Effects of Enhanced UV-B Radiation Throughout the Full Growth Period on Cotton Growth and Photosynthesis (Postprint)

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Date: 2017-11-09T00:00:00+00:00

Abstract

The plant photosynthetic system is the primary and most important target of UV-B radiation. This study conducted UV lamp irradiation treatments under field conditions to investigate the effects of enhanced UV-B radiation (20% and 40% above ambient levels) throughout the entire growth period on cotton morphology, dry matter accumulation, photosynthetic pigments, and yield, and to explore the mechanisms by which enhanced UV-B radiation affects cotton photosynthesis through analysis of gas exchange parameters and chlorophyll fluorescence parameters in functional leaves on the main stem. The results showed that enhanced UV-B radiation inhibited cotton growth and dry matter accumulation, significantly reduced seed cotton yield, and the inhibitory effect became more pronounced with increasing UV-B radiation intensity. With increasing UV-B radiation intensity, the net photosynthetic rate (Pn) of functional leaves on the cotton main stem decreased significantly at all growth stages, chlorophyll content showed a trend of first increasing then decreasing, stomatal conductance (Gs) and transpiration rate (Tr) remained unchanged, while intercellular CO2 concentration (Ci) instead increased, indicating that the decline in Pn was primarily caused by non-stomatal limiting factors. Analysis of chlorophyll fluorescence parameters revealed that the maximum photochemical quantum yield of PS (Fv/Fm), actual photochemical quantum efficiency (ΦPSII), linear electron transport rate (ETR), and photochemical quenching coefficient (qP) decreased with increasing UV-B radiation intensity, while the non-photochemical quenching coefficient (NPQ) significantly increased, and all chlorophyll fluorescence parameters were significantly correlated with changes in Pn; both slowly relaxing NPQ (NPQS) and its proportion in NPQ significantly increased with enhanced UV-B radiation, indicating damage to the PS reaction center and reduced photochemical efficiency. These results demonstrate that enhanced UV-B radiation throughout the entire growth period reduced cotton photosynthetic leaf area,

chlorophyll content, and net photosynthetic rate, leading to suppressed cotton growth and matter accumulation and decreased yield. The decline in photosynthetic rate induced by enhanced UV-B radiation was closely related to damage to the PS reaction center.

Full Text

Preamble

Chinese Journal of Eco-Agriculture, May 2017, Vol. 25, No. 5: 708–719
ChinaXiv Partner Journal DOI: 10.13930/j.cnki.cjea.160801

Effect of Enhanced UV-B Radiation on Cotton Growth and Photosynthesis Throughout the Entire Growth Period

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Abstract

The photosynthetic system is the initial and most important target of UV-B radiation in plants. This study investigated the effects of enhanced UV-B radiation (20% and 40% above ambient levels) throughout the entire growth period on cotton morphology, dry matter accumulation, photosynthetic pigments, and yield under field conditions. By analyzing gas exchange parameters and chlorophyll fluorescence parameters in functional leaves on the main stem, we explored the mechanisms through which enhanced UV-B radiation affects cotton photosynthesis. The results demonstrated that enhanced UV-B radiation significantly inhibited cotton growth and dry matter accumulation, with seed cotton yield decreasing markedly as UV-B intensity increased. Net photosynthetic rate (Pn) of main-stem functional leaves decreased significantly at all growth stages with increasing UV-B radiation, while chlorophyll content initially increased then decreased. Stomatal conductance (Gs) and transpiration rate (Tr) remained unchanged, whereas intercellular CO concentration (Ci) increased, indicating that the decline in Pn was primarily caused by non-stomatal limitation factors. Analysis of chlorophyll fluorescence parameters revealed that maximum photochemical quantum yield of PSII (Fv/Fm), actual photochemical quantum efficiency (ΦPSII), linear electron transport rate (ETR), and photochemical quenching coefficient (qP) all decreased with enhanced UV-B radiation, whereas non-photochemical quenching coefficient (NPQ) increased significantly. All chlorophyll fluorescence parameters were significantly correlated

with changes in Pn. Slowly relaxing NPQ (NPQS) and its proportion in NPQ increased significantly with enhanced UV-B radiation, indicating PSII reaction center damage and reduced photochemical efficiency. These results confirm that enhanced UV-B radiation throughout the growth period reduces photosynthetic leaf area, chlorophyll content, and net photosynthetic rate in cotton, thereby inhibiting growth, material accumulation, and yield. The photosynthetic rate decline induced by enhanced UV-B radiation is closely associated with damage to the PSII reaction center.

Keywords: Enhanced UV-B radiation; Cotton growth; Gas exchange; Photosystem II (PSII); Chlorophyll fluorescence parameters; Slowly relaxing NPQ

Introduction

Human activities have released chlorofluorocarbons (CFCs) that deplete the ozone layer, resulting in continuously increasing ultraviolet radiation reaching the Earth' s surface, particularly UV-B radiation in the 280–320 nm wavelength range [1–2]. Currently, UV-B radiation intensity in the Southern Hemisphere has increased by 40% compared to 1979–1992 levels, while the Northern Hemisphere has seen a 14% increase [3]. Given that CFCs have a half-life of 50–150 years [4], organisms will continue to be exposed to enhanced UV-B radiation for the foreseeable future. The impacts of enhanced UV-B radiation on plants and entire ecosystems have become a major focus of scientific research worldwide. Previous studies have shown that UV-B radiation can attack plant DNA [5], proteins [6], and membrane systems [7], negatively affecting plant growth, development, and physiological metabolism [8]. Among various physiological processes, the photosynthetic system is the initial and most important target of UV-B radiation [9]. Under enhanced UV-B radiation, photosynthesis in crops such as rapeseed (*Brassica campestris* L.) [10], sorghum [*Sorghum bicolor* (L.) Moench] [11], danshen (*Salvia miltiorrhiza* Bge.) [12], rice (*Oryza sativa* L.) [13], and maize (*Zea mays* L.) [14] has been inhibited to varying degrees. The decline in photosynthesis may be related to reduced photosynthetic pigment content [7], inhibited photosynthetic enzyme activity [15], and decreased photosystem II (PSII) efficiency [16]. However, most of these results were obtained from growth chamber or greenhouse experiments. Booij-James et al. [17] found that under photosynthetic active radiation (PAR) of 50–200 μmol·m ^{2}·s ^{1}, increasing UV-B radiation by just 1.24 μmol·m ^{2}·s ^{1} caused substantial degradation of D1 and D2 proteins in Arabidopsis PSII. In contrast, when PAR increased to 450–500 μmol·m ^{2}·s ^{1}, even a 32–40 kJ·m ^{2}·d ^{1} increase in UV-B radiation did not significantly change the maximum photochemical efficiency (Fv/Fm) or actual photochemical efficiency (ΦPSII) of pea (*Pisum sativum* L.) PSII [18]. This indicates that UV-B damage to plants depends largely on PAR intensity. Since PAR in growth chambers or greenhouses is far lower than in field conditions, the damaging effects of enhanced UV-B radiation on plants and photosynthetic systems can be easily overestimated [19–20]. Therefore, studying the effects of enhanced UV-B radiation throughout the entire growth period on crop photosynthetic systems and growth under field conditions has important theoretical and practical significance.

Cotton (*Gossypium hirsutum* L.) is an important economic crop that is highly sensitive to enhanced UV-B radiation. Under both greenhouse and field conditions, enhanced UV-B radiation causes cotton plants to become shorter, reduces leaf area, decreases dry weight [21–22], lowers chlorophyll content and photosynthetic rate [23–24], and significantly reduces yield and quality [25]. However, the mechanisms through which enhanced UV-B radiation affects cotton photosynthesis remain poorly understood. Using cotton as the test material, this study investigated the effects of enhanced UV-B radiation throughout the entire growth period on cotton growth, material production, photosynthetic pigment content, and yield under field conditions. We also examined changes in leaf gas exchange and chlorophyll fluorescence parameters to explore the mechanisms of UV-B effects on cotton photosynthesis.

Materials and Methods

1.1 Experimental Design

The transgenic insect-resistant cotton cultivar 'CCRI 41' was used as the experimental material. The experiment was conducted over three years: morphological and developmental indices were measured in 2012–2013, leaf gas exchange and chlorophyll fluorescence parameters were determined in 2013, and fluorescence dark relaxation kinetics were measured in 2014. Field experiments were carried out at Dongzhangzhuang Village, Zaoyuan Township, Weixian County, Xingtai City, Hebei Province (36°56 N, 115°26 E). The experimental site had been continuously planted with cotton and represented medium fertility soil containing 8.53 $g \cdot kg^{1}$ organic matter, 0.578 $g \cdot kg^{1}$ total nitrogen, 40.3 $mg \cdot kg^{1}$ available phosphorus, and 124 $mg \cdot kg^{1}$ rapidly available potassium.

Three treatments were established: U0 (control, ambient UV-B radiation intensity), U1 (20% above ambient UV-B radiation), and U2 (40% above ambient UV-B radiation). One row of UV lamps (1.2 m length, 297 nm center wavelength, 40 W) was suspended above each cotton row, wrapped with cellulose acetate film to filter out wavelengths below 280 nm. The lamp height was adjusted to control UV radiation intensity reaching the cotton canopy. On clear days during mid-May, mid-June, mid-July, and mid-August 2012, UV-B radiation intensity at the cotton canopy was measured every 15 minutes from 8:00 to 18:00. Curves were plotted with time on the x-axis and UV-B intensity on the y-axis, and equations were fitted. The area enclosed by the parabola and x-axis was calculated as the ambient UV-B radiation intensity ($kJ \cdot m^{2} \cdot d^{1}$). Treatment doses were adjusted monthly based on changes in ambient UV-B radiation intensity. The UV-B treatment intensities for 2013 and 2014 were set according to the 2012 ambient levels, with actual treatment intensities shown in . Ambient and treatment UV-B intensities were measured at 297 nm using a UV radiometer (Huandi Brand, Beijing Normal University Photoelectric Instrument Factory). Enhanced UV-B radiation treatments began at the three-leaf stage and continued until the boll opening stage, with 10 hours of daily exposure (8:00-18:00). UV lamps were turned off on cloudy or rainy days. Each treatment had four replicates arranged in a completely randomized design. Each replicate consisted of four cotton rows (3.6 m length) with a plot area of 10.8 m^2. The experiment used plastic film direct seeding with wide-narrow row spacing (105 cm for wide rows, 45 cm for narrow rows) and plant spacing of 22 cm, resulting in a density of 60,000 plants · ha ^{1}.

1.2.1 Growth, Dry Matter Accumulation, and Yield

On June 5, June 25, July 15, August 5, and August 25 in 2012 and 2013, plant height, node number, and cotyledonary node stem diameter were measured for 20 consecutive plants in each plot, with arithmetic means calculated. Simultaneously, three random plants were sampled to measure total fruit branch length and leaf number indoors. Single-plant total leaf area was determined using an SHY-150 scanning leaf area meter, and leaf area index (LAI) was calculated [26] as:

$$\text{LAI} = \frac{\text{Total leaf area per plant}}{\text{Land area per plant}} \tag{1}$$

Plants were separated into aboveground and root components, which were oven-dried and weighed. Relative growth rate (PGR) was calculated [27] as:

$$\text{PGR} = \frac{\ln W_2 - \ln W_1}{t_2 - t_1} \tag{2}$$

where W_1 and W_2 represent individual plant dry weight at times t_1 and t_2, respectively.

On September 10, boll number per plant was determined by counting bolls on 20 consecutive plants in each plot, with the average taken as the single-plant boll number. Opened bolls from the middle fruiting positions were harvested, and seed cotton yield was calculated as:

$$\text{Seed cotton yield} = \text{Bolls per plant} \times \text{Density} \times \text{Boll weight} \times 0.85 \tag{3}$$

1.2.2 Gas Exchange Parameters and Chlorophyll Fluorescence Measurements

Cotton leaf gas exchange and chlorophyll fluorescence parameters were measured using a Li-6400 portable photosynthesis system. On clear mornings (9:00-11:00) during the bud stage (June 24), full-bloom stage (July 15), full-boll stage (August 8), and boll opening stage (August 27) in 2013, net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), and intercellular CO concentration (Ci) were measured on the third leaf from the top of the main stem. An open gas path was used with LED red-blue light source set at 1,400 μmol · m 2 · s 1 and gas flow rate of 500 μmol · s 1.

Before dawn, initial fluorescence (Fo) and maximum fluorescence (Fm) of the third main-stem leaf were measured. Under light-adapted conditions, light-adapted initial fluorescence (Fo), light-adapted maximum fluorescence (Fm), and steady-state fluorescence (Fs) were determined. The following PSII parameters were calculated:

Maximum quantum yield:

$$\mathrm{Fv/Fm} = \frac{\mathrm{Fm} - \mathrm{Fo}}{\mathrm{Fm}} \tag{4}$$

Photochemical quantum efficiency:

$$\Phi\mathrm{PSII} = \frac{\mathrm{Fm}\ - \mathrm{Fs}}{\mathrm{Fm}} \tag{5}$$

Linear electron transport rate:

$$\mathrm{ETR} = \mathrm{PPFD} \times \Phi\mathrm{PSII} \times 0.84 \times 0.5 \tag{6}$$

Photochemical quenching coefficient:

$$\mathrm{qP} = \frac{\mathrm{Fm}\ - \mathrm{Fs}}{\mathrm{Fm}\ - \mathrm{Fo}} \tag{7}$$

Non-photochemical quenching coefficient:

$$\mathrm{NPQ} = \frac{\mathrm{Fm} - \mathrm{Fm}}{\mathrm{Fm}} \tag{8}$$

In higher plants, NPQ can be divided into two components: high-energy-state quenching (qE) and photoinhibitory quenching (qI) [28]. The composition of NPQ in cotton leaves was analyzed using fluorescence dark relaxation kinetics, following the method of Griffiths and Maxwell [29] with modifications. NPQ was separated into rapidly relaxing NPQ (NPQF), representing qE, and slowly relaxing NPQ (NPQS), representing qI. Fully light-adapted third main-stem leaves were placed in the Li-6400 fluorescence chamber, and maximum fluorescence was measured every 5 minutes under dark conditions for 1 hour using saturating light (1,500 μmol · m 2 · s 1). NPQF was calculated as:

$$\mathrm{NPQF} = \mathrm{NPQ} - \mathrm{NPQS}$$

where Fmr is the maximum fluorescence value after relaxation equilibrium.

1.2.3 Photosynthetic Pigment Content Determination

Following the method of Cambrollé [30], after gas exchange measurements, 0.5 g of the same leaf (midrib removed) was extracted in 10 mL of 80% acetone solution. After thorough extraction and filtration, 1 mL of supernatant was mixed with 2 mL acetone solution, and absorbance was measured at 663 nm and 646 nm. Chlorophyll a (Chla), chlorophyll b (Chlb), and total chlorophyll (Chla+b) contents were calculated using the method of Lichtenthaler [31].

1.3 Statistical Analysis

All data were analyzed statistically using DPS 7.55 software.

Results

2.1 Effects of Different UV-B Radiation Levels on Cotton Growth

As shown in , results were consistent across the two experimental years. Plant height, total fruit branch length, and cotyledonary node stem diameter at all growth stages decreased with increasing UV-B radiation, indicating that enhanced UV-B radiation inhibited both longitudinal elongation and lateral thickening of cotton stems. However, except for the U2 treatment at the seedling stage, node number remained unchanged across growth stages, suggesting that the inhibitory effect on stem elongation was primarily due to shorter internodes. Leaf growth was also suppressed by enhanced UV-B radiation, with LAI decreasing significantly in both years as UV-B radiation increased. In terms of inhibition degree, cotton was more sensitive to UV-B radiation at the seedling stage. Under U2 treatment, LAI at the seedling stage (June 5) decreased by 56.6% and 48.3% in 2012 and 2013, respectively, compared to U0, while at the boll opening stage (August 25), the decreases were 39.4% and 30.3%, respectively.

2.2 Effects of Different UV-B Radiation Levels on Dry Matter Accumulation and Yield

Dry matter accumulation and distribution results across two years are presented in . Both aboveground and root dry matter decreased significantly with increasing UV-B radiation, while the root/shoot ratio increased, indicating that enhanced UV-B radiation inhibited aboveground growth more than root growth. Relative growth rate (PGR), representing plant growth capacity, decreased gradually with advancing growth stages. PGR was significantly inhibited by enhanced UV-B radiation during early growth stages but increased with UV-B enhancement after entering the flowering and boll stage (August 5), likely due to vigorous vegetative growth resulting from fewer bolls under enhanced UV-B conditions. Seed cotton yield decreased significantly with increasing UV-B radiation across all three years. Both single boll weight and bolls per plant tended to decrease with enhanced UV-B radiation ().

2.3 Effects of Different UV-B Radiation Levels on Cotton Gas Exchange Parameters

As shown in [Figure 1: see original paper], Pn of main-stem functional leaves decreased significantly with increasing UV-B radiation at all growth stages, while Gs and Tr showed no significant changes. In contrast, Ci tended to increase with enhanced UV-B radiation. The inhibition of Pn by UV-B radiation was greater during early growth stages than in later stages. At the bud stage (June 24), Pn under U1 and U2 treatments decreased by 15.0% and 56.4% compared to the control, respectively. By the initial flowering stage (July 15), these differences were reduced.

2.4 Effects of Different UV-Based Radiation Levels on Photosynthetic Pigment Content and Composition

Chlorophyll is the primary pigment for photosynthesis. Under U1 treatment, Chla and Chlb contents in main-stem functional leaves increased slightly with no significant difference in Chla/Chlb ratio. However, under U2 treatment, Chla and Chlb contents decreased significantly, and the Chla/Chlb ratio was significantly reduced ().

2.5 Effects of Different UV-B Radiation Levels on Chlorophyll Fluorescence Parameters of Main-Stem Functional Leaves

Chlorophyll fluorescence serves as a probe for photosynthesis, and its parameters reveal how photosynthesis responds to environmental changes [32]. Results for main-stem functional leaves showed that Fv/Fm, ΦPSII, ETR, and qP decreased with increasing UV-B radiation, while NPQ increased significantly ([Figure 2: see original paper]). The magnitude of differences in chlorophyll fluorescence parameters gradually decreased with prolonged UV-B treatment duration. Using ΦPSII as an example, at the bud stage (June 24), U1 and U2 treatments decreased ΦPSII by 24.1% and 29.5% compared to the control, respectively. By the full-bloom stage (July 15), these reductions were 3.4% and 12.9%, respectively, and at the full-boll stage (August 8), U1 showed no significant difference from the control, while U2 decreased ΦPSII by only 6.2%. These results indicate that cotton is more sensitive to enhanced UV-B radiation during early growth stages.

Plant leaf dark relaxation kinetics can analyze the mechanisms of NPQ changes. Based on net photosynthetic rate and chlorophyll fluorescence measurements, the most sensitive bud stage (June 24) was selected for dark relaxation kinetic analysis of main-stem functional leaves under different UV-B treatments (). Under enhanced UV-B radiation, NPQF increased significantly but was higher under U1 than U2 treatment. In contrast, NPQS increased substantially with UV-B enhancement, with U1 and U2 treatments showing 2.48-fold and 8.87-fold increases over the control, respectively. In terms of composition proportion, NPQF proportion in NPQ decreased with enhanced UV-B radiation, while NPQS proportion increased significantly.

2.6 Correlation Analysis of Cotton Leaf Photosynthetic Characteristics Under Different UV-B Radiation Intensities

Correlations between gas exchange parameters, chlorophyll content, and chlorophyll fluorescence parameters are presented in . Pn showed the highest correlation with qP (r = 0.901), and correlations with other chlorophyll fluorescence parameters exceeded 0.83, all reaching significance at the 0.01 level. Chla+b showed the second-highest correlation with Pn (r = 0.708, significant at the 0.05 level). No significant correlations were found between Pn and other gas exchange parameters (Gs, Ci, and Tr).

Discussion

3.1 Enhanced UV-B Radiation Inhibits Cotton Growth

Enhanced UV-B radiation is a major global environmental change issue that affects plant morphology, growth, physiological metabolism, dry matter accumulation, and yield [33–35]. Our results show that enhanced UV-B radiation inhibited cotton stem elongation and thickening, significantly reduced LAI, and slowed growth, consistent with findings in danshen [12], Arabidopsis [7], sunflower (*Helianthus annuus* L.) [36], wheat (*Triticum aestivum* L.) [37], and pea [38]. Leaves are the primary organs for photosynthesis, and leaf area is significantly positively correlated with crop biomass [4]. The reduction in leaf area caused by enhanced UV-B radiation inevitably affects cotton dry matter accumulation and yield formation.

3.2 Enhanced UV-B Radiation Reduces Net Photosynthetic Rate and Chlorophyll Content in Cotton Leaves

Photosynthesis provides material and energy for green plants and forms the basis of plant growth and development. Leaf photosynthetic rate is a primary determinant of crop material production capacity. This study shows that Pn of cotton main-stem functional leaves decreased with enhanced UV-B radiation, while Gs remained unchanged and Ci increased, indicating that the Pn reduction was not caused by stomatal opening changes. Jansen et al. [39] found that enhanced UV-B radiation does not cause stomatal opening or closing but rather causes guard cells to lose their regulatory capacity. Therefore, the Pn decline induced by UV-B radiation is unrelated to stomatal conductance and is mainly caused by non-stomatal limitation factors [40–41]. The lack of significant correlation between Pn and Gs or Ci under different UV-B radiation intensities in this study confirms this conclusion.

Chlorophyll is the primary pigment absorbing photosynthetically active radiation, and its content and composition significantly affect plant photosynthesis and assimilation function [42]. However, chlorophyll is extremely sensitive to

UV-B radiation, and chloroplast thylakoid membranes and stacking structures are easily damaged by enhanced UV-B radiation [43]. Under 40% enhanced UV-B radiation, this study found significant decreases in Chla and Chlb contents and Chla/Chlb ratio. Reduced chlorophyll content directly decreases light energy absorption efficiency and transfer rate, interfering with light energy distribution and conversion between PSII and PSI and inhibiting material synthesis [44]. The Chla/Chlb ratio reflects thylakoid membrane stability [45]; a smaller ratio indicates looser thylakoid membrane stacking and lower photochemical activity [46]. The decreased Chla/Chlb ratio under enhanced UV-B radiation indicates reduced chloroplast structural stability and photosynthetic phosphorylation activity, adversely affecting photosynthesis.

3.3 Photosynthetic Rate Decline Induced by Enhanced UV-B Radiation Is Closely Related to PSII Reaction Center Damage

Among various non-stomatal limitation factors affecting plant photosynthesis, PSII photochemical activity is most susceptible to UV-B radiation interference [8]. This study demonstrates that Pn changes are extremely significantly correlated with chlorophyll fluorescence parameters under different UV-B radiation intensities, with Pn level closely related to PSII photochemical activity. PSII status and activity can be assessed through chlorophyll fluorescence induction kinetic parameters, revealing light energy absorption, transfer, dissipation, and distribution and elucidating the intrinsic mechanisms of photosynthetic rate changes [47]. Fv/Fm represents PSII primary light energy conversion efficiency [48] and is generally stable around 0.83 [49]. The decreased Fv/Fm in cotton leaves under enhanced UV-B radiation indicates PSII activity inhibition under stress, with greater inhibition at higher UV-B levels. Concurrently, ΦPSII, ETR, and qP decreased with increasing UV-B radiation intensity, indicating reduced PSII light energy conversion efficiency, slower electron transport chain rates on thylakoid membranes, gradual reaction center closure, and decreased PSII photochemical activity.

Plants exhibit photoinhibition under stress environments, with excess light energy dissipated as heat to protect photosynthetic components from damage. NPQ is linearly positively correlated with PSII heat dissipation [50]. In this study, cotton leaf NPQ increased with enhanced UV-B radiation, indicating increasing excess light energy and decreasing proportion of excitation energy used for photosynthesis. In higher plants, NPQ can be divided into high-energy-state quenching (qE) and photoinhibitory quenching (qI) [28]. The former is related to xanthophyll cycle energy dissipation and represents a photoprotective mechanism in response to stress [51], represented by NPQF in dark relaxation kinetics. The latter is related to PSII reaction center D1 protein damage and is represented by NPQS. Our results show that under U1 treatment, both NPQF and NPQS increased, with NPQF being the main NPQ component. However, under U2 treatment, NPQS increased significantly compared to U1 and became the main factor for NPQ elevation. This indicates that under slightly increased

UV-B radiation, cotton primarily relies on active high-energy-state quenching to dissipate excess light energy and protect photosynthetic organs. Under substantially increased UV-B radiation, high-energy-state quenching capacity decreases, and PSII reaction center damage becomes the primary cause of leaf photoinhibition.

3.4 Biological Effects of Enhanced UV-B Radiation Are Influenced by Experimental Conditions and Cotton Growth Stage

Different cultivation conditions yield varying results regarding UV-B enhancement effects on cotton. Shi et al. [52] treated cotton seedlings with UV-B radiation in growth chambers and found that only 1.5 hours of UV-B radiation at 0.32 kJ · m ^{2} · h ^{1} caused severe leaf wilting and cell death. In contrast, under our U2 treatment (continuous 8-hour daily exposure at 1.53–2.24 kJ · m ^{2} · h ^{1}), cotton leaves could still photosynthesize, indicating that low PAR conditions in greenhouses make plants more sensitive to UV-B radiation. This study also found that cotton stem and leaf growth, leaf net photosynthetic rate, and chlorophyll fluorescence parameters all showed greater inhibition during early stages than later stages, indicating that different cotton growth stages respond differently to UV-B radiation, with seedlings being more sensitive to enhanced UV-B radiation.

Conclusion

Under field conditions, enhanced UV-B radiation throughout the entire growth period inhibits cotton growth, dry matter accumulation, photosynthesis, PSII reaction center photochemical efficiency, and yield formation, with greater inhibition at higher UV-B radiation intensities. Chlorophyll content initially increased then decreased with enhanced UV-B radiation. The photosynthetic rate decline induced by enhanced UV-B radiation was primarily caused by non-stomatal limitation factors and was closely related to decreased photochemical activity resulting from PSII reaction center damage.

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Note: Figure translations are in progress. See original paper for figures.