Turkish Journal of Agriculture - Food Science and Technology, 12(12): 2606-2614, 2024
DOI: https://doi.org/10.24925/turjaf.v12i12.2606-2614.7099

Turkish Journal of Agriculture - Food Science and Technology

Available online, ISSN: 2148-127X | www.agrifoodscience.com | Turkish Science and Technology Publishing (TURSTEP)

Impact of Boron Toxicity and Humic Substance Applications on Cotton Fiber Quality and Yield

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ARTICLE INFO

Research Article

Received : 28.08.2024
Accepted : 03.11.2024

Keywords:
Boron
Humic Substance
Cotton
Toxicity
Hyperaccumulator

ABSTRACT

This study investigated the effects of boron toxicity and humic substance applications on cotton fiber quality and yield over two consecutive years, targeting boron toxicity issues in soils affected by agricultural and geothermal activities. The experiment evaluated varying concentrations of boron (0.6–1.8–5.4–16.2 mg B l^{-1}) and humic substances (0–200–400 kg ha^{-1}), with a focus on their effects on seed cotton yield, fiber length, fineness, strength, and gin efficiency. In the first year, the highest seed cotton yield was recorded at 452.5 kg da^{-1} with the B1 application, followed by 428.3 kg da^{-1} with B2. In the second year, increased boron application led to a notable decrease in seed cotton yield, with the lowest yield at 99.3 kg da^{-1} for the B4 application. The highest dose of boron also significantly reduced fiber strength, with the lowest recorded at 31.57 g/tex, and gin efficiency, which dropped to 37.98%. Humic substance applications showed limited influence on fiber quality parameters; however, the highest dose (H3) led to a significant increase in fiber strength to 33.47 g/tex in the second year. Cotton leaves accumulated substantial amounts of boron, reaching concentrations of 2048 mg B kg^{-1} during the flowering period of the second year, suggesting that cotton could serve as a hyperaccumulator in phytoremediation efforts for boron-contaminated soils. The study further determined that cotton can tolerate boron concentrations in irrigation water ranging from 1.8 to 5.4 mg B l^{-1}, making it a viable crop in boron-affected regions. These findings provide critical insights into the potential of cotton as a resilient crop in environments with elevated boron levels, underscoring the need for further research to optimize cotton cultivation under such conditions.

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Introduction

Boron (B) is an essential micronutrient for plants, typically found in combination with oxygen and widely distributed in the Earth's crust, where it has an average concentration of 8 mg kg^{-1} (Anonymous, 2010). For optimal plant growth, boron concentrations in soil generally range from 0.1 to 0.5 mg kg^{-1}, depending on the species (Butterwick et al., 1989). Boron plays a crucial role in regulating plant hormone levels, flower production and retention, pollen tube elongation and germination, as well as seed and fruit development. However, due to the narrow range between deficiency and toxicity, boron concentrations that fall outside of the optimal range can lead to significant yield losses in crops (Chapman et al., 1997). Boron is naturally released into the soil and water through various processes, including rainfall, the weathering of boron-containing minerals, desorption from clays, and the decomposition of organic matter. Anthropogenic activities, such as the application of boron-containing fertilizers, the use of fly ash as a soil amendment, irrigation with wastewater, and the discharge of industrial and geothermal wastewater, further contribute to boron levels in the environment (Butterwick et al., 1989; Mumma et al., 1984; Koç, 2011). Geothermal water resources, which often contain high levels of boron along with other potentially harmful substances like heavy metals, pose a significant risk to agricultural production (Gemici & Tarcan, 2002). These geothermal waters emerge at varying temperatures (51-163°C), depending on the geological reserve and geographical conditions. The elevated temperatures of geothermal waters increase the solubility of boron, making it a potent pollutant. One of the primary sources of high boron concentrations in irrigation water is the contamination of these waters with boron-rich geothermal effluents. Soil type significantly influences the impact of boron on plant health. For example, sandy soils tend to exhibit faster and more severe damage from high boron irrigation water compared to loamy or clayey soils, due to the differing boron binding characteristics of these soils (Keren & Bingham, 1985). Boron compounds in the soil are transformed into borates, which do not degrade further and thus accumulate over time, leading to boron toxicity (Bradford, 1966). This issue has become particularly pronounced in regions where geothermal water sources have been used for agricultural irrigation over the past 2-3 decades. In the Büyük Menderes River basin, for instance, the discharge of wastewater containing boron has led to significant pollution. Prior to these discharges, boron levels in irrigated soils were around 0.15 mg kg^{-1}, but have since increased to 13.90 mg kg^{-1} at a depth of 0–20 cm (Akar, 2007). Similarly, soil boron levels have been found to range from 0.43 to 2.34 mg kg^{-1} (Aydın et al., 2010). Cotton (*Gossypium hirsutum* L.), a major crop in the region, exhibits remarkable resistance to boron toxicity. For instance, the permissible boron concentration in irrigation water is 0.33 mg l^{-1} for sensitive plants and about 0.67 mg l^{-1} for semi-tolerant plants like cotton (US Salinity Laboratory, 1954). This resilience is largely due to the plant's anatomical adaptations, such as a well-developed root system that efficiently excludes and sequesters boron, preventing its excessive uptake and translocation to the aerial parts of the plant. Nevertheless, there is a threshold beyond which boron toxicity can impair cotton growth and yield. To mitigate this, farmers in the region have increasingly applied humic substances, which enhance nutrient availability in the soil and facilitate nutrient uptake and transport. Humic substances are characterized by their dark brown to black color, high molecular weight, large specific surface area, and stable molecular structure, which does not easily degrade in the soil (Stevenson, 1994). Boron is a crucial micronutrient for plants, yet its narrow effective concentration range in soil makes both deficiency and toxicity significant concerns for crop production. The issue of boron toxicity is particularly acute in regions where geothermal waters, rich in boron, contaminate agricultural lands. The Büyük Menderes River basin serves as a prime example, where the discharge of boron-laden geothermal wastewater has led to elevated boron levels in soils, threatening agricultural productivity. Cotton, a key crop in the region, has shown a notable resilience to boron toxicity due to its anatomical adaptations. However, there are limits to this resilience, and once surpassed, boron toxicity can lead to reduced growth and yield. Farmers in the region have increasingly turned to the application of humic substances to mitigate the adverse effects of boron toxicity and enhance nutrient availability and uptake in soils. Given the growing importance of sustainable agricultural practices, this project aims to investigate the combined effects of boron and humic substances on cotton growth dynamics, yield, and fiber quality. By exploring the potential of humic substances to alleviate boron toxicity, this research seeks to contribute to the development of effective soil management strategies that can sustain cotton production in boron-affected areas. The findings will have implications not only for the Büyük Menderes River basin but also for other regions facing similar challenges, thereby supporting broader efforts to enhance agricultural sustainability in the face of environmental stressors.

Material and Methods

Experimental Site

The experiment was carried out at field conditions at University of Adnan Menderes, Aydin, Turkey (Figure 1). The site is located in the western regions of Turkey (37° 45′ N, 27° 45′ E, 34 m).

The site receives a long-term seasonal rainfall 106.9 mm and an average temperature of 24.05 °C. According to climatic data, the season of 2012 was drier and warmer than in 2011. Between May and October 2011, there were 210.2 mm and 109.6 mm rainfall in the same period of 2012 (Table 1).

The soil (*Typic Xerofluvent*) is sandy loam in texture that facilitates leaching and no drainage problem occurs even with heavy rains. In addition, there is no salinity problem observed in the soil. A bulk of silt loam was collected from Ap horizon. The soil was air- dried, crushed and sieved through 2 mm sieve. The soil analyses were carried out by the methods of Ryan et al. (2001). The soil was deep, well-drained, coarse silty, moderately calcareous, hyperthermic, Typic Haplocambids. The chemical analyses revealed that soil had: pH 8.31; organic matter content: 0.90%; Total N content 0.10%; NH_4Oac extractable-K, 173 mg kg^{-1}; $NaHCO_3$ available-P, 26 mg kg^{-1}; and extractable B, 0.92 mg kg^{-1} (Table 2).

Upon examining the properties of the irrigation water, it was found that the pH was slightly alkaline 7.75, EC was within usable limits 0.97 dS m^{-1}, SAR value was low 1.04, B was satisfactory 0.6 mg l^{-1}, Cl^{-1} and SO_4^{-2} were within acceptable levels 0.024, 0.86 me l^{-1}, HCO_3^{-1} was concerning 4.69 me l^{-1}, and the irrigation water was classified as C_3S_1 (Table 3).

Table 1. Some seasonal climatic conditions on experimental site

Year	Parameters	May	June	July	August	September	October
2011	Average Temperature (°C)	19.18	24.72	27.49	26.87	23.49	15.43
	Relative Humidity (%)	71.55	56.70	54.58	53.23	58.93	74.48
	Precipitation (mm)	49.00	50.00	0.40	0.00	38.40	72.40
2012	Average Temperature (°C)	20.08	27.02	29.60	27.89	22.69	19.88
	Relative Humidity (%)	73.39	55.30	50.74	45.32	52.70	72.39
	Precipitation (mm)	43.60	2.40	3.20	0.00	0.00	60.40
Long-Term Average	Average Temperature (°C)	20.90	25.90	28.40	27.40	23.30	18.40
	Relative Humidity (%)	54.00	46.50	43.40	46.00	51.70	62.50
	Precipitation (mm)	34.00	13.40	3.30	2.00	12.30	41.90

Table 2. Soil chemical properties sampled at 0-30 cm depth, during experiment

B rates mg l^{-1}	Years	Period	pH	OM	N	B	P	K
				%		mg kg^{-1}		
B1 0.6	2011	initial	8.31	0.90	0.10	0.92	26	173
	2012	final	7.99	1.68	0.09	1.84	18	127
B2 1.8	2011	initial	8.31	0.90	0.10	0.92	26	173
	2012	final	7.93	1.68	0.10	4.28	20	134
B3 5.4	2011	initial	8.31	0.90	0.10	0.92	26	173
	2012	final	7.90	1.64	0.10	8.49	19	139
B4 16.2	2011	initial	8.31	0.90	0.10	0.92	26	173
	2012	final	8.13	1.44	0.10	21.04	21	145

OM: % Organic matter; N: % Total Nitrogen; B: Available Boron; P: Available Phosphor; K: Extractable Potassium.

Table 3. Some chemical properties of the irrigation water

Class	pH	EC	TDS	B	TH	SAR	HCO_3^{-1}	SO_4^{-2}	Cl^{-1}
		dS m^{-1}	mg l^{-1}		°d			me l^{-1}	
C_3S_1	7.75	0.97	0.80	0.6	32.48	1.04	4.69	0.86	0.024

EC: Electrical Conductivity, TDS: Total dissolved solids, B: Boron, TH: Total Hardness, SAR: Sodium absorption ratio, HCO_3: Bicarbonate, SO_4: Sulphate, Cl: Chlorine.

Figure 1. A satellite image of the experimental site. It was taken from Google Earth software in 2013

The Experiment

Irrigation water containing four different B levels (0.6–1.8–5.4–16.2 mg B l^{-1}), three different humic substances doses applied to the soil before sowing (H1:0 – H2: 200 – H3: 400 kg HS ha^{-1}) and the commercially renowned Carmen cotton variety in the region (*Gossypium hirsutum* L. Carmen) were determined as the subject of the study. The experiment was set up in a split-plot design with 4 replications, using the same parcels pegged to the same coordinates. Boron treatments were designated as main plots, while humic substance treatments constituted the sub-plots. The material used as a source of humic substance was sprinkled on the soil surface by hand and then mixed with a rake and disc harrow on May 16, 2011 in the first year of the experiment and on May 05, 2012 in the second year of the experiment. Cotton plant was sowed on May 20 in 2011 and on May 23 in 2012, with a planting density of 70×3.5 cm. The distance between rows was adjusted to 70×20 cm and above to have a plant density of 70.000 plants/hectare by making rarefy and single treatment hoe. Irrigation was conducted using the drip irrigation method, with a schedule of every other day, while also considering the daily evaporation losses. This method ensured a more consistent and efficient application of water to meet the specific water requirements of the crops, thus optimizing irrigation practices and resource utilization. In the first year of the experiment, the amount of water applied to the soil through the drip irrigation system was 4874 tons ha^{-1}, while in the second year, it was 5525 tons ha^{-1}. The boron quantities applied along with the irrigation water are provided in Table 4.

Table 4. The amounts of boron applied to the soil with irrigation water throughout the experiment (kg B ha^{-1})

B rates (mg l^{-1}) in irrigation water	Amount of Applied Boron (kg B ha^{-1})		
	First year	Second year	Total
B1 0.6	3.0	3.3	6.3
B2 1.8	8.7	10	18.7
B3 5.4	26.3	29.8	56.1
B4 16.2	79.0	89.5	168.5

Table 5. Seed cotton yields according to different boron and humic substance applications (kg da^{-1})

kg HS ha^{-1} mg B l^{-1}	First year				Second year			
	H1	H2	H3	Average	H1	H2	H3	Average
B1	448.3	450.7	458.4	452.5 a	377.3	398.0	341.7	372.3 a
B2	430.9	416.3	437.7	428.3 ab	353.7	377.7	415.3	382.2 a
B3	428.9	400.2	399.8	409.6 bc	314.7	336.3	265.7	305.6 b
B4	385.5	408.5	376.8	390.3 c	94.7	112.0	91.3	99.3 c
Average	423.4	418.9	418.2	420.2	285.1	306.0	278.5	289.9
LSD B	34.51				54.93			
LSD HM	-				-			
LSD B × HM	-				-			

Sampling and Analysis

The samples were collected 3rd true leaf, squaring, blooming, and harvest period in accordance with the phenological stages of cotton. 10 plants were randomly selected for observations and analyses of plant samples in each parcel and in each period (Oosterhuis et al., 1983). These randomly selected plants were removed from the soil along with their roots. Plant samples taken from each parcel were brought to the laboratory straight away in perforated plastic bags and first carefully washed with tap water to remove surface contamination and then passed through pure water twice. Plant samples were dehydrated with drying paper and divided into components such as root, stem, leaf, petiole, square/boll and kept in the drying-oven at 70 °C for 48 hours. Boron concentrations of plant components determinations were made by dry ashing 0.5 g of dry tissue material, placing it in porcelain crucibles, and heating a muffle furnace at 500 °C for 6 h (Kacar & Inal, 2008). The ash was dissolved in 0.1 N H_2SO_4 and B was determined colorimetrically (430 nm) by the Azomethine-H method (Wolf, 1974). Fiber length (mm), fiber fineness (micronaire), fiber strength (g/tex) and gin efficiency (%) on fiber cotton obtained after the ginning of 20 boll samples that reached harvest maturity collected from each parcel have been examined using the High Volume Instrument (HVI) device.

Statistical Analysis

The analysis of variance was performed among different treatments. The significant differences between treatments were evaluated by LSD multiple range tests ($P<0.05$) using the SPSS statistical software (PASW Statistics 18).

Results and Discussion

Seed Cotton Yield (kg da^{-1})

In the first year of the study, a significant reduction in seed cotton yield was observed with increasing boron levels. The highest yield was recorded in the B1 treatment (452.5 kg da^{-1}), followed by B2 (428.3 kg da^{-1}), while the lowest yield was observed in B4 (390.3 kg da^{-1}), indicating a 5.34% decrease in B2, 9.47% in B3, and 13.75% in B4 compared to B1. Although humic substance application slightly improved yield, the differences were not statistically significant. No positive interaction between boron and humic substances on yield was detected in the first year. In the second year of the study, a significant decline in seed cotton yield was also noted with higher boron doses. The highest yield was in the B2 treatment (382.2 kg da^{-1}), followed by B1 (372.3 kg da^{-1}), with the lowest in B4 (99.3 kg da^{-1}), representing a decrease of -2.66% in B2, 17.93% in B3, and 73.32% in B4 relative to B1. Humic substance application outcomes differed from the previous year, with the highest yield was obtained from H2 (306.0 kg da^{-1}) and a statistically insignificant decrease in yield with higher doses of humic substances. No significant interaction between boron and humic substances was found in the second year (Table 5).

These results indicate that increasing boron application reduces unginned cotton yield, with particularly severe losses at doses above the irrigation water toxicity limit (Oertli & Roth, 1969; Ahmed et al., 2008). The residual boron in the soil from the first year contributed to more pronounced yield losses in the second year, leading to plant death in some cases. While cotton exhibited some tolerance at the B3 dose, it failed to tolerate the B4 dose. The highest yield in the first year was achieved with B1, while in the second year, it was with B2, likely due to cotton's higher boron demand and the B2 concentration being at the critical level for optimal yield (Nable et al., 1997; Reid, 2010; Kumar et al., 2018). Humic substance applications showed limited beneficial effects, with no statistically significant impact observed. In the first year, while yields increased in control plots, other plots showed fluctuations, suggesting humic substances may have been ineffective due to interactions with other soil minerals and incubation time Evangelou et al., 2004). In the second year, H2 increased yield while H3 decreased it, possibly due to humic acid enhancing boron uptake to toxic levels (Ören & Başal, 2006; Karakaya & Paksoy, 2008). These findings align with previous research.

Plant Boron Content (mg kg^{-1})

In the first year of the study, boron content in plants varied according to sampling times and plant organs. Boron levels in all plant organs were similar before and during squaring, increased during flowering, and peaked at harvest. Post-harvest, boron content decreased due to the cessation of irrigation and boron application. The highest boron content was observed in the leaves (B4; 1020 mg B kg^{-1}), with other organs showing negligible differences (Figure 2). The ranking of boron content among organs was leaf > petiole > boll > root > stem. The increase in boron content compared to B1 was 1.45% in B2, 79.10% in B3, and 468.56% in B4. Regarding humic substance applications, significant increases in boron content were noted only in the leaves during the squaring period. The distribution of boron by sampling periods and organs was similar, and the impact of humic substances was statistically insignificant. Interactions between boron and humic substances in the first year did not show significant effects. In the second year, boron accumulation began during pre-squaring and continued similarly during squaring, peaking during flowering and declining post-harvest. The highest boron content was recorded in the leaves (B4; 2048.4 mg B kg^{-1}), followed by the square/boll organs (659.1 mg B kg^{-1}). Boron content ranking was leaf > boll > petiole > stem > root (Figure 3). Increases compared to B1 were 79.46% in B2, 423.29% in B3, and 1152.08% in B4. Notably, square/boll boron content increased by 147.45% in B2, 403.00% in B3, and 1879.28% in B4 during flowering. Humic substance applications showed varying effects. During the pre-squaring period, significant increases in boron content were observed in the stem, while during squaring, significant increases were noted in leaves and stem. The highest boron content in leaves was from the B4H2 application (2090 mg B kg^{-1}), followed by B4H3 (2039 mg B kg^{-1}). Increased boron doses significantly elevated boron content in organs, but the effect of humic substances varied across organs and sampling periods. In the flowering period, humic substances increased boll boron content up to B3 but decreased it at B4.

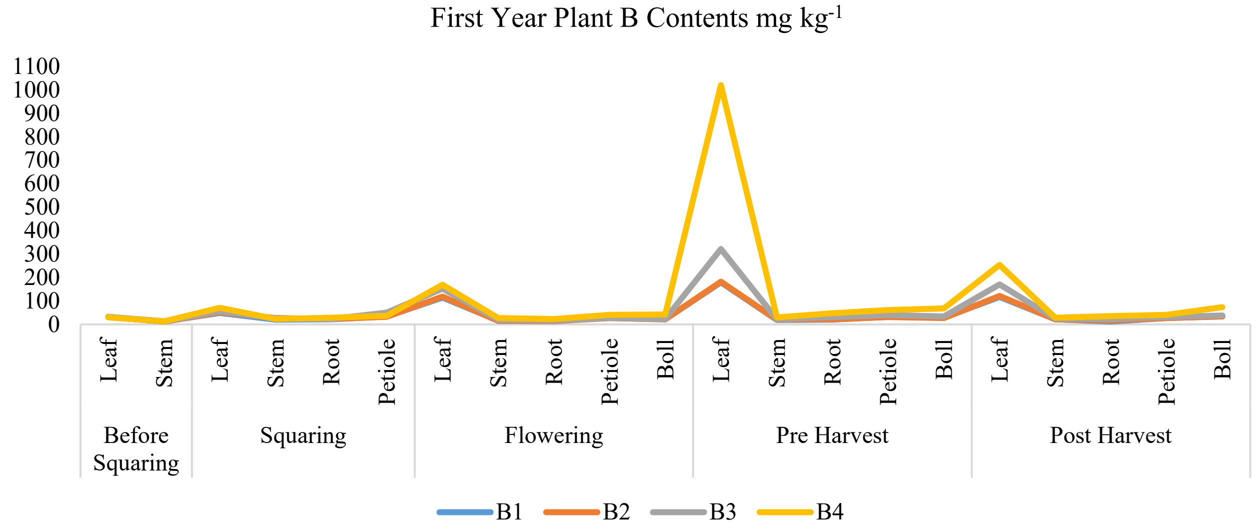

Figure 2. Distribution of plant boron content across phenological stages and plant components in the first year

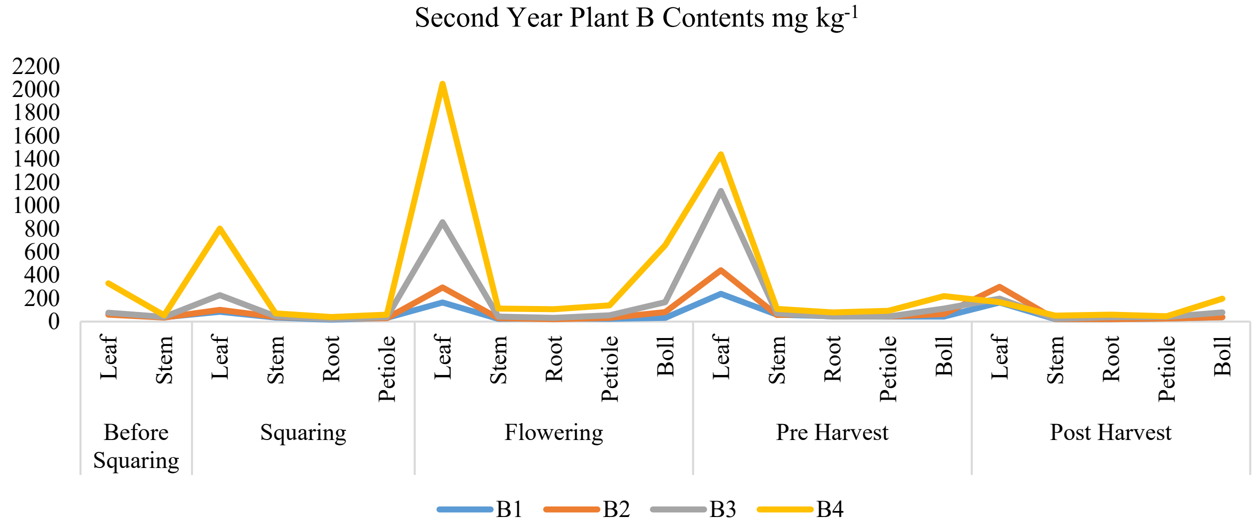

Figure 3. Distribution of plant boron content across phenological stages and plant components in the second year

Overall, increased boron applications were positively correlated with plant boron content, leading to boron toxicity symptoms such as chlorosis and necrosis, especially in older leaves and in severe cases, plant death. In the first year, toxicity was evident only at the B4 dose, while in the second year, both B3 and B4 showed symptoms. The highest accumulation of boron was in leaves, with minor accumulation in generative organs. These observations are consistent with previous studies (Bergmann, 1992; Ahmed et al., 2008; Chatzissavvidis et al., 2008; Chatzissavvidis & Therios, 2010; de Souza Júnior et al., 2022). Humic substance applications improved soil boron availability, likely due to their chelating properties and hormone-like effects on nutrient uptake. However, this positive effect was not clearly reflected in plant boron content, possibly due to interactions with biomass yield and boron content relationships. These findings align with research by Evangelou et al. (2004), Turan & Angin (2004), and Angin et al. (2008).

Fiber Length (mm)

In the first year, the boron treatment B4 achieved the highest fiber length at 28.82 mm, with B2 closely following at 28.64 mm. The lowest fiber length was recorded in the B3 treatment at 28.43 mm. While fiber length tended to increase with higher boron doses, these differences were not statistically significant. Among humic substance applications, the H3 treatment resulted in the longest fiber length at 28.79 mm, followed by H2 at 28.63 mm, though these increases were also statistically insignificant. Interactions between boron and humic substances revealed variations, but these differences did not reach statistical significance. In the second year, the B3 treatment yielded the highest fiber length at 27.86 mm, with B1 at 27.65 mm, and B4 producing the shortest fiber length at 27.38 mm. The impact of increasing boron doses on fiber length was inconsistent (Table 6). For humic substance applications, the H3 treatment provided the greatest fiber length at 27.68 mm, followed with H1 at 27.67 mm. Fluctuations in fiber length due to varying humic substance doses were noted, but these differences were statistically insignificant. The interaction between boron and humic substances showed that the B3H3 treatment achieved the longest fiber length at 28.24 mm, followed by B4H1 at 28.13 mm. The lowest fiber length, 26.85 mm, was observed with the B4H2 treatment, and these results were statistically significant. In conclusion, Boron applications did not significantly affect fiber elongation or length. These observations are consistent with findings by Eleyan et al. (2014), Ahmed et al. (2010) and Rosolem & Bogiani (2011), which suggest that fiber quality is primarily influenced by genetic factors, with environmental and climatic conditions having a secondary effect. The role of boron toxicity in fiber development is likely modulated by genetic factors. Although humic substance applications showed a positive trend in fiber length, this effect was not statistically significant, in line with Ören (2007).

Fiber Fineness (micronaire, mic)

In the initial year of boron applications, the B1 and B3 treatments yielded the highest fiber fineness at 5.23 mic. The B4 treatment recorded the lowest fineness at 5.00 mic. Although an overall decrease in fiber fineness was observed with increasing boron levels, these variations were not statistically significant. Regarding humic substance applications, the H1 treatment produced the highest fiber fineness at 5.24 mic, followed by H2 at 5.18 mic. Despite a slight reduction in fineness with higher humic substance doses, these differences also lacked statistical significance. When evaluating the interaction between boron and humic substances, no significant statistical differences were detected, although some variability was present (Table 7)..

Table 6. Fiber length measurements according to different boron and humic substance applications (mm)

kg HS ha^{-1}	First year				Second year			
mg B l^{-1}	H1	H2	H3	Average	H1	H2	H3	Average
B1	28.33	28.61	28.71	28.55	27.23	28.06	27.67	27.65
B2	28.40	28.58	28.95	28.64	27.76	27.21	27.65	27.54
B3	28.44	28.70	28.14	28.43	27.54	27.79	28.24	27.86
B4	28.47	28.64	29.36	28.82	28.13	26.85	27.17	27.38
Average	28.41	28.63	28.79	28.61	27.67	27.48	27.68	27.61
LSD B	-				-			
LSD HM	-				-			
LSD B × HM	-				0.99			

Table 7. Fiber fineness measurements according to different boron and humic substance applications (mic)

kg HS ha^{-1}	First year				Second year			
mg B l^{-1}	H1	H2	H3	Average	H1	H2	H3	Average
B1	5.28	5.19	5.24	5.23	4.86	4.87	4.94	4.89a
B2	5.21	5.18	5.08	5.16	5.01	4.99	4.83	4.94a
B3	5.38	5.38	4.93	5.23	5.14	4.58	4.77	4.83a
B4	5.08	4.97	4.96	5.00	4.22	4.62	4.69	4.51b
Average	5.24	5.18	5.05	5.16	4.81	4.76	4.81	4.79
LSD B	-				0.24			
LSD HM	-				-			
LSD B × HM	-				0.52			

Table 8. Fiber strength measurements according to different boron and humic substance applications (g/tex)

kg HS ha^{-1} mg B l^{-1}	First year				Second year			
	H1	H2	H3	Average	H1	H2	H3	Average
B1	33.00	33.45	33.08	33.18	33.43	33.73	33.77	33.64a
B2	33.33	33.10	32.13	32.85	34.47	32.17	33.70	33.44a
B3	33.05	32.83	33.25	33.04	32.70	32.23	34.28	33.07a
B4	33.58	32.28	33.50	33.12	32.05	30.53	32.12	31.57b
Average	33.24	32.91	32.99	33.05	33.16a	32.17b	33.47a	32.93
LSD B	-				1.12			
LSD HM	-				0.94			
LSD B × HM	-				-			

Table 9. Gin efficiency measurements according to different boron and humic substance applications (%)

kg HS ha^{-1} mg B l^{-1}	First year				Second year			
	H1	H2	H3	Average	H1	H2	H3	Average
B1	41.15	41.78	41.84	41.59	39.66	39.65	39.81	39.71ab
B2	41.84	41.67	41.54	41.68	40.26	40.62	39.35	40.08a
B3	42.06	41.17	41.04	41.42	39.88	38.59	38.59	39.02b
B4	41.15	40.90	40.75	40.93	37.11	38.18	38.65	37.98c
Average	41.55	41.38	41.29	41.41	39.23	39.26	39.10	39.20
LSD B	-				0.76			
LSD HM	-				-			
LSD B × HM	-				1.67			

In the second year, the B2 application resulted in the highest fiber fineness at 4.94 mic, followed by B1 at 4.89 mic, with the B4 treatment showing the lowest value at 4.51 mic. This demonstrates a trend of decreasing fiber fineness with increasing boron doses. Among humic substance treatments, highest fineness value was achieved in H3 and H1 treatment at 4.81 mic. Despite observed fluctuations, the differences were again not statistically significant. Notably, in the interaction between boron and humic substances during this period, the B3H1 combination produced the highest fiber fineness at 5.14 mic, followed by B2H1 at 5.01 mic, while the B4H1 treatment resulted in the lowest fineness at 4.22 mic, with these findings were statistically significant. Humic substance applications revealed a decrease in fiber fineness in the first year and negligible impact in the second year. These outcomes contrast with Rosolem & Bogiani's (2011) findings, which suggest that fiber quality is predominantly genetically determined

Fiber Strength (g/tex)

In the first year, the B1 application resulted in the highest fiber strength at 33.18 g/tex, followed closely by the B4 application at 33.12 g/tex. The lowest fiber strength was observed in the B2 application, with a value of 32.85 g/tex. These results indicated that increasing boron doses led to fluctuations in fiber strength, making the effect of boron uncertain. Similarly, with humic substance applications, the H1 application yielded the highest fiber strength at 33.24 g/tex, followed by the H3 application at 32.99 g/tex. As with boron, increasing doses of humic substances caused variations in fiber strength, leading to inconclusive results. The interaction between boron and humic substances also did not produce statistically significant differences in fiber strength (Table 8). In the second year, the B1 application again produced the highest fiber strength at 33.64 g/tex, with the B2 application following at 33.44 g/tex. The lowest fiber strength was recorded in the B4 application at 31.57 g/tex. A decrease in fiber strength was observed with increasing boron doses, and these differences were statistically significant. For humic substance applications, the H3 application resulted in the highest fiber strength at 33.47 g/tex, followed by the H1 application at 33.16 g/tex. While the H2 application showed a decrease in fiber strength compared to the control, the H3 application led to an increase. These differences were also statistically significant. However, the interaction between boron and humic substances in the second year did not yield statistically significant differences in fiber strength. The results indicate a negative relationship between boron application and fiber strength, with increasing boron doses leading to reduced fiber strength in the second year. Our findings do not align with the results of Eleyan et al. (2014), who reported that boron treatments increased fiber strength. The increase humic substance doses led to a decrease in fiber strength in the first year and had no significant effect in the second year. These findings contradict previous research by Grimes & El-Zik (1990) and Rosolem & Bogiani (2011), which suggested that fiber quality is predominantly influenced by genetic factors.

Gin Efficiency (%)

In the first year, the B2 application resulted in the highest gin efficiency at 41.68%, followed by the B1 application at 41.59%. The lowest value was observed in the B4 application at 40.93%. These findings suggest that increasing boron doses led to fluctuations in gin efficiency, making the impact of boron uncertain. Regarding humic substance applications, the highest gin efficiency was recorded in the H1 application at 41.55%, followed by the H2 application at 41.38%. Although there was a slight decrease in gin efficiency with higher humic substance doses, the differences were statistically insignificant. The interaction between boron and humic substances also did not yield statistically significant differences in gin efficiency (Table 9).

In the second year, the B2 application again produced the highest gin efficiency at 40.08%, with the B1 application following at 39.71%. The lowest efficiency was recorded in the B4 application at 37.98%. A decrease in gin efficiency was noted with increasing boron doses, and these differences were statistically significant. For humic substance applications, the H2 application had the highest gin efficiency at 39.26%, followed by the H1 application at 39.23%. As with boron, humic substance doses caused fluctuations in gin efficiency, leading to an uncertain effect. However, when examining the interaction between boron and humic substances in the second year, the B2H2 application yielded the highest gin efficiency at 40.62%, followed by the B2H1 application at 40.26%. The lowest efficiency was observed in the B4H1 application at 37.11%, and these results were statistically significant. The data indicate that boron toxicity tends to reduce gin efficiency, with the highest efficiency consistently associated with the B2 application in both years. Humic substance applications appeared to decrease efficiency in the first year and had no significant effect in the second year. Karademir and Karademir (2019) revealed that boron applications have non- significant effect on cotton ginning percentage. These findings align with the results of Ören (2007), although the specific impact of boron toxicity on ginning efficiency has not been widely studied.

Conclusion

In the first year of the experiment, boron toxicity effects were minimal, but they became more apparent in the second year due to reduced soil leaching and B accumulation. Boron toxicity most affected seed cotton yield, fiber fineness, followed by strength, gin efficiency, and length. Humic substances did not significantly affect fiber length, or gin efficiency in either year, although higher levels improved fiber strength and fineness in the second year. The interaction between boron and humic substances showed inconsistent results. Boron applications led to a significant increase in plant boron content, with the highest level observed in the leaves during the second year's flowering period (2048 mg B kg^{-1}). This high accumulation capacity in cotton leaves highlights their potential for use as hyperaccumulators in phytoremediation efforts targeting boron-contaminated soils. This experiment aimed to address boron toxicity issues in soils from agricultural and geothermal activities. The study further determined that cotton can tolerate boron concentrations in irrigation water ranging from 1.8 to 5.4 mg B l^{-1}, making it a viable crop in boron-affected regions. These findings provide critical insights into the potential of cotton as a resilient crop in environments with elevated boron levels, underscoring the need for further research to optimize cotton cultivation under such conditions.

Declarations

This manuscript was derived from PhD Thesis.

Ethical Approval Certificate

There is no need for ethical approval.

Author Contribution Statement

Mustafa Ali KAPTAN: Data collection, investigation, formal analysis, writing the original draft, and review and editing

Mehmet AYDIN: Project administration, supervision, conceptualization, methodology, review and editing

Fund Statement

This work was funded by Scientific Research Projects Coordination Unit of Aydın Adnan Menderes University as the project numbered ZRF-12012.

Conflict of Interest

The authors declare no conflict of interest.

References

Ahmed, N., Abid, M., & Ahmad, F. (2008). Boron toxicity in irrigated cotton (*Gossypium hirsutum* L.). *Pakistan Journal of Botany, 40*, 2443. [DOI bulunamadı]

Ahmed, N., Abid, M., & Rashid, A. (2010). Zinc fertilization impact on irrigated cotton grown in an aridisol: Growth, productivity, fiber quality, and oil quality. *Communications in Soil Science and Plant Analysis, 41*, 1627–1643. http://dx.doi.org/10.1080/00103624.2010.485242

Akar, D. (2007). Potential boron pollution in surface water, crop, and soil in the Lower Buyuk Menderes Basin. *Environmental Engineering Science, 24*(9), 1273–1279. http://dx.doi.org/10.1089/ees.2006.0218

Angin, I., Turan, M., Ketterings, Q. M., & Çakıcı, A. (2008). Humic acid addition enhances B and Pb phytoextraction by vetiver grass (*Vetiveria zizanioides* (L.) Nash). *Water, Air, & Soil Pollution, 188*, 335–343. http://dx.doi.org/10.1007/s11270-007-9548-0

Anonymous. (2010). Agency for Toxic Substances and Disease Registry. *Toxicological profile for boron*. United States Department of Health and Human Services. Atlanta, GA. [DOI bulunamadı]

Aydın, M., Kaptan, M. A., & Dalkılıç, Z. (2010). Relationship between fruit cracking and nutritional status of fig (*Ficus carica* L. cv. Sarilop) plantations in the lowland of Aydın, Turkey. *International Soil Fertility Congress*, Germany. [DOI bulunamadı]

Bergmann, W. (1992). *Nutritional disorders of plants*. Gustav Fischer Verlag. [DOI bulunamadı]

Bradford, G. R. (1966). Boron. In H. D. Chapman (Ed.), *Diagnostic criteria for plants and soils* (pp. 33–61). University of California, Division of Agricultural Sciences. [DOI bulunamadı]

Butterwick, R. F., Weekes, T. E. C., Rowlinson, P., Parker, D. S., & Armstrong, D. G. (1989). The effect of long-term daily administration of bovine somatotrophin on the performance of dairy cows over a second consecutive lactation. *Proceedings of the British Society of Animal Production (1972)*, 1989, 20. http://dx.doi.org/10.1017/S0308229600010217

Chapman, V. J., Edwards, D. G., Blamey, F. P. C., & Asher, C. J. (1997). Challenging the dogma of a narrow supply range between deficiency and toxicity of boron. In *Boron in soils and plants: Proceedings of the International Symposium on Boron in Soils and Plants* (pp. 151–155). Springer Netherlands. http://dx.doi.org/10.1007/978-94-011-5564-9_29

Chatzissavvidis, C., & Therios, I. (2010). Response of four olive (*Olea europaea* L.) cultivars to six B concentrations: Growth performance, nutrient status, and gas exchange parameters. *Scientia Horticulturae, 127*, 29–38. http://dx.doi.org/10.1016/j.scienta.2010.09.008

Chatzissavvidis, C., Therios, I., Antonopoulou, C., & Dimassi, K. (2008). Effects of high boron concentration and scion-rootstock combination on growth and nutritional status of olive plants. *Journal of Plant Nutrition, 31*, 638–658. http://dx.doi.org/10.1080/01904160801926343

de Souza Júnior, J. P., de M Prado, R., Campos, C. N., Sousa Junior, G. S., Oliveira, K. R., Cazetta, J. O., & Gratão, P. L. (2022). Addition of silicon to boron foliar spray in cotton plants modulates the antioxidative system attenuating boron deficiency and toxicity. BMC Plant Biology, 22(1), 338. https://doi.org/10.1186/s12870-022-03721-7

Eleyan, S.E.D., Abodahab, A.A., Abdallah, A.M. & Rabeh, H.A. (2014). Foliar application of boron and zinc effects on growth, yield and fiber properties of some Egyptian cotton cultivars (Gossypium barbadense L.). IJACS, 7(13): 1274-1282. [DOI bulunamadı]

Evangelou, M. W. H., Daghan, H., & Schaeffer, A. (2004). The influence of humic acids on the phytoextraction of cadmium from soil. *Chemosphere, 57*, 207–213. http://dx.doi.org/10.1016/j.chemosphere.2004.06.017

Gemici, Ü., & Tarcan, G. (2002). Hydrogeochemistry of the Simav geothermal field, Western Anatolia, Turkey. *Journal of Volcanology and Geothermal Research, 116*, 215–233. http://dx.doi.org/10.1016/S0377-0273(02)00217-2

Grimes, D. W., & El-Zik, K. M. (1990). Cotton. In *Irrigation of agricultural crops*. American Society of Agronomy. [DOI bulunamadı]

Kacar, B., & İnal, A. (2008). *Bitki analizleri*. Nobel Yayın Dağıtım. [DOI bulunamadı]

Karademir, E., & Karademir, Ç., (2019). Effect of different boron application on cotton yield components and fiber quality properties. Cercetări Agronomice în Moldova, 4 (180), 341-352. [DOI: 10.2478/cerce-2019-0033]

Karakaya, Z., & Paksoy, M. (2008). Yaz sezonunda yetiştirilen brokkolide (*Brassica oleracea* L.) bazı organik maddelerin bitki gelişimi, verim ve kaliteye etkileri. *Selçuk Üniversitesi Ziraat Fakültesi Dergisi, 22*, 1–6. [DOI bulunamadı]

Keren, R., & Bingham, F. T. (1985). Boron in water, soils, and plants. *Advances in Soil Science, 1*, 230–276. http://dx.doi.org/10.1007/978-1-4612-5046-3_7

Koç, C. (2011). Effects of boron pollution in the lower Buyuk Menderes Basin on agricultural areas and crops. *Environmental Progress & Sustainable Energy, 30*, 347–357. http://dx.doi.org/10.1002/ep.10485

Kumar, S., Kumar, D., Sekhon, K.S. & Choudhary, O.P. (2018). Influence of levels and methods of boron application on the yield and uptake of boron by cotton in a calcareous soil of Punjab. Commun. Soil Sci. Plant Anal., 49 (4): 499-514, DOI: 10.1080/00103624.2018.1431268

Mumma, R. O., Raupach, D. C., Waldman, J. P., Tong, S. S. C., Jacobs, M. L., Babish, J. G., Hotchkiss, J. H., Wszolek, P. C., Gutenmann, W. H., Bache, C. A., & Lisk, D. J. (1984). National survey of elements and other constituents in municipal sewage sludges. *Archives of Environmental Contamination and Toxicology, 13*, 75–83. http://dx.doi.org/10.1007/BF01055648

Nable, R. O., Banuelos, G. S., & Paull, J. G. (1997). Boron toxicity. *Plant and Soil, 193*, 181–198. http://dx.doi.org/10.1007/978-94-011-5580-9_12

Oertli, J. J., & Roth, J. A. (1969). Boron nutrition of sugar beet, cotton, and soybean. *Agronomy Journal, 61*, 191–195. https://doi.org/10.2134/agronj1969.00021962006100020006x

Oosterhuis, D. M., Chipamaunga, J., & Bate, G. C. (1983). Nitrogen uptake of field grown cotton. I. Distribution in plant components in relation to fertilization and yield. *Experimental Agriculture, 19*, 91–101. http://dx.doi.org/10.1017/S0014479700010553

Ören, Y. (2007). *Farklı zamanlarda uygulanan hümik asit ve çinko (Zn) uygulamasının pamukta (Gossypium hirsutum L.) verim, verim komponentleri ve lif kalite özellikleri üzerine olan etkisinin saptanması*. ADÜ Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, Aydın. [DOI bulunamadı]

Ören, Y., & Başal, H. (2006). Humik asit ve çinko (Zn) uygulamalarının pamukta (*Gossypium hirsutum* L.) verim, verim komponentleri ve lif kalite özelliklerine etkisi. *ADÜ Ziraat Fakültesi Dergisi, 3*, 77–83. [DOI bulunamadı]

Reid, R. (2010). Can we really increase yields by making crop plants tolerant to boron toxicity? *Plant Science, 178*, 9–11. http://dx.doi.org/10.1016/j.plantsci.2009.10.006

Rosolem, C. A., & Bogiani, J. C. (2011). Stress physiology in cotton. In *Physiology of boron stress in cotton*. Tennessee, ABD. [DOI bulunamadı]

Ryan, J., Estefan, G., & Rashid, A. (2001). *Soil and plant analysis laboratory manual*. ICARDA. [DOI bulunamadı]

Salinity Laboratory Staff. (1954). *Diagnosis and improvement of saline and alkali soils*. USDA Handbook. [DOI bulunamadı]

Stevenson, F. J. (1994). *Humus chemistry, genesis, composition, reactions*. Wiley. [DOI bulunamadı]

Turan, M., & Angin, I. (2004). Organic chelate assisted phytoextraction of B, Cd, Mo and Pb from contaminated soils using two agricultural crop species. *Acta Agriculturae Scandinavica, Section B: Soil and Plant Science, 54*, 221–231. http://dx.doi.org/10.1080/09064710410035622

Wolf, B. (1974). Improvement in the Azomethine-H method for the determination of boron. *Communications in Soil Science and Plant Analysis, 5*, 39–44. http://dx.doi.org/10.1080/00103627409366478