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Role of boron, potassium, and iron in improving productivity and fruit characteristics of squash (*Cucurbita pepo* L.)

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A B S T R A C T

Balanced mineral nutrition, especially macronutrients and micronutrients involved in plant physiological and biochemical activities, is a key factor in improving the productivity and fruit quality of squash (*Cucurbita pepo* L.). The study was conducted at the Zakho Technical Institute, Kurdistan Region, Iraq, under greenhouse conditions during the 2025–2026 growing season to examine the effects of boron (B), potassium (K), and iron (Fe) on the growth and fruit characteristics of squash. The experiment was laid out as a split-split plot, Randomized Complete Block Design (RCBD) with three replications. Two levels of iron fertigation (0 and 2 g L^{-1}), two levels of potassium fertilizer (0 and 2 g L^{-1}), and two levels of boron foliar (0 and 2 mL L^{-1}) were applied. The results indicated that plant fertigation with an Iron concentration of 2 g L^{-1} improved the number of fruits to 8.250 fruit $plant^{-1}$. However, foliar application of potassium at a concentration of 2 g L^{-1} increased the number of fruits to 8.583 fruit $plant^{-1}$, fruit length to 12.900 cm, plant height to 81.500 cm, fruit weight to 100.588 g, and fruit diameter to 3.850 cm. Furthermore, spraying Boron at a concentration of 2 mL L^{-1} increased the number of fruits to 8.417 fruits $plant^{-1}$ and plant height to 80.124 cm. The study emphasized the need to properly manage nutrients in greenhouse squash production and the possibility for balanced potassium fertilization to greatly increase fruit quality and yield.

Keywords: Summer squash, Boron, Potassium, Iron, Greenhouse cultivation

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Introduction

Edible summer squash (*Cucurbita pepo* L.) of the very diverse family Cucurbitaceae is grown worldwide in temperate and subtropical regions and is native to Mexico and North America (Paris, 1996). Also, due to its widespread cultivation, summer squash has been shown to be a nutritional and medicinal treasure, having a low energy density but high amounts of vitamins (ß-carotene, A, B_2, C, and E), amino acids, fiber, carbohydrates, phenolics, and flavonoids (Adnan *et al.*, 2017; Martínez-Valdivieso *et al.*, 2017). Its attributes highlight its significance in human nutrition and health.

The availability of essential nutrients, primarily supplied through inorganic fertilizers, is directly related to plant growth and productivity. Fertilizers contain specific proportions of micro- and macronutrients, which play a key role in achieving optimal yields in commercial farming (Rekaby *et al.*, 2024). Boron is an essential micronutrient for cucurbitaceous plants and plays roles in physiological processes including protein synthesis, cell wall integrity, glucose metabolism, sugar translocation, hormone regulation, pollen grain germination, and pollen tube development (Rasheed, 2009).

El-Shoura (2020) reported that foliar application of boric acid significantly improved vegetative growth, yield, and fruit quality of summer squash under high-temperature stress conditions. Similarly, Abou El-Yazeid *et al.* (2007) found that application of boron via foliar spray, when combined with bio-dissolving microorganisms, improved vegetative growth, plant pigments, nutrients (N, P, K, Mg, and B), and finally resulted in a better sex ratio and early fruit production with higher yield in squash. These results confirm the importance of boron in the quantity and quality of squash production.

One macronutrient that significantly affects a variety of physiological and biochemical processes in plants is potassium (K). These include regulating water flow, energy transfer, and cation-anion balance (Hasanuzzaman *et al.*, 2018; Wang *et al.*, 2013). Additionally, potassium plays direct roles in enzymes involved in protein and carbohydrate synthesis, which are important for fruit quality (Lester *et al.*, 2010; Hasanuzzaman *et al.*, 2018). Potassium has been shown to increase the number of pistillate flowers for a variety of reasons, including its effects on hormone production, such as gibberellins. This increases the quantity of fruits and the overall yield per plant (de Souza *et al.*, 2023; Budak and Güneş, 2023; Nassar *et al.*, 2019). Potassium was reported by Nassar *et al.* (2019) and the North Carolina Cooperative Extension (2024) to synergistically enhance vegetative growth, yield, and nutritional composition of squash fruits when applied to soils, especially at higher levels. This means that the effects of potassium are overall on both fruit yield and quality. The other micronutrient of concern is iron (Fe), which is required for plant health and productivity, especially in photosynthesis and energy production in plants, as it is needed for chlorophyll formation (Bacaicoa and García-Mina, 2009). Peppermint is prone to chlorosis due to iron deficiency and is particularly affected in alkaline, calcareous soils (Haifa Group, 2026). In cucurbit species, the use of iron is key to achieving good growth and fruit quality (Gupta *et al.*, 2022). The foliar application of iron has been reported to increase growth parameters, chlorophyll content, and fruit and seed iron content in cucumbers, thereby resulting in higher seed productivity and quality (Shebl *et al.*, 2019). Shebl *et al.* (2019) reported that the application of Fe_3O_4 NPs as a foliar spray significantly increased the organic matter, protein, lipid, and energy contents in squash fruits. This study aims to investigate the effects of boron, potassium, and iron on the productivity and fruit characteristics of squash (*Cucurbita pepo* L.) under greenhouse cultivation in Zakho, Kurdistan, Iraq.

Materials and Methods

The experiment was conducted during the 2025-2026 growing season in the greenhouse of the Protected Cultivation Department at Zakho Technical Institute/Dohuk Polytechnic University to evaluate the role of boron, potassium, and iron in improving productivity and fruit characteristics of squash (*Cucurbita pepo* L.). Squash seeds were sown in seedling trays with peat moss medium on 15th March 2026. Healthy seedlings were transplanted into the greenhouse on 8th April 2026. Plants were spaced 50 cm apart and 120 cm between rows. The experiment included three factors: Iron fertigation at two concentrations (0 and 2 g L^{-1}), potassium fertilizer at two concentrations (0 and 2 g L^{-1}), and boron fertilizer at two concentrations (0 and 2 mL L^{-1}). The treatments were arranged in a split-split plot system, Randomized Complete Block Design (RCBD) with three replications. Iron fertigation treatments were assigned to the main plots. Potassium fertilizer treatment to the subplots and boron fertilizer treatment to the sub-subplots. A Total of eight treatment combinations (2×2×2) were evaluated, resulting in 24 experimental units. Each experimental unit consisted of 10 plants. Foliar fertilizer application was initiated on 20 April 2026 and repeated twice at 7-day intervals. All recommended greenhouse management practices, including irrigation, weed control, and pest management, were uniformly applied throughout the growing period. The recorded parameters included: No. Number of fruits per plant, plant height (cm), fruit weight (g), fruit length (cm), fruit diameter (cm). The results will be analyzed statistically using Duncan's multiple range test at 0.05 (SAS, 2007).

Results

Number of fruits per plant

The results in Table 1 indicated that fertigation with Iron and spraying potassium and Boron on Squash plants at any concentration did not significantly increase the number of fruits per plant compared with the control.

However, the interaction between iron and potassium showed no significant difference. Whereas, the highest increase in number of fruits per plant reached 9.333 fruit plant^{-1} for the interaction between 2 g L^{-1} potassium and 2 mL L^{-1} Boron, when compared with the least value, which reached to 7.833 fruit plant^{-1} for the plant treat with 2 g L^{-1} potassium interacted with 0 ml L^{-1} Boron, In addition, the interaction between Iron and Boron also did not had any significant difference between them

The triple interaction among Iron, potassium and Boron fertilizers factors indicated that the plants which fertigation with 0 g L^{-1} Iron, and spraying 2 g L^{-1} potassium and 2 mL L^{-1} Boron fertilizers gave the highest value of number of fruits per plant reached 10.333 fruit plant^{-1}, when compared with least value which reached to 7.000 fruit plant $^{-1}$ for the plant treat with 0 g L^{-1} for both Iron and potassium interacted with 2 mL L^{-1} Boron.

Table 1. Effect of boron, potassium, iron, and their interaction on the number of fruits per squash plant.

Iron g L^{-1}	Potassium g L^{-1}	Boron mL L^{-1} 0	Boron mL L^{-1} 2	Iron * potassium	Iron
0	0	8.000b	7.000b	7.500 a	8.167 a
	2	7.333b	10.333a	8.833 a	
2	0	8.333ab	8.000b	8.167a	8.250 a
	2	8.333ab	8.333ab	8.333a	
Iron * Boron	0	7.667a	8.667a	potassium	
	2	8.333a	8.167a		
potassium * Boron	0	8.167ab	7.500a	7.833 a	
	2	7.833b	9.333a	8.583 a	
Boron		8.000a	8.417 a		

Means with the same letter for every component and interaction do not differ significantly at the 5% level.

Fruit Length (cm)

The results in Table 2 showed that not applying fertigation with iron to the squash plant caused a significant increase in Fruit Length, reaching 13.525 cm, compared with the lowest value of 11.400 cm for the plant fertilized with Iron at a concentration of 2 mL L^{-1}. On the other hand, the Fruit Length also increased significantly when sprayed with 2 g L^{-1} potassium fertilizer, reaching 12.900 cm, compared with the control at 12.025 cm. However, an increase in Boron concentration did not result in a significant increase when compared with the control.

The highest fruit length increased to 14.000 cm when fertigation with 0 g L^{-1} Iron was combined with spraying 2 g L^{-1} potassium, compared with the lowest value of 11 cm for the plant treated with 0 g L^{-1} and sprayed with 2 g L^{-1} potassium. However, the interaction between potassium and boron at concentrations of 2 g L^{-1} and 0 mL L^{-1} significantly increased fruit length, reaching 12.725 cm, compared with the lowest value of 10.800 cm for the plant treated with 0 g L^{-1} potassium and 2 mL L^{-1} Boron. Moreover, the interaction between Iron and boron in control plants significantly increases fruit length, reaching 15.125 cm, compared with the lowest value for the plant treated with 2 g L^{-1} iron and 0 mL L^{-1} boron, which is 10.850 cm.

The triple interaction among Iron, potassium and Boron fertilizers factors indicated that the plants which fertigation with 0 g L^{-1} Iron, and spraying 2 g L^{-1} potassium and 0 mL L^{-1}

Boron fertilizers gave the highest value of fruits length reached 15.500 cm, when Iron and 0 g L^{-1} potassium interacted with 2 mL L^{-1} Boron.

Iron g L^{-1}	Potassium g L^{-1}	Boron mL L^{-1}		Iron * potassium	Iron
		0	2		
0	0	71.500 e	75.500 d	73.500 d	80.000 a
	2	88.500 a	84.500 b	86.500 a	
2	0	81.000 bc	83.000 b	82.000 b	79.250 a
	2	75.500 d	77.500 cd	76.500 c	
Iron * Boron	0	80.000 a	80.000 a	potassium	
	2	78.250 a	80.250 a		
Potassium * Boron	0	76.250 b	79.250 a	77.750 b	
	2	82.000 a	81.000 a	81.500 a	
Boron		79.125 a	80.125 a		

compared with least value which reached to 10.250 cm for the plant treat with 2 g L^{-1} for

Table 2. Effect of boron, potassium, iron, and their interaction on the length (cm) of the fruit of the squash plant.

Means with the same letter for every component and interaction do not differ significantly at the 5% level.

Iron g L^{-1}	Potassium g L^{-1}	Boron mL L^{-1}		Iron * potassium	Iron
		0	2		
0	0	4.300 a	3.300 c	3.800 a	3.867 a
	2	4.367 a	3.500 bc	3.933 a	
2	0	3.433 c	3.233 c	3.333 b	3.550 b

Plant height (cm)

The results in Table 3 showed that fertigation with Iron and spraying Boron on Squash plants at any concentration did not significantly increase Plant height compared with the control. Increasing potassium concentration to 2 g L^{-1} in squash plants significantly increased plant height to 81.500 cm, compared with 77.750 cm in control plants.

Table 3. Effect of boron, potassium, iron, and their interaction on plant height (cm) of squash plant.

	2	3.500 bc	4.033 ab	3.767 a	
Iron * Boron	0	4.333 a	3.400 b	potassium	

Iron g L^{-1}	Potassium g L^{-1}	Boron mL L^{-1}		Iron * potassium	Iron
		0	2		
0	0	14.750 ab	11.350 de	13.050 a	13.525 a
	2	15.500 a	12.500 cd	14.000 a	0 a
2	0	11.750 d	10.250 e	11.000 b	11.400 b
	2	9.950 e	13.650 bc	11.800 b	
Iron * Boron	0	15.125 a	11.925 b	potassium	
	2	10.850 c	11.950 b		
Potassium * Boron	0	13.250 a	10.800 b	12.025 b	
	2	12.725 a	13.075 a	12.900 a	
Boron		12.988 a	11.938 b		

Means with the same letter for every component and interaction do not differ significantly at the 5% level.

The highest plant height increased to 86.500 cm when fertigation of 0 g L^{-1} Iron interacted with spraying 2 g L^{-1} potassium, respectively, compared with the least value, which reached 76.500 cm for the plant treated with 2 g L^{-1} Iron interacted with spraying 2 g L^{-1} potassium. However, the interaction between potassium and boron caused a significantly increase in plant height, which reached 82.000 cm for plant spraying 2 g L^{-1} interacted with fertigation with 0 mL L^{-1} boron when compared with the control, which reached 76.250 cm. Additionally, the interaction between Iron and Boron did not show a significant increase.

The triple interaction among Iron, potassium, and Boron fertilizer factors indicated that the plants that were fertigated with 0 g L^{-1} Iron and sprayed with 2 g L^{-1} potassium and 0 mL L^{-1} Boron fertilizers gave the highest value of plant height, reaching 88.500 cm, compared with the control, which reached 71.500 cm.

Fruit weight (g)

The results in Table 4 showed that fertigation with Iron on the squash plant did not significantly increase fruit weight. On the other hand, Fruit weight increased significantly when the plant was sprayed with 2 g L^{-1} potassium fertilizer, reaching 100.588 g, compared with 82.375 g in the control. Whereas increasing boron concentration decreases fruit weight: at 2 mL L^{-1}, it reached 79.763 g compared with the control at 103.200 g.

Table 4. Effect of Boron, Potassium, Iron, and their interaction on fruit weight (g) of squash plant.

Means with the same letter for every component and interaction do not differ significantly at the 5% level

The highest fruit weight increased to 115.200 g when the fertigation plant at a concentration of 0 g L^{-1} Iron interacted with spraying 2 g L^{-1} potassium, respectively, compared with the least value, which reached 58.800 g for the plant treated with 2 g L^{-1} Iron interacted with spraying 0 g L^{-1} potassium. Additionally, the interactions between potassium and Boron, and between iron and boron, did not differ significantly from the control at any concentration, with values of 104.500 g and 143.675 g, respectively.

The triple interaction among iron, potassium and boron fertilizers factors indicated that the plants which fertigation with 0 g L^{-1} iron, and spraying 2 g L^{-1} potassium, 0 mL L^{-1} boron fertilizers gave the highest value of fruit weight reached 148.150 g, respectively, compared with least value which reached to 82.250 g for plant treated with 0 g L^{-1} iron interacted with 2 g L^{-1} and 2 mL L^{-1} boron.

Fruit diameter (cm)

The results in Table 5 showed that fertigation OF iron on the squash plant at 2 g L^{-1} caused a significant decrease in fruit diameter, which reached 3.550 cm when compared with the control. On the other hand, Fruit diameter increased significantly when the plant was sprayed with 2 g L^{-1} potassium fertilizer, reaching 3.850 cm, compared with 3.567 cm in the control. Whereas increasing boron concentration decreases fruit diameter: at 2 mL^{-1}, it reached 3.900 cm, compared with 32.517 cm in the control.

The highest fruit diameter increased to 3.933 cm when fertigation with 0 g L^{-1} iron was combined with spraying 2 g L^{-1} potassium, compared with the lowest value of 3.333 cm for the plant treated with 2 g L^{-1} iron combined with spraying 0 g L^{-1} potassium. Additionally, the interaction between potassium and Boron significantly increases fruit diameters to 3.933 cm for the plant treated with a concentration of 2 g L^{-1} potassium combined with 0 mL L^{-1} boron, compared with the lowest value, which reached 3.267 cm for the plant treated with a concentration of 0 g L^{-1} potassium combined with 2 mL L^{-1} boron.

The triple interaction among Iron, potassium and boron fertilizer factors indicated that the plants that were fertigated with 0 g L^{-1} Iron, and spraying 2 g L^{-1} potassium, 0 mL L^{-1} Boron fertilizers gave the highest value of fruit diameter reached 4.367 cm, respectively compared with least value which reached to 3.233 cm for plant treated with 2 g L^{-1} Iron interacted with 0 g L^{-1} and 2 mL L^{-1} boron.

Table 5. Effect of boron, potassium, and iron, and their interaction, on fruit diameter (cm) of squash plants.

Iron g L^{-1}	Potassium g L^{-1}	Boron mL L^{-1}		Iron * potassium	Iron
		0	2		
0	0	139.200 ab	72.700 cd	105.950 a	110.575 a
	2	148.150 a	82.250 c	115.200 a	
2	0	69.800 cd	47.800 d	58.800 b	72.388 a
	2	55.650 d	116.300 b	85.975 ab	
Iron * Boron	0	143.675 a	77.475 bc	potassium	
	2	62.725 c	82.050 b		
Potassium * Boron	0	104.500 a	60.250 b	82.375 b	
	2	101.900 a	99.275 a	100.588 a	
Boron		103.200 a	79.763 b		

Means with the same letter for every component and interaction do not differ significantly at the 5% level

Discussion

The application of potassium (K), boron (B), and iron (Fe) has a substantial impact on the growth, productivity, and fruit qualities of *Cucurbita pepo* L. squash, according to the study's findings. The complex physiological roles of these nutrients and their interactions that influence crop performance are reflected in the reported impacts. The number of fruits per plant, plant height, fruit length, fruit weight, and fruit diameter were all improved by potassium, which was the most consistent parameter among all those measured. Tables 1 and 3 show that the number of fruits and plant height were significantly higher at (2 g L^{-1}) potassium application, which may be explained by the fact that K is essential for enzyme activation, photosynthesis, and osmotic regulation (Hasanuzzman *et al.*, 2018). The translocation of photosynthates from leaves to reproductive organs is known to be promoted by potassium (Lester *et al.*, 2010), thereby enhancing fruit set and fruit development. Moreover, it helps maintain turgor pressure and stomatal conductance, thereby improving gas exchange and water-use efficiency, which are essential for vegetative growth and biomass accumulation (Wang *et al.*, 2013). The results are in line with those reported earlier, which showed that K fertilization increased the production of pistillate flowers and fruit production in cucurbit crops (de Souza *at al.*, 2023; Budak and Güneş, 2023), Interestingly, the results for Boron and Iron showed a different trend, where the control treatments often resulted in better outcomes in fruit length, weight, and diameter (Tables 2, 4 and 5), especially when compared with the (2 mL L^{-1} Boron) or (2 g L^{-1}) Iron fertigation. The concentrations used in this study suggest they may have been near or at the toxic limit for squash. Boron is needed for cell wall synthesis and reproductive development, with a narrow range between deficiency and toxicity (Rasheed, 2009). A decrease in fruit weight (Table 4) and fruit diameter (Table 5) was observed with Boron application, consistent with previous reports of B toxicity in squash, which causes yield loss due to physiological stress and metabolic dysfunction (South, 2021). In the same way, Fe is essential for chlorophyll biosynthesis and energy generation (Bacaicoa and García-Mina, 2009), and a high level of Fe may result in the production of Reactive Oxygen Species (ROS), which are responsible for oxidative damage to plant tissues and growth inhibition (Schmidt *et al.*, 2020). The fruits from the control plants had greater fruit length (Table 2) and diameter (Table 5), indicating that the Fe applied to the squash plants may have been a stress factor on the plants, or that the Fe application interacted with other plant essential nutrients in an antagonistic manner (Marschner, 2012). The interactions between the factors were found to be significant, especially that of Iron x Potassium. The interaction of 0 Iron 2 g L^{-1} Potassium invariably resulted in the highest fruit number, fruit length, fruit height, fruit weight, and fruit diameter. This indicates a potentiated effect of Potassium, suggesting that stress may have been induced by Iron at the concentration used, a phenomenon that occurs in the absence of iron. However, Potassium-Boron had a positive synergistic effect on the number of fruits and fruit length (Tables 1 and 2), with the highest value being obtained from 2 g L^{-1} potassium and 2 mL L^{-1} Boron. This suggests that Potassium can, at least partially, counteract the impact of Boron and/or that its two physiological functions, involved in sugar transport and reproductive development, are complementary. The fruit weight and diameter showed the highest values in the (2 g L^{-1} potassium and 0 mL L^{-1} Boron) interaction, indicating that K did not fully compensate for the negative effect of Boron on fruit size.

Conclusion

Finally, it can be said that the productivity and vegetative growth of squash are greatly enhanced by a potassium application rate of 2 g L^{-1}. However, some fruit traits appeared to be inhibited by the application of Boron and Iron at the test rates, most likely due to toxicity or nutrient imbalance. The study's findings emphasize the need for optimal nutrient management and further research to determine the appropriate Boron and Iron concentrations for squash, given the specific conditions of the Kurdistan region.

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