab	30.9 ± 0.7 a	3.9 ± 0.1 a

*Notes: All data are mean ± SE (n = 9). Different lowercase letter indicate significant difference between treatments ($p < 0.05$)

In summary of these results, the drip application of CO_2 solutions had little effect on the quality indices of cotton, and the quality indices of all treatments were maintained within an ideal range.

Discussion

Drip application of CO_2 solutions induced slow release of soil CO_2, maintaining a high CO_2 concentration in the environment for a long time

This study found that after drip application of CO_2 solutions, the CO_2 concentration in the cotton canopy did not change immediately (Figure 5). After a period of time, the canopy CO_2 concentration first increased and then gradually decreased to the atmospheric CO_2 concentration. This may be due to the fact that most of the CO_2 is fixed by the soil in the initial period after drip application of CO_2 solutions. The CO_2 gradually releases from soil and affects the distribution of CO_2 in the canopy (Hagedorn *et al.*, 2003; Manning and Renforth, 2013; He *et al.*, 2015). That is, the drip application of CO_2 solutions induced about 3 - 5 days of slow release of soil CO_2, and the peak of CO_2 release was reached on the 3rd - 4th day. At the field level, the absorption of CO_2 solutions by soil and the slow release of CO_2 from soil can improve the CO_2 use efficiency (Zhang *et al.*, 2014; Fong *et al.*, 2020). This prevents the escape of large amounts of CO_2 from the solution at the beginning of the drip application, and also protects crops from the stress of high environmental CO_2 concentration (He *et al*., 2021; Xue *et al*., 2021), allowing more CO_2 to be absorbed and utilized by plant photosynthesis for a long duration (Yang *et al*., 2014; Luo *et al*., 2015).

Biological and economic yield balance is an important means to increase cotton yield

The analysis of the yield data found that the lint yield of the C3 treatment with a strong growth promotion effect was the lowest, while that of the C2 treatment with a moderate growth promotion effect was the highest. This phenomenon is related to the growth and development characteristics of cotton. Cotton has a long growth period, with the vegetative and reproductive parallel-growth stage lasts for a long time (Constable and Bange, 2015). Therefore, during the whole growth period, the nutrient demand of cotton plants is large, and the nutrient competition in various tissues and organs is fierce, resulting in vigorous growth but low yield (Reddy *et al*., 2004).

The differentiation of flower buds of cotton plants marks the beginning of reproductive growth, entering the budding stage where vegetative growth and reproductive growth are parallel until the boll-opening stage (Silvertooth *et al*., 1996). During this parallel-growth stage, vegetative growth provides the necessary substances and nutrients for reproductive growth. However, over vegetative growth causes the stems and leaves to get most of the nutrients, reducing the supply of nutrients to reproductive organs (Khan *et al*., 2020; Pabuayon *et al*., 2021). For example, usually when LAI is within a certain range, the yield of cotton increases with the increase of LAI (Yao *et al*., 2016). However, when LAI increases to a certain value, the complex canopy structure may lead to an increase in the limitation in water vapor exchange in the canopy and a decrease in the photosynthetically active radiation obtained by the middle and lower leaves, reducing the overall photosynthetic efficiency of cotton plants and yield (Li *et al*., 2020; Chen *et al*., 2021). Similarly, the significant increases in AGB and plant height also indicate that the vegetative growth of cotton is too vigorous under C3 treatment, which inhibits the reproductive growth and yield formation.

Vegetative growth and reproductive growth promote and also restrain each other. Cotton yield can be increased by drip application of CO_2 solution at appropriate concentrations, that is, optimizing field management measures to balance the relationship between vegetative growth and reproductive growth in combination with the characteristics of cotton growth and development and optimize the canopy structure. This can improve the carbon assimilation of cotton plants, improve the CO_2 use efficiency, and finally obtain high yields (Zhou *et al*., 2024; Feng *et al*., 2024).

Conclusions

This study examined the effects of drip irrigation with CO_2 solutions at different concentrations on cotton field growth, yield, and canopy CO_2 concentrations under real-world field production conditions. The results indicate: (i) Drip application of CO_2 solutions induced slow release of CO_2 from the soil, and significantly increased the CO_2 concentration and uniformity in the cotton canopy. (ii) This application method enhances nutrient utilization efficiency in cotton and accelerates plant growth. Among the treatments, the C3 group achieved the most significant promotion of vegetative growth, while the C2 group yielded the highest lint cotton output without compromising fibre quality. (iii) Based on practical production requirements, under these experimental conditions, 0.08 $kg\cdot m^{-3}$ represents the optimal concentration for drip application of CO_2 aqueous solution in cotton fields.

In subsequent studies, CO_2 management will be integrated with agronomic practices such as water and nutrient management to investigate the patterns of CO_2 demand in cotton fields during different growth stages. More precise CO_2 management will enhance resource utilization efficiency while achieving cost savings and increased productivity in cotton production.

Authors' Contributions

Conceptualization: HR; Data curation: MY, YRM; Formal analysis: ZLZ; Funding acquisition: ZZ; Investigation: LCL, DEM, YW; Methodology: ZZ; Project administration: JLW; Resources: ZZ, JLW; Supervision: ZZ; Validation: YW; Visualization: HR, YRM; Writing - original draft: HR, MY; and Writing - review & editing: HR, ZZ. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

Acknowledgements

This work was supported by the Xinjiang Production and Construction Corps Major Science and Technology Program, grant number (2023AB017); Tianshan Talents Project of autonomous region (2022TSYCCX0118); and The Corps Leading Talent Project (Xin Lv).

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

References

Araus JL, Sanchez-Bragado R, Vicente R (2021). Improving crop yield and resilience through optimization of photosynthesis: Panacea or pipe dream? Journal of Experimental Botany 72:3936-3955. *https://doi.org/10.1093/jxb/erab097*

Bailey-Serres J, Parker JE, Ainsworth EA, Oldroyd GED, Schroeder JI (2019). Genetic strategies for improving crop yields. Nature 575:109-118. *https://doi.org/10.1038/s41586-019-1679-0*

Brodrick R, Bange MP, Milroy SP, Hammer GL (2013). Physiological determinants of high yielding ultra-narrow row cotton: Canopy development and radiation use efficiency. Field Crops Research 148:86-94. *https://doi.org/10.1016/j.fcr.2012.05.008*

China Cotton Association (2024). The ninth session of the fourth council Xuhong Su: the development of Xinjiang cotton industry. Retrieved 2024 March 15 from *https://www.china-cotton.org/app/html/2024/03/19/96757.html*

Chen M, Liang F, Yan Y, Wang Y, Zhang Y, Tian J, … Zhang W (2021). Boll-leaf system gas exchange and its application in the analysis of cotton photosynthetic function. Photosynthesis Research 150:251-262. *https://doi.org/10.1007/s11120-021-00856-w*

Chen Z, Niu Y, Zhao R, Han C, Han H, Luo H (2019). The combination of limited irrigation and high plant density optimizes canopy structure and improves the water use efficiency of cotton. Agricultural Water Management 218:139-148. *https://doi.org/10.1016/j.agwat.2019.03.037*

Chiba M, Terao T (2015). Open-top chambers with solar-heated air introduction tunnels for the high-temperature treatment of paddy fields. Plant Production Science 17:152-165. *https://doi.org/10.1626/pps.17.152*

Constable GA, Bange MP (2015). The yield potential of cotton (*Gossypium hirsutum* L.). Field Crops Research 182:98-106. *https://doi.org/10.1016/j.fcr.2015.07.017*

Dabros A, Fyles JW, Strachan IB (2010). Effects of open-top chambers on physical properties of air and soil at post-disturbance sites in northwestern Quebec. Plant and Soil 333:203-218. *https://doi.org/10.1007/s11104-010-0336-z*

Dai J, Li W, Tang W, Zhang D, Li Z, Lu H, … Dong H (2015). Manipulation of dry matter accumulation and partitioning with plant density in relation to yield stability of cotton under intensive management. Field Crops Research 180:207-215. *https://doi.org/10.1016/j.fcr.2015.06.008*

Dai J, Dong H (2014). Intensive cotton farming technologies in China: Achievements, challenges and countermeasures. Field Crops Research 155:99-110. *https://doi.org/10.1016/j.fcr.2013.09.017*

Drake BG, Gonzàlez-Meler MA, Long SP (1997). More efficient plants: A consequence of rising atmospheric CO_2? Annual Review of Plant Physiology and Plant Molecular Biology 48:609-639. *https://doi.org/10.1146/annurev.arplant.48.1.609*

Engineer CB, Hashimoto-Sugimoto M, Negi J, Israelsson-Nordström M, Azoulay-Shemer T, Rappel W, … Schroeder J (2016). CO_2 sensing and CO_2 regulation of stomatal conductance: Advances and open questions. Trends in Plant Science 21:16-30. *https://doi.org/10.1016/j.tplants.2015.08.014*

Feng L, Wan S, Zhang Y, Dong H (2024). Xinjiang cotton: Achieving super-high yield through efficient utilization of light, heat, water, and fertilizer by three generations of cultivation technology systems. Field Crops Research 312:109401. *https://doi.org/10.1016/j.fcr.2024.109401*

Fong BN, Reba ML, Teague TG, Runkle BRK, Suvočarev K (2020). Eddy covariance measurements of carbon dioxide and water fluxes in US mid-south cotton production. Agriculture, Ecosystems and Environment 292:106813. *https://doi.org/10.1016/j.agee.2019.106813*

Hagedorn F, Spinnler D, Bundt M, Blaser P, Siegwolf R (2003). The input and fate of new C in two forest soils under elevated CO_2. Global Change Biology 9:862-872. *https://doi.org/10.1046/j.1365-2486.2003.00638.x*

He W, Yoo G, Ryu Y (2021). Evaluation of effective quantum yields of photosystem II for CO_2 leakage monitoring in carbon capture and storage sites. PeerJ 9:e10652. *https://doi.org/10.7717/peerj.10652*

He Y, Siemens J, Amelung W, Goldbach H, Wassmann R, Alberto MCR, … Lehndorff E (2015). Carbon release from rice roots under paddy rice and maize–paddy rice cropping. Agriculture, Ecosystems and Environment 210:15-24. *https://doi.org/10.1016/j.agee.2015.04.029*

Jans Y, Bloh WV, Schaphoff S, Müller C (2021). Global cotton production under climate change - Implications for yield and water consumption. Hydrology and Earth System Sciences 25:2027-2044. *https://doi.org/10.5194/hess-25-2027-2021*

Kaiser E, Morales A, Harbinson J, Kromdijk J, Heuvelink E, Marcelis LFM (2015). Dynamic photosynthesis in different environmental conditions. Journal of Experimental Botany 66:2415-2426. *https://doi.org/10.1093/jxb/eru406*

Khan N, Han Y, Xing F, Feng L, Wang Z, Wang G, … Li Y (2020). Plant density influences reproductive growth, lint yield and boll spatial distribution of cotton. Agronomy 10(1):14. *https://doi.org/10.3390/agronomy10010014*

Lawlor DW, Mitchell RAC (1991). The effects of increasing CO_2 on crop photosynthesis and productivity: A review of field studies. Plant, Cell and Environment 14:807-818. *https://doi.org/10.1111/j.1365-3040.1991.tb01444.x*

Li N, Lin H, Wang T, Li Y, Liu Y, Chen X, Hu X (2020). Impact of climate change on cotton growth and yields in Xinjiang, China. Field Crops Research 247:107590. *https://doi.org/10.1016/j.fcr.2019.107590*

Luo Q, Bange M, Johnston D, Braunack M (2015). Cotton crop water use and water use efficiency in a changing climate. Agriculture, Ecosystems and Environment 202:126-134. *https://doi.org/10.1016/j.agee.2015.01.006*

Makino A, Mae T (1999). Photosynthesis and plant growth at elevated levels of CO_2. Plant and Cell Physiology 40:999-1006. *https://doi.org/10.1093/oxfordjournals.pcp.a029493*

Manning DAC, Renforth P (2013). Passive sequestration of atmospheric CO_2 through coupled plant-mineral reactions in urban soils. Environmental Science and Technology 47:135-141. *https://doi.org/10.1021/es301250j*

Miglietta F, Peressotti A, Vaccari FP, Zaldei A, DeAngelis P, Scarascia-Mugnozza G (2001). Free-air CO_2 enrichment (FACE) of a poplar plantation: the POPFACE fumigation system. New Phytologist 150:465-476. *https://doi.org/10.1046/j.1469-8137.2001.00115.x*

National Bureau of Statistics of China (2023). Announcement of the national bureau of statistics on cotton production in 2023. Retrieved 2024 March 15 from *https://www.stats.gov.cn/sj/zxfb/202312/t20231225_1945745.html*

Pabuayon ILB, Kelly BR, Mitchell-McCallister D, Coldren CL, Ritchie GL (2021). Cotton boll distribution: A review. Agronomy Journal 113:956-970. *https://doi.org/10.1002/agj2.20516*

Reddy KR, Koti S, Davidonis GH, Reddy VR (2004). Interactive effects of carbon dioxide and nitrogen nutrition on cotton growth, development, yield, and fiber quality. Agronomy Journal 96:1148-1157. *https://doi.org/10.2134/agronj2004.1148*

Silvertooth JC, Norton ER, Brown PW (1996). Cotton growth and development patterns. Cotton: A College of Agriculture Report 370103:75-97. doi: *http://hdl.handle.net/10150/210757*

Stitt M (1991). Rising CO_2 levels and their potential significance for carbon flow in photosynthetic cells. Plant, Cell and Environment 14:741-762. *https://doi.org/10.1111/j.1365-3040.1991.tb01440.x*

Sun J, Xia Z, He T, Dai W, Peng B, Liu J, … Bai E (2017). Ten years of elevated CO_2 affects soil greenhouse gas fluxes in an open top chamber experiment. Plant and Soil 420:435-450. *https://doi.org/10.1007/s11104-017-3414-7*

Tom-Dery D, Eller F, Jensen K, Reisdorff C (2018). Effects of elevated carbon dioxide and climate change on biomass and nutritive value of Kyasuwa. Journal of Applied Botany and Food Quality 91:88-95. *https://doi.org/10.5073/JABFQ.2018.091.012*

Xu Z, Jiang Y, Zhou G (2015). Response and adaptation of photosynthesis, respiration, and antioxidant systems to elevated CO_2 with environmental stress in plants. Frontiers in Plant Science 6:701. *https://doi.org/10.3389/fpls.2015.00701*

Xue L, Ma J, Hu Q, Cheng M, Wen X, Wu N, … Ma J (2021). Identification of CO_2 leakage from geological storage based on maize spectral characteristic indexes. International Journal of Greenhouse Gas Control 112:103342. *https://doi.org/10.1016/j.ijggc.2021.103342*

Yang Y, Yang Y, Han S, Macadam I, Liu DL (2014). Prediction of cotton yield and water demand under climate change and future adaptation measures. Agricultural Water Management 144:42-53. *https://doi.org/10.1016/j.agwat.2014.06.001*

Yao H, Zhang Y, Yi X, Zhang X, Zhang W (2016). Cotton responds to different plant population densities by adjusting specific leaf area to optimize canopy photosynthetic use efficiency of light and nitrogen. Field Crops Research 188:10-16. *https://doi.org/10.1016/j.fcr.2016.01.012*

Zhang Q, Yang L, Xu Z, Zhang Y, Luo H, Wang J, Zhang W (2014). Effects of cotton field management practices on soil CO_2 emission and C balance in an arid region of Northwest China. Journal of Arid Land 6:468-477. *https://doi.org/10.1007/s40333-014-0003-y*

Zhou Y, Li F, Xin Q, Li Y, Lin Z (2024). Historical variability of cotton yield and response to climate and agronomic management in Xinjiang, China. Science of the Total Environment 912:169327. *https://doi.org/10.1016/j.scitotenv.2023.169327*

Zuo W, Wu B, Wang Y, Xu S, Chen, M., Liang F, … Zhang W (2024). Optimal row spacing configuration to improve cotton yield or quality is regulated by plant density and irrigation rate. Field Crops Research 305:109187. *https://doi.org/10.1016/j.fcr.2023.109187*

Zuo W, Wu B, Wang Y, Xu S, Tian J, Jiu X, … Zhang W (2023). Optimal planting pattern of cotton is regulated by irrigation amount under mulch drip irrigation. Frontiers in Plant Science 14:1158329. *https://doi.org/10.3389/fpls.2023.1158329*

The journal offers free, immediate, and unrestricted access to peer-reviewed research and scholarly work. Users are allowed to read, download, copy, distribute, print, search, or link to the full texts of the articles, or use them for any other lawful purpose, without asking prior permission from the publisher or the author.

License - Articles published in ***Notulae Botanicae Horti Agrobotanici Cluj-Napoca*** are Open-Access, distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) License.
© Articles by the authors; Licensee UASVM and SHST, Cluj-Napoca, Romania. The journal allows the author(s) to hold the copyright/to retain publishing rights without restriction.

Notes:

- Material disclaimer: The authors are fully responsible for their work and they hold sole responsibility for the articles published in the journal.
- Maps and affiliations: The publisher stay neutral with regard to jurisdictional claims in published maps and institutional affiliations.
- Responsibilities: The editors, editorial board and publisher do not assume any responsibility for the article's contents and for the authors' views expressed in their contributions. The statements and opinions published represent the views of the authors or persons to whom they are credited. Publication of research information does not constitute a recommendation or endorsement of products involved.