Journal of Elementology ISSN 1644-2296

Haliloglu, H. and Ceylan, C. (2023)
'Impact of various boron doses applied at different growth stages
on fiber quality traits of cotton (*Gossypium hirsutum* L.)'
Journal of Elementology, 28(2), 375-392,
available: http://dx.doi.org/10.5601/jelem.2023.28.2.2372

RECEIVED: 20 January 2023
ACCEPTED: 30 May 2023

ORIGINAL PAPER

Impact of various boron doses applied at different growth stages on fiber quality traits of cotton (*Gossypium hirsutum* L.)

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Abstract

Cotton (*Gossypium hirsutum* L.) requires boron (B), which plays a crucial role in the development of fruiting branches and bolls, in the pollination, boll retention and fiber quality of this plant. However, B is mostly unavailable during flower development and pollination stages; therefore, it must be supplied in order to harvest higher yield and high-quality fiber. This study investigated the impact of different B doses (applied at various growth stages) on some of the fiber quality traits of cotton crop. Four B doses (i.e., 0, 1000, 2000 and 3000 ml ha^{-1}) were applied at three growth stages (i.e., square initiation, flower initiation and peak flowering). The cotton genotype 'Stoneville-468', widely cultivated in the study region, was submitted to this experiment. Data relating to fiber uniformity, fiber strength, fiber fineness, fiber maturity, uniformity index, short fiber index, fiber elongation, reflectance, and yellowness were recorded. The results revealed that the application of 2000 ml ha^{-1} B at the square initiation stage resulted in the highest fiber length and uniformity. Similarly, higher B application during peak flowering resulted in the finest fiber. The increase in B application doses decreased fiber strength, negatively affected short fiber index, and had a non-significant effect on fiber maturity. The application of 1000 ml ha^{-1} B at flowering initiation resulted in the highest uniformity index. Similarly, the application of 2000 ml ha^{-1} B at flowering initiation resulted in the highest reflectance value. Likewise, the B application resulted in the lower yellowness values compared to the control treatment of the study. It is concluded that B should be applied to cotton grown on B-deficit soils. However, fiber quality traits are differently affected by B doses and application timing. Therefore, B application dose and timing should be decided according to the desired fiber traits.

Keywords: cotton, fiber quality, boron supplementation, application timing, doses

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INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is an important raw material for several industries (Tokel et al. 2022). Thus, it is of interest to a wide range of people in the society, apart from cotton producers (Khan et al. 2020). The quality of cotton fiber exerts a direct impact on the quality of the raw material processed in the textile industry, and consequently the quality of textile products (Mathangadeera et al. 2020).

Anatomically, cotton fiber is a seed fiber, a single hyper-long cell that arises from the protoderm cells of the outer integument layer of the seed coat (Bradow, Davidonis 2000). The cotton fibers originate from a single cell on the seed surface. Soon after flowering, cotton starts to produce fibers (Jan et al. 2022). This period determines the length of the fiber for about twenty days. The thickening of fiber does not begin until 28 days after flowering, during which there is a daily accumulation of cellulose on the inner surface of the fiber wall. The physical characteristics of cotton fibers are important as they have a direct effect on the characteristics of the yarn produced from these fibers (Mathangadeera et al. 2020).

Micronutrients play diverse and vital roles in plant physiological and biochemical processes (Mondal, Bose 2019, Putra et al. 2012). Environmental problems like nutrient insufficiency are among the most significant factors restricting the growth and yield of cotton crop (Fontana et al. 2020). Cotton undergoes continual flowering; however, the plant cannot store every blossom produced (Jackson 1990). About 40-50% of flowers and bolls are shed due to pest attack and/or feeding stress (Tariq et al. 2017). It is necessary to supplement the plants with proper micronutrients for significant yield improvement (Yaseen et al. 2013). The supplied micronutrients must be retained until the flowers mature into bolls for ultimate harvest (Eleyan et al. 2014). Within the past 50 years, much information has been gathered on the specific nutritional requirements of cotton. It is generally agreed that boron (B) is the most crucial micronutrient for cotton growth. While plants always need B, it is especially important during the blooming and boll formation phases.

Boron is one of the 16 essential plant nutrients important for plant growth. Most of the B in the upper layers of soil originates from decaying plant tissues (Bolaños et al. 2004). Plant hormone activity, photosynthesis, root development, and carbon dioxide uptake are improved in the presence of B (Camacho-Cristóbal et al. 2008). Boron also aids in cell development and structure, and its deficiency may cause cell walls to shrink. However, B causes toxicity if applied at extremely high doses (Garrett 1998, Camacho-Cristóbal et al. 2008). Boron is always crucial for cotton's development, especially during boll formation. Cotton benefits from B because it increases the number of fruit-bearing nodes, enhances pollination and boll retention, and plays an important role in the production of high-quality fiber.

Plant cell walls contain B, which is necessary for the transport of sugars, cell wall synthesis, lignification process, carbohydrate metabolism, RNA, phenolic compounds, indole-acetic acid metabolism, cell membrane integrity, and cell wall integrity (Marschner 1995). Boron is essential for optimal plant growth under normal circumstances and all plants require B for their normal growth and development (Camacho-Cristóbal et al. 2008). Increased sugar and nutrient transport from leaves to fruit, improved pollination and seed development are attributed to B (Rasheed 2009). Cotton requires B during boll development periods. However, B deficiency during the boll development causes boll shedding, which is one of the major factors reducing cotton yield (U.S. Borax Inc. 2002). It is difficult define the value for B resistance in crop plants. However, the critical B range for cotton is 0.4-0.55 mg kg^{-1} of soil (Oosterhuis 2001). Boron is a micronutrient; hence, plants require little B is for their optimal growth and development (Roberts et al. 2000). Nevertheless, a high B concentration in the soil could have a toxic effect since its deficiency and toxicity range is too narrow (Camacho--Cristóbal et al. 2008). Excessive B supply is highly detrimental for plant growth like its deficiency. Boron deficiency in cotton results in small, deformed bolls, lower number of boll and reduced fiber yield (Camacho--Cristóbal et al. 2008). Boron deficiency results in stunted plant growth, abnormalities in the pollen structure, curled and yellowish petioles, abnormal reproductive organs and drying of the plant tips (Gupta, Solanki 2013). Boron takes part in the transport of sugars produced during photosynthesis, especially in the sugar transport towards growth regions and developing fruits (Rasheed 2009).

Boron deficiency during early development stages of cotton considerably slows down photosynthesis and transportation of carbohydrates from leaves to fruits, which leads to slow plant growth and flower shedding (Gupta, Solanki 2013). Therefore, soil or foliar application of B is necessary for optimal cotton growth, physiology, and fiber output in B-deficient environments (Zhao, Oosterhuis 2000). Boron deficiency is a widespread problem in cotton producing regions, especially in the areas where soils are acidic with a low percentage of organic matter. Cotton productivity and fiber quality are severely hampered under B-deficiency (Ahmed et al. 2020, Rehman et al. 2020, Wahid et al. 2020).

Boron can be applied to soil at or before planting, or to the leaves at or just before flowering. Several studies have investigated the impact of soil and foliar applied B on cotton growth and productivity. Sun and Xu (1986) reported that foliar application of B improved the fiber quality and seed cotton yield. Abid et al. (2007) reported that B application had a non-significant effect on fiber length, fiber fineness and fiber strength. Similarly, Kaptan (2013) reported no effect of B application on fiber length. Numerous studies have demonstrated that fiber quality parameters are largely genotypic and less affected by environmental and climatic conditions (Ahmed et al. 2010, Rosolem, Bogiani 2011). Kaptan (2013) showed a negative relationship between B application and fiber fineness and strength. It was further noted that fiber fineness and strength decrease with increasing B doses.

Although sufficient literature is available on the impact of soil and foliar applied B on cotton growth and development, and fiber quality, little is known about the impact of B application at different growth stages of cotton. This study investigated the effect of different B doses (applied at different growth stages) on fiber quality traits of cotton. It was hypothesized that different B doses and growth stages will have significant impact on the fiber quality traits.

MATERIALS AND METHODS

Field experiments were conducted at the research area of Department of Field Crops, Harran University, Eyyubiye Campus, during the cotton growing seasons of 2014 and 2015. The experiments were laid out according to a randomized complete block design with split-plot arrangements and three replications. Growth stages (i.e., square initiation, flowering initiation and peak flowering) were kept in main plots, whereas B doses (i.e., 0, 1000, 2000 and 3000 ml ha^{-1}) were randomized in sub-plots. The cotton genotype 'Stoneville-468', widely cultivated in the study region, was used as the experimental material. Likewise, SupaBor® containing boron ethanol amine (water soluble (8% w/w) was used as the B source.

Boron at the designed doses was applied at square initiation (1-2 squares per meter), flowering initiation (1-2 flowers per meter) and peak flowering (8-10 flowers per meter or 3-5 flowers per plant) growth phases of cotton (Chen et al. 1997). Boron was foliar applied with a knapsack sprayer after 19.00 in the evening when the weather was cool. Control plots were sprayed with water.

Soil properties

Before the initiation of the experiments, soil samples were collected and analyzed for physical and chemical properties. The experimental soil consisted of alluvial material, had a deep profile with a high lime and potassium ratio and but low in available phosphorus (Dinç et al. 1988).

The soil of the experimental area was clay-textured with high lime content. The pH was slightly alkaline, and B was lower than 0.5 ppm (0.24 and 0.22), which is the critical limit for cotton (Table 1). The weather data of the experimental site are given in Figure 1 (MGM, 2015).

Deep ploughing was done in the experimental area during the autumn. A cultivator was used for ploughing in the spring, and then a disc harrow was used. Afterwards, a fine seedbed was prepared by using the harrow. Cotton was planted on 2 May and 22 April of 2014 and 2015, respectively.

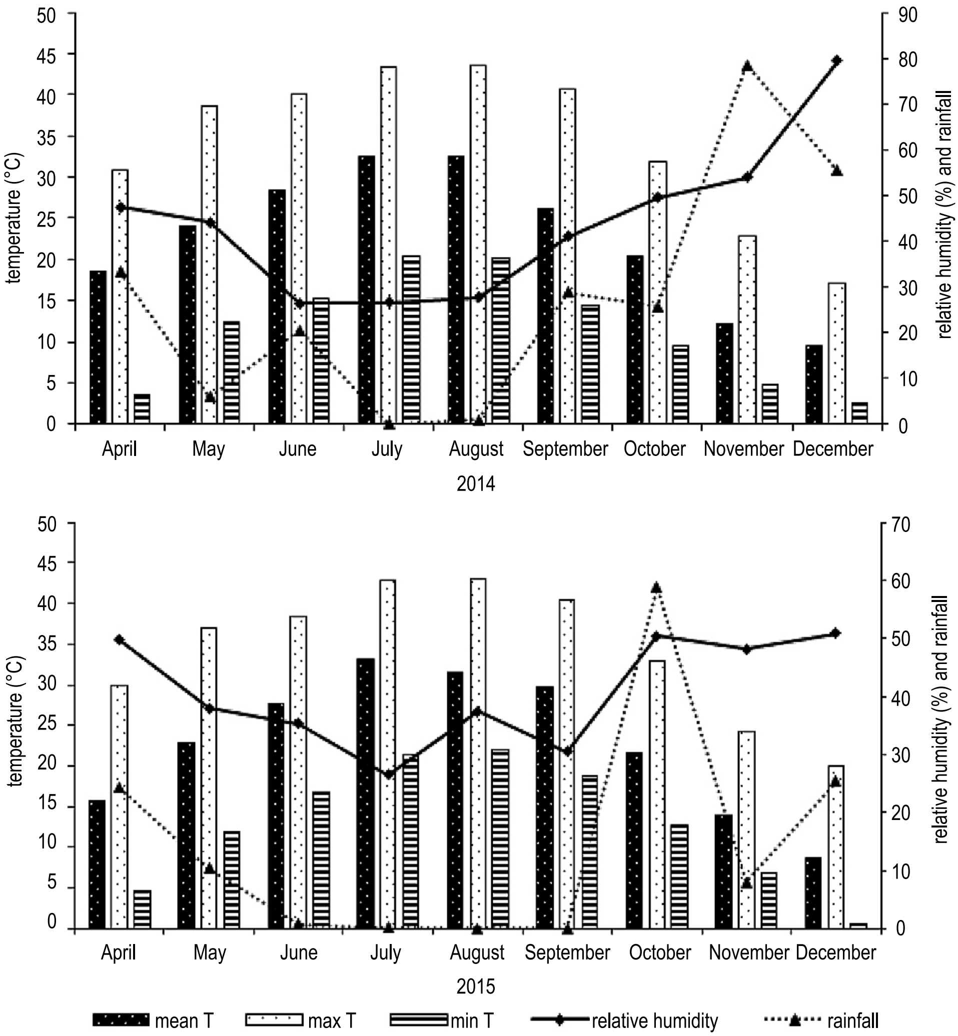

Fig. 1. Weather data of the experimental site during the cotton growing periods of 2014 and 2015

Table 1

Physical and chemical properties of the experimental soil

Year	Total Salt (%)	pH	Lime (%)	Sand (%)	Clay (%)	Silt (%)	Organic matter (%)	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	Fe (ppm)	Zn (ppm)	B (ppm)
2014	0.098	7.70	5.4	24.16	53.84	22.00	1.23	36	1093	2.11	0.46	0.24
2015	0.089	7.65	5.6	25.13	54.61	20.26	1.26	34	1139	2.18	0.39	0.22

Anonymous (2015)

Each experimental unit was 10 m in length with 4 cotton rows. The inter and intra row spacing was maintained as 70 and 10 cm, respectively.

The crop was provided with 80 kg ha^{-1} pure N and P (20-20-0) at the time of sowing. Afterwards, 80 kg ha^{-1} N (33% ammonium nitrate) was applied just before first irrigation by using lister equipment. Considering the economic threshold level of insects, Zetacypermethrin (1250 ml ha^{-1}) was used to control thrips and American bollworm during 2014. However, no insecticide was applied during 2015. No disease infestation was recorded in the experimental site in either year of the study.

Since there was not enough moisture in the soil after cotton planting in either year, sprinkler irrigation was used to ensure seed germination. The crop was irrigated 4 times with sprinkler and 7 times with drip irrigation in 2014 and a total of 1100 mm water was applied in total. Similarly, the crop received 3 sprinkler and 7 drip irrigations in 2015 and a total 1250 mm water was applied to the crop.

The seed cotton was harvested from the two central rows starting from 1 m inside the field edge from both sides of the experimental unit (8 m × 1.4 m =11.2 m^2). The first and second picking in 2014 was done on 27 September and 23 October, respectively. Similarly, the first and second picking was done on 29 September and 27 October, respectively, in 2015.

For fiber analysis, 500 g seed cotton samples were taken from each experimental unit and ginned in a rollergin. The fiber quality traits were analyzed on Uster®HVI 1000 and Uster®AFIS Pro devices.

Statistical analysis

The Ryan-Joiner normality test was used to determine the normality of the data obtained, and the results showed normal distribution. Therefore, the statistical analysis was done using the original data. The differences between the years were tested by taking the year as a factor in three-way analysis of variance (ANOVA), the results of which indicated that the year effect was significant. Therefore, the data of both years were analyzed and presented separately. Two-way ANOVA was used to infer the significance in the data. The Tukey's honest significant difference (HSD) *post-hoc* test at 95% probability was used to infer the differences among treatment means where ANOVA denoted significant differences. All statistical computations were done in the Minitab 18 statistics programme.

RESULTS AND DISCUSSION

Fiber quality traits of cotton were significantly altered by individual and interactive effects of growth stages and B doses during both years, with some exceptions (Table 2). Fiber maturity was not altered by individual and inter-

Table 2

Analysis of variance (significance) for fiber quality traits of cotton grown under different boron doses applied at various growth stages

Treatments	Fiber length (mm)		Fiber fineness (micronaire)		Fiber strength (g/tex)	
	1st year	2nd year	1st year	2nd year	1st year	2nd year
Growth stages (G)	**	**	**	**	**	**
B doses (B)	**	*	**	**	**	**
G × B	**	**	**	**	**	**
	fiber maturity ratio		uniformity index (%)		short fiber index (%)	
Growth stages (G)	ns	*	*	**	ns	**
B doses (B)	ns	**	**	**	**	**
G × B	ns	**	ns	ns	**	**
	elongation (%)		reflectance (rd)		yellowness (+b)	
Growth stages (G)	**	**	ns	*	ns	ns
B doses (B)	ns	**	**	**	*	**
G × B	**	**	**	**	**	**

active effects of growth stages and B doses during 1st year of the study. Boron application at different growth stages had a non-significant effect on short fiber index and reflectance during 1st year and yellowness during both years. Different B doses had non-significant effect on fiber elongation during 1st year of the study. Similarly, fiber uniformity index was not affected by growth stages by B doses interaction during both years of the study (Table 2). The mean values for fiber length, fiber fineness, and fiber strength along with standard deviation and CV were given in Table 3. Similarly, fiber maturity, uniformity index and short fiber index value along with their standard deviation and CV values were presented in Table 4. Likewise, mean values for fiber elongation, reflectance and yellowness were given in Table 5.

Fiber length (mm)

Fiber length is one of the most crucial measures of fiber's physical characteristics. Fiber length is the distance between its ends when stretched to a uniform tension. Fiber length is a genetically inherited trait. However, excessive washing and/or drying during the ginning process, environmental conditions, nutritional deficiency and the weather exert significant impacts on fiber length, which affect yarn quality. The fibers must be held together and wrapped to make yarn from any fiber. Therefore, fibers must be of sufficient length.

The highest fiber length (27.78 and 29.22 mm) was recorded for the treatment where B was applied at the square initiation (SI) stage, whereas the application of 2000 ml ha^{-1} resulted in the longest (27.84 and 28.47 mm) fiber length (Table 3). Regarding interactions between growth stages and

Table 3

Fiber length, fiber fineness and fiber strength of cotton as affected by the foliar application of different boron doses at various growth stages

Growth stages	Fiber length (mm)		Fiber fineness (micronaire)		Fiber strength (g/tex)	
	1st year	2nd year	1st year	2nd year	1st year	2nd year
SI	27.78±0.58 *a**	29.22±0.96 *a**	3.83±0.13 *a**	4.37±0.42 *c**	32.45±2.03 *b**	30.56±1.19 *b**
FI	27.32±0.66 *b*	27.72±0.75 *b*	3.75±0.18 *b*	4.59±0.32 *b*	33.12±1.76 *a*	31.61±2.77 *a*
PF	27.58±0.50 *a*	27.45±1.27 *b*	3.87±0.27 *a*	4.73±0.46 *a*	33.33±1.00 *a*	30.30±1.41 *b*
Application doses						
0 ml	27.28±0.40 *b**	28.17±0.95 *ab**	3.92±0.09 *a**	4.71±0.27 *b**	33.76±1.68 *a**	31.89±0.88 *a**
1000 (ml)	27.87±0.30 *a*	28.12±0.85 *ab*	3.75±0.21 *b*	4.37±0.13 *c*	33.77±1.57 *a*	30.62±0.64 *b*
2000 (ml)	27.84±0.85 *a*	28.47±1.50 *a*	3.78±0.16 *b*	4.30±0.34 *c*	31.52±1.42 *c*	32.19±2.40 *a*
3000 (ml)	27.23±0.44 *b*	27.77±1.69 *b*	3.82±0.29 *ab*	4.88±0.55 *a*	32.82±0.89 *b*	28.59±0.75 *c*
Interactions						
SI × 0 (ml)	27.20±0.35 *def**	28.44±0.78 *b**	3.99±0.08 *ab**	4.48±0.05 *c**	35.50±1.10 *a**	32.23±0.78 *bc**
SI × 1000 (ml)	27.88±0.35 *abcd*	28.97±0.45 *b*	3.82±0.03 *bc*	4.20±0.01 *e*	31.83±0.21 *de*	30.17±0.15 *de*
SI × 2000 (ml)	28.54±0.12 *a*	30.34±0.40 *a*	3.84±0.09 *bc*	3.86±0.04 *f*	30.40±0.17 *e*	30.40±0.36 *de*
SI × 3000 (ml)	27.48±0.30 *cde*	29.12±1.0 *ab*	3.67±0.06 *cd*	4.95±0.07 *b*	32.07±0.47 *cde*	29.43±0.06 *ef*
FI × 0 (ml)	27.70±0.27 *bcd*	27.12±0.42 *c*	3.88±0.09 *bc*	5.04±0.10 *b*	33.87±0.57 *ab*	32.43±0.78 *b*
FI × 1000 (ml)	28.10±0.10 *abc*	28.26±0.26 *bc*	3.95±0.05 *b*	4.48±0.08 *c*	35.20±0.87 *a*	30.33±0.45 *de*
FI × 2000 (ml)	26.74±0.22 *f*	27.02±0.09 *c*	3.59±0.04 *d*	4.60±0.04 *c*	30.80±0.20 *e*	35.37±0.35 *a*
FI × 3000 (ml)	26.72±0.30 *f*	28.48±0.50 *b*	3.60±0.04 *d*	4.22±0.07 *de*	32.60±0.20 *bcd*	28.32±0.67 *fg*
PF × 0 (ml)	26.94±0.05 *ef*	28.96±0.37 *b*	3.87±0.04 *bc*	4.59±0.15 *c*	31.90±0.20 *de*	31.00±0.27 *cd*
PF × 1000 (ml)	27.63±0.23 *bcde*	27.13±0.14 *c*	3.49±0.08 *d*	4.42±0.03 *cd*	34.27±0.15 *ab*	31.37±0.40 *bcd*
PF × 2000 (ml)	28.25±0.16 *ab*	27.99±0.27 *bc*	3.92±0.09 *b*	4.44±0.02 *c*	33.37±0.40 *bcd*	30.80±0.10 *d*
PF × 3000 (ml)	27.48±0.16 *cde*	25.70±0.28 *d*	4.21±0.01 *a*	5.48±0.04 *a*	33.80±0.72 *abc*	28.03±0.35 *g*
CV (%)	0.83	1.52	1.82	1.43	1.74	1.34

* Means in a column followed by different letters are statistically different from one another at 95% probability. SI – square initiation, FI – flowering initiation, PF – peak flowering

B doses, the application of 2000 ml B ha^{-1} at SI resulted in the longest fiber length (28.54 and 30.34 mm). According to statistical analysis, foliar application of 2000 ml ha^{-1} B at SI produced the longest fiber. Boron plays a crucial role in cellulose synthesis, which is the fundamental constituent of cotton fibers. It facilitates the cellulose chain formation during fiber maturation. Enhanced fiber quality is achieved through effective cellulose synthesis under sufficient B availability. Earlier studies inferring the impact of B application on fiber quality traits have reported varying results. Increased fiber length by foliar applied B has been reported by Rashidi and Gholami (2011). Similarly, Rehman et al. (2020) reported that foliar application 2.6 mg kg^{-1} B improved fiber length. Likewise, Wahid (2020) determined that foliar application of 6 g L^{-1} B significantly improved fiber length. However, Gormus (2004), Abid et al. (2007), Kaptan (2013), and Karademir and Karademir (2020) claimed that B application had no effect on fiber length.

Fiber fineness (micronaire)

The maturity and fineness of a fiber are quantified by its micronaire. Compressing a known amount of cotton fibers into a known volume and then measuring the air permeability is frequently used to measure fiber fineness (Anonymous 2021*a*). Humidity, temperature, sunshine, plant nutrients and the number of bolls per plant significantly impact fiber fineness (Zhao et al. 2013). Processing performance and end-product quality are both affected by the fiber fineness. Humidity, temperature, sunshine, plant nutrients, and the number of bolls on the plant may all have an impact on the final fiber fineness. Cotton's processing performance and end-product quality are both affected by the fiber's fineness. To prevent fiber damage during opening, cleaning, and carding, fine-fiber cottons must be processed at slower rates. Fine fiber cotton requires slower processing speed to avoid damage during opening, cleaning, and carding during spinning process. Generally, B performs diverse functions in enhancing fiber quality of cotton through cellulose synthesis, hormonal regulation, enzyme activation, and nutrient absorption. Sufficient B levels are crucial for the appropriate growth and ripening of cotton fibers, leading to improved fiber characteristics and favorable attributes (de Souza Júnior et al. 2022).

The results of the current study revealed that the finest fiber (3.75 mic.) was achieved owing to the B application at flowering initiation (FI) during the first year of the experiment, while B application at SI during the second year produced the finest fiber (4.59 mic.). Similarly, applications of 1000 and 2000 ml ha^{-1} B resulted in the finest fiber during both years of the study. The interactive effect of growth stages and B doses indicated that flower initiation (FI) × 1000 ml ha^{-1} during 1^{st} year (3.49 mic.) and SI × 2000 ml ha^{-1} (3.86 mic.) during 2^{nd} year resulted in the finest fiber. However, peak flowering (PF) × 3000 ml ha^{-1} resulted in the thickest fiber (4.21 and 5.48 mic.) during both years of the study. It was noted that the thinnest fiber was produced with the application of high B doses during PF (Table 3).

Rehman et al. (2020) reported that the application of 2.6 mg kg^{-1} B increased fiber fineness. However, Gormus (2004), Abid et al. (2007), and Karademir and Karademir (2020) reported that fiber fineness was not altered by B application.

Fiber strength (g/tex)

The application of B at FI and PF in 1st year (33.12 and 33.33 g/tex) and FI in 2nd year (31.61 g/tex) resulted in the highest fiber strength. Regarding B doses, no application of B resulted in the highest fiber strength during both years of the study (33.76 and 31.89 g/tex). Regarding the interactive effect of growth stages and B doses, SI × 0 ml ha^{-1} (35.50 g/tex) and FI × 1000 ml ha^{-1} (35.20 g/tex) in 1st year and FI × 2000 ml ha^{-1} (35.37 g/tex) in 2nd year resulted in the highest fiber strength (Table 3). Variations in the environmental conditions, such as climate and soil, are responsible for different results for the application timing by B dose interaction. Characteristics of cotton fiber are determined by genetic effects. However, it has been reported that environmental variability may inhibit the complete expressions of fiber traits due to interactions between environmental parameters and genotypes (Green, Culp 1990). Fiber strength was recorded between 15-40 g/tex in the HVI system. For good fiber, this value should be >25 g/tex. All treatments in the current study helped achieve the fiber strength values of >25 g/tex.

It was observed that fiber strength decreased with increasing B application doses during both years of the study. Some of the earlier studies have reported increased fiber strength with the increase in B application dose (Rehman et al. 2020, de Souza Júnior et al. 2022). However, several studies have recorded no change in fiber strength with B application (Gormus 2004, Abid et al. 2007, Rashidi, Gholami 2011, Karademir, Karademir 2020).

Fiber maturity ratio

The individual and interactive effects of growth stages and B doses had non-significant effect on the fiber maturity ratio (Table 2). However, B application at FI resulted in the highest fiber maturity ratio (0.91) in 2nd year of the study (Table 4). Similarly, 0 ml (0.92) and 3000 ml ha^{-1} (0.90) B doses resulted in the highest fiber maturity ratio during both years of study. Regarding the interactions, FI × 0 ml ha^{-1} (0.94) resulted in the highest fiber maturity ratio. Fiber maturity is a unique characteristic of cotton among textile fibers. Fiber maturity is achieved once the bolls open 45-50 days after anthesis, causing the fibers to dry and warp (Snider et al. 2021). The secondary wall thickness of cotton fiber is correlated with its maturity. Cotton fiber consists of lumen and cell wall. Fiber is more mature if the cell wall is thicker, and less mature with thinner cell wall. Fiber is deemed mature when its moistened cell wall makes up 50–80% of its circular cross-section, unripe when it makes 30-45%, and dead when it makes <25% (Anonymous 2021*b*).

Table 4

Fiber maturity ratio, uniformity index and short fiber index of cotton as affected by the foliar application of different boron doses at various growth stages

Growth stages	Fiber maturity ratio		Uniformity index (%)		Short fiber index (%)	
	1st year	2nd year	1st year	2nd year	1st year	2nd year
SI	0.87^{ns}	0.89±0.03 *b**	83.49±1.43 *b**	82.20±1.03 *c**	6.34^{ns}	7.64±1.13 *b**
FI	0.87	0.90±0.03 *ab*	84.43±1.16 *a*	84.44±1.63 *a*	6.20	7.74±0.72 *b*
PF	0.87	0.91±0.02 *a*	84.30±1.14 *ab*	83.27±1.70 *b*	6.18	8.22±0.51 *a*
Application doses						
0 (ml)	0.87^{ns}	0.92±0.02 *a**	84.23±0.82 *b**	83.80±0.95 *b**	6.07±0.70 *bc**	7.59±0.85 *bc**
1000 (ml)	0.87	0.88±0.02 *bc*	85.39±0.88 *a*	85.15±1.66 *a*	5.82±0.49 *c*	7.27±0.70 *c*
2000 (ml)	0.86	0.88±0.02 *c*	83.02±0.49 *c*	82.12±0.94 *c*	6.33±0.44 *b*	8.06±0.46 *ab*
3000 (ml)	0.87	0.90±0.02 *b*	83.64±1.45 *bc*	82.13±1.03 *c*	6.73±1.20 *a*	8.56±0.79 *a*
Interactions						
SI × 0 (ml)	0.88^{ns}	0.91±0.03 *abc**	84.00^{ns}	82.87^{ns}	6.40±0.46 *cd**	6.53±0.21 *e**
SI × 1000 (ml)	0.87	0.87±0.01 *cd*	84.97	83.20	5.47±0.21 *e*	7.03±0.23 *cde*
SI × 2000 (ml)	0.86	0.87±0.02 *d*	82.90	81.30	5.90±0.27 *cde*	7.67±0.21 *bcde*
SI × 3000 (ml)	0.86	0.92±0.02 *ab*	82.10	81.43	7.60±0.10 *a*	9.33±0.42 *a*
FI × 0 (ml)	0.87	0.94±0.00 *a*	84.80	84.63	5.20±0.17 *e*	8.27±0.38 *abc*
FI × 1000 (ml)	0.88	0.87±0.01 *cd*	85.67	86.67	5.60±0.40 *de*	6.67±0.25 *de*
FI × 2000 (ml)	0.85	0.89±0.01 *bcd*	83.23	83.20	6.57±0.25 *bc*	7.93±0.31 *bcd*
FI × 3000 (ml)	0.86	0.87±0.01 *cd*	84.00	83.27	7.43±0.25 *ab*	8.10±0.40 *abc*
PF × 0 (ml)	0.86	0.91±0.02 *ab*	83.90	83.90	6.60±0.10 *bc*	7.97±0.31 *bcd*
PF × 1000 (ml)	0.86	0.91±0.02 *abc*	85.53	85.60	6.40±0.36 *cd*	8.10±0.44 sbc
PF × 2000 (ml)	0.87	0.89±0.01 *bcd*	82.93	81.87	6.53±0.35 *bc*	8.57±0.25 *ab*
PF × 3000 (ml)	0.89	0.91±0.02 *ab*	84.83	81.70	5.17±0.35 *e*	8.23±0.90 *abc*
CV (%)	2.06	1.44	1.00	0.73	4.76	5.47

* Means in a column followed by different letters are statistically different from one another at 95% probability. SI – square initiation, FI – flowering initiation, PF – peak flowering

Additionally, several studies have noted that fiber maturity is also influenced by the genetic make-up, environmental variables, and farming techniques in addition to physiological development (Kohel, McMichael 1990, Pettigrew 1995, Bange et al. 2010). Immature cotton fibers may break during the spinning process, generate neps in the yarns, and result in uneven dyeing because they do not fully absorb the dye compared to mature fiber. The fiber obtained from all treatments of the current study was fully matured (Table 4).

Uniformity index (%)

The degree of fiber uniformity is defined as the percentage difference between the mean fiber length and the mean fiber length of the upper half of the fibers. Short fiber content (the percentage of fibers that are shorter than half an inch) is correlated with fiber uniformity. A high number of short fibers is indicative of a poor uniformity index in cotton. Genetically, cotton fiber is not consistently uniform in length. The B application at FI (84.43% and 84.44 %) 1000 ml ha^{-1} dose (85.39% and 85.15%) resulted in the highest fiber uniformity index during both years of the study. The interactive effect of growth stages and B application doses was non-significant in this regard (Table 4). These findings support the recommendation that 1000 ml ha^{-1} B should be applied at FI stage to obtain higher fiber uniformity. Uniformity index data collected from the current study revealed that fibers produced over a range of B doses and growth stages fall into a moderate to high uniformity index range (Table 4). Wahid (2020) indicated that the application of 6 g L^{-1} B improved fiber uniformity. However, Gormus (2004), Abid et al. (2007), and Karademir and Karademir (2020) indicated that B application had no effect on the fiber uniformity index of cotton. The differences among the results of the current and earlier studies can be attributed to variations in B application doses, cotton genotypes used and prevailing climatic conditions.

Short fiber index (%)

Short fibers are those measuring <0.50 inches (12.7 mm) in length. The short fiber is of greater quality and better suited for yarn manufacturing. Less waste is produced during the yarn production process, which lowers the cost. The proportion of short fibers has a significant impact on the uniformity, durability, and hairiness of yarns.

The B application x growth stages had a non-significant impact on the short fiber index during 1st year of the study (Table 2). The B application at FI during 2nd year resulted in the highest short fiber index (8.22%). Application of 3000 ml ha^{-1} B recorded the highest short fiber index (6.73 and 8.56%) during both years. Regarding interactions, SI × 3000 ml ha^{-1} (7.60 and 9.33%) resulted in the highest short fiber index during both years of the study. The results revealed that B application at high doses during FI period increased short fiber index values, which is not desired. Short fiber index values recorded during the current study belong to low and very low groups (Table 4). The short fiber index values of the current study are within the desired range. de Souza Júnior et al. (2022) indicated that B application lowered the short fiber index in cotton. However, Karademir and Karademir (2020) reported that B application has no impact on the short fiber index.

Fiber elongation (%)

Elongation is a measure of the elastic behavior of fibers in the bundle. The fibers are interlocked in the bundle with 1/8-inch distance between the clamps. The first pair of clamps is fixed, and the rear pair of clamps is pulled at a constant speed. The distance the fibers extend before breaking is recorded and expressed as percent elongation (Anonymous 2022).

The signaling pathways of several phytohormones control fiber elongation. Since the fiber is put under pressure while manufacturing yarn, elastic fibers are desirable. The elastic fiber is considered as a good quality fiber. Fiber elongation was not altered by B application at the tested growth stages and doses in 1st year; however, their interactive effect was significant (Table 2). The SI × 2000 ml ha^{-1} (7.53%) caused the highest fiber elongation value, while PF × 1000 ml ha^{-1} resulted in the lowest value (6.73%) of fiber elongation (Table 5). Gormus (2004), and Karademir and Karademir (2020) reported that B application had a non-significant effect on fiber elongation of cotton.

Reflectance (Rd)

Reflectance refers to the whiteness of the light reflected from cotton fibers. It corresponds to the reflection (Rd) represented in the Nickerson/ /Hunter color scheme. Reflectance is used with yellowness (+b) to determine the color grade of cotton (Anonymous 2022). The color of cotton is measured using a cotton colorimeter and expressed in degrees of reflectivity (Rd). It typically ranges between 50 and 85 units, and indicates whiteness or grayness of fiber in addition to yellowness (+b). The whiteness of fiber is directly related to the Rd value. The cotton fiber color is determined by the reflectance (Rd) and yellowness (+b) values, which are significant criteria that affect cotton pricing (Copur et al. 2018)

The growth stages at B application had a non-significant effect on Rd during both years of the study (Table 2). The application of 1000 ml ha^{-1} B resulted in the highest (76.92 and 66.04) Rd values during both years of the study. Regarding interactions, FI × 2000 ml ha^{-1} B recorded the highest (76.67 and 67.20) Rd values during both years of the study. These results revealed that the application of 2000 ml ha^{-1} B at FI phase increased Rd. However, Karademir and Karademir (2020) reported that B application had no effect on the Rd values of cotton.

Table 5

Fiber elongation, reflectance and yellowness of cotton as affected by the foliar application of different boron doses at various growth stages

Growth stages	Elongation (%)		Reflectance (Rd)		Yellowness (+b)	
	1st year	2nd year	1st year	2nd year	1st year	2nd year
SI	7.37±0.21 *a**	7.72±0.28 *a**	75.98 ns	64.79 ns	8.85 ns	10.42 ns
FI	7.03±0.25 *b*	7.60±0.12 *b*	76.53	64.83	8.82	10.17
PF	7.06±0.29 *b*	7.57±0.12 *b*	76.32	64.45	8.79	10.12
Application doses						
0 (ml)	7.21 ns	7.67±0.26 *ab**	75.86±0.74 *b**	63.36±1.27 *c**	8.87±0.27 *a**	10.50±0.73 *a**
1000 (ml)	7.17	7.58±0.12 *b*	76.92±0.63 *a*	66.04±1.07 *a*	8.70±0.13 *b*	10.19±0.32 *ab*
2000 (ml)	7.10	7.75±0.18 *a*	76.30±1.20 *ab*	64.68±2.08 *b*	8.87±0.12 *a*	10.48±0.55 *a*
3000 (ml)	7.13	7.52±0.14 *b*	76.03±0.49 *b*	64.68±1.24 *b*	8.84±0.22 *ab*	9.77±0.17 *b*
Interactions						
SI × 0 (ml)	7.30±0.17 *ab**	7.96±0.13 *a**	75.67± 1.11*bc**	64.67±0.95 *bcde**	9.13±0.25 *a**	10.80±0.10 *ab**
SI × 1000 (ml)	7.40±0.20 *ab*	7.59±0.18 *b*	77.27±0.59 *ab*	65.73±0.55 *abc*	8.57±0.12 *c*	10.10±0.35 *abc*
SI × 2000 (ml)	7.53±0.23 *a*	7.97±0.04 *a*	75.10±0.56 *c*	62.60±0.61 *f*	8.90±0.10 *abc*	11.03±0.06 *a*
SI × 3000 (ml)	7.23±0.21 *abc*	7.37±0.07 *b*	75.90±0.36 *bc*	66.17±0.58 *ab*	8.80±0.30 *abc*	9.73±0.06 *c*
FI × 0 (ml)	7.00±1.00 *bcd*	7.55±0.18 *b*	75.60±0.62 *bc*	62.60±0.56 *f*	8.67±0.21 *c*	10.90±0.95 *a*
FI × 1000 (ml)	7.37±0.12 *ab*	7.56±0.10 *b*	76.47±0.29 *abc*	65.17±0.45 *bcd*	8.77±0.06 *bc*	10.20±0.36 *abc*
FI × 2000 (ml)	6.80±0.17 *cd*	7.71±0.10 *ab*	77.67±0.32 *a*	67.20±0.72 *a*	8.80±0.20 *abc*	9.83±0.25 *bc*
FI × 3000 (ml)	6.97±0.21 *bcd*	7.59±0.02 *b*	76.40±0.30 *abc*	64.33±0.58 *b-f*	9.03±0.06 *ab*	9.73±0.25 *c*
PF × 0 (ml)	7.33±0.32 *ab*	7.49±0.19 *b*	76.30±0.36 *abc*	62.80±1.14 *ef*	8.80±0.10 *abc*	9.80±0.27 *bc*
PF × 1000 (ml)	6.73±0.06 *d*	7.58±0.11 *b*	77.03±0.81 *ab*	67.23±0.80 *a*	8.77±0.12 *bc*	10.27±0.38 *abc*
PF × 2000 (ml)	6.97±0.15 *bcd*	7.57±0.04 *b*	76.13±0.59 *abc*	64.23±0.34 *cdef*	8.90±0.00 *abc*	10.57±0.21 *abc*
PF × 3000 (ml)	7.20±0.17 *abcd*	7.62±0.12 *b*	75.80±0.66 *bc*	63.53±0.15 *def*	8.70±0.10 *bc*	9.83±0.21 *bc*
CV (%)	2.26	1.48	0.74	0.98	1.35	3.36

* Means in a column followed by different letters are statistically different from one another at 95% probability. SI – square initiation, FI – flowering initiation, PF – peak flowering

Yellowness (+b)

Yellowness refers to the yellowness of the light reflected from the cotton fibers. Yellowness (+b) is determined by using a yellow filter. It corresponds to the +b value in the Nickerson/Hunter color scheme. (Anonymous 2022). Yellowness is used in conjunction with the Rd value to determine the instrument-measured color grade of cotton. Yellowness varies depending on both the geographic location and cultivar. The normal range for yellowness is 6.0 to 11.00. It is measured with a colorimeter and directly affects the color of the yarn.

The growth stages at B application had a non-significant impact on yellowness during both years of the study. Application of 3000 ml ha^{-1} B resulted in the lowest (8.84 and 9.77) yellowness values during both years of the study (Table 5). Regarding interactions, FI × 0 ml ha^{-1} in 1st year (8.67) and FI × 3000 ml ha^{-1} (9.73) in 2nd year resulted in the lowest yellowness values. Boron applications reduce the yellowness value compared to the control, which is desirable. Gormus (2004), and Karademir and Karademir (2020) reported that B application has no impact on the yellowness of cotton.

CONCLUSION

It was concluded that the application of 2000 ml ha^{-1} B at square initiation resulted in the highest fiber length. Similarly, higher doses of B applied at peak flowering resulted in the finest fiber, reduced fiber strength, and had no impact on fiber maturity. Likewise, the application of 1000 ml ha^{-1} B at flowering initiation resulted in the highest fiber uniformity index and increasing B doses increased short fiber index. The application of 2000 ml ha^{-1} B at square and flowering initiation stages resulted in the highest fiber uniformity index and reflectance value, respectively. Nevertheless, B application resulted in lower yellowness values compared to the control treatment.

It was concluded that cotton crop must be supplemented with B if the soil boron level is low at planting. However, the effects of B on fiber quality characteristics may vary, and application timing and B doses must be decided according to the desired traits.

Acknowledgements

This study was a part of M.Sc. Thesis entitled ‘Effect of boron foliar application at different doses and different growth stages on yield and yield components of cotton (*Gossypium hirsutum* L.)’, and was partially supported by the Harran University Scientific Research Projects (HUBAP).

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