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Effect of Boron Source and Rate Addition on Potato Growth Performance and Tuber Quality

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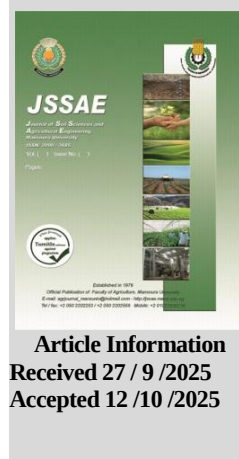
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ABSTRACT

Given the biological functions of boron, the narrow safety margin between its deficiency and toxicity, and the multiplicity of its available sources, there is a need to evaluate the most appropriate and safe forms and optimal boron concentrations for potato production. Therefore, this study was conducted via a split-plot design to investigate the effect of different boron sources (Dipotassium octaborate, boric acid, boron ethanolamine) as main factor and application rates (0, 50, 100, 150 mg B L⁻¹) as sub main factor on the growth and quality of potato plants under field conditions. The obtained results show clear differences between the studied sources and rates. For example, boron ethanolamine achieved the highest values of leaves fresh weight significantly surpassing the other sources, while boric acid recorded the highest values of plant height. Regarding tuber traits, boron ethanolamine markedly increased its content of N and Mg, while boric acid led to the highest P content in tuber. On the other hand, the dipotassium octaborate led to higher K and Ca accumulation compared to the other B sources. Concerning the studied rates, 50 and 100 mg B L⁻¹ generally improved N and P contents compared to the control, while 150 mg B L⁻¹ tended to level off or decrease these parameters. Additionally, boric acid improved carbohydrate content, while dipotassium octaborate increased starch content. Overall, the B source and its application rate affect nutrient composition and quality traits, thus the careful selection of B source at suitable rate can support sustainable potato production.

Keywords: Dipotassium-octaborate, boric-acid, boron-ethanolamine



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INTRODUCTION

Boron (B) is found in Group III of the periodic table and classified as a metalloid, and it exhibits intermediate characteristics between metals and nonmetals (Hosmane, 2011). In plant nutrition field, it is a micronutrient essential for the growth and development of higher plants (Nejad & Etesami, 2020).

It plays pivotal roles in cell wall formation, maintaining the integrity of cell membranes, transporting carbohydrates and sugars, reproductive processes, and regulating the activity of many enzymes. Adequate boron levels lead to normal root growth, pollen elongation, and seed and tuber formation. However, boron deficiency causes meristematic tissue deformities, resulting in reduced productivity (Vera-Maldonado *et al.* 2024).

The importance of this element increases for tuber crops such as potatoes, sugar beet, carrot and others, due to its direct connection with the process of forming ground stems and tubers, transporting starches, and developing healthy vascular tissues (Sarkar *et al.* 2018). Boron deficiency in these crops often leads to the phenomenon of hollow heart and thus a decrease in the marketable crop and its quality (Malek *et al.* 2021).

Furthermore, the gap between optimum boron concentrations and toxicity is relatively narrow. Even a slight excess of optimum concentrations can lead to boron toxicity, resulting in yellowing of leaf margins, tuber necrosis, and growth inhibition (Ayvaz *et al.* 2016). Therefore, boron fertilization management must be meticulous and precise. Boron sources and application rates must be understood to

maximize boron utilization and avoid toxicity (Shaker & Rasool, 2023).

Boron fertilizers are available commercially in both organic and inorganic forms (Degryse, 2017). Inorganic sources, such as boric acid and dipotassium octaborate, are widely used due to their high solubility and ease of application. Organic or chelated forms, such as boron ethanolamine, have been developed to improve foliar uptake, reduce losses, and thus increase the efficiency of boron under various environmental conditions (Mousavi *et al.* 2022).

Potato (*Solanum tuberosum* L.) is one of the world's most important strategic and food crops. Potato is characterized by their high productivity, short growth cycle, and high content of carbohydrates, vitamins, and nutrients (Ahmadu *et al.* 2021). However, it requires balanced nutrition. Boron is a nutrient that plays a pivotal role in maximizing their productivity, but improper management may result in toxicity to the plant (Ayvaz *et al.* 2016; Sarkar *et al.* 2018).

Therefore, the main objective of the current study was to evaluate different boron sources and select the most appropriate form, as well as to examine the effect of different application rates on potato performance and nutritional content under field conditions.

MATERIALS AND METHODS

A field trial was conducted during the growing season of 2023/24 in a private farm located at Al-Roba Village ,Temay El-Amdeed District, Dakahlia Governorate, Egypt (30° 57' 28.98" N Latitude and 31° 31' 44.1" E Longitude). Initial soil sample was taken from the surface layer at a depth

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of 0 -30 cm for analyzing some chemical properties, which were later, tabulated in Table 1.

Table1. Chemical properties of the initial soil

Soluble cations (meq/100g)				Soluble anions (meq/100g)				EC	pH
Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	HCO ₃ ⁻	CO ₃ ²⁻	*SO ₄ ²⁻	dSm ⁻¹	
1.25	2.91	2.26	.16	1.44	0.41	--	0.30	1.08	8.17
Available nutrients, mg kg ⁻¹									
Nitrogen			Phosphorus		Potassium		Boron		
NO ₃ ⁻		NH ₄ ⁺		6.62		515.29		56.43	
90.34		14.01							

Soluble calcium and magnesium were quantified in the soil extract through complexometric titration with EDTA, whereas soluble sodium and potassium concentrations were assessed using flame photometer apparatus. The concentration of soluble sulphate was estimated by difference between the total measured anions and cations (Jackson, 1967).

Carbonate and bicarbonate contents in the soil extract were determined by titration with a standardized hydrochloric acid solution, and chloride was measured by argentometric titration with silver nitrate. Soil salinity, expressed as electrical conductivity (EC), was determined in an extract (1:5, soil: water) employing an electrical conductivity meter, while the soil reaction (pH) was measured in a suspension (1:2.5, soil: water) using a calibrated pH meter (Jackson, 1967).

Available nitrogen was extracted using 2.0 M potassium chloride solution and determined by the micro-Kjeldahl apparatus as described by Hesse (1971). Available phosphorus was extracted with 0.5 N sodium bicarbonate solution at pH 8.5 and quantified colorimetrically using a spectrophotometer at 720 nm following Murphy and Riley (1962).

Available potassium was extracted using 1.0 N ammonium acetate solution at pH 7.0 and measured by flame photometry according to Knudsen *et al.* (1982). Available boron was determined after hot-water extraction and colorimetric analysis by the Azomethine-H method at 430 nm on a spectrophotometer following Wolf, (1971).

Three different sources were purchased from the Egyptian commercial market, including Dipotassium octaborate, boric acid, boron ethanolamine. Then the standard solutions were prepared via a known concentration by dissolving a known mass of the boron source in the solvent, then preparing the different concentrations (0, 50, 100, 150 mg L⁻¹) for each source used. Table 2 illustrates characteristics of the studied boron forms.

Table 2. Some characteristics of the studied boron forms

Source	Compound name	Chemical formula	Percentage for element, %
Dipotassium octaborate	Dipotassium octaborate tetrahydrate	K ₂ B ₈ O ₁₃ ·4H ₂ O	19.4 % B
Boric acid	Orthoboric acid	H ₃ BO ₃	18.0 % B
Boron ethanolamine	Liquid boron chelate	C ₂ H ₇ NO	15.0 % B

Potato tubers "Cv Cara" was used in the current investigation, as it was obtained from the Egyptian commercial market. It was imported from the Netherlands. Potato Cara category is one of the most cultivated by the farmers in Egypt and most consumed.

This research work was implemented via a split-plot design with three replicates. The boron sources (Dipotassium

octaborate, boric acid, boron ethanolamine) represented the main factor, while the rates of boron (0, 50, 100, 150 mg L⁻¹) were arranged in the sub plots. The experimental sub plot area was 16.8 m² (2.4 m x 7.0 m), which contained 3 ridges, where the width of the ridge was 0.8 with long of 7 m.

Three weeks before potato planting, the organic fertilizer (compost) was added at rate of 15 m³fed⁻¹ for all experimental plots before soil plowing immediately. Also, calcium superphosphate (6.6 % P) was added with compost addition at the same time at a rate of 6.6 kg P fed⁻¹. Additionally, potassium sulphate (39.8 % K) was added at a rate of 83 kg K fed⁻¹ in a single dose before planting during the soil preparation.

Tubers were divided into pieces two days before planting with an average weight of approximately 45g. The pieces of tubers were planted on 24 December 2023 in a wet soil.

Ammonium nitrate (33.5%N) was added in three equal doses at a rate of 150 kg N fed⁻¹; the first dose was added with planting, while the 2nd and 3rd doses were at 21 and 30 days from planting, respectively. Boron treatments were applied as a foliar spray twice, as the first application time was at 55 days from planting, while the 2nd application time was at 70 days after planting.

Additionally, all recommended agricultural practices, including irrigation process, control of fungal diseases, weeds and insects, were carried out according to the guidelines of the potato manual of MASR. Tubers harvest process was carried out on the 14th of May 2024.

Eighty five (85) days after planting, leaf fresh and dry weights (g plant⁻¹) as well as plant height (cm) were measured on three plants randomly selected from each treatment. A mixture of perchloric, and sulfuric acids (1:1) was used in the digestion of leaf samples (0.2 g) as described by Piper, (1950). Additionally, the leaf content of nutrient elements was determined after digesting the dry leaf samples as described by Walinga *et al.*, (2013). Nitrogen was determined via Kjeldahl method, while the phosphorus was calorimetrically estimated using spectrophotometer apparatus at wavelength 720 nm. Potassium was determined by flame photometer apparatus, while boron was determined by the azomethine- H method on a spectrophotometer at a wavelength of 430 nm. Calcium and magnesium were determined using atomic absorption spectrophotometer.

After harvest, other three plants were randomly selected from each treatment to measure the fresh and dry weights of tubers (g). The tuber content of nutrient elements (N, P, K, B, Ca and Mg) was determined as formerly mentioned in leaves. Tuber's quality parameters were estimated depending on the standard methods found in AOAC, (2000). The starch and carbohydrate were colorimetrically determined using a spectrophotometer at a wavelength of 620 nm for starch and 490 nm for carbohydrate. Additionally, total soluble solids (TSS) were measured via a hand refractometer.

All collected data were subjected to analysis of variance (ANOVA) following as outlined by Gomez and Gomez (1984), using the CoStat statistical software package. Mean separation was carried out employing the least significant difference (LSD) test at the 5% probability level according to the procedure described by Snedecor and Cochran (1989). Photo1 shows the photographic documentation of the experimental field.



Photo1. Photographic documentation of the experimental field

RESULTS AND DISCUSSIONS

1. Growth Criteria at a Period of 85 Days after Planting

Table 3 presents the individual effects of spraying potato plants with different boron sources at various rates on vegetative growth criteria [including leaves fresh weight and

dry weight (g plant^{-1}) and plant height (cm) at a period of 85 days after planting, while Table 4 shows the interaction effect among boron sources and application rates on the same vegetative growth traits at the same growth stage.

Boron ethanolamine recorded the highest leaves fresh weight ($56.95 \text{ g plant}^{-1}$), significantly surpassing the other sources, while differences among sources in leaves dry weight were statistically non-significant. For plant height, boric acid gave the highest values of plant height (66.85 cm), outperforming dipotassium octaborate. Regarding boron rates, spraying with $50, 100$ and 150 mg L^{-1} significantly increased both leaves fresh and dry weights compared with the control and the intermediate rate of 100 mg L^{-1} . Plant height did not show clear statistical differences among rates, although a slight increase was observed at 100 mg L^{-1} .

Table 3. Individual effect of spraying with different boron sources at various rates on the vegetative growth criteria of potato at a period of 85 days after planting

Parameter Treatment	Leaves fresh weight, g plant ⁻¹	Leaves dry weight, g plant ⁻¹
Individual effect of boron source		
Dipotassium octaborate	49.72 b	11.45 a
Boric acid	51.20 b	10.90 a
Boron ethanolamine	56.95 a	11.97 a
Individual effect of boron rate		
L ₁ : (0.0 mg B L ⁻¹), tap water as control	33.76 c	6.94 c
L ₂ : (50 mg B L ⁻¹)	63.11 a	14.60 a
L ₃ : (100 mg B L ⁻¹)	51.44 b	10.81 b
L ₄ : (150 mg B L ⁻¹)	62.18 a	13.41 a
Parameter Treatment	Plant height, cm	
Individual effect of boron source		
Dipotassium octaborate	56.49 b	
Boric acid	66.85 a	
Boron ethanolamine	61.18 ab	
Individual effect of boron rate		
L ₁ : (0.0 mg B L ⁻¹), tap water as control	58.03 a	
L ₂ : (50 mg B L ⁻¹)	62.51 a	
L ₃ : (100 mg B L ⁻¹)	64.40 a	
L ₄ : (150 mg B L ⁻¹)	61.09 a	

Table 4. Interaction effect of spraying with different boron sources at various rates on the vegetative growth criteria of potato at a period of 85 days after planting

	Leaves fresh weight, g plant^{-1}				Leaves dry weight, g plant^{-1}			
	L ₁	L ₂	L ₃	L ₄	L ₁	L ₂	L ₃	L ₄
Dipotassium octaborate	33.7 d	55.6c	41.2 d	68.2 ab	6.9 d	16.7 a	9.3 cd	14.8ab
Boric acid	33.7 d	75.6a	39.9d	55.4 c	6.9 d	16.0 a	8.0 cd	12.5 bc
Boron ethanolamine	33.7 d	58.0c	73.0 a	62.9bc	6.9d	10.9bc	14.9 ab	12.9 bc
	Plant height, cm							
	L ₁	L ₂	L ₃	L ₄				
Dipotassium octaborate	58.0 ab	58.3 ab	56.1 ab	53.5 b				
Boric acid	58.0 ab	69.5 ab	74.8 a	65.0 ab				
Boron ethanolamine	58.0 ab	59.7ab	62.2 ab	64.7 ab				

Table 4 reveals that the highest leaves fresh and dry weights were obtained with some specific source and rate combinations. For instance, boric acid at a rate of 50 mg L^{-1} achieved 75.6 g fresh weight and 16.0 g dry weight per plant, and dipotassium octaborate at a rate of 150 mg L^{-1} also produced high values. Conversely, all control treatments (0 mg L^{-1}) exhibited the lowest values across all parameters. For plant height, boric acid at a rate of 100 mg L^{-1} produced the tallest plants (74.8 cm).

The superior performance of boron ethanolamine in leaves fresh weight may be attributed to its organic and

complex nature, which enhances foliar absorption and translocation compared with inorganic sources. This improves carbohydrate transport and cell membrane stability, resulting in greater vegetative biomass.

The most effective response at a rate of 50 and 150 mg L^{-1} compared with 100 mg L^{-1} may reflect the narrow threshold between boron sufficiency and toxicity in potato plants. Some intermediate levels may not fully meet plant demand or may interact unfavorably with other nutrients, whereas low and high rates within a safe margin may activate different physiological pathways, leading to improved growth.

The increase in plant height observed with boric acid might be related to its relatively high solubility and rapid movement in the xylem, which stimulates cell division and elongation in meristematic tissues. The obtained results are in harmony with those of Sarkar et al. (2018); Malek et al. (2021).

2. Leaf Chemical Constituents at a Period of 85 Days after Planting

Table 5 illustrates the individual effects of foliar spraying with different boron sources and rates on the leaf chemical composition of potato plants at 85 days after planting. It reports the concentrations of nitrogen, phosphorus, potassium, calcium, magnesium (as % of dry matter), and boron (as mg kg⁻¹), while Table 6 details the interaction effects between boron sources and application rates on the same chemical parameters at the same growth stage.

From Table 5, boron ethanolamine produced the highest nitrogen content (3.27%) compared to the other sources, whereas boric acid achieved the highest phosphorus (0.19%) and potassium (5.84%) levels. Dipotassium octaborate recorded the highest magnesium percentage (1.83%) but a lower boron concentration in leaves compared with boron ethanolamine. Regarding boron rates, all sprayed treatments (50, 100, and 150 mg L⁻¹) significantly increased nitrogen, phosphorus, potassium, and calcium contents relative to the control. The highest boron content in leaves, however, was observed in the control plants (55.66 mg kg⁻¹), while magnesium decreased with increasing boron rates.

Table 6 confirms these trends at the interaction level. The highest nitrogen (3.74%) was recorded with boron ethanolamine at a rate of 100 mg L⁻¹, and the highest phosphorus (0.27%) with boric acid at the same rate. Potassium and calcium peaked under boric acid at a rate of 150 mg L⁻¹ (7.14% K and 2.27% Ca). Conversely, magnesium contents tended to decrease under high boron rates across all sources, with the highest values remaining in the control. Boron content in leaves was generally highest in

the control (55.66 mg kg⁻¹) and decreased with increasing boron application, except for a moderate recovery with boron ethanolamine at a rate of 150 mg L⁻¹ (53.24 mg kg⁻¹).

Table 5. Individual effect of spraying with different boron sources at various rates on the leaf chemical content of potato at a period of 85 days after planting

Parameter Treatment	Nitrogen, %	Phosphorus, %
Individual effect of boron source		
Dipotassium octaborate	2.94 b	0.17 a
Boric acid	3.07 ab	0.19 a
Boron ethanolamine	3.27 a	0.09 b
Individual effect of boron rate		
L1: (0.0 mg B L ⁻¹), tap water as control	2.65 b	0.09 b
L2: (50 mg B L ⁻¹)	3.29 a	0.18 a
L3: (100 mg B L ⁻¹)	3.31 a	0.18 a
L4: (150 mg B L ⁻¹)	3.11 a	0.17 a
Parameter Treatment	Potassium, %	Calcium , %
Individual effect of boron source		
Dipotassium octaborate	4.76 b	1.80 a
Boric acid	5.84 a	1.55 a
Boron ethanolamine	5.18 ab	1.01 b
Individual effect of boron rate		
L1: (0.0 mg B L ⁻¹), tap water as control	4.43 b	1.18 b
L2: (50 mg B L ⁻¹)	5.24 ab	1.81 a
L3: (100 mg B L ⁻¹)	5.41 ab	1.51 ab
L4: (150 mg B L ⁻¹)	5.93 a	1.31 b
Parameter Treatment	Magnesium %	Boron , mg kg ⁻¹
Individual effect of boron source		
Dipotassium octaborate	1.83 a	49.00 b
Boric acid	1.32 b	50.42 ab
Boron ethanolamine	1.10 b	51.83 a
Individual effect of boron rate		
L1: (0.0 mg B L ⁻¹), tap water as control	2.21 a	55.66 a
L2: (50 mg B L ⁻¹)	1.07 b	50.36 b
L3: (100 mg B L ⁻¹)	1.32 b	47.67 c
L4: (150 mg B L ⁻¹)	1.07 b	47.97 bc

Table 6. Interaction effect of spraying with different boron sources at various rates on the leaf chemical content of potato at a period of 85 days after planting

	Nitrogen, %				Phosphorus, %			
	L1	L2	L3	L4	L1	L2	L3	L4
Dipotassium octaborate	2.65 d	3.25abcd	2.86 cd	2.99 bcd	0.09cd	0.22 ab	0.17 bc	0.21 ab
Boric acid	2.65 d	3.16abcd	3.3abc	3.13 bcd	0.09cd	0.21 ab	0.27 a	0.21 ab
Boron ethanolamine	2.65 d	3.47 ab	3.74 a	3.21abcd	0.09 cd	0.10 cd	0.10 cd	0.08 d
	Potassium, %				Calcium, %			
	L1	L2	L3	L4	L1	L2	L3	L4
Dipotassium octaborate	4.43 b	4.41 b	5.03 ab	5.15 ab	1.18 bcd	2.19 a	2.03 a	1.81 ab
Boric acid	4.43 b	5.14 ab	6.63 ab	7.14 a	1.18 bcd	2.27 a	1.66 abc	1.09 cd
Boron ethanolamine	4.43 b	6.18 ab	4.58 b	5.51 ab	1.18 bcd	0.97 d	0.85 d	1.03cd
	Magnesium, %				Boron , mgkg ⁻¹			
	L1	L2	L3	L4	L1	L2	L3	L4
Dipotassium octaborate	2.21 a	1.16 cd	2.07 a	1.87 ab	55.66 a	54.93 a	44.59 de	40.81 e
Boric acid	2.21 a	1.32 bc	1.20 cd	0.57 d	55.66 a	46.88 cd	49.27 bcd	49.85 bc
Boron ethanolamine	2.21 a	0.73 cd	0.69 cd	0.77 cd	55.66 a	49.3 bcd	49.14 bcd	53.24 ab

The increase in nitrogen, phosphorus, potassium, and calcium contents under boron spraying likely reflects boron's role in maintaining cell wall integrity, enhancing membrane permeability, and facilitating nutrient uptake and translocation. Foliar-applied boron can stimulate root activity and improve the transport of other nutrients, thus elevating their concentrations in leaves.

The particularly high nitrogen content under boron ethanolamine may be due to its higher foliar absorption efficiency and highest translocation compared to inorganic

sources. Similarly, boric acid's high solubility and rapid movement in the xylem could explain its strong effect on potassium and calcium accumulation.

The reduction in magnesium percentage at higher boron rates suggests a competitive or antagonistic effect between boron and magnesium uptake or translocation. Excess boron may also alter membrane selectivity, reducing Mg²⁺ transport to leaves.

Interestingly, the highest boron concentrations in leaves were found in the untreated plants, which could reflect

a dilution effect in the sprayed plants due to greater biomass production, or possible re-distribution of boron within the plant tissues after foliar application. The results are in accordance with those of Gupta *et al.* (1985); Yau & Ryan, (2008); Ayvaz *et al.* (2016); Shaker & Rasool, (2023).

4. Weights of Tubers at Harvest Stage as a Yield Indicator

Table 7 shows the individual effects of foliar applications of different boron sources and rates on tuber weight of potato plants at harvest. Among the three boron sources, dipotassium octaborate recorded the highest fresh and dry tuber weights (430.52 and 82.72 g plant⁻¹, respectively), followed by boron ethanolamine, whereas boric acid gave the lowest values. Regarding the boron rates, increasing the application from a rate of 0 to 100 mg L⁻¹ markedly enhanced both fresh and dry tuber weights, with the maximum at 100 mg L⁻¹ (525.43 and 96.62 g plant⁻¹). A further increase to 150 mg L⁻¹ caused a slight decline but remained above the control. Additionally, Table 8 presents the interaction effects between boron source and rate. The most pronounced increase in tuber yield occurred when

dipotassium octaborate at 100 mg L⁻¹ was applied, producing 624.86 g plant⁻¹ fresh weight and 111.42 g plant⁻¹ dry weight, significantly higher than all other combinations. The control treatment (tap water) consistently showed the lowest yield (250.57 and 51.81 g plant⁻¹).

Table 7. Individual effect of spraying with different boron sources at various rates on the weights of tubers at a harvest stage

Parameter Treatment	Total potato weight (fresh, g plant ⁻¹)	Total potato weight (dry, g plant ⁻¹)
Individual effect of boron source		
Dipotassium octaborate	430.52 a	82.72 a
Boric acid	355.44 c	69.23 b
Boron ethanolamine	391.64 b	74.54 b
Individual effect of boron rate		
L ₁ : (0.0 mg B L ⁻¹), tap water as control	250.57 d	51.81 d
L ₂ : (50 mg B L ⁻¹)	360.31 c	65.34 c
L ₃ : (100 mg B L ⁻¹)	525.43 a	96.62 a
L ₄ : (150 mg B L ⁻¹)	433.83 b	88.21 b

Table 8. Interaction effect of spraying with different boron sources at various rates on the weights of tubers at a harvest stage

	Total potato weight(fresh, g plant ⁻¹)				Total potato weight(dry, g plant ⁻¹)			
	L ₁	L ₂	L ₃	L ₄	L ₁	L ₂	L ₃	L ₄
Dipotassium octaborate	250.57 e	356.99 d	624.86 a	489.65 b	51.81 f	67.92 de	111.42 a	99.71 ab
Boric acid	250.57 e	373.68 d	422.52 c	374.99 d	51.81 f	68.57 de	79.19 cd	77.34 cd
Boron ethanolamine	250.57 e	350.24 d	528.91 b	436.85 c	51.81 f	59.53 ef	99.25 ab	87.58 bc

Overall, the data indicate that boron supplementation substantially improved tuber formation and bulking, and the response depended on both source and rate. Dipotassium octaborate was clearly the most efficient source under the present conditions. The positive response plateaued or slightly decreased at the highest rate (150 mg L⁻¹), suggesting that excess boron may begin to approach a threshold of toxicity or imbalance.

As mentioned above, boron plays a pivotal role in cell wall stability, carbohydrate translocation, and the differentiation of meristematic tissues. In tuberous crops, adequate boron enhances phloem loading and sugar transport to developing stolons and tubers, resulting in heavier and more numerous tubers. Dipotassium octaborate is a highly soluble borate salt providing readily available boron plus potassium, which may synergistically stimulate both tuber initiation and bulking. Ethanolamine boron contains chelated boron that can improve uptake but releases boron more slowly; boric acid, although common, may be less efficient under the soil and environmental conditions of the study. The slight decrease at a rate of 150 mg L⁻¹ aligns with reports that excessive boron impairs root growth, disrupts membrane integrity, and reduces photosynthetic efficiency. The obtained results are in agreement with those of Degryse, (2017); Mousavi *et al.* (2022).

5. Chemical and Biochemical Traits of Tubers at Harvest Stage

Table 9 displays the individual effects of boron source and rate on the concentrations of N, P, K, Ca, Mg, and B in potato tubers. Boron ethanolamine produced the highest tuber N (1.23 %) and B (57.49 mg kg⁻¹), while dipotassium octaborate gave the highest K (2.45 %) and Ca (0.24 %). Boric acid generally ranked intermediate except for P, which peaked (0.21 %). On the other hand, compared with the control, all boron treatments raised N and P markedly, with maximum values at a rate of 50 and 100 mg L⁻¹. Potassium rose at all rates but peaked at a rate of 50 and 100 mg L⁻¹; Ca rose sharply at 150 mg L⁻¹. Magnesium percentages stayed statistically similar, while B concentrations reflected both source and rate, highest in ethanolamine and at a rate of 0 or 150 mg L⁻¹.

Table 9. Individual effect of spraying with different boron sources at various rates on the chemical traits of tubers at a harvest stage

Parameter Treatment	Nitrogen, %	Phosphorus, %
Individual effect of boron source		
Dipotassium octaborate	1.09 ab	0.20 ab
Boric acid	0.94 b	0.21 a
Boron ethanolamine	1.23 a	0.17 b
Individual effect of boron rate		
L ₁ : (0.0 mg B L ⁻¹), tap water as control	0.85 b	0.12 c
L ₂ : (50 mg B L ⁻¹)	1.28 a	0.24 a
L ₃ : (100 mg B L ⁻¹)	1.21 a	0.24 a
L ₄ : (150 mg B L ⁻¹)	1.00 ab	0.18 b
Parameter Treatment	Potassium, %	Calcium, %
Individual effect of boron source		
Dipotassium octaborate	2.45 a	0.24 a
Boric acid	2.38 a	0.16 b
Boron ethanolamine	2.35 a	0.13 b
Individual effect of boron rate		
L ₁ : (0.0 mg B L ⁻¹), tap water as control	2.09 b	0.15 b
L ₂ : (50 mg B L ⁻¹)	2.63 a	0.13 b
L ₃ : (100 mg B L ⁻¹)	2.48 a	0.16 b
L ₄ : (150 mg B L ⁻¹)	2.37 ab	0.25 a
Parameter Treatment	Magnesium, %	Boron, mg kg ⁻¹
Individual effect of boron source		
Dipotassium octaborate	0.13 a	45.91 c
Boric acid	0.12 a	51.77 b
Boron ethanolamine	0.21 a	57.49 a
Individual effect of boron rate		
L ₁ : (0.0 mg B L ⁻¹), tap water as control	0.13 a	55.66 a
L ₂ : (50 mg B L ⁻¹)	0.11 a	47.04 b
L ₃ : (100 mg B L ⁻¹)	0.20 a	49.83 b
L ₄ : (150 mg B L ⁻¹)	0.17 a	54.36 a

Table 10 presents the interaction between source and rate. The most favorable combination for N and P was boron ethanolamine at a rate of 50 and 100 mg L⁻¹, whereas for K and Ca it was dipotassium octaborate at a rate of 50 and 100 mg L⁻¹. Tuber B concentration peaked under boron ethanolamine at a rate of 150 mg L⁻¹ (64.37 mg kg⁻¹).

Table 11 details the individual effects on carbohydrate, starch, and humidity. Boric acid recorded the

highest carbohydrate content (12.46 %) with moderate starch (16.75 %), whereas dipotassium octaborate had the highest starch (17.87 %). Boron ethanolamine had the lowest carbohydrate (9.0 %) and starch (12.76 %). Carbohydrate percentages remained broadly similar across rates (10–11.5 %), while starch tended to be highest in the control and slightly decreased with boron. Humidity increased

significantly at a rate of 50 and 100 mg L⁻¹ and dropped back at a rate of 150 mg L⁻¹.

Table 12 shows interactions. Boric acid at a rate of 50–150 mg L⁻¹ raised carbohydrate content, whereas dipotassium octaborate maintained high starch across all rates. The highest moisture was achieved by boron ethanolamine at 50 mg L⁻¹ (83.0 %).

Table 10. Interaction effect of spraying with different boron sources at various rates on the chemical traits of tubers at a harvest stage

	Nitrogen, %				Phosphorus, %			
	L ₁	L ₂	L ₃	L ₄	L ₁	L ₂	L ₃	L ₄
Dipotassium octaborate	0.85 c	1.39 abc	1.04 bc	1.06 abc	0.12 b	0.23 a	0.24 a	0.21 a
Boric acid	0.85 c	0.96 bc	0.99 bc	0.96 bc	0.12 b	0.23 a	0.27 a	0.24 a
Boron ethanolamine	0.85 c	1.49 ab	1.59 a	0.96 bc	0.12 b	0.27 a	0.20 a	0.11 b
	Potassium, %				Calcium, %			
	L ₁	L ₂	L ₃	L ₄	L ₁	L ₂	L ₃	L ₄
Dipotassium octaborate	2.09 b	2.82 a	2.54 ab	2.35 ab	0.15 b	0.16 b	0.22 b	0.42 a
Boric acid	2.09 b	2.43 ab	2.55 ab	2.45 ab	0.15 b	0.12 b	0.17 b	0.20 b
Boron ethanolamine	2.09 b	2.65 ab	2.35 ab	2.30 ab	0.15 b	0.12 b	0.10 b	0.13 b
	Magnesium, %				Boron, mg kg ⁻¹			
	L ₁	L ₂	L ₃	L ₄	L ₁	L ₂	L ₃	L ₄
Dipotassium octaborate	0.13 b	0.14 b	0.10 b	0.16 b	55.66 b	39.46 f	42.84 ef	45.67 de
Boric acid	0.13 b	0.13 b	0.12 b	0.10 b	55.66 b	48.69 cd	49.71 cd	53.04 bc
Boron ethanolamine	0.13 b	0.06 b	0.39 a	0.25 ab	55.66 b	52.98 bc	56.95 b	64.37 a

Table 11. Individual effect of spraying with different boron sources at various rates on the biochemical traits of tubers at a harvest stage

Parameter Treatment	Carbohydrate, %	Starch, %
Individual effect of boron source		
Dipotassium octaborate	10.18 ab	17.87 a
Boric acid	12.46 a	16.75 ab
Boron ethanolamine	9.00 b	12.76 b
Individual effect of boron rate		
L ₁ : (0.0 mg B L ⁻¹), tap water as control	9.90 a	18.39 a
L ₂ : (50 mg B L ⁻¹)	10.78 a	15.61 a
L ₃ : (100 mg B L ⁻¹)	9.98 a	15.16 a
L ₄ : (150 mg B L ⁻¹)	11.52 a	14.01 a
Parameter Treatment	Humidity, %	
Individual effect of boron source		
Dipotassium octaborate	80.53 a	
Boric acid	80.41 a	
Boron ethanolamine	80.85 a	
Individual effect of boron rate as sub main factor		
L ₁ : (0.0 mg B L ⁻¹), tap water as control	79.33 b	
L ₂ : (50 mg B L ⁻¹)	81.86 a	
L ₃ : (100 mg B L ⁻¹)	81.54 a	
L ₄ : (150 mg B L ⁻¹)	79.65 b	

Table 12. Interaction effect of spraying with different boron sources at various rates on the biochemical traits of tubers at a harvest stage

	Carbohydrate, %				Starch, %			
	L ₁	L ₂	L ₃	L ₄	L ₁	L ₂	L ₃	L ₄
Dipotassium octaborate	9.90 abc	11.66 abc	8.92 abc	10.23 abc	18.39 a	17.87 a	16.29 a	18.93 a
Boric acid	9.90 abc	13.56 a	12.88 ab	13.51 ab	18.39 a	17.70 a	17.56 a	13.36 a
Boron ethanolamine	9.90 abc	7.13 c	8.14 bc	10.84 abc	18.39 a	11.27 a	11.62 a	9.75 a
	Humidity, %							
	L ₁	L ₂	L ₃	L ₄				
Dipotassium octaborate	79.33 c	80.97 abc	82.19 ab	79.65 c				
Boric acid	79.33 c	81.61 abc	81.31 abc	79.37 c				
Boron ethanolamine	79.33 c	83.00 a	81.12 abc	79.95 bc				

Overall, it can be concluded that adequate boron enhances N and P assimilation and affects K and Ca partitioning, reflecting improved phloem transport and cell-wall deposition. Source-specific responses matter. Dipotassium octaborate favored K and Ca enrichment, likely due to its co-supplied K whereas boron ethanolamine enhanced boron accumulation due to chelation and highest translocation.

Biochemical traits respond differently, while carbohydrate and starch contents remained relatively stable, slight shifts suggest that boron influences carbohydrate

allocation and water status of tubers, potentially affecting quality and storability. In potato tubers, high boron availability supports sucrose unloading and starch biosynthesis in amyloplasts, but excessive boron can inhibit enzymatic activity or disrupt Ca homeostasis, explaining the slight decline at a rate of 150 mg L⁻¹.

Dipotassium octaborate supplies soluble K plus boron, promoting both K accumulation and Ca uptake via improved cation exchange; boron ethanolamine, a chelated form, enhances boron absorption and internal transport,

reflected in highest B values. Variations in moisture percentage at harvest may be linked to boron's effect on cell wall porosity and osmotic regulation, which influences water retention. The results are in accordance with those of Yongzhong *et al.* (1999); Smith & McBroom, (2000).

CONCLUSION

The obtained results confirm that the foliar application of boron significantly improved the nutritional and biochemical characteristics of potato tubers, but the magnitude of response varied with the source and rate of application. Boron ethanolamine was most effective in enhancing nitrogen, magnesium, and boron accumulation, whereas boric acid and dipotassium octaborate were more associated with improved phosphorus, starch, potassium, and calcium contents. Moderate rates of 50–100 mg B L⁻¹ were generally superior to the highest rate (150 mg B L⁻¹), indicating a narrow threshold between sufficiency and potential excess. These results suggest that careful selection of boron source and application rate can optimize tuber quality and nutrient content, thereby supporting sustainable potato production.

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تأثير مصدر ومعدل إضافة البورون على أداء نمو البطاطس وجودة الدرنات

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الملخص

نظرًا للوظائف البيولوجية للبورون، و الحد الضيق بين نقصه وسميته، وتعدد مصادره المتاحة، تبرز الحاجة إلى تقييم أكثر الصور ملائمة وأمانًا والتركيزات المثلى للبورون في إنتاجية البطاطس. لذلك، نُفذت هذه الدراسة باستخدام تصميم القطع المنشقة لدراسة تأثير مصادر مختلفة من البورون (ثنائي بوتاسيوم أوكتابورات، وحمض البوريك، وإيثانولامين البورون) كمعامل رئيسي، ومعدلات الإضافة (٥٠، ١٠٠، ١٥٠ ملجم بورون/لتر) كمعامل منشق، على نمو وجودة نباتات البطاطس تحت الظروف الحقلية. أظهرت النتائج المتحصل عليها وجود فروق واضحة بين المصادر والمعدلات المستخدمة في الدراسة. فعلى سبيل المثال، حقق إيثانولامين البورون أعلى القيم للوزن الطازج للأوراق متفوقًا معنويًا على المصادر الأخرى، في حين سجل حمض البوريك أعلى القيم لطول النبات. وبالنسبة لصفات الدرنات، زاد إيثانولامين البورون بشكل ملحوظ محتواها من النيتروجين والمغنيسيوم، في حين أدى حمض البوريك إلى أعلى محتوى من الفوسفور في الدرنات. من ناحية أخرى، أدى ثنائي بوتاسيوم أوكتابورات إلى تراكم أعلى للبوتاسيوم والكالسيوم مقارنة بمصادر البورون الأخرى. وبالنسبة للمعدلات المستخدمة في الدراسة، حسن معدل ٥٠ و ١٠٠ ملجم بورون/لتر عمومًا محتوى النيتروجين والفوسفور مقارنةً بالكمترول، في حين أن المعدل ١٥٠ ملجم بورون/لتر اتجه إلى التثبيت أو الانخفاض في هذه المؤشرات. بالإضافة إلى ذلك، حسن حمض البوريك محتوى الكربوهيدرات، بينما زاد ثنائي بوتاسيوم أوكتابورات محتوى النشا. وبشكل عام، فإن مصدر البورون ومعدل تطبيقه يؤثران على تركيب العناصر الغذائية والصفات النوعية، وبالتالي فإن الاختيار الدقيق لمصدر البورون بالمعدل المناسب يمكن أن يدعم الإنتاج المستدام لمحصول البطاطس.