



Impact of drought on assimilates partitioning associated fruiting physiognomies and yield quality attributes of desert grown cotton

Muhammad Shareef^{1,2,3,4} · Dongwei Gui^{1,2,4} · Fanjiang Zeng^{1,2,4} · Zeeshan Ahmed⁵ · Muhammad Waqas^{1,3} · Bo Zhang^{1,2,3,4} · Hassan Iqbal^{1,3} · Muhammad Fiaz⁶

Received: 21 September 2017 / Revised: 27 February 2018 / Accepted: 10 March 2018
© Franciszek Górski Institute of Plant Physiology, Polish Academy of Sciences, Kraków 2018

Abstract

Deficit irrigation has great significance for sustainable cultivation of cotton in water scarce arid regions, but this technique creates drought situation that induces stress adaptive changes in cotton plants due to indeterminate growth habit. In the present experiment, the impact of drought stress on assimilates partitioning associated vegetative and reproductive development, and yield quality attributes of cotton were examined under desert conditions. Four levels of drip irrigation including 100, 80, 60, and 40% replenishment of depleted water from field capacity were applied to develop drought stress regimes during two growing seasons (2015 and 2016). Results revealed that under limited water supplies, plant's preference for allocation of photo-assimilates was roots > leaves > fruits that substantially increased root–shoot ratio and hampered reproductive growth. Consequently, boll density (m^{-2}), fresh boll weight and lint yield ($kg\ ha^{-1}$) were significantly reduced. An obvious change in partitioning of assimilates inside stressed bolls was observed that indicated relatively more accumulation in seeds than fiber, thus reducing the fiber quality. In addition, decreased starch, oil, and protein contents in seeds of stressed plants markedly reduced 100 seeds weight and also the vigor. Later, seed quality confirmatory tests of subsequent years (2016 and 2017) showed significant reduction in emergence counts (m^{-2}) and seedling biomasses of seeds harvested from deficit drip irrigated cotton. These results suggest that deficit irrigation could necessarily be an appropriate yield optimization and water saving technique for cotton in desert environment but, for the best quality fiber and cottonseeds, full irrigation should be preferred.

Keywords Photosynthesis · Sugars and starch · Assimilates distribution · Root–shoot ratio · Cottonseed oil and protein · Emergence count

Introduction

Cotton (*Gossypium hirsutum* L.) is one of the most important agronomic crops, which is cultivated worldwide in a diverse range of climates for fiber and oilseed industry. But, the scarcity of water resources in arid regions like Xinjiang,

northwest China is a persistent threat to its sustainability (Zhou et al. 2012), because cotton is a major cash crop of Xinjiang, and cultivated on a widespread area due to favorable climatic conditions. However, adoption of deficit drip irrigation for cotton in such water limited environments is considered an intellectual and feasible approach (Dağdelen et al. 2009; Kang et al. 2012; Karam et al. 2006). In this technique, the crop is irrigated less than 100% of

Communicated by S. Srivastava.

✉ Dongwei Gui
guidwei@ms.xjb.ac.cn

✉ Fanjiang Zeng
zengfj@ms.xjb.ac.cn

¹ State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, 818 South Beijing Road, Urumqi 830011, China

² Cele National Station of Observation & Research for Desert Grassland Ecosystem in Xinjiang, Cele 848300, China

³ University of Chinese Academy of Science, Beijing 100049, China

⁴ Key Laboratory of Biogeography and Bioresource in Arid Land, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China

⁵ The Islamia University of Bahawalpur, Bahawalpur, Punjab 63100, Pakistan

⁶ Universidade Federal De Viçosa, Viçosa, MG 36570-900, Brazil

its evapotranspiration requirement (Oweis et al. 2011). This irrigation deficit induces drought stress situation and cotton plants switch to their stress adaptive approaches because of indeterminate growth habit (Quisenberry and Roark 1976). Photosynthetic activity undergoes significant decline due to stomatal closure, which negatively affects plant biomass partitioning, fruiting ability, and yield formation (Bota et al. 2004; Pettigrew 2004; Pettigrew and Gerik 2007). Limited photosynthesis due to water deficit stress disrupts carbohydrate metabolism and distribution in plant body (Chaves et al. 2002), favoring the maximum proportion to leaves and roots for osmotic adjustment and the least towards fruiting fractions (Valliyodan and Nguyen 2006; Villadsen et al. 2005). Roots-shoot ratio increases due to inadequacy of assimilates in aerial parts for luxurious shoot growth. Besides, the reserve carbohydrates like starch in leaves and roots also start depleting due to high respiration to photosynthetic ratio (Galmés et al. 2007), which disturbs a balance between assimilation and utilization of photo-assimilates, causing significant reduction in assimilates transport to fruiting parts of plant (Abid et al. 2016).

The disrupted assimilates partitioning hinders the development of yield contributing factors like boll density and boll weight, which ultimately decrease cotton yield (Dai et al. 2015; Liu et al. 2015; Mert 2005; Pettigrew 2004) and its quality of production. In general, the quality of seed cotton is evaluated through analyzing its fiber index traits and seed quality parameters. Cotton fiber is primarily made up of more than 95% cellulose (Kim and Triplett 2001), while its composition and overall quantity of lint per boll are adversely affected by reduced assimilates translocation to developing bolls (Shu 2009; Wenqing et al. 2011). Fiber cells basically originate from epidermal layer of ovule and receive assimilates from developing seeds (Ruan et al. 2003), but, under abiotic stress like drought, it is uncertain that what proportion of total photosynthates is moved to developing fibers and retained by seeds themselves. Though, it has been well reported that deficit irrigation affects lint quantity per seed more adversely than seed biomass (Rabadia et al. 1999; Wang et al. 2016). Usually, seed vigor, seed germinating potential, and seedling health are the key determinants of seed quality (Han et al. 2014; Snider et al. 2016). Additionally, a particular concentration of seed energy reserves including starch, fats, and proteins also defines the quality of seeds (Abdelmagid and Osman 1975; Snider et al. 2014; Turley and Chapman 2010). Starch is essential for embryonic respiration, new protoplasm formation, and cell wall development of germinating seedlings (Kuo et al. 1988). Lipids provide energy and help in membranes formation during germination, and proteins split into amino acids, which help to make new proteins, and also provide energy during emergence (Snider et al. 2016; Turley and Chapman 2010). But, any kind of environmental stress that

causes malnourishment of seeds could be detrimental to seed vigor and viability. While, poor quality seeds could lead to deleterious consequences on crop productivity due to unhealthy seedling stand and poor vegetative growth (Sawan et al. 2009).

Several physiological, biochemical, and yield related responses of cotton to drought stress have been reported in numerous studies. But, the impact of drought disrupted assimilates distribution in plants on nourishment of developing fruits, yield components, and the qualitative traits of cottonseeds and fiber under desert ambiances has not been documented well. Accordingly, a field study was conducted on the southern rim of Taklamakan desert with particular objectives to: (1) estimate distribution of assimilates among cotton leaves, roots, and fruits under deficit drip irrigation induced drought stress, and its impact on root–shoot growth, fruiting physiognomies, lint yield, and fiber quality of cotton under desert environment, and (2) elucidate the impact of drought on qualitative traits of cottonseeds harvested from stressed cotton plants through quantifying their accumulated concentrations of starch, oil, and protein, and evaluating their germination and seedling health. This study would help to know, either deficit irrigation, “which subjects the plants to drought stress” could also be considered, if cotton is grown for seed purpose, and to what extent this water management technique would affect the quality and quantity of cotton yield in the desert ecosystem.

Materials and methods

Study site and experimental design

This field study was conducted on Cele National Station for Desert Ecosystem Research, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, during two cotton seasons (2015 and 2016). Experimental site is located on the southern rim of Taklamakan desert, northwest China. The area has particular inland continental desert climate with the maximum evaporative potential of more than 2595 mm annually. The total annual rainfall rarely exceeds 35.1 mm and the temperature extremes reach 41.9 °C in July and – 21.9 °C in January, whereas seasonal weather changes during study years are shown in Fig. 1. The soil was mainly categorized as aeolian sandy soil (loamy sand), which has bulk density and volumetric field capacity of 1.23 g cm⁻³ and 0.19 m³ m⁻³, respectively. Residual nutrient analysis of soil indicated total N 0.228 ± 0.05 g kg⁻¹, total P 0.79 ± 0.04 g kg⁻¹, and total K 7.73 ± 0.13 g kg⁻¹ in top 0–30 cm layer. The experiment was laid out in randomized complete block design (RCBD) with four replicates. Cotton cultivar used in present study was *Zhongmian-24*, which has long fiber, disease-resistant, and drought-tolerant attributes

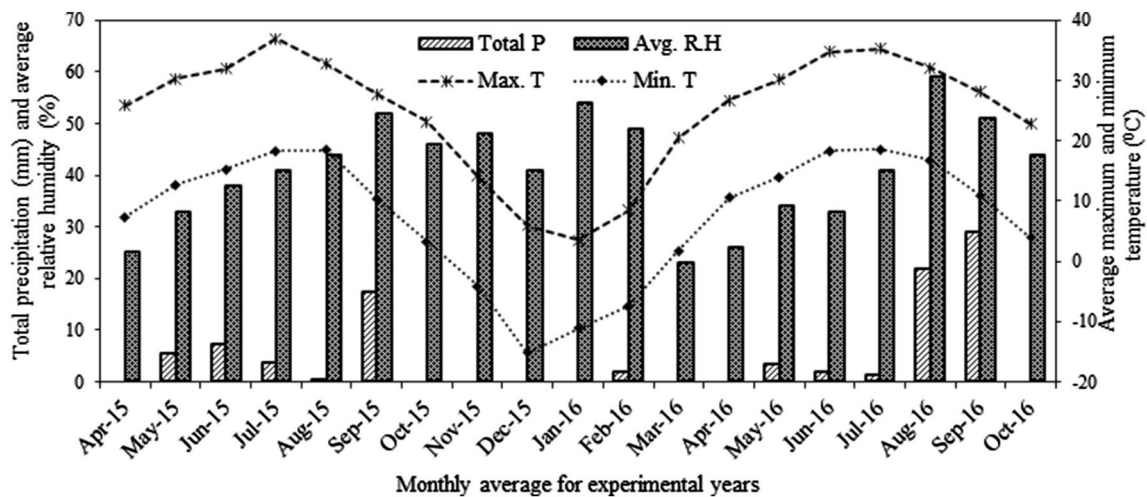


Fig. 1 Climatic data of study site for cotton growing seasons of 2015 and 2016

(Wang and Liu 1997). The crop was sown on 20th April during 2015 and 2016 using four drip irrigation regimes to develop drought stress including 100% (T_0), 80% (T_1), 60% (T_2), and 40% (T_3) replenishment of depleted moisture from field capacity. Plantation was carried out under high density planting technique with 30 and 60 cm alternate narrow and wider row spacing, and 10 cm plant-to-plant distance. The drip lines were placed between narrow rows and connected with water flow meter to quantify the amount of irrigation. Gross plot dimension was 10 × 6 m in which 1 m² quadrated areas in central parts with 25 plants per quadrat were marked for observation. The irrigation was scheduled on the basis of soil moisture status; therefore, moisture depletion from rhizosphere was monitored on weekly basis through soil sampling from 0 to 90 cm soil layer. When soil moisture in T_0 reduced to 50% of FC then T_1 , T_2 , and T_3 were replenished with 80, 60, and 40% of the volume of water applied to T_0 , respectively. Overall, the average amount of water applied to T_0 , T_1 , T_2 , and T_3 during both years was 988, 790, 593, and 395 mm ha⁻¹, respectively.

Photosynthetic measurement and determination of sugars and starch content

The rate of photosynthesis ($\mu\text{mol m}^{-2} \text{s}^{-1}$) was measured at boll maturation stage using LI-COR LI-6400 portable photosynthetic apparatus (White and Raine 2009). At same stage, the live samples of roots and leaves were also collected from each drought stress treatment for the measurement of starch and total soluble sugars content. The sampled leaves were a homogenous mixture of young, mature, and old leaves collected from upper, middle, and lower parts of cotton plants, respectively. Later, the collected

samples were immediately preserved in liquid nitrogen and moved to laboratory for biochemical analysis. The total soluble sugars (mg g^{-1}) were quantified using spectrophotometric technique (Lo and Garceau 1975) and starch content (mg g^{-1}) was determined using phenol–sulfuric acid method (Masuko et al. 2005).

Measurement of root–shoot ratio, yield components, seed density and weight, and lint yield

At boll maturation stage, ½ m rows of cotton plants were uprooted from each treatment by digging up soil and partitioned into roots, shoots, and bolls. Later, the roots and shoots samples were oven dried for 72 h at 72 °C to determine their individual biomasses. Subsequently, the root–shoot ratio (RSR) was calculated using simple mathematical equation ($\text{RSR} = \text{root biomass}/\text{shoot biomass}$). Total number of bolls (opened and unopened) m⁻² were counted before picking, and 10 mature bolls with purplish brown spots were collected from each trial unit and their fresh weights (g boll^{-1}) were measured. Two hand pickings were made on September 10 and October 5 of both study years and lint yield (kg ha^{-1}) was calculated after ginning of seed cotton (Zhi et al. 2016). Both years on first picking, 20 healthy and fully opened bolls were picked separately from each trial unit and used for seed and fiber quality analysis. The number of seeds boll^{-1} were counted and 100 seeds weight was measured after ginning and acid delinting of sampled seed cotton of 20 bolls. After that, half of the seeds from each sample were kept for germination test in subsequent years and the remaining half were used for seeds biochemical analysis.

Starch, oil, and protein content in seeds, and qualitative traits of fiber

Oil content (%) in cottonseeds was determined using Soxhlet extraction technique (Hawthorne et al. 2000), starch (mg g^{-1}) was measured by phenol–sulfuric acid method (Masuko et al. 2005), and crude protein (mg g^{-1}) was determined using Kjeldahl method (Marks et al. 1985). In addition, the cellulose content in lint was estimated as 95% of the total lint boll^{-1} (Kim and Triplett 2001). Later, the lint obtained from each sample was used to measure fiber quality attributes using high volume instrument (HVI) Uster Technologies AG, Uster, Switzerland (Conaty et al. 2015). Fiber length (mm) was measured as an average of longest 50% of fibers; length uniformity (%) was measured as the ratio of average length to upper half mean length. The strength was determined as a force (cN tex^{-1}) needed to break a bundle of fibers equal to 1-tex unit in size (Papastylianou and Argyrokastritis 2014), and micronaire was the measure of fineness and maturity of fiber (Zhi et al. 2016).

Estimation of assimilates distribution in plant, and partitioning inside bolls

After all biochemical tests, the distribution of assimilates among roots, leaves, and fruits of stressed cotton plants was estimated by totaling the concentrations of their accumulated assimilates in the respective plant parts. For leaves and roots, their respective starch and sugars contents were aggregated, and for fruits, the starch, oil, and protein contents in seeds and cellulose in fiber were all added together. Furthermore, the partitioning of assimilates between seed and fiber cells inside bolls was estimated by totaling the concentration of starch, oil, and protein in seeds that was later compared with cellulose content in lint of that boll because, cottonseeds and fibers are competing sinks, which are fed by same funiculus (Kloth and Turley 2010).

Evaluation of cottonseed quality

The germination potential of seeds harvested from each drought stress treatment was tested in subsequent years (2016 and 2017) as a seed quality measure. Fifty seeds of each treatment were sown in 1 m^2 area and their emergence was recorded on daily basis until the emergence count reached the maximum and became stable for each subsequent day. These daily germination data were later used to calculate Timson's Germination Index (TGI) using the formula given by Khan and Ungar (1998).

$$\text{TGI} = \frac{\sum G}{T}, \quad (1)$$

where $\sum G$ is the grand percentage of seeds germinated per day and T is the total germination period. Besides emergence count (m^{-2}), the emergence failure (germination but no emergence) was also calculated by digging up those slots where seeds could not emerge. Afterwards, at 3–4 leaf stage, all seedlings were uprooted and their combined root shoot biomass (g m^{-2}) was determined by oven dry method (Conaty et al. 2015).

Statistical analysis

The Fischer's analysis of variance (ANOVA) technique was used for statistical analysis of data. Later, the least significant difference (LSD) test was applied at 5% probability for appraisal and grading (lettering) of treatment means. A computer software named "Statistix" v.8.1 was used for these statistical calculations.

Results

Drought stress and the synthesis and distribution of assimilates in cotton plant

The applied water deficit stress significantly affected the rate of photo-assimilation in cotton during both study years (2015 and 2016) (Fig. 2). The highest photosynthetic rate was recorded 31.28 and $32.03 \mu\text{mol m}^{-2} \text{ s}^{-1}$ for full irrigation (T_0) in the first and second seasons, respectively, while, under T_1 , T_2 , and T_3 treatments, the average rate decreased by 10, 33, and 51%, respectively. As a result, the distribution of assimilates among leaves, roots and bolls was significantly ($p < 0.05$) affected. The biochemical analysis shown in Table 1 indicated that concentration of total soluble sugars (TSS) in leaves and roots increased with

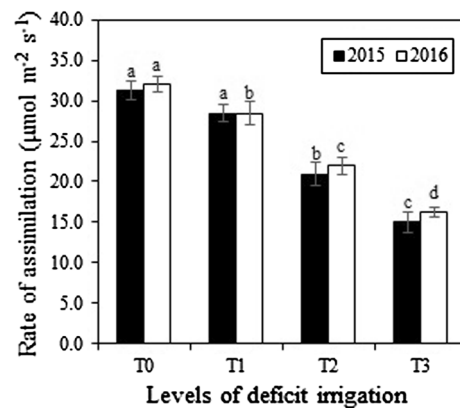


Fig. 2 Rate of photosynthesis influenced by drought stress deficit drip irrigation regimes. The values are means of four replications with standard error of means, and bars carrying different letters are significantly different from each other according to LSD test

Table 1 Dynamics of assimilates distribution in cotton plant under irrigation deficit stress

Treat	IR applied (%)	Leaf TSS (mg g ⁻¹)		Leaf starch (mg g ⁻¹)		Root TSS (mg g ⁻¹)		Root starch (mg g ⁻¹)		Assimilates in fruit (mg g ⁻¹)	
		2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
T ₀	100	6.1d	5.1d	28.6a	28.1a	8.9d	8.2d	11.4a	11.6a	586.4a	562.7a
T ₁	80	7.4c	7.9c	25.0b	23.7b	12.1c	11.3c	9.0b	9.4b	549.6a	510.5a
T ₂	60	10.1b	11.1b	18.4c	17.1c	14.7b	15.7b	7.3c	6.7c	413.4b	407.2b
T ₃	40	15.9a	15.7a	11.2d	10.7d	18.9a	19.1a	4.5d	4.8c	357.3b	349.9c
CV		6.4	8.4	9.5	13.2	9.5	13.4	9.7	16.4	10.5	8.1
LSD		1.32	1.93	3.14	4.20	2.07	2.92	1.24	2.13	80.15	56.09

The values are means of four replications

Assimilates in fruit are total carbohydrates stored in bolls as fiber cellulose and, seed starch, protein, and fats. Values with different letters are significantly different from each other according to LSD test ($p < 0.05$)

Treat treatments, IR irrigation, TSS total soluble sugars

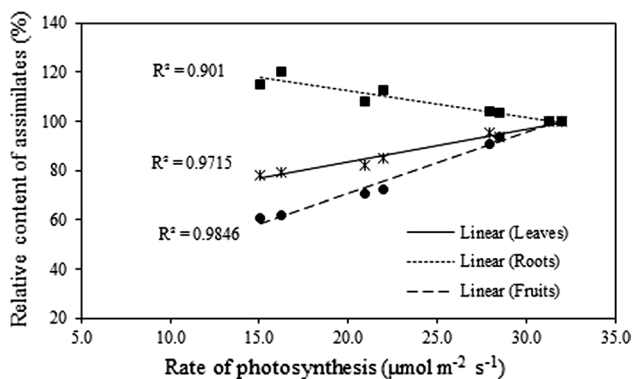


Fig. 3 Relationship between assimilates distribution in different plant parts and rate of assimilates synthesis under different drip irrigation regimes. The values are means of four replications

decreasing irrigation volume. The maximum and minimum quantities of TSS were recorded 15.9 and 6.1 mg g⁻¹ and 15.7 and 5.1 mg g⁻¹ in leaves and, 18.9 and 8.9 mg g⁻¹ and 19.1 and 8.2 mg g⁻¹ in roots from T₃ and T₀ in both experimental years, respectively. Unlike TSS, the starch content started depleting successively with decreasing amount of water. The highest in leaves and roots of T₀ was observed 28.6 and 11.2 mg g⁻¹ in 2015 and, 28.1 and 10.7 mg g⁻¹ in 2016, respectively. Similar trend for assimilates accumulation in bolls (sink) was recorded with highest 586.4 and 562.7 mg g⁻¹ for well-watered plants and lowest 357.3 and 349.9 mg g⁻¹ for T₃ in 1st and 2nd season, respectively (Table 1). Overall, drought stress significantly ($p < 0.05$) affected assimilates distribution in cotton plants that was linearly correlated with the rate of photosynthesis (Fig. 3). As the rate of photo-assimilation decreased due to irrigation deficit, the overall relative concentration of assimilates distributed in leaves and bolls of T₁, T₂, and T₃ reduced by 6, 17, and 21% and 8, 29, and 39%, respectively, than accumulated in T₀, while the concentration in roots significantly

increased by 4, 11, and 18%, respectively, irrespective of reduced assimilation rate during both years of study. However, relative accumulation of assimilates in leaves and bolls showed a linear positive correlation with the rate of assimilates synthesis with r^2 values of 0.96 and 0.98, respectively (Fig. 3), while the enrichment of assimilates in roots depicted linear negative correlation with assimilation (biennial mean $r^2 = 0.91$).

Plant height and root–shoot biomass ratio

Plant height was significantly affected by drought disrupted assimilates partitioning during both study years (Table 2). On an average, the maximum plant height was recorded 64.2 cm from T₀, which decreased by 17, 47, and 60% in T₁, T₂, and T₃ treatments, respectively. Significant variation in assimilates distribution between above and below ground plant parts under drought stress significantly ($p < 0.05$) affected the root and shoot biomass accumulation of cotton (Table 2). Well-irrigated plants accumulated the maximum shoot biomass of 39.5 and 38.5 g plant⁻¹ in 2015 and 2016, respectively, that was on an average 11, 43, and 61% higher than T₁, T₂, and T₃, respectively. On the other hand, the accumulation of root biomass was recorded the highest 4.2 and 4.1 g plant⁻¹ from T₁ that followed the sequence of T₁ > T₀ > T₂ > T₃ during both seasons, respectively. Root to shoot biomass ratio was also affected by drought influenced assimilates distribution. Unlike their individual biomasses, the root/shoot biomass ratio was the maximum 0.16 (2015) and 0.17 (2016) in least irrigated (T₃) plants and it followed the pattern of T₃ > T₂ > T₁ > T₀ during both trial years.

Number of bolls, boll weight, lint yield, and fiber quality

Data presented in Table 3 exhibit the significant ($p < 0.05$) effect of drought disrupted assimilates distribution on boll

numbers, weight, and final lint yield of cotton. The highest number of bolls was observed 124.3 and 121.0 m⁻² in T_0 that was statistically at par with T_1 , while the lowest was recorded 70.5 and 60.8 m⁻² for T_3 during 2015 and 2016, respectively. Likewise, fresh boll weight was the maximum 20.6 g boll⁻¹ (2015) and 21.4 g boll⁻¹ (2016) under full irrigation that decreased by an average of 9, 31, and 43% in T_1 , T_2 , and T_3 treatments, respectively. As a consequence, the lint yield also decreased and it varied from 1817.7 and 1880.2 kg ha⁻¹ under T_0 to 887.9 and 862.9 kg ha⁻¹ under T_3 treatment in 2015 and 2016,

respectively. Moreover, the drought influenced assimilates distribution also affected the main fiber quality attributes including length, strength, and micronaire but, not the uniformity. Data presented in Table 4 are the average of both years fiber quality analysis due to close similarity of two years results. Length and strength were recorded the maximum 29.6 mm and 29.9 cN tex⁻¹, respectively, under full irrigation replenishment, which decreased successively in T_1 , T_2 , and T_3 with reducing irrigation amount. On the other hand, fiber thickness reduced with decreasing irrigation input and it was measured as fiber fineness

Table 2 Root–shoot biomass ratio affected by irrigation deficit disrupted assimilates partitioning

Treatments	IR applied (%)	Plant height (cm)		Shoot biomass (g plant ⁻¹)		Root biomass (g plant ⁻¹)		Root/Shoot biomass ratio	
		2015	2016	2015	2016	2015	2016	2015	2016
T_0	100	62.3a	66.0a	39.5a	38.5a	4.0a	3.9a	0.11b	0.11b
T_1	80	51.9a	54.4a	35.4a	33.9a	4.2a	4.1a	0.12ab	0.13ab
T_2	60	35.0b	33.5b	22.6b	21.6b	3.2ab	3.0ab	0.14ab	0.14ab
T_3	40	24.6b	26.6b	15.7b	14.7b	2.6b	2.6b	0.16a	0.17a
CV		21.73	20.23	20.5	25.3	18.8	22.5	20.6	23.3
LSD		15.1	14.6	9.27	10.99	1.06	1.22	0.04	0.05

Values are means of four replicates

Values with different letters are significantly different from each other according to LSD test ($p < 0.05$)

IR irrigation

Table 3 Effect of disrupted assimilates distribution on yield components and lint yield of cotton

Treatments	Irrigation volume (m ³ ha ⁻¹)	Drought stress (%)	No. of bolls (m ⁻²)		Fresh boll weight (g boll ⁻¹)		Lint yield (kg ha ⁻¹)	
			2015	2016	2015	2016	2015	2016
T_0	9880	0	124.3a	121.0a	20.6a	21.4a	1817.7a	1880.2a
T_1	7950	20	118.3ab	116.0a	19.5a	18.8b	1704.3a	1636.8b
T_2	5930	40	92.5bc	90.0ab	13.9b	14.9c	1192.4b	1214.9c
T_3	3950	60	70.5c	60.8b	12.3b	11.8d	887.9c	862.9d
CV			17.8	21.7	10.7	7.0	9.6	7.1
LSD			28.26	33.86	2.82	1.88	214.35	157.69

The values are means of four replicates

Values with different letters are significantly different from each other according to LSD test ($p < 0.05$)

Table 4 Fiber index attributes influenced by irrigation deficit disrupted assimilates partitioning

Treatments	IR applied (%)	Fiber length (mm)	Micronaire	Fiber strength (cN Tex ⁻¹)	Uniformity (%)
T_0	100	29.6a	4.7b	29.9a	84.6
T_1	80	28.8ab	4.7ab	29.2ab	84.4
T_2	60	28.0ab	4.9ab	28.2bc	84.0
T_3	40	27.2b	5.0a	27.5c	83.8
CV		4.3	3.8	2.9	0.6
LSD		1.96	0.29	1.33	0.85 ns

The values are means of four replicates of two study years 2015 and 2016

Values with different letters are significantly different from each other according to LSD test ($p < 0.05$)

Table 5 Seeds density and weight and, biochemical constituents of cottonseed quality affected by irrigation deficit disrupted assimilates distribution

Treat	IR applied (%)	No. of seeds (boll ⁻¹)		100 seeds weight (g)		Seed starch (g kg ⁻¹)		Seed oil (%)		Seed protein (g kg ⁻¹)	
		2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
T ₀	100	28.3a	27.3a	11.4a	11.7a	46.8a	45.6a	30.6a	30.0a	277.5a	267.6a
T ₁	80	27.8a	26.8a	10.7a	11.2ab	41.0b	40.1b	29.8a	29.1a	261.2a	243.9a
T ₂	60	25.8b	24.5ab	9.6b	9.6ab	33.6c	34.8c	24.6b	23.3b	207.4b	195.0b
T ₃	40	22.5c	22.3b	9.1b	9.0b	31.1c	30.5d	19.9c	20.6b	180.5b	170.6b
CV		4.6	6.9	6.6	14.2	4.8	5.6	8.4	9.2	11.6	9.4
LSD		1.93	2.77	1.07	2.34	2.95	3.36	3.51	3.78	42.88	33.07

The values are means of four replicates

Values with different letters are significantly different from each other according to LSD test ($p < 0.05$)

(micronaire) that was found the maximum 5.0 in the least irrigated (T₃) plants that was about 6% thinner than T₀.

Seed numbers, weight, and biochemical analysis

Number of seeds per boll and seeds weight (g) significantly ($p < 0.05$) reduced due to induced drought stress treatments during both years of study (Table 5). Well-watered plants produced the maximum seeds and 100 seed weight of 28.3.0 boll⁻¹ and 11.4 g during 2015, and 27.3 boll⁻¹ and 11.7 g in 2016, respectively. However, on an average in T₃ treatment, seed numbers and weight reduced by 41 and 28%, respectively. Seeds biochemical analysis indicated that starch, protein and oil content in cottonseeds reduced with increasing drought stress (Table 5). The pattern of accumulation of these biochemical substances in cottonseeds was recorded as T₀ > T₁ > T₂ > T₃ during both study years. In 2015, the maximum and minimum concentrations of starch, oil, and protein were 46.8 and 31.1 g kg⁻¹, 30.6 and 19.9%, and 277.5 and 180.5 g kg⁻¹ in T₀ and T₃ treatments, respectively, while in 2016 the highest and lowest concentrations were recorded 45.6 and 30.5 g kg⁻¹ (starch), 30.0 and 20.6% (oil), and 267.6 and 170.6 g kg⁻¹ (protein), respectively. In another aspect, the biochemical analysis indicated that developing seeds retained relatively more fraction of assimilates and shifted lesser proportion to fiber cells for lint production (Fig. 4). However, it elaborated a linear relationship between the total amount of assimilates accumulated in boll and the fraction retained in cottonseeds and used for lint formation with r^2 values of 0.80 and 0.80, respectively.

Emergence rate and seedling biomass of the seeds harvested from deficit irrigated cotton

Timson's germination index (TGI) in Fig. 5 illustrates the emergence rate of seeds harvested from drought stressed cotton during 2015 and 2016, and tested in subsequent years 2016 and 2017. The seeds of T₀ and T₁ treatments started emerging on third day after sowing (DAS), while

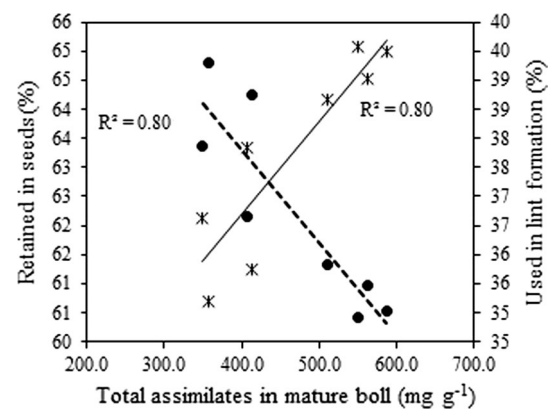


Fig. 4 Relationship between the proportions of total assimilates used in lint formation (solid line) and accumulated in seeds (dotted line) of mature bolls under deficit drip irrigation regimes. Values are means of four replicates of 2 years observation

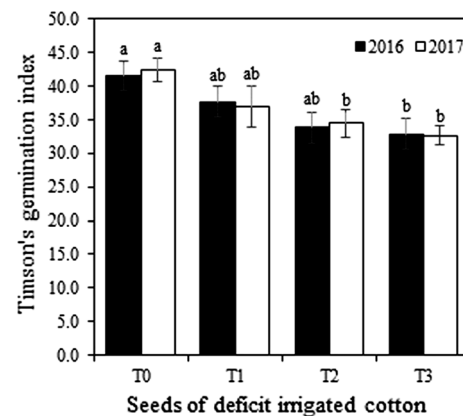


Fig. 5 Timson's germination index calculated to determine the germination rate Emergence count of seeds obtained from deficit irrigated cotton of 2015 and 2016, which that were as tested in subsequent years (2016 and 2017). The values are means of four replications with the standard error of means

the others started from fourth DAS. The emergence count of all treatment's seeds kept raising with the passage of time at different rates and stabilized 12 DAS. The maximum TGI values of 41.5 (2016) and 42.4 (2017) indicated the highest emergence rate of T_0 cottonseeds, while the lowest TGI values of 32.8 and 32.6 were obtained from T_3 seeds in 2016 and 2017, respectively. At climax, the germination count (m^{-2}) of T_0 and T_1 was 80.4 and 79.0% (2016) and 83.2 and 81.1% (2017), respectively, which were statistically similar, while the lowest 66.5 and 69.9% were recorded for T_3 seeds of first and second seasons, respectively (Fig. 6). On the other hand, Fig. 6 also demonstrates the maximum emergence failure of 14.2 and 12.5% of T_3 seeds in 2016 and 2017, respectively, while the lowest was recorded from seeds of fully irrigated cotton. Additionally, at three leaf stage, the highest oven dried seedling biomass was recorded 6.2 and 6.4 $g\ m^{-2}$ from seedlings of T_0 seeds in 2016 and 2017, respectively, that was at par with T_1 (Fig. 7). However, the lowest biomass was recorded for the seedlings of T_3 cottonseeds of both study years.

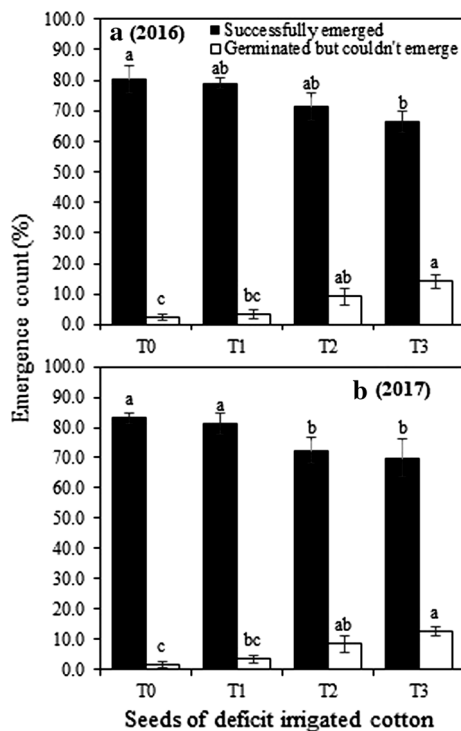


Fig. 6 Maximum germination count of successfully emerged seedlings and of those which germinated but could not emerge. The values are means of four replications with standard error of means, and the bars carrying different letters indicate significant difference among treatments according to LSD test

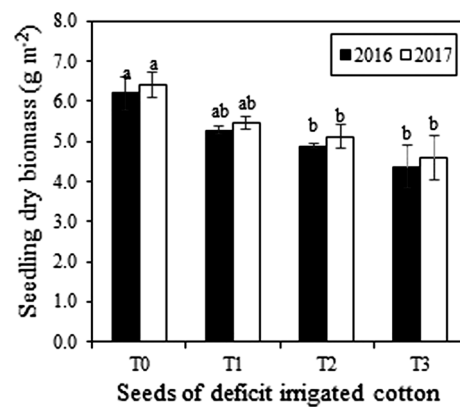


Fig. 7 Seedling biomass of the seeds obtained from deficit irrigated cotton of 2015 and 2016, which were sown in subsequent years (2016 and 2017). The values are means of four replications with standard error of means, and the bars carrying different letters indicate significant difference among treatments according to LSD test

Discussion

The process of photo-assimilation is indeed highly susceptible to water deficit stress. For that reason, cotton showed significant decline in rate of photosynthesis in T_0 to T_3 treatments with decreasing irrigation amounts (Fig. 2), and it would have happened due to reduced stomatal conductance under soil moisture dryness that has also been confirmed by Deeba et al. (2012). In the line of these observations, Yi et al. (2016) and Shareef et al. (2018) have also reported substantial downfall in photosynthetic activity of cotton due to reduced stomatal conductance under soil water deficit. However, under this induced drought stress, cotton plants modified their distribution of assimilates as a stress adaptive strategy and accumulated more soluble sugars in leaves and root cells to concentrate the cytosol for osmotic adjustment and comparatively reduced transport to reproductive parts. According to Bray et al. (2000), Chaves et al. (2002), Mafakheri et al. (2010), Valliyodan and Nguyen (2006), Villadsen et al. (2005), and several others, such alteration in assimilates partitioning becomes inevitable for indeterminate plants during water limitation in rhizosphere. Contrarily, the reduction in starch content in leaves and roots with decreasing water supply would be due to conversion of starch into simple sugars for osmoregulation (Wang and Stutte 1992) and increased respiration to photosynthetic ratio (Galmés et al. 2007). Consistent with these results, Zaher-Ara et al. (2016) reported substantial decline in starch content and enrichment of TSS in leaves and roots under drought stress. Cotton bolls are indeed the main sinks, which receive a major share of total assimilates, while, as a result of water deficit stress, the reduced accumulation of photo-assimilates in bolls of drought stressed cotton plants is an evidence of decreased transport to fruiting parts. These

results are also in agreement with Abid et al. (2016) who documented similar pattern of assimilates partitioning in desiccated cotton plants. In addition, the correlation (Fig. 3) gives a clear explanation of disrupted photosynthates partitioning in cotton plant due to reduced photo-assimilation caused by irrigation deficit stress. Comparatively, more enrichment of assimilates in root and leaf tissues than in fruits indicated that cotton plant preferred survival over reproductive growth, which resulted in poor development of yielding attributes.

Reduction in plant height and biomass is the most prominent consequence of hampered growth due to reduced photosynthesis under water deficit stress (Anjum et al. 2011). Likewise, in the present study, plant height and shoot biomass underwent successive decline at each lower level of irrigation and the same happened with root biomasses of all treatments except T_1 . However, this induced stress led to significant proliferation in root–shoot ratios (Table 2). In the line of these results, Chaves et al. (2002), Hu et al. (2009), and Chen et al. (2017) found that root–shoot biomass ratio had a direct relation with the intensity of drought stress. However, this enhancement in root to shoot ratio would be due to more assimilates transport by cotton plant to roots (Fig. 3) for more vertical and lateral growth. In accordance, De Souza and Da Silv (1987) noted that during drought adaptation, cotton favors root growth by allocating more proportion of photo-assimilates. Therefore, under mild stress (T_1) in present investigation, the roots dry matter was recorded even higher than well-watered plants and also in T_2 and T_3 plants, root growth was comparatively less affected than above ground biomass.

The boll numbers (m^{-2}) and weight ($g\ boll^{-1}$) significantly reduced because, relatively low fraction of total synthesized assimilates partitioned to fruiting organs (Fig. 3) under drought stress. In accordance with these results, Wang et al. (2016) reported that drought stressed cotton produced small sized bolls with lesser density and significantly lower biomass. Besides that, according to Liu et al. (2015), boll numbers directly influence the amount of lint yield. However, this reduced density of bolls would have been the result of accelerated shedding of squares and premature bolls under soil moisture deficit (Cetin and Bilgel 2002), while lower boll weight would have been the consequence of poor boll nourishment due to inadequate allocation of photosynthates by stressed plants (Abid et al. 2016). Yet, the poor development of this major yield component (boll) of cotton resulted in considerable decline in lint yield (Table 3). Chuanjie et al. (2015), Karam et al. (2006), Li and Lascano (2011), and many others have also reported linear decline in cotton yield with reducing irrigation amount. These results are well supported by Pettigrew (2004), Wang et al. (2004), and Mert (2005) who found that cotton yield reduction under water deficit stress is primarily caused by reduced boll density

and weight. Besides yield, the fiber quality traits including length, strength, and micronaire except uniformity (Table 4) were also noticeably degraded by drought disrupted assimilates partitioning. The findings of Basal et al. (2009), Dağdelen et al. (2009), and Zhang et al. (2016) are also consistent with these observations, which illustrated markedly adverse effects of deficit irrigation on fiber quality of cotton. No doubt, the stressed cotton plants partitioned the lowest fraction of photosynthates to reproductive organs, but this inadequacy of assimilates in developing bolls also gave rise to a competition between cottonseeds and fiber cells. Figure 4 illustrates that as, the supply of assimilates reduced to boll, the seeds retained relatively more fraction and shifted lesser quantity to fiber cells for lint formation, and it would have been the key reason behind lint yield reduction and fiber quality deterioration. Similar to these interpretations, Kloth and Turley (2010) reported that developing seeds and fibers are the competing sinks in bolls, which are fed by the same assimilates transporting funiculus.

Remarkable reduction in seeds density $bol\ l^{-1}$ and 100 seeds weight was also ascribed to relatively low assimilate shift to developing fruits by stressed plants (Table 5). Consistent with these results, Wang et al. (2016) also reported an adverse effect of drought on number of seeds per boll and seeds weight. Unlike seed density, the seed biomass is a key indicator of seed vigor, which is the prime factor that is considered while evaluating seed quality (Snider et al. 2016). Indeed the seed vigor primarily depends on the amount of photosynthates enriched inside seeds as biochemical substances including fats, proteins, and carbohydrates, which are the most essential energy reserves used by protruding seedlings for growth until their cotyledons become photosynthetically active (Abdelmagid and Osman 1975; Bartee and Krieg 1974; Snider et al. 2016; Turley and Chapman 2010). In the present research, the observed momentous decline in starch, oil, and protein contents in seeds of deficit irrigated cotton (Table 5) would have also been caused by reduced assimilates transport towards fruiting parts. The impact of this insufficient accumulation of metabolites in seeds was observed as reduced emergence rate shown as Timson's germination index (Fig. 5), which illustrated a slower and the lowest rate of seedling establishment by the seeds obtained from least irrigated (T_3) cotton plants. The depreciation of seed vigor due to malnourishment of bolls would have been the reason behind, because Snider et al. (2016) also agreed that healthy seedling establishment is always associated with amount of energy reserves (metabolites) in cottonseeds. Ultimately, the seeds of stressed plants resulted in lowest emergence count m^{-2} due to unsuccessful emergence of a significant number of germinated seeds in soil (Fig. 6). The emergence failure could be another supportive evidence for the inadequacy of calories in seeds, because an ample quantity of energy is needed to stretch

the hypocotyl enough to break the soil crust and take the cotyledons out. In accordance with these interpretations, Snider et al. (2016) and Turley and Chapman (2010) also reported the significance of stored energy for successful germination of cottonseeds. Therefore, the low emergence of seeds of deficit irrigated cotton resulted in noticeable reduction in seedlings biomass m^{-2} (Fig. 7), which also indicates the poor seedling health. While, according to Snider et al. (2016), healthy seedling vigor assures better crop stand and profitable cotton yield. Conclusively, all these implications highlight the importance of seed quality that was affected by disrupted assimilates partitioning in cotton plants due to induced water deficit stress.

Conclusions

It is concluded that imposition of drought stress substantially reduced photosynthetic rate and cotton plants switched to drought adaptive mode due to indeterminate growth habit and noticeably altered assimilates partitioning with the least preference to fruiting organs. Stressed plants allocated relatively more assimilates to roots as per intensity of drought stress that resulted in significant increase in root–shoot ratio while, on the other hand, vegetative and reproductive growths were substantially hampered. The reduced assimilate transport to fruiting fractions caused malnourishment of bolls, which decreased fresh boll weight. Besides, this inadequacy of photosynthates in bolls increased competition for assimilates between developing seeds and fibers, because fiber cells originate from embryonic wall and completely depend on developing embryo for their nourishment. The developing seeds in stressed bolls retained relatively more assimilates and shifted lesser to fiber cells that resulted in poor fiber quality and significantly reduced lint yield. No doubt, the seeds got better nourishment than fibers, but their energy reserves (starch, oil, and protein contents) remarkably reduced due to overall shortage of assimilates thus, degraded the seed vigor. As a result, the seeds harvested from drought stressed cotton showed slower and significantly lower emergence count than well-watered plants, which also highlights the drawback of deficit irrigation from seed quality point of view. Hence, the use of mild stress (80% drip irrigation) in desert environment could provide optimum yield due to its negligible impact on fruiting physiognomies but, for the best quality fiber and cottonseeds, full irrigation should be preferred.

Authors contribution statement MS, DG, and FZ generated the idea and designed a research plan. MS, BZ, MW, and HI conducted field trial, collected required samples, performed laboratory analysis, and organized data for statistically analysis. MS, ZA, and BZ accomplished the initial manuscript

draft. MF generated figures and tables, performed statistical analysis, and corrected grammatical shortcomings. All authors critically reviewed the manuscript and contributed to its subsequent development and approved the final shape of this research article for publication.

Acknowledgements The authors delightedly acknowledge CAS-TWAS President's Fellowship Program for Ph.D., the National Natural Science Foundation of China (U1603343 and 41471031), and the China 1000 Talent Program (Y672071) for sponsoring this research.

References

- Abdelmagid A, Osman A (1975) Influence of storage period and temperature on viability and chemical composition of cotton seeds. *Ann Bot* 39:237–248
- Abid M et al (2016) Improved tolerance to post-anthesis drought stress by pre-drought priming at vegetative stages in drought-tolerant and-sensitive wheat cultivars. *Plant Physiol Biochem* 106:218–227
- Anjum SA, X-y Xie, L-c Wang, Saleem MF, Man C, Lei W (2011) Morphological, physiological and biochemical responses of plants to drought stress. *Afr J Agric Res* 6:2026–2032
- Bartee S, Krieg D (1974) Cottonseed density: associated physical and chemical properties of 10 cultivars. *Agron J* 66:433–435
- Basal H, Dagdelen N, Unay A, Yilmaz E (2009) Effects of deficit drip irrigation ratios on cotton (*Gossypium hirsutum* L.) yield and fibre quality. *J Agron Crop Sci* 195:19–29
- Bota J, Medrano H, Flexas J (2004) Is photosynthesis limited by decreased Rubisco activity and RuBP content under progressive water stress? *New Phytol* 162:671–681
- Bray E, Bailey-Serres JW, Weretilnyk E (2000) Responses to abiotic stresses. In: Buchanan BB, Gruissem W, Jones RL (eds) *Biochemistry and molecular biology of plants*, American Society of Plant Physiologists, Rockville, Md, pp 1158–1203
- Cetin O, Bilgel L (2002) Effects of different irrigation methods on shedding and yield of cotton. *Agric Water Manage* 54:1–15
- Chaves MM et al (2002) How plants cope with water stress in the field? Photosynthesis and growth. *Ann Bot* 89:907–916
- Chen Z, Niu Y, Ma H, Hafeez A, Luo H, Zhang W (2017) Photosynthesis and biomass allocation of cotton as affected by deep-layer water and fertilizer application depth. *Photosynthetica* 55:638–647
- Chuanjie Y, Yi L, Lin S, Na W (2015) Effect of deficit irrigation on the growth, water use characteristics and yield of cotton in arid Northwest China. *Pedosphere* 25:910–924
- Conaty WC, Mahan JR, Neilsen JE, Tan DK, Yeates SJ, Sutton BG (2015) The relationship between cotton canopy temperature and yield, fibre quality and water-use efficiency. *Field Crops Res* 183:329–341
- Dağdelen N, Başal H, Yılmaz E, Gürbüz T, Akçay S (2009) Different drip irrigation regimes affect cotton yield, water use efficiency and fiber quality in western Turkey. *Agric Water Manage* 96:111–120
- Dai J et al (2015) Manipulation of dry matter accumulation and partitioning with plant density in relation to yield stability of cotton under intensive management. *Field Crops Res* 180:207–215
- De Souza JG, Da Silv JV (1987) Partitioning of carbohydrates in annual and perennial cotton (*Gossypium hirsutum* L.). *J Exp Bot* 38:1211–1218
- Deeba F et al (2012) Physiological and proteomic responses of cotton (*Gossypium herbaceum* L.) to drought stress. *Plant Physiol Biochem* 53:6–18

- Galmés J, Medrano H, Flexas J (2007) Photosynthetic limitations in response to water stress and recovery in Mediterranean plants with different growth forms. *New Phytol* 175:81–93
- Han Z et al (2014) QTLs for seed vigor-related traits identified in maize seeds germinated under artificial aging conditions. *PLoS One* 9:e92535
- Hawthorne SB, Grabanski CB, Martin E, Miller DJ (2000) Comparisons of Soxhlet extraction, pressurized liquid extraction, supercritical fluid extraction and subcritical water extraction for environmental solids: recovery, selectivity and effects on sample matrix. *J Chromat A* 892:421–433
- Hu X-T, Hu C, Jing W, Meng X-B, Chen F-H (2009) Effects of soil water content on cotton root growth and distribution under mulched drip irrigation. *Agric Sci China* 8:709–716
- Kang Y, Wang R, Wan S, Hu W, Jiang S, Liu S (2012) Effects of different water levels on cotton growth and water use through drip irrigation in an arid region with saline ground water of Northwest China. *Agric Water Manage* 109:117–126
- Karam F, Lahoud R, Masaad R, Daccache A, Mounzer O, Rouphael Y (2006) Water use and lint yield response of drip irrigated cotton to the length of irrigation season. *Agric Water Manage* 85:287–295
- Khan MA, Ungar IA (1998) Germination of the salt tolerant shrub *Suaeda fruticosa* from Pakistan: salinity and temperature responses. *Seed Sci Technol* 26:657–667
- Kim HJ, Triplett BA (2001) Cotton fiber growth in planta and in vitro. Models for plant cell elongation and cell wall biogenesis. *Plant Physiol* 127:1361–1366
- Kloth RH, Turley RB (2010) Physiology of seed and fiber development. In: Stewart JM, Oosterhuis DM, Heitholt JJ, Mauney JR (eds) *Physiology of cotton*, Springer, Dordrecht. https://doi.org/10.1007/978-90-481-3195-2_11
- Kuo TM, VanMiddlesloep JF, Wolf WJ (1988) Content of raffinose oligosaccharides and sucrose in various plant seeds. *J Agric Food Chem* 36:32–36
- Li H, Lascano RJ (2011) Deficit irrigation for enhancing sustainable water use: comparison of cotton nitrogen uptake and prediction of lint yield in a multivariate autoregressive state-space model. *Environ Exp Bot* 71:224–231
- Liu J, Meng Y, Lv F, Chen J, Ma Y, Wang Y, Chen B, Zhang L, Zhou Z (2015) Photosynthetic characteristics of the subtending leaf of cotton boll at different fruiting branch nodes and their relationships with lint yield and fiber quality. *Front Plant Sci* 6:747. <https://doi.org/10.3389/fpls.2015.00747>
- Lo S, Garceau J (1975) A spectrophotometric method for quantitative analysis of sugar mixtures containing known sugars. *Can J Chem Eng* 53:582–587
- Mafakheri A, Siosemardeh A, Bahramnejad B, Struik P, Sohrabi Y (2010) Effect of drought stress on yield, proline and chlorophyll contents in three chickpea cultivars. *Aust J Crop Sci* 4:580
- Marks DL, Buchsbaum R, Swain T (1985) Measurement of total protein in plant samples in the presence of tannins. *Anal Biochem* 147:136–143
- Masuko T, Minami A, Iwasaki N, Majima T, Nishimura S-I, Lee YC (2005) Carbohydrate analysis by a phenol–sulfuric acid method in microplate format. *Anal Biochem* 339:69–72
- Mert M (2005) Irrigation of cotton cultivars improves seed cotton yield, yield components and fibre properties in the Hatay region, Turkey. *Acta Agric Scand Sect B Soil Plant Sci* 55:44–50
- Oweis T, Farahani H, Hachum A (2011) Evapotranspiration and water use of full and deficit irrigated cotton in the Mediterranean environment in northern Syria. *Agric Water Manage* 98:1239–1248
- Papastylianou PT, Argyrokastritis IG (2014) Effect of limited drip irrigation regime on yield, yield components, and fiber quality of cotton under Mediterranean conditions. *Agric Water Manage* 142:127–134
- Pettigrew W (2004) Moisture deficit effects on cotton lint yield, yield components, and boll distribution. *Agron J* 96:377–383
- Pettigrew W, Gerik T (2007) Cotton leaf photosynthesis and carbon metabolism. *Adv Agron* 94:209–236
- Quisenberry J, Roark B (1976) Influence of indeterminate growth habit on yield and irrigation water-use efficiency in upland cotton. *Crop Sci* 16:762–765
- Rabadia V, Thaker V, Singh Y (1999) Relationship between water content and growth of seed and fibre of three cotton genotypes. *J Agron Crop Sci* 183:255–261
- Ruan Y-L, Llewellyn DJ, Furbank RT (2003) Suppression of sucrose synthase gene expression represses cotton fiber cell initiation, elongation, and seed development. *Plant Cell* 15:952–964
- Sawan ZM, Fahmy AH, Yousef SE (2009) Direct and residual effects of nitrogen fertilization, foliar application of potassium and plant growth retardant on Egyptian cotton growth, seed yield, seed viability and seedling vigor. *Acta Ecol Sin* 29:116–123
- Shu HM (2009) Mechanism on genotypic differences in cotton (*Gossypium hirsutum* L.) fiber strength formation. Doctor, Nanjing Agricultural University
- Snider J, Collins G, Whitaker J, Chapman K, Horn P, Grey T (2014) Seed size and oil content are key determinants of seedling vigor in *Gossypium hirsutum*. *J Cotton Sci* 18:1–9
- Snider JL, Collins GD, Whitaker J, Chapman KD, Horn P (2016) The impact of seed size and chemical composition on seedling vigor, yield, and fiber quality of cotton in five production environments. *Field Crops Res* 193:186–195
- Turley RB, Chapman KD (2010) Ontogeny of cotton seeds: gametogenesis, embryogenesis, germination, and seedling growth. In: Stewart JM, Oosterhuis DM, Heitholt JJ, Mauney JR (eds) *Physiology of cotton*, Springer, Dordrecht. https://doi.org/10.1007/978-90-481-3195-2_29
- Valliyodan B, Nguyen HT (2006) Understanding regulatory networks and engineering for enhanced drought tolerance in plants. *Curr Opin Plant Biol* 9:189–195
- Villadsen D, Rung JH, Nielsen TH (2005) Osmotic stress changes carbohydrate partitioning and fructose-2, 6-bisphosphate metabolism in barley leaves. *Funct Plant Biol* 32:1033–1043
- Wang XY, Liu YN (1997) Characteristics and key cultivation techniques of cotton-24 in northern Xinjiang. *Xinjiang Agric Sci* 4:165 (In Chinese)
- Wang Z, Stutte GW (1992) The role of carbohydrates in active osmotic adjustment in apple under water stress. *J Am Soc Hortic Sci* 117:816–823
- Wang C, Isoda A, Wang P (2004) Growth and yield performance of some cotton cultivars in Xinjiang, China, an arid area with short growing period. *J Agron Crop Sci* 190:177–183
- Wang R, Ji S, Zhang P, Meng Y, Wang Y, Chen B, Zhou Z (2016) Drought effects on cotton yield and fiber quality on different fruiting branches. *Crop Sci* 56:1265–1276
- Wenqing Z, Yali M, Binglin C (2011) Effects of fruiting-branch position, temperature-light factors and nitrogen rates on cotton (*Gossypium hirsutum* L.) fiber strength formation. *China Agric Sci* 44(18):3721–3732
- White SC, Raine SR (2009) Physiological response of cotton to a root zone soil moisture gradient: implications for Partial Root Zone Drying irrigation. *J Cotton Sci* 13:67–74
- Shareef M, Zeng F, Gui D, Waqas M, Zhang B, Fiaz M (2018) Drought induced interactive changes in physiological and biochemical attributes of cotton (*Gossypium hirsutum* L.). *Int J Agr Biol*. <https://doi.org/10.17957/ijab/15.0513>
- Yi X-P, Zhang Y-L, Yao H-S, Luo H-H, Gou L, Chow WS, Zhang W-F (2016) Rapid recovery of photosynthetic rate following soil water deficit and re-watering in cotton plants (*Gossypium herbaceum* L.) is related to the stability of the photosystems. *J Plant Physiol* 194:23–34

- Zaher-Ara T, Boroomand N, Sadat-Hosseini M (2016) Physiological and morphological response to drought stress in seedlings of ten citrus. *Trees* 30:985–993
- Zhang D, Luo Z, Liu S, Li W, Dong H (2016) Effects of deficit irrigation and plant density on the growth, yield and fiber quality of irrigated cotton. *Field Crops Res* 197:1–9
- Zhi X-y et al (2016) Effects of plant density on cotton yield components and quality. *J Integr Agric* 15:1469–1479
- Zhou S, Wang J, Liu J, Yang J, Xu Y, Li J (2012) Evapotranspiration of a drip-irrigated, film-mulched cotton field in northern Xinjiang, China. *Hydrol Proce* 26:1169–1178