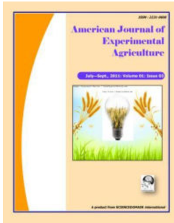

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Effect of Nitrogen Rates and Flowering Dates on Fiber Quality of Cotton (*Gossypium hirsutum* L.)

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Research Article

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ABSTRACT

Nitrogen (N) supply during boll setting and maturation period of cotton can be critical in determining fiber quality. The study aims to investigate the relationship between N rates and formation of fiber length, strength, maturity and micronaire in bolls with different flowering dates. Field experiments were conducted using two cotton cultivars (Kemian 1 and NuCOTN 33B) and three N fertilization rates (0, 240, and 480 kg N ha^{-1}) in Nanjing and Xuzhou in 2005 and in Anyang in 2007, China. The fiber length, strength, maturity, micronaire, and N concentration per unit area (N_A) of the subtending leaf of cotton boll were analyzed.
N fertilization rates, flowering dates, and N fertilization rates × flowering dates significantly ($P \leq 0.05$) affected N_A and the formation of fiber length, strength, maturity and micronaire. N fertilization rates affected fiber quality by influencing N_A which was significantly related to rate and duration of the fiber quality formation process. The optimal N_A for fiber quality formation was varied. For bolls flowering before August 25, when mean daily temperature during boll maturation period (MDT_{BMP}) was higher than 21℃, N_A in the 240 kg N ha^{-1} treatment was optimal for fiber length, fiber strength, maturity, and micronaire formation. For bolls flowering after September 10 when MDT_{BMP} was lower than 21℃, N_A in the 480 kg N ha^{-1} treatment was optimal for fiber quality development. Higher N application rate can sustain a higher N_A level in its subtending leaf, leading to the less decrease magnitude of fiber length, strength, maturity, micronaire in late flowering dates. 240 kg N ha^{-1} is the recommended N application strategy for optimal quality, but we could diminish

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the negative influence of climate stress on fiber quality by supplemented N fertilizer in later flowering season.

Keywords: Cotton; nitrogen rates; flowering dates; N_A; fiber length; fiber strength; fiber maturity; fiber micronaire.

ABBREVIATIONS

DPA: Days Post Anthesis; BMP: boll maturation period, the same as cotton fiber developmental period; FEP: fiber elongation period; SWSP: fiber secondary wall synthesis period; MDT_{BMP}: mean daily temperature during BMP; MDR_{BMP}: mean daily radiation during BMP; TR_{BMP}: total rainfall during BMP; MDT_{FEP}: mean daily temperature during FEP; MDR_{FEP}: mean daily radiation during FEP; TR_{FEP}: total rainfall during FEP; MDT_{SWSP}: mean daily temperature during SWSP; MDR_{SWSP}: mean daily radiation during SWSP; TR_{SWSP}: total rainfall during SWSP; CV: Coefficient of variation; N_A: N concentration per unit area in the subtending leaf; N_A-BMP: average of daily N_A during the boll maturation period (BMP); $V(Len)_{max}$: the maximum fiber elongation rate; T(Len): duration of fiber rapid-elongation; V_{RG}: mean strengthen rate of rapid growth period of fiber strength; V_{SG}: mean strengthen rate of steady growth period of fiber strength; T_{RG}: duration of rapid growth period of fiber strength; T_{SG}: duration of steady growth period of fiber strength; $V(Mat)_{max}$: The maximum fiber maturation rate; T(Mat): The duration of fiber rapid-maturation; $V(Mic)_{max}$: The maximum increase rate of fiber micronaire; T(Mic): The duration of fiber micronaire rapid increase.

1. INTRODUCTION

Cotton is one of the most important economic crops in the world. The highly variable properties of cotton fiber are associated with the yarn quality and machining efficiency (Bradow et al., 1996). As the textile industry is modernizing by shifting to high-speed ring, open-end, and air jet spinning, the new machinery requires higher fiber quality (Mishra et al., 2001). Higher fiber quality is related to the cooperation of genetics (Richard et al., 2006), environment (Liakatas et al., 1998; Pettigrew, 2001; Yeates et al., 2010; Zhao and Oosterhuis, 2000), and management (Girma et al., 2007; Pettigrew and Adamczyk, 2006; Read et al., 2006) factors. Since a highly optimized genetic background of cotton were developed and most environmental variables under field conditions is difficult to control, management plays a more and more important role in maintaining high fiber quality.

Nitrogen (N) is one of the most important management practices. N nutrient is an essential element for canopy area development and photosynthesis (Wullschleger and Oosterhuis, 1990). It is required most consistently and in larger amounts than other nutrients for cotton production (Hou et al., 2007; Rosolem and van Melis, 2010). One aspect of N nutrition in cotton is its effect on fiber quality. However, the results are varied (Seagull et al., 2000; Reddy et al., 2004). Boquet (2005) believe that fiber properties such as fiber length, strength, and micronaire will not be appreciably compromised or improved by N application rate unless the crop is under severe N-deficient condition. Rashidi and Gholami (2011), Saleem et al., (2010), Seilsepour and Rashidi (2011) showed that effect of different application rates of N was not significant for fiber length, strength and micronaire. Bilalis et al., (2010), Pettigrew and Adamczyk (2006) indicated varying the source, amount, or application timing of the N fertilization did not affect fiber length, strength, maturity and micronaire. By contrast, several other studies have observed significant effect of N on fiber quality (Fritschi et al., 2003; Read et al., 2006). Constable and Hearn (1981), Rochester et al., (2001), indicated that increasing N fertilizer rates generally increased fiber length and fiber strength, whereas micronaire tended to decline. Ali and Hameed (2011) also stated that increased N fertilization increased fiber length. Bauer and Roof (2004) observed lower fiber length and strength in plots that did not receive N fertilization. Boman et al., (1997), reported that micronaire readings were reduced by applied N in low-micronaire environments and increased by applied N in high-micronaire environments. Girma et al., (2007), reported that N rates greater than 90 kg ha^{-1} significantly reduce fiber length, strength, and micronaire. Tewolde and Fernandez (2003) indicated that increasing rate of applied nitrogen significantly increased fiber length and micronaire.

The difference in these fiber quality traits responses to N fertilization from study to study is presumably related to cultivar differences and to differences in the performance of the same cultivars because of weather and soil-related factors (Bradow and Davidonis, 2010; Girma et al., 2007; Pettigrew and Adamczyk, 2006). On one hand, the indeterminate growth habit of cotton determines that cotton bolls are initiated over a long period of time during the season, and fiber properties of bolls on the same plants can differ because of different environmental conditions during boll growth and development (Bauer and Frederick, 2005; Boquet and Breitenbeck, 2000). Davidonis et al., (2004) and Jenkins et al., (1990), found seasonal shifts in plant growth and metabolism are manifest in higher levels of fiber maturation in bolls from July flowers, as compared to fibers in bolls from August flowers. Bradow et al. (1997), and Reddy et al., (1999), found that weather factors that affect carbon assimilation, such as temperature, influence micronaire. Reddy et al., (1999), showed that fibers were longer when bolls grew at less than optimal temperatures (25 °C) for boll growth, maturity and micronaire increased linearly with the increase in temperature up to 26 °C but decreased at 32 °C. Dong et al.,(2006), found late-season fiber exhibited significantly lower strength and micronaire than early-season fiber. However, little information is currently available on how the flowering date shifts influence N effects on fiber quality.

On the other hand, amount of N fertilization cannot represent the plant nutrition status because N fertilization is susceptible to NH_3 volatilization losses and the losses depended on fertilizer practices, soil type and environmental conditions (Kawakami et al., 2010) and bolls undergo different soil-applied nutrients intakes as flowering dates shifts (Boquet and Breitenbeck, 2000). The leaf nitrogen is a more precise indicator than soil nitrogen application (Reddy et al., 2004). The nitrogen concentration per unit area (N_A) in the subtending leaf, containing both the information of subtending leaf N concentration per unit weight (N_M) and specific leaf area (Yoshida et al., 2007), can reflect the N nutrition level of cotton plant in any nitrogen and soil conditions (Bondada et al., 1996; Grindlay, 1997). Thus investigations on the relationship between formation of fiber quality and N_A may be an available method to explain the contradicted N fertilization effects on fiber quality to some extent.

Therefore, the objectives of this study were to explore (1) the response of N_A and fiber quality to N fertilization rates at different flowering dates, (2) the change in N_A and fiber quality among flowering dates in relation to the N fertilization rate change, and (3) the relationship among N fertilization rate, N_A, and fiber quality. The results may guide further research on the impacts of N on cotton fiber quality formation.

2. MATERIALS AND METHODS

2.1 Experimental Design

Field experiments were conducted in Nanjing (32°02′ N, 118°50′ E) and Xuzhou (34°12′ N, 117°36′ E) in Jiangsu Province in 2005, Anyang (36°04′ N, 114°13′ E) in Henan Province in 2007, China. The soil type and soil nutrient contents are listed in Table 1.

The plots were eight rows wide (0.9 m row spacing) by 21 m long. The experiments were designed as randomized complete blocks with three replications in Nanjing and Anyang as well as four replications in Xuzhou. Six treatments containing two cultivars (Kemian 1 and NuCOTN 33B) and different rates of N (0, 240, and 480 kg N ha^{-1}) were evaluated. Cotton were planted on April 25 (normal planting date) and transplanted on May 25 with 0.9 m row spacing and 0.3 m plant spacing. The N source was urea (50% N). Half of the N fertilizer was applied basally before transplanting and the rest was top-dressed at the first flowering stage. For the three fields, the soils were subjected to irrigation immediately after transplanting and then throughout the growing season in fields, irrigation was not applied. Other management practices were conducted according to local agronomic practices.

Table 1. Soil types and soil nutrient contents at the experimental sites

Site	Year	Soil type	Total N content (g kg^{-1})	Available N content (mg kg^{-1})	Available P content (mg kg^{-1})	Available K content (mg kg^{-1})
Nanjing	2005	Yellow brown Loam	10.3	40.13	28.95	79.17
Xuzhou	2005	Alluvial soil	11.7	47.83	29.00	77.54
Anyang	2007	Sandy loam	9.4	39.28	23.57	71.19

2.2 Sampling and Weather Data

In the field, different environmental conditions during the fiber developmental period were provided based on the flowering dates. White flowers at the sympodial fruiting boll position 1 and 2 of the cotton plants were tagged on July 15 and 25, August 10 and 25, and September 10 in Nanjing and Xuzhou in 2005, and on July 18 and 27, and August 15 in Anyang in 2007, respectively. 20 to 30 tagged bolls and their subtending leaves were picked at 5, 10, 17, 24, 31, 38, 45, 52 d post anthesis (DPA), and at boll opened day (BO) in Nanjing and Xuzhou in 2005, and at 5, 10, 17, 24, 31, 38, 45 DPA, and BO in Anyang in 2007, respectively. For each sampling DPA, 3 sampled bolls were preserved for measurements of cotton fiber length. The shells, seeds, and fiber of the other bolls were separated. The immature cotton fibers were hand-ginned and allowed to dry at ambient room temperature. The dried fibers were preserved to determine biomass and fiber quality. To obtain fiber-quality measurements, the immature fibers were treated as mature fibers and equilibrated under the same humidity and temperature conditions.

Weather data was collected from the Nanjing, Xuzhou and Anyang weather stations. The mean daily temperature (MDT), mean daily radiation (MDR) and total rainfall (TR) during the cotton boll maturation period (BMP, 0–50 DPA, the same as cotton fiber developmental period), fiber elongation period (FEP, 0–30 DPA) and secondary wall synthesis period (SWSP, 10–50 DPA) in different flowering dates and sites are shown in Table 2. The coefficients of variation (CVs) of MDT (MDT_{SWSP}), MDR (MDR_{SWSP}), and TR (TR_{SWSP}) were often higher than MDT (MDT_{FEP}), MDR (MDR_{FEP}), and TR (TR_{FEP}) during FEP. The three sites offered three distinct weather conditions for conducting the research. At each site, MDT_{BMP} decreased as flowering dates delayed. Compared with Xuzhou, the growing season was warmer from July 15 to September 10 in Nanjing, with greater MDR_{BMP} and lesser TR_{BMP}.

2.3 Measurements

Cotton fiber length (Len, mm) of the harvested bolls was measured using the water washing method (Thaker et al., 1989) within 30 DPA, and with a Y-146 cotton fiber photodometer (Taicang Electron Apparatus Co. Ltd, China) after 30 DPA. Cotton fiber strength (Str, cN tex^{-1}) was determined by USTER *HVI 1000 CLASSING* (Uster Technologies Ltd, Switzerland). Cotton fiber maturity (Mat) was measured with a Y-147 cotton fiber maturity tester (Taicang Electron Apparatus Co. Ltd, China).

Cotton fiber micronaire (Mic) was determined by High Volume Instrument at the Cotton Quality Supervision, Inspection, and Testing Center of China Ministry of Agriculture. N_A was calculated by the product of N concentration per unit gram (N_M) and specific leaf weight (SLW). N_M of the subtending leaves was measured using the Kjeldahl method (Feil et al., 2005). SLWs of the subtending leaves were obtained by leaf dry weight divided by leaf area.

2.4 Data Analysis

Microsoft Excel 2003 was adopted for data processing and drawing of figures. An analysis of variance was performed using SPSS. The means were separated using the least significance difference (LSD) test at 5% or 1% of probability level. CV was calculated as the ratio of the standard deviation to the mean to assess variations of N_A–BMP and fiber quality of opened boll between flowering date and N rates.

Models for N_A and fiber quality changes with DPA in different N rates and flowering dates were simulated. The data for N_A and fiber quality changes with DPA were statistically analyzed with software SPSS or Microsoft Excel 2003. In Anyang in 2007, fiber strength, maturity and micronarie was detected at 31, 38, 45 DPA, and BO. Four observed spot is not sufficient to fitting the regression models. Thus, only the data obtained from Nanjing and Xuzhou (seven spots for N_A and fiber length, five spots for fiber strength, maturity and micronaire with DPA progress in each flowering dates) were analyzed in this part.

Changes of N_A can be simulated by the equation,

$$N_A = \alpha \times DPA^{-\beta} \tag{1}$$

where α and β are parameters. Daily N_A was calculated by the equation. N_A during BMP (N_A-BMP) was the average of daily N_A during the BMP.

Table 2. Weather condition during BMP, FEP, and SWSP in Nanjing, Xuzhou and Anyang

Site (Year)	Flowering Date (mm dd)	BMP			FEP			SWSP		
		MDT_{BMP} (℃)	MDR_{BMP} ($MJ\ m^{-2}$)	TR_{BMP} (mm)	MDT_{FEP} (℃)	MDR_{FEP} ($MJ\ m^{-2}$)	TR_{FEP} (mm)	MDT_{SWSP} (℃)	MDR_{SWSP} ($MJ\ m^{-2}$)	TR_{SWSP} (mm)
Nanjing (2005)	July 15	27.7	17.8	292.5	29.1	19.9	201.9	27.2	16.3	289.0
	July 25	26.6	16.1	350.5	28.0	17.5	276.3	26.0	15.5	279.0
	August 10	25.4	14.2	172.4	25.9	16.4	134.4	24.5	12.4	127.7
	August 25	23.4	12.2	114.3	25.2	13.8	81.7	23.0	12.1	62.8
	September 10	20.8	11.1	75.9	23.2	10.1	60.8	19.3	10.4	51.8
	CV (%)	11.06	19.28	58.15	8.83	24.02	58.77	12.68	18.69	71.01
Xuzhou (2005)	July 15	26.1	15.0	488.9	27.3	15.3	301.5	25.7	14.7	410.8
	July 25	25.2	15.0	421.9	26.5	15.2	265.4	24.7	15.5	237.4
	August 10	23.4	13.7	287.6	24.6	16.2	195.1	22.2	12.3	260.6
	August 25	21.0	11.8	289.6	22.8	13.0	196.6	20.5	11.5	143.6
	September 10	18.4	10.6	144.3	20.3	9.7	143.6	17.0	10.6	119.4
	CV (%)	13.78	14.90	40.97	11.66	18.93	28.43	15.87	16.26	49.25
Anyang (2007)	July 18	24.8	20.4	153.9	25.6	22.7	84.9	24.8	18.5	140.5
	July 27	24.3	18.9	141.8	26.1	21.0	76.8	23.8	17.3	69.4
	August 15	21.7	15.5	94.5	23.3	16.9	69.1	20.6	14.4	94.4
	CV (%)	7.09	13.75	24.13	6.10	14.86	10.27	9.58	12.74	35.56

BMP: boll maturation period, the same as cotton fiber developmental period; FEP: fiber elongation period; SWSP: fiber secondary wall synthesis period. MDT_{BMP}: mean daily temperature during BMP; MDR_{BMP}: mean daily radiation during BMP; TR_{BMP}: total rainfall during BMP; MDT_{FEP}: mean daily temperature during FEP; MDR_{FEP}: mean daily radiation during FEP; TR_{FEP}: total rainfall during FEP; MDT_{SWSP}: mean daily temperature during SWSP; $MDRs_{SWSP}$: mean daily radiation during SWSP; TR_{SWSP}: total rainfall during SWSP

The formation of cotton fiber length, maturity, and micronaire can be described by the logistic regression model,

$$Len\ (Mat\ or\ Mic) = \frac{Len_m\ (Mat_m\ or\ Mic_m)}{1 + ae^{b*\mathrm{DPA}}} \quad (2)$$

where *Len* (*Mat or Mic*) is the cotton fiber length (maturity or micronaire), Len_m (Mat_m *or* Mic_m) is the theoretical maximum of fiber length (maturity or micronaire), whereas *a* and *b* are parameters. The start (DPA_1), termination time (DPA_2), and duration {*T*(*Len*) [*T*(*Mat*), or *T*(*Mic*)]= DPA_2-DPA_1} of the fiber rapid-elongation (rapid-maturation, or fiber micronaire rapid-increase) period, and the maximum elongation rate {$V(Len)_{max}$, maximum maturation rate [$V(Mat)_{max}$], or maximum increase rate of micronaire [$V(Mic)_{max}$]} were derived from the formula (3), (4), and (5):

$$\mathrm{DPA}_1 = \frac{1}{b}\ln\frac{2+3^{\frac{1}{2}}}{a} \quad (3)$$

$$\mathrm{DPA}_2 = \frac{1}{b}\ln\frac{2-3^{\frac{1}{2}}}{a} \quad (4)$$

$$V(Len\,[Mat\ or\ Mic])_{\max} = -\frac{b \times Len_m\ (Mat_m\ or\ Mic_m)}{4} \quad (5)$$

According to Feng et al. (2009), the formation of cotton fiber strength can be divided into rapid and steady growth periods. Thus, the change in the fiber strength is simulated by equation (6).

$$Str = \begin{cases} a_1 * \ln(\mathrm{DPA}) - b_1 & \mathrm{DPA} \le \mathrm{DPA}_b \\ a_2 + b_2 * \mathrm{DPA} & \mathrm{DPA} > \mathrm{DPA}_b \end{cases} \quad (6)$$

where *Str* (mm) is the cotton fiber strength, $\mathrm{DPA_b}$ represents the end of the duration of cotton fiber strength rapid growth period, whereas a_1, a_2, b_1, and b_2 are parameters. From the formula, the duration of the rapid (T_{RG}) and steady (T_{SG}) growth periods of fiber strength are calculated by the equation T_{RG} (d) = $\mathrm{DPA_b}$-OSWSP and T_{SG} (d) = BMP-$\mathrm{DPA_b}$, respectively. OSWSP means the onset DPA of fiber secondary wall synthesis period. It was calculated according to Zhao et al., (2010). The mean strengthen rate of rapid growth (V_{RG}) and steady growth period (V_{SG}) growth periods of fiber strength can be calculated by $V_{RG}=\sum(FS_{DPA}-FS_{DPA-1})/T_{RG}$ and $V_{SG}= b_2$, respectively.

3. RESULTS

3.1 N Fertilization Effects on N_a

N_A decreased from 5 DPA for both cultivars Kemian 1 and NuCOTN 33B (Figure 1, the response of N_A and fiber quality to N rates in different flowering dates were the same for the two cultivars, so data for NuCOTN 33B not shown). N_A was significantly (P<0.01) affected by flowering dates, N fertilization rates and flowering dates × N fertilization rates (Table 3).

Table 3. Results from analysis of variance for N_A in the subtending leaf in different nitrogen rates and flowering dates at three locations, Nanjing, Xuzhou and Anyang, for cultivar Kemian 1

Site (Year)		Analysis of variance for N_A							
		5 DPA	10 DPA	17 DPA	24 DPA	31 DPA	38 DPA	45 DPA	52 DPA
Nanjing (2005)	Flowering dates	**	**	**	**	**	**	**	**
	Nitrogen rates	**	**	**	**	**	**	**	**
	Flowering dates × Nitrogen rates	**	**	**	**	**	**	**	**
Xuzhou (2005)	Flowering dates	**	**	**	**	**	**	**	**
	Nitrogen rates	**	**	**	**	**	**	**	**
	Flowering dates × Nitrogen rates	ns	**	**	**	**	**	**	**
Anyang (2007)	Flowering dates	**	**	**	**	**	**	**	
	Nitrogen rates	**	**	**	**	**	**	**	
	Flowering dates × Nitrogen rates	ns	**	ns	*	**	ns	*	

*: significant at 0.05 level; **: significant at 0.01 level; ns: no significant difference

At each sampling stage, N_A was significantly higher ($P<0.05$) in the 480 kg N ha^{-1} treatment, followed by 240 and 0 kg N ha^{-1}. Under the same N fertilization rates, N_A significantly ($P<0.05$) increased as the flowering date was delayed. Thus, higher N application rate (such as 480 kg N ha^{-1}) can sustain higher NA level in the subtending leaf of the cotton boll in any flowering dates (different temperature).

N_A-BMP was estimated according to Eq. (1) to evaluate the overall performance of N_A in the present study (Table 4). A delayed flowering date resulted in a gradual increase in the difference in N_A-BMP between 0 and 240 kg N ha^{-1} in contrast to the decreased N_A-BMP between 240 and 480 kg N ha^{-1}. N_A-BMP in Xuzhou was lower compared with that in Nanjing at same flowering date, which may be related to the greater TR in Xuzhou (Table 2), leading to loss of soil N and a decrease in plant nitrogen absorption.

CVs of N_A-BMP among N fertilization rates and among flowering dates were then calculated and are listed in Table 13. For both Kemian 1 and NuCOTN 33B, the CVs of N_A-BMP among N rates increased as the flowering date changed from July 15 to September 10. CVs of N_A-BMP among different flowering rates increased in the 240 and 480 kg N ha^{-1} treatment.

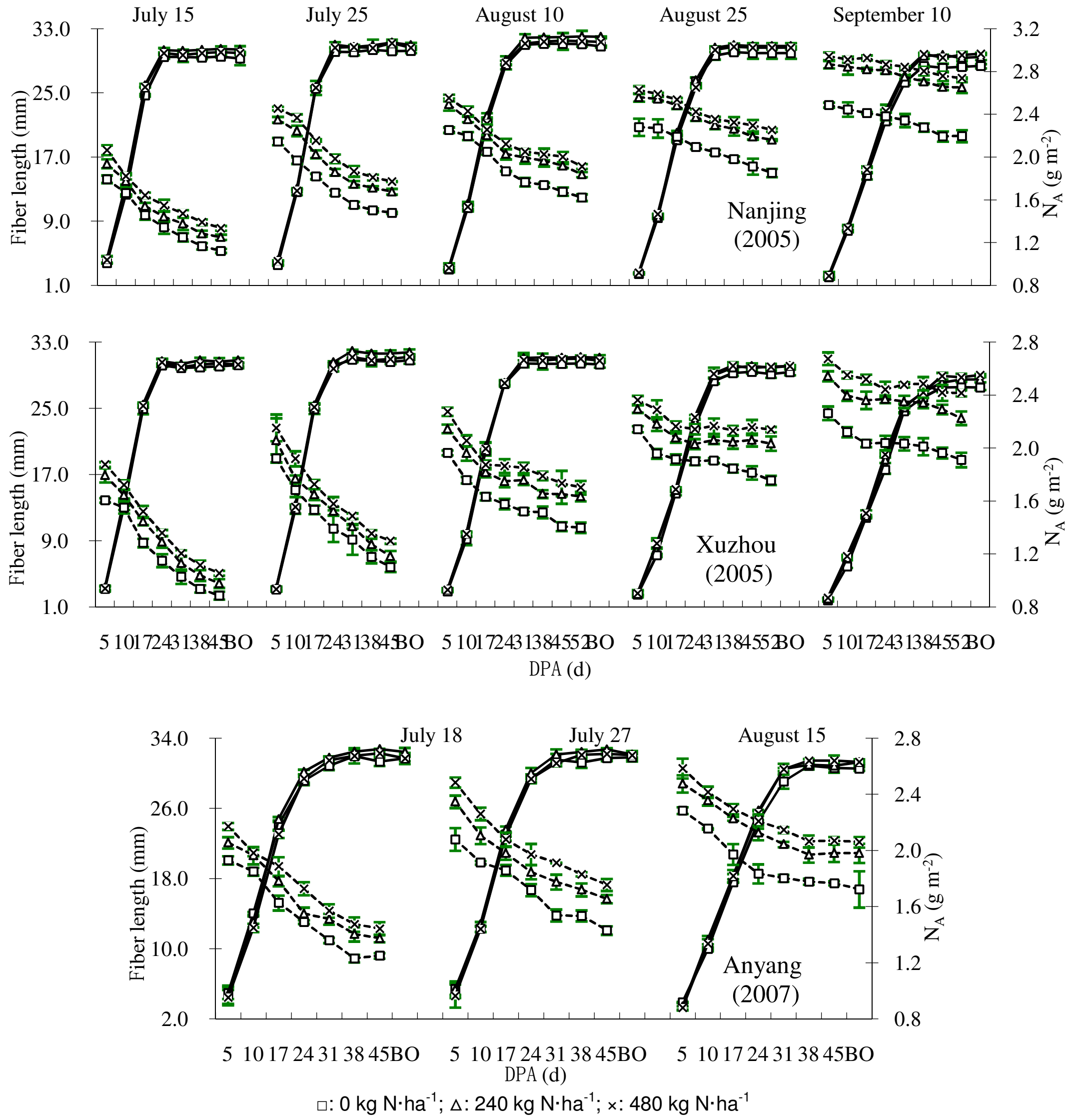

Fig.1. Dynamic changes of cotton fiber length (solid lines) and N_A (dot lines) in the subtending leaf of cotton boll at three locations, Nanjing, Xuzhou and Anyang, for cultivar Kemian 1

DPA means days post anthesis; BO stands for cotton boll opened day. July 15, July 25, August 10, August 25 and September 10 in Nanjing and Xuzhou, July 18, July 27 and August 15 in Anyang means flowering dates. Vertical bars represent standard errors

Table 4. Effects of nitrogen rates on changing characteristics of nitrogen concentration in the subtending leaf of cotton boll in Nanjing and Xuzhou

Flowering date (mm dd)	Nitrogen rate (Kg N ha^{-1})	Nanjing			Xuzhou		
		Equation	R^2	N_A-BMP (g m^{-2})	Equation	R^2	N_A-BMP (g m^{-2})
	0	N_A=2.67 DPA$^{-0.22}$	0.9740**	1.44	N_A =2.78 DPA$^{-0.29}$	0.9389**	1.24
July 15	240	N_A =2.77 DPA$^{-0.21}$	0.9874**	1.54	N_A =3.05 DPA$^{-0.29}$	0.9473**	1.36
	480	N_A =2.85 DPA$^{-0.20}$	0.9959**	1.63	N_A =3.09 DPA$^{-0.27}$	0.9531**	1.43
	0	N_A =2.99 DPA$^{-0.19}$	0.9864**	1.77	N_A =3.07 DPA$^{-0.26}$	0.9601**	1.46
July 25	240	N_A =3.24 DPA$^{-0.17}$	0.9748**	1.97	N_A =3.22 DPA$^{-0.25}$	0.9545**	1.55
	480	N_A =3.37 DPA$^{-0.17}$	0.9682**	2.07	N_A =3.33 DPA$^{-0.24}$	0.9694**	1.63
	0	N_A =2.61 DPA$^{-0.12}$	0.9812**	1.85	N_A =2.45 DPA$^{-0.14}$	0.9825**	1.61
August 10	240	N_A =2.71 DPA$^{-0.10}$	0.9578**	1.98	N_A =2.57 DPA$^{-0.12}$	0.9792**	1.80
	480	N_A =2.78 DPA$^{-0.10}$	0.9626**	2.07	N_A =2.70 DPA$^{-0.12}$	0.9652**	1.89
	0	N_A =2.70 DPA$^{-0.10}$	0.9859**	2.00	N_A =2.36 DPA$^{-0.07}$	0.9109**	1.90
August 25	240	N_A =2.87 DPA$^{-0.08}$	0.9717**	2.22	N_A =2.44 DPA$^{-0.05}$	0.8397**	2.09
	480	N_A =2.86 DPA$^{-0.05}$	0.8360**	2.42	N_A =2.50 DPA$^{-0.04}$	0.8451**	2.19
	0	N_A =2.80 DPA$^{-0.07}$	0.8935**	2.25	N_A =2.47 DPA$^{-0.06}$	0.9205**	2.05
September10	240	N_A =3.04 DPA$^{-0.05}$	0.9495**	2.56	N_A =2.70 DPA$^{-0.04}$	0.8568**	2.36
	480	N_A =3.16 DPA$^{-0.05}$	0.8776**	2.71	N_A =2.82 DPA$^{-0.04}$	0.8848**	2.50

**: significant at 0.05 level; **: significant difference at 0.01 probability level (n=7, $R^2_{0.05}$=0.5693, $R^2_{0.01}$=0.7653)*

Table 5. Results from analysis of variance for cotton fiber length in different nitrogen rates and flowering dates at three locations, Nanjing, Xuzhou and Anyang, for cultivar Kemian 1

Site (Year)		Analysis of variance for fiber length								
		5 DPA	10 DPA	17 DPA	24 DPA	31 DPA	38 DPA	45 DPA	52 DPA	BO
Nanjing (2005)	Flowering dates	**	**	**	**	**	**	**	**	**
	Nitrogen rates	**	**	**	**	**	**	**	**	**
	Flowering dates × Nitrogen rates	**	**	*	*	ns	ns	ns	ns	ns
Xuzhou (2005)	Flowering dates	**	**	**	**	**	**	**	**	**
	Nitrogen rates	*	**	**	**	**	**	**	**	**
	Flowering dates × Nitrogen rates	ns	*	*	**	ns	ns	*	ns	**
Anyang (2007)	Flowering dates	**	**	**	**	**	**	**		**
	Nitrogen rates	ns	*	**	**	**	*	**		*
	Flowering dates × Nitrogen rates	ns	**	*	*	ns	ns	ns		ns

*: significant at 0.05 level; **: significant at 0.01 level; ns: no significant difference

3.2 N Fertilization Effects on Cotton Fiber Length Formation

Fiber length increased markedly before 31 DPA and showed relative stability with slight promotion from approximately 31 DPA to open boll (Figure 1). Fiber length was significantly (P<0.01) affected by the N fertilization rates and flowering dates (Table 5) as well as by flowering dates × N fertilization rates (P<0.05) before 31 DPA. During fiber development, the fiber length was longest in the 240 kg N ha^{-1} treatment with bolls flowering before August 25 when MDT_{BMP}>21 ℃ and in the 480 kg N ha^{-1} treatment with bolls flowering after August 25 when MDT_{BMP}<21 ℃ (Figure 1 and Table 2). The fiber length was always shortest (P<0.05) in the 0 kg N ha^{-1} treatment.

CV of fiber length among nitrogen rates was larger in September 10 compared with those in other flowering dates (Table 13). CV of fiber length among flowering dates decreased gradually as N application rate increased. Although 480 kg N ha^{-1} can decrease the CV of fiber length among flowering dates, it did not increase fiber length with bolls flowering before August 25. Thus, 240 kg N ha^{-1} was the optimal N rate to achieve the maximum fiber length in most flowering dates in the current experiment.

Fiber length formation was determined by the rate and the duration of the fiber elongation process (Braden and Smith, 2004). The changes in fiber length can be simulated by the logistic regression model (Eq.2). Maximum elongation rate [$V(Len)_{max}$] and duration [$T(Len)$] of fiber rapid-elongation can then be calculated from the equation (Table 6). Before the flowering date August 25, as N fertilization rate increased, $T(Len)$ became prolonged, and $V(Len)_{max}$, as well as fiber length, increased and then decreased. At flowering dates after

August 25, $T(Len)$ also became longer, and $V(Len)_{max}$ and fiber length increased as N fertilization rate increased. Variations in the $V(Len)_{max}$ response to N fertilization were consistent with fiber length, indicating that the response of fiber length to N application rates was related ($P \leq 0.01$) to $V(Len)_{max}$. This was also proven by the correlation analysis (Table 14).

Table 6. Eigen values of cotton fiber elongation in different nitrogen rates at two locations, Nanjing and Xuzhou, for cultivar Kemian 1

Site	Flowering date (mm dd)	Nitrogen rate (Kg N ha^{-1})	R^2	V_{max} (mm)	T (d)	Len_m (mm)	Len_{obs} (mm)
Nanjing	July 15	0	0.9248*	1.348	14.50	29.68	29.3 b
		240	0.9361*	1.371	14.70	30.61	30.4 a
		480	0.9343*	1.344	14.81	30.23	29.9 a
	August 10	0	0.9701*	1.249	16.51	31.32	30.8 b
		240	0.9728*	1.280	16.58	32.23	32.0 a
		480	0.9727*	1.231	16.97	31.71	31.4 ab
	August 25	0	0.9788*	1.184	16.84	30.28	30.0 b
		240	0.9789*	1.218	16.87	31.20	30.8 a
		480	0.9830*	1.202	16.97	30.98	30.6 a
	September 10	0	0.9939*	1.121	16.78	28.57	28.3 b
		240	0.9938*	1.153	17.09	29.93	29.5 a
		480	0.9934*	1.157	17.10	30.05	29.9 a
Xuzhou	July 15	0	0.9131*	1.244	16.08	30.40	30.2 b
		240	0.9189*	1.261	16.19	31.01	30.8 a
		480	0.9155*	1.249	16.21	30.75	30.3 b
	August 10	0	0.9727*	1.254	16.09	30.63	30.3 b
		240	0.9793*	1.276	16.19	31.39	31.1 a
		480	0.9747*	1.242	16.56	31.22	30.8 a
	August 25	0	0.9926*	1.163	16.79	29.64	29.4 b
		240	0.9919*	1.188	16.81	30.34	30.1 a
		480	0.9898*	1.184	16.89	30.37	30.1 a
	September 10	0	0.9952*	1.067	17.23	27.91	27.5 c
		240	0.9951*	1.077	17.58	28.76	28.5 b
		480	0.9953*	1.092	17.59	29.18	29.0 a

V_{max}: the maximal speed of fiber elongation; T: duration for fiber speedy elongation; Len_m: the theoretical maximum of fiber length; Len_{obs}: fiber length (observed value).
**: significant at 0.05 level; **: significant difference at 0.01 probability level (n=7, $R^2_{0.05}$=0.5693, $R^2_{0.01}$=0.7653). Values followed by a different small letter within the same column are significantly different at 0.05 probability levels*

3.3 N Fertilization Effects on Cotton Fiber Strength Formation

Cotton fiber strength is closely related to secondary cell wall synthesis (Bradow and Davidonis, 2000). From approximately 24 DPA to BO, fiber strength continuously increased (Figure 2). Fiber strength for Kemian 1 was always higher than that for NuCOTN 33B. Fiber strength was significantly affected by N fertilization, flowering dates, and flowering dates × N fertilization rates for both cultivars (Table 7).

For bolls flowering before August 10 when MDT_{BMP}>23 ℃ (Table 2), fiber strength was higher (*P*<0.05) in the 0 kg N ha^{-1} treatment at 24 DPA and in 240 kg N ha^{-1} at BO. With bolls flowering between August 10 and September 10 when MDT_{BMP} was 21~23 ℃, it was higher (*P*<0.05) in 240 kg N ha^{-1}, and for bolls flowering after September 10 when MDT_{BMP}<21 ℃ (Figure 2 and Table 2), strength was higher (*P*<0.05) with 480 kg N ha^{-1}. These results suggest that the advantage of 480 kg N ha^{-1} becomes positive gradually as the flowering date was delayed. For 0, 240, and 480 kg N ha^{-1}, fiber strength of BO increased and then decreased as flowering date was postponed (Table 7), the peak value occurring July 25, between July 25 and August 10, and in August 10, respectively, indicated that increased N fertilization rate could delay the time of the peak value of fiber strength (Figure 2).

As flowering date was delayed, the effects of N fertilization rate on strength became larger as the CV of fiber strength among nitrogen rates gradually increased (Table 13). In contrast with the response of the CV of N_A-BMP among flowering dates to N fertilization rates, the CV of fiber strength among flowering dates decreased as N fertilization rates increased.

The dynamics of fiber strength formation were simulated, and the parameters were calculated. From the parameters (Table 8) and the correlation analysis (Table 14), fiber strength was significantly related to ($P \le 0.01$) the mean strength rate of its rapid (V_{RG}) and steady (V_{SG}) growth periods as well as the duration of its rapid growth period (T_{RG}).

Table 7. Results from analysis of variance for cotton fiber strength in different nitrogen rates flowering dates at three locations, Nanjing, Xuzhou and Anyang, for cultivar Kemian 1

Site (Year)		Analysis of variance for fiber strength					
		24 DPA	31 DPA	38 DPA	45 DPA	52 DPA	BO
Nanjing (2005)	Flowering dates	**	**	**	**	**	**
	Nitrogen rates	**	**	**	**	**	**
	Flowering dates × Nitrogen rates	ns	**	**	**	**	**
Xuzhou (2005)	Flowering dates	**	**	**	**	**	**
	Nitrogen rates	**	**	**	**	**	**
	Flowering dates × Nitrogen rates	ns	**	**	**	**	**
Anyang (2007)	Flowering dates		**	**	**		**
	Nitrogen rates		**	**	**		**
	Flowering dates × Nitrogen rates		**	**	**		*

*: significant at 0.05 level; **: significant at 0.01 level; ns: no significant difference*

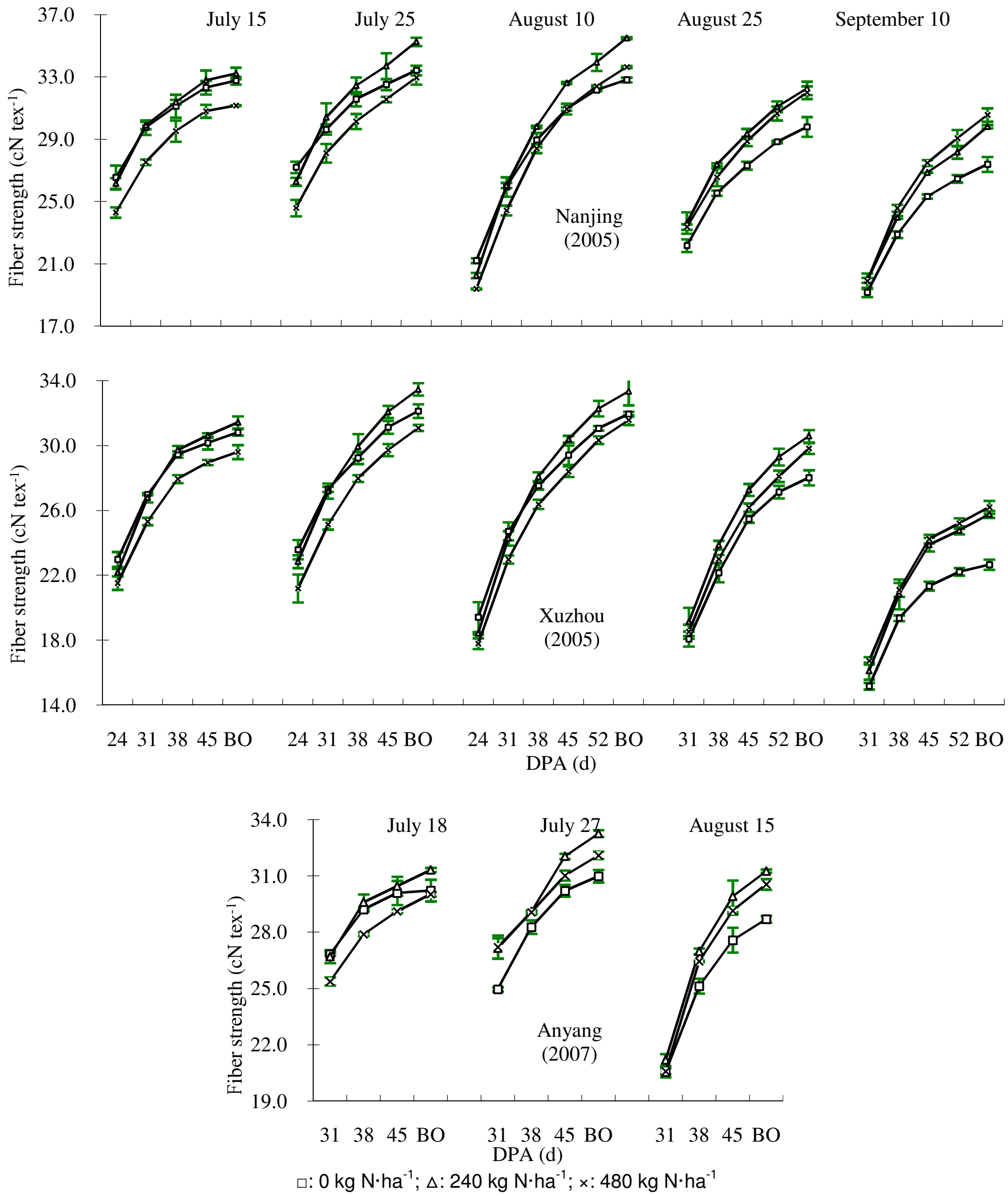

Fig. 2. Dynamic changes of cotton fiber strength in different nitrogen rates and flowering dates at three locations, Nanjing, Xuzhou and Anyang, for cultivar Kemian 1

DPA means days post anthesis; BO stands for cotton boll opened day. July 15, July 25, August 10, August 25 and September 10 in Nanjing and Xuzhou, July 18, July 27 and August 15 in Anyang means flowering dates.

Vertical bars represent standard errors

Table 8. Eigen values of cotton fiber strength in different nitrogen rate at two locations, Nanjing and Xuzhou, for cultivar Kemian 1

Site	Flowering date (mm dd)	Nitrogen rate (Kg N ha^{-1})	R^2	V_{RG} (cN tex^{-1})	T_{RG} (d)	V_{SG} (cN tex^{-1})	T_{SG} (d)	Str_{obs} (cN tex^{-1})
Nanjing	July 15	0	0.9248**	1.75	15	0.21	15	32.8 a
		240	0.9361**	1.80	14	0.23	17	33.2 a
		480	0.9343**	1.66	14	0.24	18	31.2 b
	August 10	0	0.9701**	1.22	18	0.25	16	32.8 c
		240	0.9728**	1.45	18	0.33	19	35.5 a
		480	0.9727**	1.42	17	0.29	20	33.6 b
	September 10	0	0.9939**	1.06	22	0.12	20	27.4 c
		240	0.9938**	1.16	21	0.16	21	29.8 b
		480	0.9934**	1.20	21	0.17	21	30.6 a
Xuzhou	July 15	0	0.9131*	1.63	15	0.25	15	30.8 b
		240	0.9189*	1.62	15	0.28	17	31.4 a
		480	0.9155*	1.61	14	0.25	18	29.6 c
	August 10	0	0.9727**	1.43	16	0.24	22	31.9 b
		240	0.9793**	1.47	16	0.27	23	33.3 a
		480	0.9747**	1.37	16	0.25	24	31.6 b
	September 10	0	0.9952**	0.99	19	0.11	15	22.7 b
		240	0.9951**	1.15	18	0.15	15	25.8 a
		480	0.9953**	1.16	18	0.16	15	26.2 a

V_{RG} and V_{SG}: mean strengthen rate of rapid growth and steady growth period of fiber strength,respectively; T_{RG} and T_{SG}: stands for duration of rapid growth period and steady growth period of fiber strength, respectively; Str_{obs}: observed fiber strength.

**: significant at 0.05 level; **: significant difference at 0.01 probability level (n=5, $R^2_{0.05}$=0.7710, $R^2_{0.01}$=0.9191).*

Values followed by a different small letter within the same column are significantly different at 0.05 probability levels

3.4 N Fertilization Effects on Cotton Fiber Maturity Formation

Fiber maturity increased gradually from 24 DPA to BO as the fiber developed (Figure 3). Both N fertilization rate and flowering dates significantly (P<0.01) affect fiber maturity. The flowering dates × nitrogen rates showed nonsignificant (P>0.05) influence to maturity at 24 DPA and significant (P<0.01) influence for the other sampling DPA (Table 9). For bolls flowering before August 25 when MDT_{BMP}>21 °C, fiber maturity was higher in the 240 kg N ha^{-1} treatment, whereas fiber maturity was higher in the 480 kg N ha^{-1} treatment with bolls flowering after August 25 when MDT_{BMP}<21 °C (Figure 3 and Table 2). For 0, 240, and 480 kg N ha^{-1}, fiber maturity of opened bolls decreased as the flowering date was delayed (Figure 3). Generally, good maturity for fibers is in the range of 1.6 to 1.75 (Zhang and Chen, 2005). In the present experiment, under any N fertilization rates, the fiber maturity of bolls flowering between July 25 to August 10 ranged from 1.6 to 1.75, whereas fiber maturity of those that flowering before July 25 or after August 10 was higher than 1.75 or lower than 1.6, respectively, indicated that flowering date plays a more important role in determining maturity than N fertilization rates.

The CV of fiber maturity among nitrogen rates increased as the flowering dates were delayed (Table 13). The CV of fiber maturity among flowering dates decreased as N fertilization rates increased.

The characteristics of cotton fiber maturity formation were also calculated by logistic regression model (Table 10). From the correlation analysis, both the maximal maturation rate [$V(Mat)_{max}$] and the duration of fiber rapid-maturation [$T(Mat)$] play important roles (P ≤ 0.01) in fiber maturity formation (Table 14).

Table 9. Results from analysis of variance for cotton fiber maturity in different nitrogen rates flowering dates at three locations, Nanjing, Xuzhou and Anyang, for cultivar Kemian 1

Site (Year)		Analysis of variance for fiber maturity					
		24 DPA	31 DPA	38 DPA	45 DPA	52 DPA	BO
Nanjing (2005)	Flowering dates	**	**	**	**	**	**
	Nitrogen rates	**	**	**	**	**	**
	Flowering dates × Nitrogen rates	ns	**	**	**	*	**
Xuzhou (2005)	Flowering dates	**	**	**	**	**	**
	Nitrogen rates	**	**	**	**	**	**
	Flowering dates × Nitrogen rates	ns	**	**	**	*	**
Anyang (2007)	Flowering dates		**	**	**		**
	Nitrogen rates		**	**	**		**
	Flowering dates × Nitrogen rates		**	*	**		**

*: significant at 0.05 level; **: significant at 0.01 level; ns: no significant difference

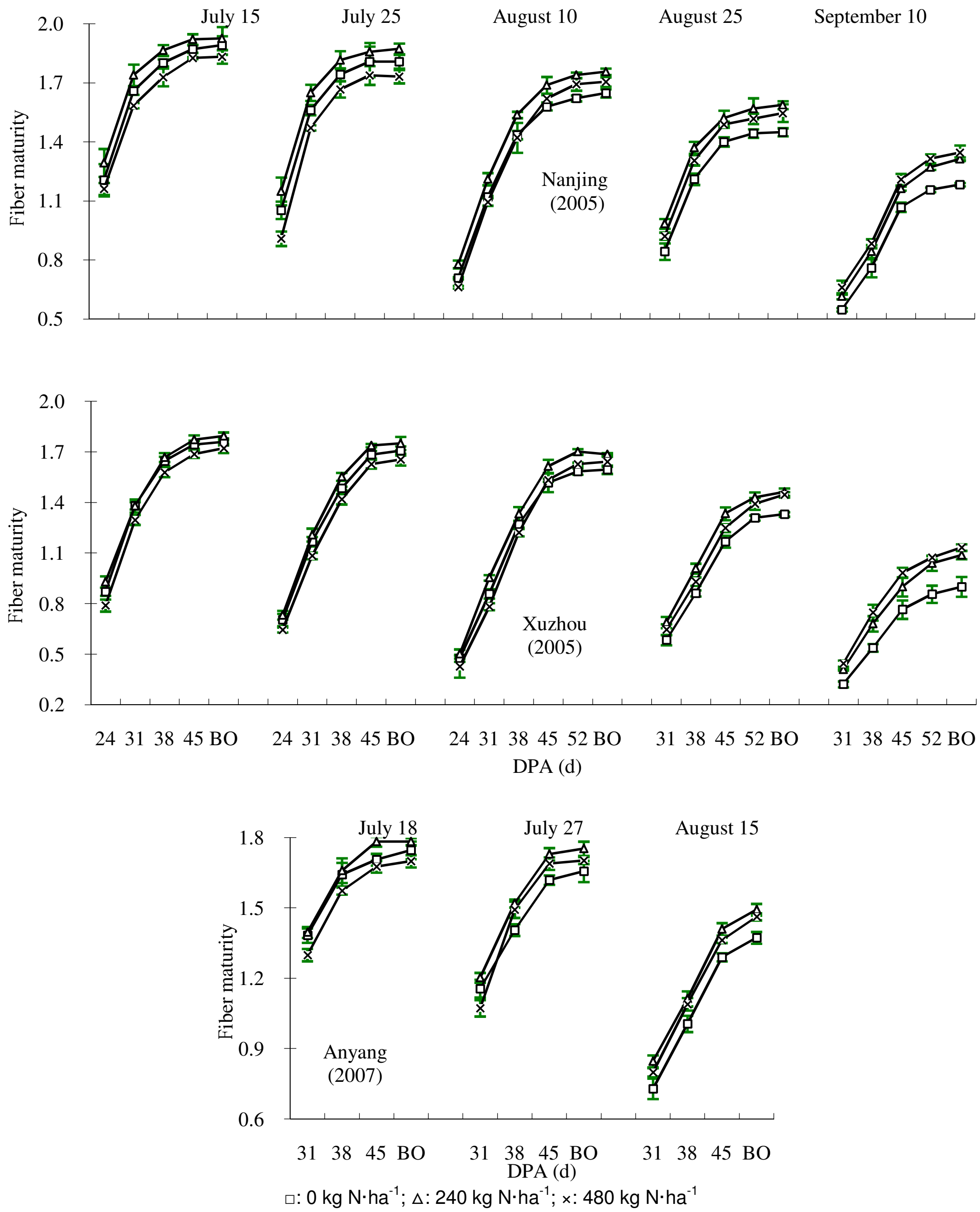

Fig. 3. Dynamic changes of cotton fiber maturity in different nitrogen rates and flowering dates at three locations, Nanjing, Xuzhou and Anyang, for cultivar Kemian 1

Note: DPA means days post anthesis; BO stands for cotton boll opened day. July 15, July 25, August 10, August 25 and September 10 in Nanjing and Xuzhou, July 18, July 27 and August 15 in Anyang means flowering dates.

Vertical bars represent standard errors

Table 10. Eigen values of cotton fiber maturation in different nitrogen rate at two locations, Nanjing and Xuzhou, for cultivar Kemian 1

Site	Flowering date (mm dd)	Nitrogen rate (Kg N ha^{-1})	R^2	$V(Mat)_{max}$	$T(Mat)$ (d)	Mat_m	Mat_{obs}
Nanjingssss	July 15	0	0.9995**	0.093	13.41	1.90	1.89 ab
		240	0.9984**	0.094	13.57	1.94	1.92 a
		480	0.9976**	0.088	13.84	1.85	1.83 b
	August 10	0	0.9983**	0.064	17.05	1.67	1.65 b
		240	0.9995**	0.066	17.77	1.78	1.76 a
		480	0.9997**	0.063	18.09	1.73	1.70 a
	August 25	0	0.9872**	0.054	18.11	1.47	1.45 b
		240	0.9866**	0.058	18.37	1.61	1.59 a
		480	0.9859**	0.055	18.66	1.57	1.55 a
	September 10	0	0.9721**	0.043	18.49	1.20	1.18 b
		240	0.9797**	0.047	18.57	1.33	1.31 a
		480	0.9576**	0.047	19.02	1.36	1.34 a
Xuzhou	July 15	0	0.9992**	0.082	14.49	1.80	1.76 ab
		240	0.9994**	0.080	14.98	1.82	1.79 a
		480	0.9995**	0.075	15.34	1.76	1.72 b
	August 10	0	0.9985**	0.061	17.57	1.63	1.60 c
		240	0.9948**	0.064	17.81	1.73	1.69 a
		480	0.9963**	0.061	18.18	1.68	1.64 b
	August 25	0	0.9814**	0.049	18.27	1.36	1.33 b
		240	0.9873**	0.053	18.52	1.48	1.46 a
		480	0.9920**	0.052	18.60	1.47	1.45 a
	September 10	0	0.9953**	0.033	19.03	0.94	0.90 c
		240	0.9999**	0.039	19.63	1.15	1.09 b
		480	0.9969**	0.040	19.70	1.18	1.13 a

*$V(Mat)_{max}$: The maximal speed of cotton fiber maturation; $T(Mat)$: The duration for cotton fiber speedy maturation; Mat_m: The theoretical maximum of cotton fiber maturity; Mat_{obs}: cotton fiber maturity (observed value). *: significant at 0.05 level; **: significant difference at 0.01 probability level (n=5, $R^2_{0.05}$=0.7710, $R^2_{0.01}$=0.9191). Values followed by a different small letter within the same column are significantly different at 0.05 probability levels*

3.5 N Fertilization Effects on Cotton Fiber Micronaire Formation

Fiber micronaire also increased gradually from 24 DPA to BO as the fiber developed (Figure 4). Nitrogen rates, flowering dates, and flowering dates × nitrogen rates significantly (P<0.01) affect micronaire formation (Table 11). For bolls flowering before August 10 when MDT_{BMP}>23 ℃, micronaire was higher in 0 kg N ha^{-1} treatment. For bolls flowering between August 10 and September 10 when MDT_{BMP} was 21~ 23 ℃ (Table 2), it was higher in 240 kg N ha^{-1}. Bolls flowering after September 10 when MDT_{BMP}<21 ℃ (Table 2), micronaire was higher in the 480 kg N ha^{-1} treatment. For 0, 240, and 480 kg N ha^{-1}, an inconsistent trend of micronaire to flowering date was observed.

As flowering date was delayed, micronaire decreased gradually in the 0 and 240 kg N ha^{-1} treatment, whereas it increased and then decreased in the 480 kg N ha^{-1} treatment. The acceptable upland micronaire range is 3.5 to 4.9, with a premium range of 3.7 to 4.2. Micronaire values that are either very low or very high (outside the 3.5 to 4.9 range) are undesirable and subject to price penalties (Bradow and Davidonis, 2000; Ge, 2007). In the present experiment, the micronaire range for mature fiber mostly belonged in the 3.5 to 4.9 range, except for bolls that grown under 0 kg N ha^{-1} and flowered on September 10. Thus, although N fertilization rates significantly affected the fiber micronaire, the evaluation of this index was not affected only when the bolls flowered after September 10.

Table 11. Results from analysis of variance for cotton fiber micronaire in different nitrogen rates flowering dates at three locations, Nanjing, Xuzhou and Anyang, for cultivar Kemian 1

Site (Year)		Analysis of variance for fiber micronaire					
		24 DPA	31 DPA	38 DPA	45 DPA	52 DPA	BO
Nanjing (2005)	Flowering dates	**	**	**	**	**	**
	Nitrogen rates	**	**	**	**	**	**
	Flowering dates × Nitrogen rates	ns	**	**	ns	*	*
Xuzhou (2005)	Flowering dates	**	**	**	**	**	**
	Nitrogen rates	**	**	**	**	**	**
	Flowering dates × Nitrogen rates	ns	**	**	**	**	**
Anyang (2007)	Flowering dates		**	**	**		**
	Nitrogen rates		**	*	ns		*
	Flowering dates × Nitrogen rates		ns	**	*		*

*: significant at 0.05 level; **: significant at 0.01 level; ns: no significant difference

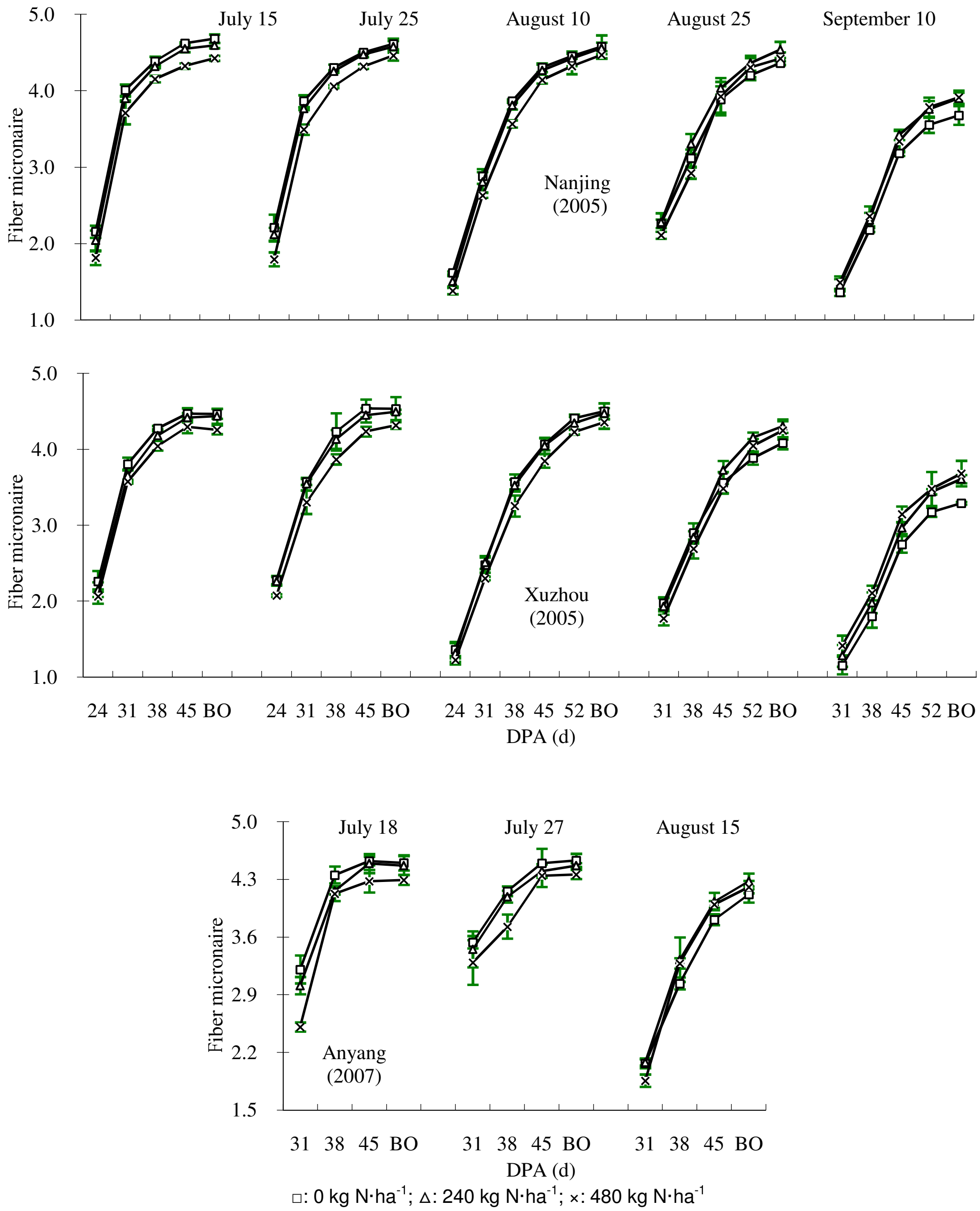

Fig. 4. Dynamic changes of cotton fiber micronaire in different nitrogen rates and flowering dates at three locations, Nanjing, Xuzhou and Anyang, for cultivar Kemian 1

DPA means days post anthesis; BO stands for cotton boll opened day. July 15, July 25, August 10, August 25 and September 10 in Nanjing and Xuzhou, July 18, July 27 and August 15 in Anyang means flowering dates.

Vertical bars represent standard errors

Table 12. Eigen values of cotton fiber micronarie in different nitrogen rate at two locations, Nanjing and Xuzhou, for cultivar Kemian 1

Site	Flowering date (mm dd)	Nitrogen rate (Kg N ha^{-1})	R^2	$V(Mic)_{max}$	$T(Mic)$ (d)	Mic_m	Mic_{obs}
Nanjing	July 15	0	0.9883**	0.266	11.61	4.70	4.7 a
		240	0.9792**	0.262	11.58	4.62	4.6 a
		480	0.9701**	0.241	12.19	4.46	4.4 b
	August 10	0	0.9959**	0.202	14.97	4.60	4.6 a
		240	0.9967**	0.193	15.67	4.59	4.6 a
		480	0.9957**	0.183	16.25	4.51	4.5 a
	August 25	0	0.9951**	0.177	16.37	4.41	4.4 a
		240	0.9993**	0.182	16.56	4.58	4.5 a
		480	0.9965**	0.177	16.65	4.47	4.4 a
	September 10	0	0.9910**	0.148	16.63	3.74	3.7 b
		240	0.9869**	0.153	17.03	3.96	3.9 a
		480	0.9917**	0.148	17.74	3.98	3.9 a
Xuzhou	July 15	0	0.9984**	0.229	13.01	4.53	4.5 a
		240	0.9984**	0.216	13.68	4.49	4.4 a
		480	0.9975**	0.211	13.53	4.33	4.3 b
	August 10	0	0.9989**	0.170	17.74	4.58	4.5 a
		240	0.9987**	0.166	17.94	4.53	4.5 a
		480	0.9992**	0.156	18.80	4.44	4.4 a
	August 25	0	0.9986**	0.148	18.37	4.13	4.1 b
		240	0.9948**	0.150	19.24	4.38	4.3 a
		480	0.9974**	0.147	19.38	4.33	4.2 a
	September 10	0	0.9924**	0.119	19.41	3.52	3.3 b
		240	0.9949**	0.127	20.21	3.88	3.6 a
		480	0.9900**	0.127	20.29	3.91	3.7 a

$V(Mic)_{max}$: The maximal speed of cotton fiber micronaire; T(Mic): The duration for cotton fiber micronaire speedy enlarge; Mic_m: The theoretical maximum of cotton fiber micronaire; Mic_{obs}: cotton fiber micronaire (observed value).

**: significant at 0.05 level; **: significant difference at 0.01 probability level (n=5, $R^2_{0.05}$=0.7710, $R^2_{0.01}$=0.9191).*

Values followed by a different small letter within the same column are significantly different at 0.05 probability levels

As expected, the CV of fiber micronaire among flowering dates decreased as N fertilization rates increased (Table 13).

The characteristics of cotton fiber micronaire formation were also calculated by the logistic regression model. From the parameters (Table 12), both the maximum increase rate of micronaire [$V(Mic)_{max}$] and the duration of fiber micronaire rapid increase [$T(Mic)$] contributing significantly ($P \leq 0.01$) to micronaire formation (Table 14).

Table 13. Coefficient of variation (CV) of NA–BMP cotton fiber length, strength, maturity and micronaire of Kemian 1 and NuCOTN 33B among different nitrogen rates or flowering dates at three locations Nanjing, Xuzhou and Anyang

Site (Year)	Fiber quality indices	CV (%) of N_A–BMP and fiber quality (Kemian 1/NuCOTN 33B)							
		Among nitrogen rates					Among flowering dates		
		July 15	July 25	August 10	August 25	September 10	0 kg N ha^{-1}	240 kg N ha^{-1}	480 kg N ha^{-1}
Nanjing (2005)	N_A–BMP (g m^{-2})	6.2/6.9	7.8/6.3	5.8/4.8	9.5/9.1	9.4/8.8	15.9/14.3	18.2/16.4	18.5/15.5
	length (mm)	1.9/1.0	1.2/1.3	1.9/0.9	1.5/1.5	2.7/2.7	3.2/3.8	2.9/2.9	2.0/2.5
	Strength (cN tex^{-1})	3.3/3.7	3.6/4.1	4.0/4.1	4.3/4.6	5.7/5.2	8.2/11.6	7.0/10.1	3.9/6.8
	maturity	2.4/2.4	3.9/3.2	3.5/3.5	4.4/5.5	6.7/10.0	18.0/24.0	14.7/19.4	11.8/16.2
	micronaire	5.2/3.8	3.4/3.2	1.7/1.0	2.0/2.1	3.5/5.2	9.4/13.7	6.7/10.1	5.4/8.3
Xuzhou (2005)	N_A–BMP (g m^{-2})	6.9/7.8	5.5/5.9	8.2/6.3	7.0/7.8	10.0/8.1	19.7/20.1	22.1/21.9	22.2/20.8
	length (mm)	1.0/1.6	1.6/1.1	1.3/1.4	1.4/1.4	2.7/2.4	4.4/5.2	4.1/4.8	2.7/4.0
	Strength (cN tex^{-1})	3.0/2.7	3.7/4.2	2.9/3.1	4.5/4.8	7.8/10.0	13.6/20.1	10.2/15.6	7.1/11.9
	maturity	2.0/2.6	3.0/3.2	2.7/4.4	5.1/6.3	11.8/15.5	24.3/31.0	18.6/24.5	15.7/20.4
	micronaire	4.5/4.4	4.3/5.2	2.1/3.4	3.7/3.1	5.9/6.5	13.4/17.8	9.2/13.2	6.7/9.3
		July 18	**July 27**	**August 15**			**0 kg N ha^{-1}**	**240 kg N ha^{-1}**	**480 kg N ha^{-1}**
Anyang (2007)	N_A–BMP (g m^{-2})	6.7/6.8	8.4/6.6	7.6/7.6			11.6/12.9	12.3/14.5	12.4/13.4
	length (mm)	1.3/1.6	0.6/1.9	1.4/2.2			2.3/2.7	1.9/2.8	1.2/1.1
	Strength (cN tex^{-1})	2.3/2.6	3.5/2.7	4.4/4.9			3.9/3.1	3.6/2.7	3.5/2.0
	maturity	2.4/2.0	2.8/3.5	4.3/3.8			12.2/14.8	9.5/12.5	8.5/11.8
	micronaire	2.5/3.5	1.9/1.3	1.9/2.5			5.3/7.3	2.5/3.3	1.8/2.8

N_A–BMP: average daily N_A during boll maturation period (BMP).

Table 14. Correlation coefficient of NA-BMP and fiber quality formation characters with fiber quality of opened cotton bolls of Kemian 1 for five flowering dates and three N fertilization rates in Nanjing and Xuzhou (n=30)

Correlation with	N_A–BMP (g m^{-2})	Length (mm)	Strength (cN tex^{-1})	Maturity	Micronaire
N_A–BMP (g m^{-2})		-0.330	-0.335	-0.671**	-0.590**
$V(Len)_{max}$ (mm)	-0.679**	0.678**			
$T(Len)$ (d)	0.716**	-0.304			
V_{RG} (cN tex^{-1})	-0.636**		0.704**		
T_{RG} (d)	0.550**		-0.503**		
V_{SG} (cN tex^{-1})	-0.529**		0.836**		
T_{SG} (d)	0.386*		0.256		
$V(Mat)_{max}$	-0.763**			0.938**	
$T(Mat)$ (d)	0.785**			-0.797**	
$V(Mic)_{max}$	-0.679**				0.762**
$T(Mic)$ (d)	0.647**				-0.652**

$V(Len)_{max}$: the maximum fiber elongation rate; $T(Len)$: duration of fiber rapid-elongation. V_{RG} and V_{SG}: mean strengthen rate of rapid and steady growth period of fiber strength, respectively; T_{RG} and T_{SG}: duration of rapid and steady growth period of fiber strength, respectively. $V(Mat)_{max}$: The maximum fiber maturation rate; $T(Mat)$: The duration of fiber rapid-maturation; $V(Mic)_{max}$: The maximum increase rate of fiber micronaire; $T(Mic)$: The duration of fiber micronaire rapid increase. * or **: significant difference at 0.05 or 0.01 probability level (n=30, $R^2_{0.05}$=0.361, $R^2_{0.01}$=0.463).

4. DISCUSSION

N nutrition, unequivocally, is one of the most pivotal facets of cotton production (Bondada and Oosterhuis, 2001), and the reproductive growth stage is the critical period for N supply (Mullins and Burmester, 1990). The present study determined changes in fiber quality, solely caused by N fertilization rates, in developed bolls grouped according to flowering date.

In agreement with several previous studies (Ali and Hameed, 2011; Bauer and Roof, 2004; Girma et al., 2007; Ma et al., 2009; Rochester et al., 2001), N fertilization significantly (P<0.05) affected N_A and formation of fiber length, strength, maturity and micronaire in the current study. From flowering date July 15 to September 10, N_A was significantly (P<0.05) increased by N fertilization rates increased. However, inconsistent effects of N rates on fiber quality were detected at different flowering dates. Before the flowering date August 25, fiber length and strength was higher, maturity and micronaire was optimal in the 240 kg N ha^{-1} treatment. For bolls flowering after August 25, fiber length, strength, maturity and micronaire was higher in the 480 kg N ha^{-1} treatment. The cotton boll and its subtending leaf exhibit a "sink-source" relationship (Ashley, 1972; Sun et al., 2007). The N_A in the leaf relates to the translocation capacity of the photosynthate and carbohydrates to the subtending boll (Sun et al., 2007). Thus, it exerts an effect on cotton fiber development. In the present study, results of correlation analysis show that fiber quality formation process significantly related to N_A-BMP (Table 14), thus N fertilization rates may be affected fiber quality by influencing N_A. In early flowering dates, N_A in 240 kg N ha^{-1} was not the maximal, but longer, stronger and more matured fibers were formed, while in late flowering dates, N_A was optimal in 480 kg N ha^{-1}. The same N fertilization rates but different trends between N_A and fiber quality in different flowering dates suggested that the optimal N_A for fiber quality formation is variable at different flowering dates. The results can explain the different conclusions regarding the effect of N fertilization on fiber quality to some extent.

The flowering dates also significantly (P<0.05) affected N_A and the formation of fiber length, strength, maturity and micronaire. In the present study, as the flowering date was delayed, fiber length and strength first increased and then decreased, fiber maturity and micronaire decreased. This is due to the gradually decreased MDT_{BMP} as the flowering dates shifts. In the present study, 23~25 °C was the optimal temperature for fiber quality formation. This is consistent with results of Reddy et al., (1999), which indicated that fibers were longer when bolls grew at less than optimal temperatures (25 ℃) for boll growth, maturity and micronaire increased linearly with the increase in temperature up to 26 ℃ but decreased at 32 ℃. But the trends are inconsistent with Dong et al., (2006). The latter reported decreased fiber length, strength, maturity and micronaire as flowering dates were delayed. This may be related to the different environmental conditions between the two studies. For the three N fertilization rates, the fiber quality of later flowering bolls decreased compared with the earlier flowering bolls because of the decreased MDT.

Optimized fertilizers application can decrease the adversely influence of environment stress. Read et al., (2006), indicated that cotton crop response to N stress was influenced by environment, as flowering groups with low quality fiber also comprised a large fraction of total lint, and thus placed heavy demands on plant N and carbohydrate reserves, Gormus and Yucel (2002) stated that K fertilizatin may allow the crop to partly compensate for the potential yield loss because of delayed planting. Here we found that increasing nitrogen application rates can decrease the CV of fiber quality among flowering dates, indicating that optimal N management could decrease the adversely influence of stress. However, this effect was not precisely evaluated and further studies with more N fertilization rates are needed to confirm this hypothesis.

5. CONCLUSIONS

N fertilization rates, flowering dates, and N fertilization rates × flowering dates significantly ($P \leq 0.05$) affected N_A and the formation of fiber length, strength, maturity and micronaire. N fertilization rates affected fiber quality formation by influencing N_A. The optimal N_A for fiber quality formation is variable. In early flowering season, comparatively lower fertilized is optimal to fiber quality formation while in later flowering season, higher fertilized is more optimal. The decrease magnitude of fiber quality is lower in higher N_A because of higher N fertilization rates. Supplemented N application could be conducted to diminish the negative influence of low temperature on fiber quality development in late-flowering date.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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