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Effects of Fertigation and Foliar Application of Boron on Fruit Yield and Several Physiological Traits of Bell Pepper

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ABSTRACT

Boron deficiency is a prevalent challenge for plant nutrition supply in many alkaline/calcareous soils. The current research aimed to examine the effects of boron supply to bell pepper plants through fertigation and foliar application. The experiment had seven treatments, comprising a control group, boric acid as fertigation (0.5, 1, and 2 g L^{-1}), and foliar application (0.5, 1, and 2 g L^{-1}) with three replications in controlled greenhouse conditions. The treatments were applied on Lorca bell peppers in a completely randomized design. The results showed that fertigation and foliar application increased all measured characteristics compared to the control group. Increasing the boric acid concentration in foliar application caused a decrease in fruit count per plant, fruit fresh weight, fruit yield per plant, and fruit width. Both fertigation and foliar boric acid applications at a low level (0.5 g L^{-1}) and as separate treatments caused the highest fruit weight, length, width, and fruit count per plant. Higher boric acid concentrations increased chlorophyll a, b, total chlorophyll, leaf carotenoid content, soluble sugars, total soluble solids, titratable acidity, total phenols, and fruit ascorbic acid content. The highest chlorophyll a, b, total chlorophyll, leaf carotenoid content, and fruit ascorbic acid were observed in response to the high concentration of boric acid foliar application (2 g L^{-1}). Overall, the boron supplement as a foliar application (0.5 to 1 g L^{-1}) or fertigation (0.5 to 1 g L^{-1}) improved quantitative and qualitative performance in bell peppers.

Introduction

A rapid increase in the world population has caused a need for more food production. Vegetable cultivation is gradually increasing in different regions (Dursun et al., 2010), and plants are cultivated in areas other than their primary source of origin. It is necessary to provide optimal conditions for their growth to obtain the highest yield and quality. Among agricultural resources, the balance of chemical fertilizers and their

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addition to soils is more effective in increasing agricultural production (Nagendran, 2011; Das and Mandal, 2015). With the ever-increasing price of chemical fertilizers in the world, there is a necessity for economic production, a challenge of groundwater pollution, and the destruction of soil structure due to the excessive and uninformed use of chemical fertilizers. Several research attempts have led to practical methods of supplementing plant nutrition (Malakouti et al., 2014). Foliar feeding or foliar application, especially in the case of low consumption elements, is a method that can provide a specific and small amount of nutrients directly to the foliage or fruit, requiring fertilizers to be rapidly effective compared to their soil application. This comparison is particularly true in soils with high pH, drought stress, and lack of organic matter. With more efficiency, the plant responds faster to fertilizer application (Fageria et al., 2009). Another optimal nutrition method is fertigation, in which water-soluble fertilizers are uniformly distributed in the required concentrations at each irrigation time or at certain time intervals based on the plant's physiological needs through drip irrigation in the root development area (Feng et al., 2017).

Bell pepper (*Capsicum annuum* L.) is a versatile horticultural product among fruit vegetables of the nightshade family. It is not only because of its economic value but also because of its high nutritional value and variety of consumption that it has received much attention for cultivation worldwide (Sarafi et al., 2018; Buczkowska et al., 2016; Bosland and Votova, 2000). Pepper fruits are a rich source of natural colors and various antioxidant compounds, such as phenolic compounds, vitamins A, E, and C, and carotenoids that effectively maintain human health (Bosland and Votova, 2000). Obtaining marketable products from sweet peppers in less favorable conditions depends on cultivars and treatments, including the type and amount of mineral nutrition. Proper mineral nutrition highly assists in shaping plant growth, development, quantitative indices, and qualitative crop yield (Buczkowska et al., 2016).

Micronutrient elements have a special place in agricultural production despite their low need. Boron deficiency is one of the most common challenges, and boron absorption decreases with increasing soil pH. In other words, its availability decreases in alkaline soils (Dursun et al., 2010). Boron in plants functions variedly, depending on water-dependent relations, cation exchange, anion absorption, pollen tube germination, nitrogen, phosphorus, carbohydrates, and lipids metabolism. Boron also assists in cell wall synthesis, sugar transport, cell division, cellular differentiation, membrane function, root development, regulation of plant hormone levels, and relative plant growth (Dordas and Brown, 2005). Plants vary widely in their requirements for boron, and knowledge of the range of deficiency and toxicity levels by this element to plants is limited. Boron management is challenging due to a small range of optimal boron applications, and its optimal application rate differs depending on soil type. The boron requirement in vegetables is generally higher than in other crops (Dursun et al., 2010). Reinbott and Blevins (1995) noted that boron application can enhance crop yield, even without boron deficiency in the soil. Extensive research has led to proven evidence that boron contributes significantly to bell pepper growth, as demonstrated by Mello et al. (2002). Their findings revealed that boron deficiency adversely affected bell pepper growth, including root volume, leaf area, photosynthesis, lateral shoot development, flower production, and overall yield.

However, there is little knowledge about the requirement of vegetables such as bell peppers for this element until the final stages of cultivation. Bell pepper cultivation mainly occurs in hot and dry regions, where there is a lack of microelements, especially boron, insufficient organic matter, inappropriate and calcareous texture, and soil salinity. On the other hand, a lack of organic material in soils may increase the need for organic fertilizer consumption. The high price of composted and quality organic fertilizers, or changing the soil texture and reaction, can impose huge costs on farmers. With costs rising, agricultural production becomes increasingly unappealing to many producers. Therefore, the present study aimed to evaluate the effects of boron fertigation and foliar application at different concentrations on several quantitative and qualitative characteristics of bell peppers in greenhouse conditions.

Materials and Methods

Initial soil sampling, characterization and fertility management

Before starting the experiment, soil samples were collected from a greenhouse. Sampling depth was 0-30 cm. Chemical properties and soil structure were analyzed (Table 1). The soil texture of the site was relatively heavy (texture: CL; silt: 35%; sand: 33%; clay: 32%). Gypsum was not observed in soil sampling. There was an evident deficiency of all analyzed micronutrient elements.

Table 1. Soil analysis before starting the experiment.

EC	pH	Physical test				Gyps.	TNV	OC	N	P	K	Fe	Zn	Mn	Cu	B
ds/m		S	Si	C	test	%				mg kg^{-1}						
0.59	7.90	29	43	28	CL	0.0	34	0.99	0.1	10.9	485	17.5	8.2	13.9	2.1	0.9

According to the soil test results, triple super phosphate fertilizers (100 kg ha^{-1}) was used along with ammonium sulfate (300 kg ha^{-1}), and potassium sulfate (200 kg ha^{-1}). The fertilizers were applied deeply to reach a depth of 30 cm in the soil and were mixed thoroughly.

Plant materials and growth conditions

Bell pepper seeds ('Lorca' cultivar) were planted in peat and perlite (50:50 v/v) in seedling trays, where the seeds germinated and grew. Six weeks after seed germination, healthy seedlings were transferred to the greenhouse and planted (120 × 65 × 45 cm spacing). After the establishment of the seedlings, the experimental treatments started from the second week after transplanting. Three replications appeared per treatment, including rows of paired cultivation with 270 plants. The treatments continued for five months on the plants and were applied once every two weeks until the end of the period. The experiment was in greenhouse conditions in Tiran and Karvan city (latitude 32º 42′ N, longitude 51º 09′ E) in 2018-2019. Environmental conditions in the greenhouse comprised a relative humidity of 60-70%, 18-25 °C temperature, and PPFD of 1000 µmol m^{-2} s^{-1} near the canopy top, controlled by a sensor (Farab).

Experimental design and treatments

Effects of boron fertigation and foliar application in this research were comparable in a completely randomized design with seven treatment groups, including the control treatment (without foliar application and no fertigation), fertigation with boric acid at three levels (0.5, 1, and 2 g L^{-1}), and boric acid foliar application at three levels (0.5, 1, and 2 g L^{-1}). All treatment groups had three replications.

Plant measurements

Growth and yield parameters

We counted the number of fruits per plant during plant growth and measured the fresh fruit weight in each plant with a digital scale (0.1 g accuracy). Plant yield was calculated per plant by adding the sum of fruit weight in each plant. The distance between two internodes on each plant and the length and width of the fruits were measured and recorded via a digital caliper.

Chlorophyll a, b, total chlorophyll, and carotenoid content

In measuring the amount of chlorophyll and carotenoids, 0.1 g of leaf sample was extracted via 10 mL of 80% acetone. Then, each extract absorbance was measured at 470, 663, and 645 nm with a spectrophotometer (model T80 + UV/VIS, PG Instruments, England). Equations 1, 2, 3, and 4 were used for calculating the photosynthetic pigment content (Lichtenthaler, 1987).

$$Chl\ a\ (mg\ g^{-1}) = \frac{\{0.0127\ (A_{663}) - 0.00269\ (A_{645})\} \times 100}{W}$$
(Equation 1)

$$Chl\ b\ (mg\ g^{-1}) = \frac{\{0.0229\ (A_{645}) - 0.00468\ (A_{663})\} \times 100}{W}$$
(Equation 2)

$$Total\ Chl = Chl\ a + Chl\ b$$
(Equation 3)

$$Carotenoids = \frac{1000\ (A_{470}) - 2.270\ Chla - 81.4\ Chl\ b}{227}$$
(Equation 4)

In the equations above, W is the tissue sample weight (mg). A663, A645, and A470 represent the absorbance values of each sample at 663, 645, and 470 nm.

Total soluble solids content (TSSC)

TSSC is an indicator of soluble solid content in fruits. After grinding and homogenizing pepper fruit tissue, it was filtered and its TSSC was measured in terms of °Brix at 25 °C by a refractometer (CETI-BELGUM) for each of the samples (Ghasemnezhad et al., 2011).

Titratable acids (TA)

To measure TA, 10 mL of fruit extract was titrated by adding 0.1 normal sodium to reach pH = 8.1. TA was expressed as a percentage of citric acid (Navarro et al., 2002).

Total phenol content

Total phenolic compounds in samples were measured according to Ghasemnejad et al. (2011) according to the Folin-Ciocalteu method. Fresh plant tissue was completely powdered with liquid nitrogen with a mortar and pestle. One gram of the powdered sample was extracted by 10 mL of pure cold methanol solvent. The methanolic extract (125 µL) was diluted with distilled water (375 µL) in a test tube, and then 2.5 mL of a 10% Folin-Ciocalteu reagent solution was added and maintained for 6 min in a dark room at ambient temperature. Then, 2 mL of a 7.5% sodium carbonate solution was added to neutralize the reaction. Each sample was placed in the dark for 90 min at room temperature, and then the absorbance of the blue solution was read at a wavelength of 765 nm using a spectrophotometer (UV-2100 Spectrophotometer, USA). In the blank solution, pure methanol was used instead of the plant extract. Gallic acid (50-1000 L mg^{-1}) was used for illustrating the standard curve. Total phenol content was expressed as mg 100 g^{-1} FW equivalent of gallic acid.

Soluble sugars
To evaluate the soluble sugar content, 0.1 g of each sample was placed inside the test tube in each repetition, and 5 mL of hot 80% ethanol alcohol was added, followed by centrifuging for 10 min at 8000 rpm. Repeating the same steps brought the final volume to 10 mL with 80% ethanol. This extract was used for measuring the soluble sugar content, according to Dubois et al. (1956). Two mL of the extract was poured into the test tube and 1 mL of 5% phenol solution was added. Then, 5 mL of concentrated sulfuric acid was added and the resulting mixture was vortexed for one minute. Finally, the mixture was placed at laboratory temperature for 10-15 min to form a brick-brown color. The same steps were performed on different concentrations of standard sugars. Glucose was used as a standard sugar. The soluble sugar content was read at 488 nm by a spectrophotometer and expressed as mg g^{-1} fresh weight.

Ascorbic acid
To determine the ascorbic acid content, 0.1 g of fruit sample was extracted with 10 mL of 1% metaphosphoric acid solution, followed by a centrifuge process. Then, 1 mL of the resultant extract was added to 9 mL of 2,6–dichlorophenolindophenol (DCPIP) and then vortexed. Ultimately, the absorbance value of each sample was read by a spectrophotometer (UV-2100 spectrophotometer) at a wavelength of 515 nm (Klein and Perry, 1982). Ascorbic acid was used for preparing a standard sample. Ascorbic acid content was calculated as mg 100 g-1 fresh weight.

Statistical analysis
Analysis of variance and comparison of mean values was performed by an LSD test ($P \leq 0.01$ and 0.05) using SAS software (version 9.2). Microsoft Excel (version 2016) was used for drawing the graphs. To determine correlations between the measured traits, Pearson's correlation analysis ($p < 0.05$) was used.

Results
The analysis of variance indicated that fertigation and foliar application with boric acid had significant effects on all measured traits in this research ($P \leq 0.01$) (Table 2).

Number of fruits per plant
Comparisons of mean values showed that in the fertigation and boric acid foliar application treatments, all three concentrations increased the number of fruits per plant compared to the control treatment. However, foliar application in all three concentrations resulted in better outcomes than in the fertigation treatment. With a further increase in boric acid concentration via foliar application, a decrease in fruit count per plant was observed. The highest count was reported in the foliar application treatment (0.5 g L^{-1} boric acid), which was statistically different from the other two concentrations of the foliar application treatment ($P \leq 0.05$) (Fig. 1A).

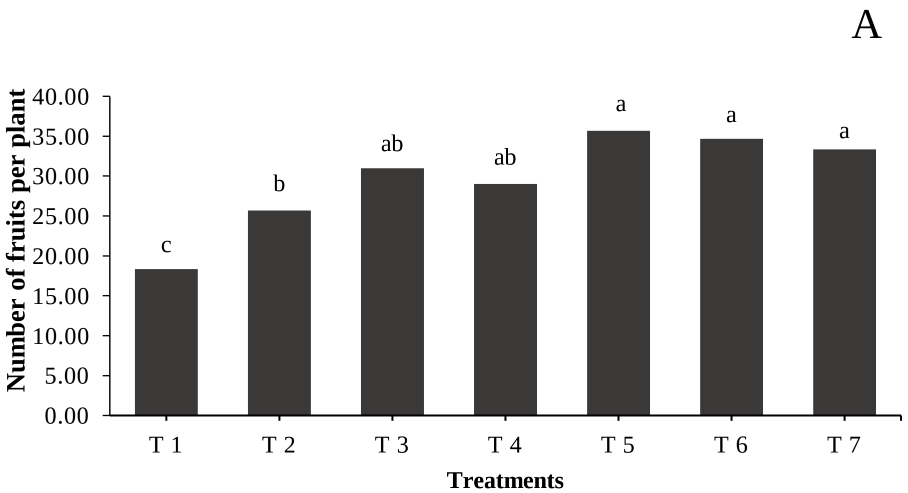
Fruit fresh weight
Average fruit fresh weight in the control treatment was lower than in the two treatments of fertigation and foliar application in all three concentrations. Also, in fertigation and foliar application treatments, the fresh weight of fruits decreased with increasing boric acid concentration. The highest fruit fresh weight was observed in 0.5 g L^{-1} boron treatment (Fig. 1B).

Fruit yield per plant
Treatments with foliar application and fertigation of boric acid increased the fruit yield in plants compared to the control treatment. Fruit yield decreased by increasing the boric acid concentration in the foliar application method. Meanwhile, increasing the concentration up to one kilogram in the fertigation method increased the yield but then decreased it. In general, foliar application resulted in a higher yield per plant compared to the fertigation method (Fig. 2A).

Table 2. Variance analysis of some morphological and biochemical traits of bell pepper plants under fertigation and foliar application with boric acid.

S.V.	d.f.	M.S.															
		NFPP	FFW	FYPP	FL	FW	IL	PH	Chl a	Chl b	TChl	CC	TSS	TA	TPC	SS	AsA
Treatments	6	110.56**	1539.13**	9429334.89**	0.85**	0.17**	0.11**	1346.98**	0.51**	0.54**	2.06**	0.16**	2.18**	0.63**	304.37**	45.83**	421.13**
Error	14	16.81	4565.99	800096.13	0.10	0.07	0.07	206.64	0.02	0.03	0.09	0.003	0.06	0.01	47.56	0.79	70.78
CV (%)		13.82	8.62	12.15	3.69	3.68	3.23	7.66	9.49	13.58	9.84	6.578	4.25	3.38	6.89	3.88	7.09

NFPP: Number of fruits per plant, FFW: Fruit fresh weight, FYPP: Fruit yield per plant, FL: Fruit length, FW: Fruit width, IL: Internode length, PH: Plant height, Chl a: Chlorophyll a, Chl b: Chlorophyll b, TChl: Total chlorophyll, CC: Carotenoid content, TSS: Total soluble solids, TA: Titratable acidity, TPC: Total phenol content, SS: Soluble sugar, AsA: Ascorbic acid content, S.V.: Source of variation, d.f.: Degree of freedom, M.S.: Mean squares, CV: Coefficient of variation. **; significance at P≤0.01.



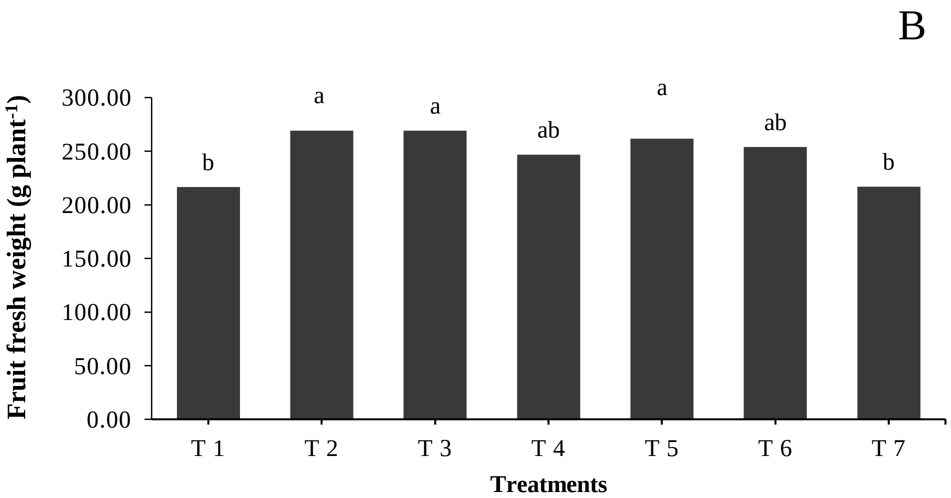


Fig. 1. Effects of fertigation and foliar application of boric acid treatments on the number of fruits per plant (A) and fruit fresh weight per plant (B). T1: control, T2: fertigation (0.5 g L^{-1}), T3: fertigation (1 g L^{-1}), T4: fertigation (2 g L^{-1}), T5: foliar application (0.5 g L^{-1}), T6: foliar application (1 g L^{-1}), T7: foliar application (2 g L^{-1}). Different letters on each column indicate significant differences between the treatments according to the LSD test (α = 0.05).

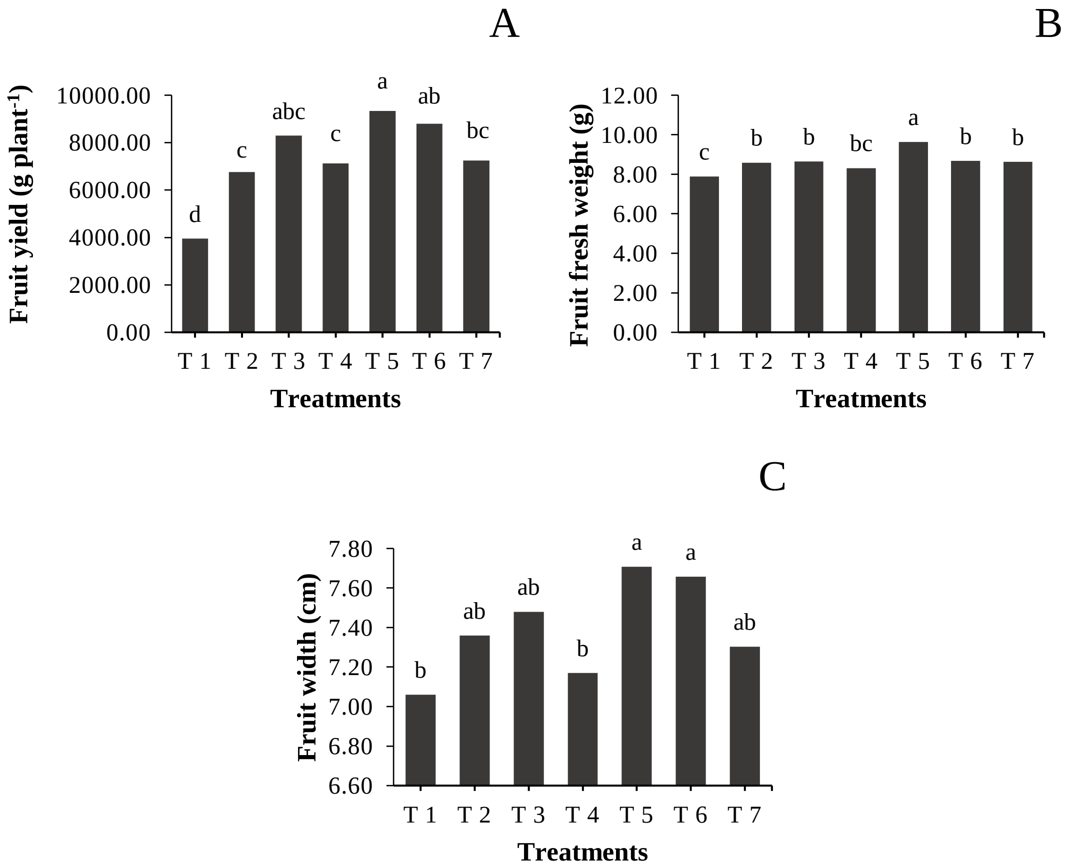


Fig. 2. Effects of fertigation and foliar application of boric acid treatments on fruit yield per plant (A), fruit length (B), and fruit width (C). T1: control, T2: fertigation (0.5 g L^{-1}), T3: fertigation (1 g L^{-1}), T4: fertigation (2 g L^{-1}), T5: foliar application (0.5 g L^{-1}), T6: foliar application (1 g L^{-1}), T7: foliar application (2 g L^{-1}). Different letters on each column indicate significant differences between the treatments according to the LSD test ($\alpha = 0.05$).

Fruit length
Fruit length in fertigation and foliar application with boron was greater than the control treatment in all three concentrations, and maximum length was observed in response to 0.5 g L^{-1} boric acid foliar application (Fig. 2B).

Fruit width
Fruit width became larger in response to boron fertigation and foliar application, compared to the control treatment. Maximum fruit width occurred in response to the foliar application of 0.5 g L^{-1} boric acid, which was not significantly different from the foliar application of 1 g L^{-1} boric acid treatment ($P \leq 0.05$). Fruit width decreased in response to increasing the boron concentration in the foliar application (Fig. 2C).

Internode length
Fertigation and boron foliar application in all three concentrations caused higher internode lengths than the control group. The internode length increased in response to higher boron concentrations in fertigation and foliar application treatments (Fig. 3A).

Plant height
Trends of change in average stem height were similar to those of the fruit yield in plants. The highest average stem height was observed in response to foliar application at 0.5 g L^{-1} and 1 g L^{-1} in fertigation. At the end of the experiment, high concentrations of fertigation and boron foliar application had not caused a significant difference in stem height compared to the control group (Fig. 3B).

Chlorophyll a, b, and total
Highest amounts of chlorophyll a, b, and total were observed in the foliar application treatment using 2 g L^{-1} boron. Boron application increased chlorophyll a, b, and total pigments compared to the control group (Fig. 4A, B, and C).

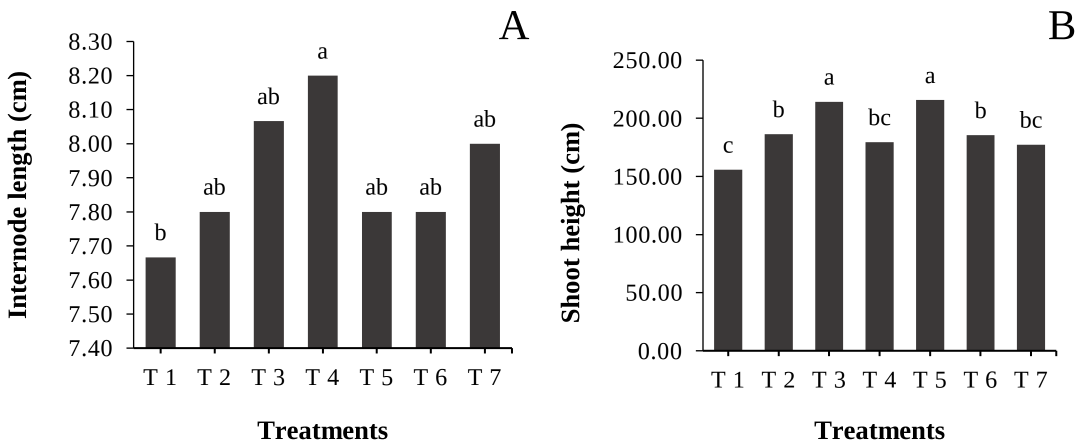


Fig. 3. Effects of fertigation and foliar application of boric acid treatments on internode length (A), and stem length (B). T1: control, T2: fertigation (0.5 g L^{-1}), T3: fertigation (1 g L^{-1}), T4: fertigation (2 g L^{-1}), T5: foliar application (0.5 g L^{-1}), T6: foliar application (1 g L^{-1}), T7: foliar application (2 g L^{-1}). Different letters on each column indicate significant differences between the treatments according to the LSD test (α = 0.05).

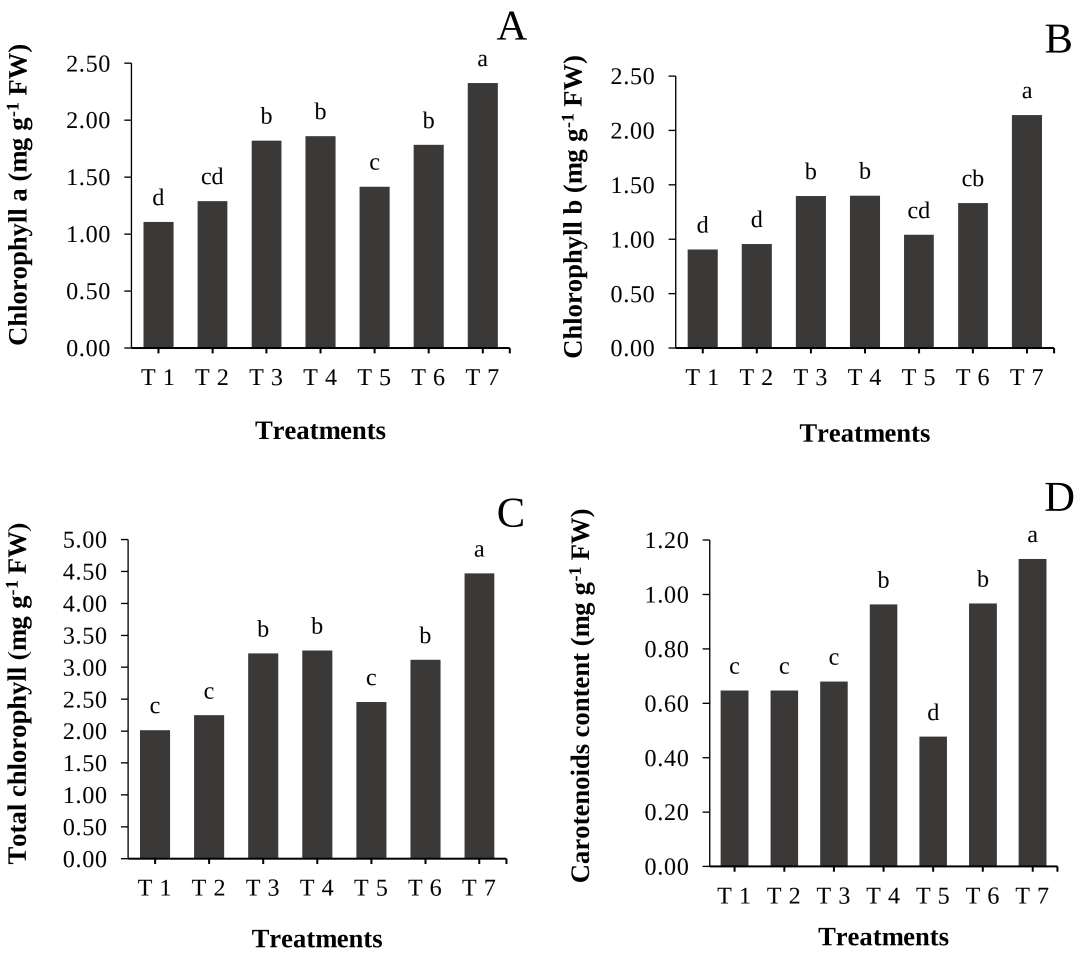


Fig. 4. Effects of fertigation and foliar application of boric acid treatments on the amounts of chlorophyll a (A), b (B), total (C), and carotenoids (D) in pepper leaves. T1: control, T2: fertigation (0.5 g L^{-1}), T3: fertigation (1 g L^{-1}), T4: fertigation (2 g L^{-1}), T5: foliar application (0.5 g L^{-1}), T6: foliar application (1 g L^{-1}), T7: foliar application (2 g L^{-1}). Different letters on each column indicate significant differences between the treatments according to the LSD test (α = 0.05).

Leaf carotenoid content

Highest and lowest levels of carotenoids in leaf samples were observed in 2 g L^{-1} boron foliar application treatment and 0.5 g L^{-1} boron foliar application treatment, respectively. By increasing the boron concentration in fertigation and foliar application treatments, the carotenoid content increased in leaf samples (Fig. 4D).

Fruit soluble solids

Highest concentrations of boric acid in fertigation and foliar application treatments caused the highest total soluble solids in fruits. In both fertigation and foliar application treatments, the total soluble solids increased in response to increasing the boron concentration (Fig. 5A).

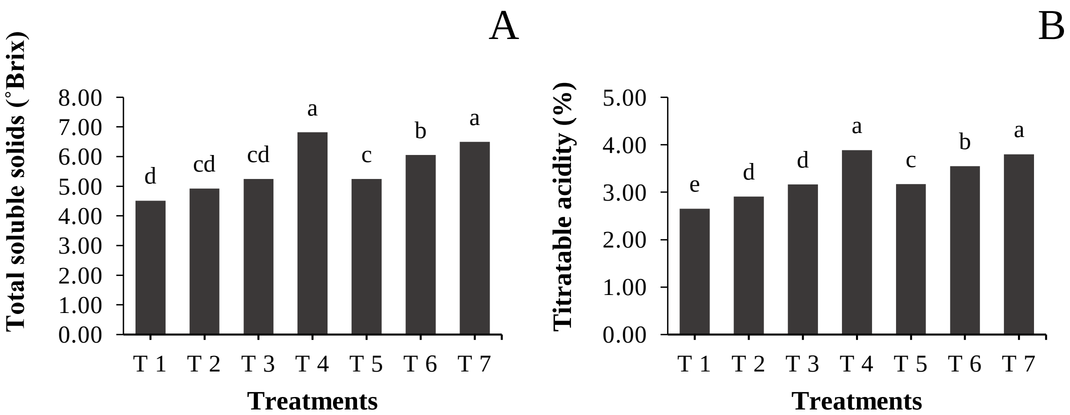


Fig. 5. Effects of fertigation and foliar application of boric acid treatments on fruit soluble solids content (A) and titratable acidity (B). T1: control, T2: fertigation (0.5 g L^{-1}), T3: fertigation (1 g L^{-1}), T4: fertigation (2 g L^{-1}), T5: foliar application (0.5 g L^{-1}), T6: foliar application (1 g L^{-1}), T7: foliar application (2 g L^{-1}). Different letters on each column indicate significant differences between the treatments according to the LSD test ($\alpha = 0.05$).

Fruit titratable acidity

Higher values of fruit titratable acidity occurred in response to fertigation and boron foliar application compared to the control treatment. The highest titratable acidity occurred in response to the highest concentration of the applied treatments. Also, the titratable acidity showed an increasing trend when using higher boron concentrations in the treatments (Fig. 5B).

Total fruit phenol content

Highest and lowest amounts of total fruit phenol were observed in 2 g L^{-1} boron fertigation treatment and 2 g L^{-1} foliar application, respectively. These two treatments did not have a significant difference from the 1 g L^{-1} foliar application treatment. By increasing the boron concentration in fertigation and foliar application treatments, the total phenol content increased in the fruits (Fig. 6A).

Fruit soluble sugar content

Boron treatments as fertigation and foliar application caused an increase in fruit soluble sugar content compared to the control treatment. The highest amount was observed in the fertigation treatment of 2 g L^{-1} boric acid (Fig. 6B).

Ascorbic acid content in fruits

Highest concentrations of boric acid in fertigation and foliar application treatments caused the highest amounts of ascorbic acid in the fruits. In both fertigation and foliar application treatments, the ascorbic acid content increased when using higher boron concentrations (Fig. 6C).

Correlation coefficients

According to the correlation coefficients of traits in this research (Table 3), it was observed that plant height had a positive and significant correlation with the number of fruits, plant yield, fruit length, fruit width ($P \leq 0.01$), and fruit fresh weight ($P \leq 0.05$). Thus, fertigation and foliar application of boric acid improved plant height, fruit yield, fruit count, fruit length, fruit width, and fresh fruit weight (Table 3). Also, photosynthetic pigments (chlorophyll a, b, total, and carotenoids) correlated positively and significantly ($P \leq 0.01$) with fruit quality characteristics, i.e., soluble solids, titratable acidity, total phenol, soluble sugars, and ascorbic acid. These correlations showed that fertigation and foliar application of boric acid improved fruit quality by accumulating photosynthetic pigments.

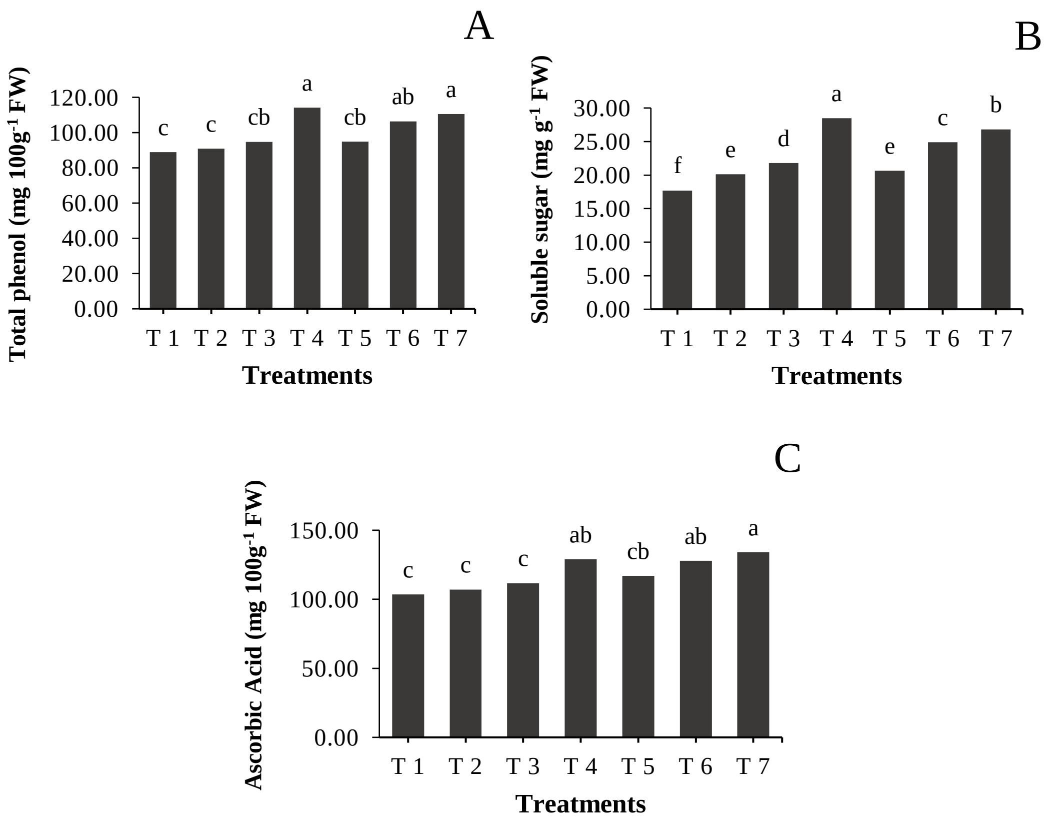


Fig. 6. Effects of fertigation and foliar application of boric acid treatments on total phenol content (A), soluble sugar content (B), and fruit ascorbic acid (C). T1: control, T2: fertigation (0.5 g L^{-1}), T3: fertigation (1 g L^{-1}), T4: fertigation (2 g L^{-1}), T5: foliar application (0.5 g L^{-1}), T6: foliar application (1 g L^{-1}), T7: foliar application (2 g L^{-1}). Different letters on each column indicate significant differences between the treatments according to the LSD test ($\alpha = 0.05$).

Discussion

While boron deficiency symptoms did not appear in the control group, the foliar application and boron fertigation treatments caused no visible signs of toxicity, such as color change, yellowing, and deformity in growth. This research showed that in both the fertigation and boric acid foliar application treatments, there was an increase in the number of fruits per plant, fruit fresh weight, and total yield compared to the control treatment. In foliar application with 0.5 g L^{-1} boric acid and fertigation with 1 g L^{-1}, we observed a higher average in these traits. In the foliar application treatment with 2 g L^{-1} boric acid and fertigation with 2 g L^{-1} boric acid, a significant decrease occurred in the number of fruits per plant, fruit fresh weight, and yield, compared to the foliar and fertigation treatments with 0.5 g L^{-1}. These findings are consistent with previous research by Nabi et al. (2006) that providing pepper plants with appropriate boron nutrition promotes their growth and yield. However, excessive boron levels adversely affected pepper development and fruit yield. This toxicity highlights the importance of maintaining the right balance of boron for optimal plant performance. Boron is an essential element for plant growth and development, playing a crucial role in essential processes such as cell division, elongation, and metabolism. It also affects plant fertility directly and indirectly (Power and Woods, 1997; Blevins and Lukaszewski, 1998). While vegetative growth requires a certain amount of boron, fruit and seed production often demand higher levels (Marschner, 1995). Insufficient boron levels disrupt cell division in all plants, leading to irregular and incomplete division, weak leaf development, reduced photosynthesis, and decreased carbohydrate levels, ultimately affecting quantitative traits (Hanson, 1991). The positive effects of boron on fruit yield are attributable to its involvement in essential physiological processes such as lignification, cell wall composition, respiration, sugar transport, nitrogen fixation, and cell membrane structure (Zeist et al., 2018).

Table 3. Correlation coefficient values of some morphological and biochemical traits of bell pepper plants under boric acid fertigation and foliar application.

	SH	I	NF	FFW	Y	FL	FW	Chl a	Chl b	Tchl	Ca	TSS	TA	TPC	SS
I	0.28^{ns}														
NF	0.58**	0.28^{ns}													
FFW	0.52*	0.06^{ns}	0.05^{ns}												
Y	0.74**	0.27^{ns}	0.92**												
FL	0.59**	0.13^{ns}	0.67**	0.42^{ns}	0.73**										
FW	0.59**	0.20^{ns}	0.64**	0.33^{ns}	0.72**	0.67**									
Chl a	0.05^{ns}	0.38^{ns}	0.51*	0.36^{ns}	0.34^{ns}	0.07^{ns}	0.01^{ns}								
Chl b	-0.15^{ns}	0.27^{ns}	0.36^{ns}	-0.20^{ns}	0.15^{ns}	-0.019	-0.1^{ns}	0.91**							
Tchl	-0.05^{ns}	0.33^{ns}	0.45*	-0.34^{ns}	0.25^{ns}	0.03^{ns}	-0.05^{ns}	0.98**	0.98**						
Ca	-0.28^{ns}	0.36^{ns}	0.24^{ns}	-0.27^{ns}	0.04^{ns}	-0.264	-0.13^{ns}	0.74**	0.7**	0.73**					
TSS	-0.09^{ns}	0.39^{ns}	0.44*	-0.33^{ns}	0.32^{ns}	-0.01	-0.02^{ns}	0.77**	0.72**	0.76**	0.76**				
TA	0.02^{ns}	0.43^{ns}	0.53*	-0.10^{ns}	0.41^{ns}	0.09^{ns}	0.06^{ns}	0.81**	0.74**	0.79**	0.75**	0.99**			
TPC	-0.04^{ns}	0.57**	0.38^{ns}	-0.08^{ns}	0.25^{ns}	0.07^{ns}	-0.01^{ns}	0.66**	0.55**	0.62**	0.76**	0.82**	0.83**		
SS	-0.09^{ns}	0.49*	0.44*	-0.17^{ns}	0.32^{ns}	0.02^{ns}	-0.03^{ns}	0.81**	0.73**	0.79**	0.79**	0.98**	0.97**	0.84**	
AsA	0.05^{ns}	0.34^{ns}	0.39^{ns}	-0.12^{ns}	0.28^{ns}	0.04^{ns}	0.04^{ns}	0.68**	0.62**	0.67**	0.69**	0.80**	0.84**	0.76**	0.75**

I: internode length, SH: plant height, NF: number of fruits per plant, FFW: fruit fresh weight, Y: fruit yield per plant, FL: fruit length, FW: fruit width, Chl a: chlorophyll a, Chl b: chlorophyll b, Tchl: total chlorophyll, Car: carotenoid content, TSS: total soluble solids, TA: titratable acidity, TPC: total phenol content, SS: soluble sugar, AsA: ascorbic acid content. ^{ns} not significant, ** significant at P≤0.01 and * significant at P≤0.05.

However, excessive concentrations of boron in plants, as in high concentrations, can decrease fruit yield (Hu and Brown, 1997). Boron toxicity reduces leaf area and photosynthesis, ultimately impacting plant productivity (Ben-Gal, 2002). The adverse physiological effects associated with excessive boron include reduced cell division and growth, increased deposition of lignin and suberin, reduced proton release from the root, heightened membrane leakage, alterations in antioxidant pathway activity, and oxidative stress (Ardic et al., 2009). Maintaining appropriate boron levels is thus crucial to avoid these negative impacts on plant physiology and yield.

According to the results, the internode length increased in response to increasing boron concentration in both fertigation and foliar application methods. The current findings align with previous observations by Buoso et al. (2020) that a lack of boron in grapes shortened internode distance. Boron affects the apical meristems of stems and roots, further causing leaf growth, so the internode distance decreases with the decrease in boron content (Marschner, 1995).

In this research, we observed that plant height was affected by boric acid, and the concentrations of 0.5 g L^{-1} foliar application and 1 g L^{-1} fertigation most significantly increased plant height. Increasing the concentration of boric acid decreased the plant height. At the beginning of the experiment, all boric acid treatments showed a higher growth trend than the control. Through time, the high concentrations of boric acid caused toxicity symptoms (data not published) and caused a decrease in growth. Nabi et al. (2006) documented that increasing boron concentrations in calcareous soils with boron deficiency enhanced plant growth and development. However, as the boron concentration continued to rise, the detrimental effects of boron toxicity started to inhibit plant growth, thus corresponding with the current findings.

The results indicate that both fertigation and foliar application treatments increased the chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids in leaf samples as the boron concentration increased. This finding agrees with previous observations by Xu et al. (2021) on tomato leaves, where boron application resulted in elevated levels of chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids. A similar outcome reportedly occurred in alfalfa, where Taherian et al. (2019) documented findings that align with the current results. It is noteworthy that boron, as an essential micronutrient, influences various physiological processes, including photosynthetic pigment content (Taherian et al., 2019).

Increasing the boron concentration in all treatments improved fruit quality parameters, including soluble sugars, fruit ascorbic acid, TSSC, TA, and total phenol. This observation was consistent with findings by Babu (2002), who noted that increasing boron concentration in foliar application treatments enhanced the soluble sugar content, fruit ascorbic acid, TSSC, TA, and total phenol in tomato fruits. The current results are consistent with previous findings by other researchers who reported that applying boron, either through foliar application or in the soil, increased vitamin C content in tomatoes (Islam et al., 2019; Milagres et al., 2019; Xu et al., 2021). This correlation further validates the findings of the present study. Boron substantially regulates metabolism and contributes to carbohydrate availability for flowers and fruit development (Haleema et al., 2018). It is an essential microelement in various physiological reactions, including sugar metabolism, which improves membrane integrity and cell wall strength. Ultimately, it leads to a higher carbohydrate content and vitamin C in fruits (Khoshghalb et al., 2013; Milagres et al., 2019).

Conclusion

The results showed that in both fertigation and boric acid foliar application treatments, all three concentrations increased the number of fruits per plant, fruit fresh weight, fruit yield per plant, fruit length and width, internode length, chlorophyll a, chlorophyll b, and total chlorophyll compared to the control group. The highest concentration of boric acid in the foliar application and fertigation treatments decreased the number of fruits per plant, fruit fresh weight, yield, length, and fruit width compared to the other treatments. Fertigation and foliar application with 0.5 g L^{-1} caused the highest fruit weight, number of fruits per plant, length, and width. The highest amount of leaf chlorophyll a, b, total chlorophyll, and carotenoid appeared in response to 2 g L^{-1} boric acid foliar application. This research showed that treating bell pepper plants with boron fertigation and foliar application improved fruit yield and quality characteristics. Since boron is a micronutrient in plant nutrition, selecting an appropriate boron concentration for application requires time and effort to avoid high boron concentrations and toxicity.

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Conflict of Interest

The authors indicate no conflict of interest for this work.

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