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RESEARCH ARTICLE

Synergistic Role of Calcium and Cobalt in Enhancing Sugar Beet Yields under Water Deficit Conditions

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Abstract

Two field experiments were conducted during the 2021-2022 and 2022-2023 seasons at Mallawi Research Station, Minya, Egypt, to evaluate the effect of foliar applications of calcium chloride and cobalt chloride on sugar beet yields under different irrigation regimes. A split-plot design with three replicates was used, where irrigation regimes (full irrigation, one omitted irrigation, and two omitted irrigations) were assigned to the main plots, while subplots were foliarly applied with calcium chloride 0,0 4,0, and 8.0 kg/fed. (1.0 fed. = 4200 m^2) and cobalt chloride (0, 10, 20, and 30 ppm). Growth and yield components, including root length, diameter, weight, root-to-shoot ratio, and root and sugar yields, were evaluated.

Results showed that moderate water stress (after a single irrigation) with calcium and cobalt supplementation significantly improved root growth and sugar yield compared to full irrigation alone. Calcium chloride improved root elongation, root thickness, and root-to-shoot ratio, with the highest results recorded at 8.0 kg/fed. Cobalt chloride at 20 ppm improved root weight and sugar yield, while higher concentrations reduced performance. The best combination was moderate irrigation with 8.0 kg of calcium chloride and 20 ppm cobalt, which improved sugar yield (6.70 ton/fed.) and root performance. Severe stress significantly reduced yield, even with nutrient supplements.

Overall, the results highlight that the integrated application of calcium and cobalt under moderate water stress can enhance sugar beet productivity while reducing irrigation requirements, providing a practical strategy for water-efficient agriculture in arid regions.

Keywords: Sugar beet; Irrigation regimes; Calcium; Cobalt; Drought stress; Micronutrient interaction.

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Introduction

Sugar beet (*Beta vulgaris* L.) is a relatively recent crop in Egypt, introduced in the mid-1990s as a strategic source of sugar. Its cultivated area has expanded rapidly, now exceeding 700,000 feddans (**USDA, 2024**). According to the annual report on sugar crops and sugar production in Egypt; about 65% of the total area is concentrated in fertile old lands under flood irrigation. El-Minya Governorate in 2024 cultivated approximately 36,000 feddans in old lands, yielding about 28 tons per feddan on average., Sugar beet cultivation under flood irrigation faces serious challenges, particularly inefficient water management, increased susceptibility to root rot, and high production costs due to reliance on water-lifting machines. Optimizing irrigation practices is therefore crucial for sustaining yield and economic viability.

Nutrient management plays a pivotal role in improving crop performance under water-limited conditions. Calcium is a vital macronutrient involved in plant structural integrity, enzyme activation, and photosynthesis. It strengthens cell walls, supports root development, and reduces the toxic effects of elements like sodium and heavy metals (**White and Broadley, 2003, Hepler, 2005,** and **Marschner, 2012**).

Calcium chloride ($CaCl_2$) functions as a potent bio stimulant, enhancing plant health and resilience by acting on key physiological processes. It significantly boosts photosynthetic capacity by increasing chlorophyll content and improving gas exchange parameters like stomatal conductance, transpiration rate, and net photosynthetic rate. Concurrently, $CaCl_2$ strengthens the plant's antioxidant defense system, inducing protective enzyme activities that reduce reactive oxygen species (ROS) and minimize oxidative damage to cell membranes. This dual action of promoting energy production while mitigating cellular stress supports overall growth, improves metabolic health by accumulating osmolytes like proline and sugars, and enhances the plant's ability to withstand environmental challenges (**Xu *et al*., 2013**, **Zhang *et al*., 2019,** and **Li *et al*., 2022)**.

Cobalt, though present in small amounts, is increasingly recognized as a beneficial micronutrient, especially under stress conditions. It enhances plant growth by supporting enzyme activity, reducing salinity damage, and preserving growth hormones such as auxin. While cobalt is essential for nitrogen fixation in legumes, recent studies also highlight its broader role in improving yield and quality in other crops (**Rady, 2011, Souri & Hatamian, 2019, Zhang *et al*. 2021, and Elshamly & Nassar, 2023**).

Given the dual challenges of water scarcity and the need for improved crop productivity, this study aimed to develop a practical strategy for rationalizing water use in sugar beet cultivation under flood irrigation in old lands, without reducing crop productivity. The proposed approach involved applying selected compounds known to enhance plant physiological traits, thereby improving the crop's tolerance to water stress while sustaining yield levels.

Materials and Methods

Experimental Site and Preparation

Two field experiments were conducted at the Mallawi Research Station, located in El-Minia Governorate, Egypt, during the 2021/2022 and 2022/2023 growing seasons. The study aimed to investigate the influence of foliar-applied by calcium chloride and cobalt chloride on selected yield-related traits of sugar beet (Sahar var.) under varying irrigation regimes. The experimental soil was classified as silty clay loam (Table 1), and standard field preparation procedures were followed, including plowing, broadcasting 100 kg of granulated superphosphate (15.5% P2O5), leveling, and planning at 60 cm between rows.

Experimental Layout and Design

The experimental field was divided into 12 large strips, each containing nine experimental plots. Each experimental plot was 18.0 m2 (5.0 rows 6.0 m long). Every four adjacent strips represented an independent irrigation regime. To prevent water transfer between regimes, each regime was surrounded by a 1.2 m border. Two irrigation ditches were constructed within each irrigation regime to facilitate equal water distribution. Sowing was carried out in early November in both seasons.

Table 1: Some physical and chemical properties of the soil at depths of 0-30 cm during 2021/ 2022 and 2022\ 2023 seasons.

Parameter	2021/2022	2022/2023
Sand %	8.47	10.11
Silt %	36.82	40.57
Clay %	54.71	49.32
Organic Matter %	1.52	1.59
pH	7.93	7.81
Ec ($ds.m^{-1}$)	1.60	1.72

The experiment was conducted using a randomized complete block design (RCBD) with a split-plot arrangement and three replications. The main plots were assigned to three irrigation regimes: full irrigation (I_1, 8 irrigations), one irrigation omitted (I_2, 7 irrigations), and two irrigations omitted (I_3, 6 irrigations). Within each main plot, the sub-plots received combinations of foliar applications of calcium chloride at three levels (Ca_1: 0.0 kg/fed., Ca_2: 4.0 kg/fed., and Ca_3: 8.0 kg/fed.) and cobalt chloride at four levels (Co_1: 0.0 ppm/fed., Co_2: 10.0 ppm/fed., Co_3: 20.0 ppm/fed., and Co_4: 30.0 ppm/fed.), which were randomly distributed. This arrangement resulted in a total of 36 treatment combinations, replicated three times, giving a total of 108 experimental plots. The irrigation regimes were tested using the main plot error term, while the effects of calcium chloride, cobalt chloride, and their interactions were evaluated using the sub-plot error term.

Table 2: Climatic conditions of the experimental site in the two growing seasons.

Month	2020/2021			2021/2022		
	Maximum temperature	Minimum temperature	Relative humidity	Maximum temperature	Minimum temperature	Relative humidity
Nov	25.3	13.5	19.0	27.6	12.5	66.0
Dec	24.0	8.8	25.5	21.0	10.0	75.1
Jan	21.1	5.4	51.8	15.8	2.4	77.5
Feb	23.1	5.6	75.7	19.3	4.0	77.0
Mar	23.1	8.9	50.6	24.5	7.3	51.5
Apr	31.3	11.3	59.9	32.0	15.0	60.0
May	38.2	18.1	46.0	37.5	19.0	37.5
Jun	34.6	21.2	50.5	38.0	37.0	48.5

Note: Weather data collected from the meteorological station at Mallawi Research Station, El-Minya Governorate, Egypt

Crop Management and Irrigation Scheduling

Calcium and cobalt were applied as foliar sprays twice during the growth period at 45 and 90 days after sowing using a spray volume of 160 L/fed. Standard agronomic practices such as manual weeding, thinning, and fertilization with urea and potassium sulfate were applied equally across all treatments.

Irrigation was applied using a medium-lift pump with a flow meter to monitor the volume of water applied. Seasonal water use was calculated for each regime. The first three irrigations were done to all of the experimental plots. The irrigation schedule was progressively reduced based on treatment:

- At 105 days: only full irrigation (I_1) plots were irrigated.
- Two additional irrigations were applied to all plots.
- In mid-April, only I_1 and I_2 were irrigated.
- After 20 more days, all plots were irrigated once more, with no further irrigation before harvest.

Based on the collection of water quantities used to irrigate each studied irrigation regime during the season, the irrigation treatments can be defined as follows:

- I_1- Full irrigation (8 irrigations) used a total of 4,320 m³ of water.
- I_2- One irrigation omitted (7 irrigations) used 3,860 m³ of water.
- I_3- Two irrigations omitted (6 irrigations) used 3,130 m³ of water.

Data Collection and Measurements

At harvest, plants from the three central rows of each sub-plot were uprooted and weighed to estimate root yield (t/fed). Moreover, a sample of roots was taken from each sub-plot the collected and separated into roots and shoots. The following traits were measured: root length (cm), root diameter (cm), single root weight (kg), root/shoot ratio and root and sugar yields (ton/fed.).

Data analyzed using MSTAT software. Mean comparisons were performed using the Least Significant Difference (LSD) test at a 5% significance level **(Gomez and Gomez, 1984)**

Results and Discussion

1) Root Length (cm)

The data in Table 3 indicate that irrigation regimes had no significant effect on root length in either season, a finding that contradicts the results reported by **Hani and El-Henawi (2011)**. Calcium chloride application had a significant impact on root length, but only in the 2nd season. Treatment with 4 kg of calcium chloride (Ca_2) consistently produced the longest roots, followed by 8 kg of calcium chloride (Ca_3), while untreated plants (Ca_1) recorded the shortest roots. The enhancing effect of calcium can be attributed to its pivotal role in regulating root system architecture. Adequate calcium availability promotes root elongation by stimulating cell division and reducing stress-induced damage. This is consistent with **White and Broadley (2003)**, who highlighted the essential role of calcium in maintaining root integrity under abiotic stress. Similarly, **Rabb and Haq (2012)** demonstrated that calcium chloride improves most vegetative traits in tomato, while **Mohammed and Basla (2015)** reported similar results in cowpea.

The interaction between irrigation regimes and calcium levels was significant only in the 2nd season. Under sufficient water supply, root length decreased as calcium levels increased. Conversely, under water-deficit conditions, calcium application markedly enhanced root length. This response may reflect calcium's function as a secondary messenger in signaling pathways that regulate protective mechanisms under water stress (**Rudd and Franklin-Tong, 2001; Tuteja, 2009**).

The data presented in the same table shows that all tested cobalt concentrations generally promoted root length, except for the CO_2 treatment in the 2nd season, where no significant difference was detected compared with the control (CO_1). Cobalt is recognized for its role in modulating ethylene production and enzyme activity; processes that strongly influence root growth, particularly under stress conditions. Consistent with this, **Palit et al. (1994)** reported that cobalt application improved root growth and enhanced stress tolerance in legumes, findings that are in agreement with the current results in sugar beet.

The interaction between irrigation regimes and cobalt concentrations was significant in both seasons. Under full irrigation (I_1), root length increased with cobalt application, except at 20 ppm. Under moderate irrigation stress (I_2), differences among treatments were less pronounced, although the control exhibited significantly shorter roots compared to the highest cobalt concentration (Co_4). Under severe stress (I_3), the 10-ppm cobalt treatment (Co_2) produced the longest roots, while other treatments showed relatively small differences. These consistent results across both seasons suggest that cobalt supplementation helps mitigate the adverse effects of water deficit, possibly by activating stress-related enzymes and modulating hormonal responses, as proposed by **Gad (2005)**.

The calcium × cobalt interaction was also significant in both seasons. In the absence of calcium, 10 ppm cobalt (Co_2) produced the longest roots, whereas in combination with 4 kg $CaCl_2$ (Ca_2), it resulted in the shortest roots. Increasing the calcium level to 8 kg (Ca_3) masked the effect of cobalt in the 1st season, while in the 2nd season; 10 ppm cobalt again exerted a positive effect.

Table 3: Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on root length (cm) of sugar beet during 2021/2022, and 2022/2023 seasons.

Irrigation regimes (I)	Calcium chloride (Ca) (kg.fed^{-1})	2021-2022 season					2022-2023 season				
		Cobalt chloride (ppm.fed^{-1})				Mean	Cobalt chloride (ppm.fed^{-1})				Mean
		0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)		0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)	
Full (I_1)	0.0 (Ca_1)	31.0	30.5	38.3	37.8	34.4	40.5	39.8	43.3	42.0	41.4
	4.0 (Ca_2)	34.5	34.0	40.5	38.3	36.8	40.0	40.5	34.8	48.0	40.8
	8.0 (Ca_3)	35.8	32.5	35.5	35.8	34.9	39.5	43.5	39.5	34.3	39.2
	Mean	33.8	32.3	38.1	37.3	35.4	40.0	41.3	39.2	41.4	40.5
Drop one (I_2)	0.0 (Ca_1)	27.8	41.3	32.5	35.5	34.3	40.8	36.5	34.5	39.3	37.8
	4.0 (Ca_2)	37.0	28.5	34.3	38.8	34.6	39.5	37.5	51.8	45.8	43.6
	8.0 (Ca_3)	34.5	32.3	34.5	36.5	34.4	40.3	50.5	40.3	42.5	43.4
	Mean	33.1	34.0	33.8	36.9	34.4	40.2	41.5	42.2	42.5	41.6
Drop two (I_3)	0.0 (Ca_1)	33.8	36.8	33.0	31.3	33.7	36.0	48.5	36.3	36.8	39.4
	4.0 (Ca_2)	30.3	38.3	35.0	37.3	35.2	45.8	36.4	42.0	47.1	42.8
	8.0 (Ca_3)	26.3	39.5	36.0	32.3	33.5	41.0	45.8	40.8	41.5	42.3
	Mean	30.1	38.2	34.7	33.6	34.1	40.9	43.5	39.7	41.8	41.5
Means of Ca	0.0 (Ca_1)	30.8	36.2	34.6	34.8	34.1	39.1	41.6	38.0	39.3	39.5
	4.0 (Ca_2)	33.9	33.6	36.6	38.1	35.5	41.8	38.1	42.8	47.0	42.4
	8.0 (Ca_3)	32.2	34.8	35.3	34.8	34.3	40.3	46.6	40.2	39.4	41.6
	Mean	32.3	34.8	35.5	35.9		40.4	42.1	40.4	41.9	

	F.test (2021-2022)	$LSD_{0.05}$ (2021-2022)	F.test (2022-2023)	$LSD_{0.05}$ (2022-2023)
I	ns	--	ns	--
Ca	ns	--	*	0.62
I x Ca	ns	--	*	1.07
Co	*	2.14	*	0.71
I x Co	*	3.70	*	1.23
Ca x Co	*	0.80	*	1.23
I x Ca x Co	ns	--	ns	--

2) Root Diameter (cm)

The tested irrigation regimes did not exert statistically significant effects on root diameter in either season (Table 4), indicating that this trait remains relatively stable under the studied range of water availability. In contrast, calcium chloride application had a significant influence on root diameter across both seasons. Notably, the intermediate calcium level (Ca_2) produced thinner roots compared to both the control (Ca_1) and the higher application rate (Ca_3), reflecting a non-linear dose response pattern. This outcome may suggest the presence of a threshold level of calcium, beyond which its role in structural reinforcement and osmotic regulation becomes more effective.

No significant effects of cobalt chloride concentrations were observed independently in either season. Nonetheless, slight improvements in root diameter were noted under moderate cobalt doses (10 and 20 ppm) compared to other levels.

The irrigation × cobalt interaction was significant in the 2nd season. Under light stress (I_2), roots treated with 10 or 20 ppm cobalt were generally thicker, while under severe stress (I_3), root diameter increased with increasing cobalt concentrations. These outcomes suggest that cobalt's physiological role in nitrogen assimilation and ethylene modulation may contribute to improved root thickening under water stress conditions (**Palit *et al.*, 1994**).

A notable calcium × cobalt interaction was significant in the second season. The Ca_3Co_2 treatment produced the largest root diameter (12.1cm), suggesting a synergistic effect of calcium and cobalt in enhancing cell expansion and nutrient transport. This aligns with **Broadley *et al.* (2011),** who emphasized the role of calcium in improving nutrient mobility and stress tolerance, and with **Palit**

***et al*. (1994)** regarding cobalt's enzymatic activity enhancement.

Although the three-way interaction (I × Ca × Co) was statistically significant in both seasons, the response pattern was inconsistent and scattered, indicating complexity without a clear trend.

Table 4: Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on root diameter (cm) of sugar beet during 2021/2022, and 2022/2023 seasons.

Irrigation regimes (I)	Calcium chloride (Ca) (kg.fed^{-1})	2021-2022 season: Cobalt chloride (ppm.fed^{-1}) 0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)	Mean	2022-2023 season: Cobalt chloride (ppm.fed^{-1}) 0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)	Mean
Full (I_1)	0.0 (Ca_1)	12.2	12.8	12.0	13.2	12.6	11.5	11.9	11.3	10.2	11.2
	4.0 (Ca_2)	14.2	10.8	12.3	11.1	12.1	10.2	11.6	10.7	11.9	11.1
	8.0 (Ca_3)	13.2	12.9	10.4	13.5	12.5	11.1	10.8	10.8	11.1	11.2
	Mean	13.2	12.2	11.6	12.6	12.4	11.3	11.4	10.9	11.0	11.2
Drop one (I_2)	0.0 (Ca_1)	11.8	12.7	12.9	13.1	12.6	10.2	11.3	11.0	10.1	10.6
	4.0 (Ca_2)	10.8	12.5	12.0	13.2	12.1	10.7	10.9	11.0	10.0	10.6
	8.0 (Ca_3)	14.3	12.1	14.3	10.4	12.8	11.7	13.4	11.7	11.5	12.1
	Mean	12.3	12.4	13.1	12.2	12.5	10.8	11.9	11.2	10.5	11.1
Drop two (I_3)	0.0 (Ca_1)	12.4	12.4	13.5	12.9	12.8	10.8	11.5	10.4	12.5	11.3
	4.0 (Ca_2)	11.6	12.8	13.1	10.8	12.1	10.8	9.3	11.5	10.5	10.5
	8.0 (Ca_3)	10.8	10.7	13.7	14.1	12.3	10.8	12.0	11.3	11.8	11.5
	Mean	11.6	12.0	13.4	12.6	12.4	10.8	10.9	11.1	11.6	11.1
Means of Ca	0.0 (Ca_1)	12.1	12.7	12.8	13.1	12.7	10.8	11.6	10.9	10.9	11.1
	4.0 (Ca_2)	12.2	12.0	12.5	11.7	12.1	10.5	10.6	11.0	10.8	10.8
	8.0 (Ca_3)	12.8	11.9	12.8	12.7	12.5	11.6	12.1	11.3	11.4	11.6
	Mean	12.4	12.2	12.7	12.5		11.0	11.4	11.1	11.1	

	2021-2022 F.test	2021-2022 $LSD_{0.05}$	2022-2023 F.test	2022-2023 $LSD_{0.05}$
I	ns	--	ns	--
Ca	*	0.47	*	0.38
I x Ca	ns	--	ns	--
Co	ns	--	ns	--
I x Co	ns	--	*	0.75
Ca x Co	ns	--	*	0.75
I x Ca x Co	*	1.62	*	1.30

3) Single Root Weight (kg)

The irrigation regime significantly influenced single root weight across both seasons (Table 5). In both years, moderate water stress (I_2) led to the highest weights, followed by full irrigation (I_1), while severe stress (I_3) resulted in marked reductions. These findings were matched with those obtained by **Carter *et al* (1980)**, and **David and Bradely (2017)**.

In the 1st season, calcium had no significant impact. However, in the 2nd season, the highest dose (Ca_3) led to significantly heavier roots; this may be due to calcium's role in improving root tissue resilience and nutrient transport under stress. In addition, the interaction between I and Ca was significant in both seasons. The I_2Ca_3 combination resulted in the maximum root weight in both seasons, while I_3Ca_3 and I_3Ca_2 interactions showed the lowest, reinforcing the idea that calcium benefits are most pronounced under moderate, not extreme, stress **(Cakmak, 2005)**.

Table 5: Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on single root weight (kg) of sugar beet during 2021/2022, and 2022/2023 seasons.

Irrigation regimes (I)	Calcium chloride (Ca) ($kg.fed^{-1}$)	2021-2022 season: Cobalt chloride ($ppm.fed^{-1}$) 0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)	Mean	2022-2023 season: Cobalt chloride ($ppm.fed^{-1}$) 0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)	Mean
Full (I_1)	0.0 (Ca_1)	2.04	2.23	1.91	2.18	2.09	1.93	1.94	1.75	1.31	1.73
	4.0 (Ca_2)	2.14	2.02	2.03	1.72	1.98	1.53	1.93	1.75	2.00	1.80
	8.0 (Ca_3)	1.63	2.62	1.90	1.85	2.00	1.67	1.77	1.70	1.80	1.82
	Mean	1.94	2.29	1.94	1.92	2.02	1.82	1.88	1.73	1.70	1.78
Drop one (I_2)	0.0 (Ca_1)	1.53	2.02	1.70	2.28	1.88	1.83	1.45	1.65	1.43	1.59
	4.0 (Ca_2)	1.92	1.94	2.00	1.91	1.94	2.06	2.04	1.64	1.78	1.88
	8.0 (Ca_3)	2.38	2.22	2.49	2.16	2.31	1.78	2.13	1.78	1.93	1.90
	Mean	1.95	2.06	2.06	2.12	2.05	1.89	1.87	1.69	1.71	1.79
Drop two (I_3)	0.0 (Ca_1)	1.96	2.33	1.97	1.97	2.06	1.53	1.78	1.43	1.98	1.68
	4.0 (Ca_2)	1.97	2.17	2.27	1.54	1.99	1.60	1.49	1.59	1.35	1.51
	8.0 (Ca_3)	1.27	1.54	1.74	2.06	1.65	1.63	1.86	1.77	1.80	1.76
	Mean	1.73	2.02	1.99	1.86	1.90	1.58	1.71	1.60	1.71	1.65
Means of Ca	0.0 (Ca_1)	1.84	2.19	1.86	2.14	2.01	1.76	1.72	1.61	1.57	1.67
	4.0 (Ca_2)	2.01	2.04	2.10	1.72	1.97	1.73	1.82	1.66	1.71	1.73
	8.0 (Ca_3)	1.76	2.13	2.04	2.02	1.99	1.80	1.92	1.75	1.84	1.83
	Mean	1.87	2.12	2.00	1.96		1.76	1.82	1.67	1.71	

	2021-2022 F.test	$LSD_{0.05}$	2022-2023 F.test	$LSD_{0.05}$
I	*	0.02	*	0.12
Ca	ns	--	*	0.06
I x Ca	*	0.07	*	0.10
Co	*	0.05	*	0.06
I x Co	*	0.08	*	0.11
Ca x Co	*	0.08	ns	--
I x Ca x Co	*	0.15	*	0.19

Cobalt chloride also showed significant effects on root weight in the two growing seasons. The 10 ppm dose (Co_2) consistently achieved the highest weights (2.12 and 1.82 kg in the 1st and 2nd seasons, respectively), confirming that moderate cobalt enhances root development. Higher concentrations may introduce toxicity, explaining reduced efficacy at Co_4.

The interaction between irrigation and cobalt was significant in both seasons. Notably, the treatment I_1Co_2 produced the heaviest root weight across both seasons. In the 2nd season, the combinations I_2Co_1, I_2Co_2, and I_1Co_1 also performed well. In contrast, severe water stress (I_3) combined with either low or high cobalt concentrations resulted in poor root development, indicating that under stress conditions, cobalt must be maintained within a narrow optimal range (**Palit *et al*., 1994**).

The calcium × cobalt interaction was significant only in the 1st season, with Ca_1Co_2 and Ca_3Co_2 interaction achieving superior root weights. The second season's data showed a numerical advantage with Ca_3Co_2, indicating that the Co_2 level was generally optimal across calcium levels **(Mengel and Kirkby, 2001**).

The triple interaction exerted the most pronounced effects on single root weight across both seasons. In the 1st season, the combination of full irrigation (I_1), high calcium (Ca_3), and 10 ppm cobalt (Co_2) produced the maximum single root weight of 2.62 kg. Conversely, in the 2nd season, the highest value (2.13 kg) was obtained under light stress irrigation combined with high calcium rate and 10 ppm cobalt ($I_2Ca_3Co_2$). These findings emphasize the crucial role of integrated water management and nutrient supplementation in optimizing sugar beet productivity. This is consistent with the results of **Kaya *et al*. (2006)**, who demonstrated that the combined application of micronutrients and calcium can markedly enhance crop tolerance to water stress.

4) Root/Shoot Ratio

Irrigation regimes significantly affected the root/shoot ratio of sugar beet, with the highest values recorded under severe stress (I_3) in the 1st season and under light stress (I_2) in the second. This variability likely reflects seasonal environmental differences such as temperature and humidity (Table 2).

Moderate water stress can enhance root growth and biomass partitioning to belowground organs (**Bacher *et al.*, 2022**), whereas severe stress mainly restricts shoot growth, raising the ratio without improving total biomass (**Chaves *et al.*, 2003**). Such responses are regulated by hormonal signaling under water deficit conditions (**Sharp *et al.*, 2004**; **Davies *et al.*, 2005**).

Table 6: Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on root/shoot ratio of sugar beet during 2021/2022, and 2022/2023 seasons.

Irrigation regimes (I)	Calcium chloride (Ca) ($kg.fed^{-1}$)	2021-2022 season					2022-2023 season				
		Cobalt chloride ($ppm.fed^{-1}$)				Mean	Cobalt chloride ($ppm.fed^{-1}$)				Mean
		0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)		0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)	
Full (I_1)	0.0 (Ca_1)	4.86	5.00	5.42	5.14	5.11	4.81	4.99	5.16	5.09	5.01
	4.0 (Ca_2)	5.19	5.25	5.51	5.48	5.36	5.10	5.17	4.86	4.70	4.95
	8.0 (Ca_3)	5.50	5.99	5.93	5.54	5.74	5.09	5.66	5.06	4.83	5.24
	Mean	5.18	5.41	5.62	5.39	5.40	5.10	5.27	5.03	4.87	5.07
Drop one (I_2)	0.0 (Ca_1)	4.70	5.18	6.75	4.44	5.26	5.89	6.36	5.28	4.63	5.54
	4.0 (Ca_2)	4.92	5.00	4.99	4.65	4.89	5.63	5.52	5.40	4.84	5.35
	8.0 (Ca_3)	6.36	5.29	5.34	4.57	5.39	6.05	6.76	5.25	5.31	5.84
	Mean	5.33	5.16	5.69	4.55	5.18	5.85	6.21	5.31	4.93	5.58
Drop two (I_3)	0.0 (Ca_1)	5.01	6.30	6.12	5.76	5.80	4.68	5.16	4.92	4.11	4.72
	4.0 (Ca_2)	5.93	5.66	6.35	5.94	5.97	5.63	5.87	4.18	4.67	5.09
	8.0 (Ca_3)	5.35	5.48	5.65	5.22	5.43	5.97	5.02	5.23	4.93	5.29
	Mean	5.43	5.81	6.04	5.64	5.73	5.43	5.35	4.78	4.57	5.03
Means of Ca	0.0 (Ca_1)	4.85	5.49	6.10	5.11	5.39	5.13	5.50	5.12	4.61	5.09
	4.0 (Ca_2)	5.35	5.30	5.62	5.36	5.41	5.45	5.52	4.81	4.74	5.13
	8.0 (Ca_3)	5.74	5.59	5.64	5.11	5.52	5.80	5.81	5.18	5.02	5.45
	Mean	5.31	5.46	5.78	5.19		5.46	5.61	5.04	4.79	

	2021-2022 F.test	2021-2022 $LSD_{0.05}$	2022-2023 F.test	2022-2023 $LSD_{0.05}$
I	*	0.05	*	0.03
Ca	*	0.03	*	0.08
I x Ca	ns	--	ns	--
Co	*	0.03	*	0.03
I x Co	ns	--	ns	--
Ca x Co	ns	--	ns	--
I x Ca x Co	ns	--	ns	--

Calcium chloride treatments significantly influence this trait. The highest ratio was consistently observed under the high calcium dose (Ca_3) in both seasons. Calcium not only supports structural stability but also acts as a secondary messenger in stress signaling, facilitating root elongation and ion transport while limiting shoot expansion (**Reddy *et al.*, 2011**).

Cobalt chloride significantly affected the root/shoot ratio in both seasons, with medium concentrations (Co_3 in the first and Co_2 in the second)

producing the highest values, while the highest

concentration (Co_4) reduced the ratio. This reduction is likely related to cobalt-induced delays in senescence, leading to prolonged chlorophyll retention and sustained shoot growth at the expense of roots. Similar patterns were noted by **Almeida *et al.* (2021)**, who reported increased leaf chlorophyll but reduced root biomass in sugar beet, and by **Srivastava *et al.* (2018)**, who observed enhanced shoot growth accompanied by reduced root diameter in carrot.

5) Root Yield

Root yield is a key indicator of sugar beet productivity and is responsive to environmental conditions and agronomic inputs. The current study revealed that irrigation regimes significantly affect root yield in both growing seasons. According to Table 7, full irrigation (I_1) led to the highest yields, while withholding one irrigation event (I_2) resulted in yield reductions of 6.9% and 3.2% in the first and second seasons, respectively. A more pronounced decline was observed under severe stress (I_3), with reductions of 19.7% and 24.4%, highlighting the detrimental effects of water scarcity. These results underscore the critical importance of adequate water supply in supporting root development and maximizing yield. Similar findings were reported by **Mahmoodi *et al.* (2008)** and **Li *et al.* (2021),** who emphasized that optimal irrigation maintains favorable soil moisture, enhancing photosynthetic efficiency and translocation to roots. Furthermore, **Abdel-Nasser *et al.* (2014)** demonstrated that sugar beet is particularly sensitive to water stress, and that yield losses under such conditions are mainly due to disrupted carbon allocation and reduced root expansion.

Table 7: Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on root yield (tons.fed^{-1}) of sugar beet during 2021/2022, and 2022/2023 seasons.

Irrigation regimes (I)	Calcium chloride (Ca) (kg.fed^{-1})	2021-2022 season: Cobalt chloride (ppm.fed^{-1}) 0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)	Mean	2022-2023 season: Cobalt chloride (ppm.fed^{-1}) 0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)	Mean
Full (I_1)	0.0 (Ca_1)	40.11	40.38	40.32	37.26	39.52	45.53	45.74	49.00	32.05	43.08
	4.0 (Ca_2)	38.02	39.75	40.50	39.92	39.55	36.81	43.89	39.83	50.79	42.83
	8.0 (Ca_3)	42.74	40.00	42.01	48.07	43.21	37.07	42.37	40.16	42.53	43.70
	Mean	40.29	40.04	40.94	41.75	40.76	44.03	44.00	43.00	41.79	43.20
Drop one (I_2)	0.0 (Ca_1)	35.18	37.23	34.37	34.25	35.26	27.93	35.20	36.06	33.69	33.22
	4.0 (Ca_2)	33.23	36.94	47.15	44.03	40.34	41.57	46.45	50.15	53.15	47.83
	8.0 (Ca_3)	33.09	41.93	45.31	32.80	38.28	40.43	52.39	43.06	41.58	44.36
	Mean	33.83	38.70	42.27	37.03	37.96	36.65	44.68	43.09	42.81	41.81
Drop two (I_3)	0.0 (Ca_1)	28.87	29.57	26.83	26.41	27.92	26.91	36.17	41.72	34.78	34.89
	4.0 (Ca_2)	27.95	33.03	34.84	28.88	31.18	23.80	24.76	46.67	30.73	31.49
	8.0 (Ca_3)	28.08	32.00	36.12	37.22	33.36	29.87	37.18	44.11	39.65	37.70
	Mean	28.30	31.53	32.60	30.84	30.82	26.86	32.70	44.17	35.05	34.69
Means of Ca	0.0 (Ca_1)	34.72	35.73	33.84	32.64	34.23	33.46	39.04	42.26	33.51	37.07
	4.0 (Ca_2)	33.07	36.58	40.83	37.61	37.02	34.06	38.36	45.55	44.89	40.71
	8.0 (Ca_3)	34.63	37.98	41.15	39.37	38.28	40.02	43.98	42.44	41.25	41.92
	Mean	34.14	36.76	38.61	36.54		35.84	40.46	43.42	39.88	

	2021-2022 F.test	$LSD_{0.05}$	2022-2023 F.test	$LSD_{0.05}$
I	*	0.18	*	1.14
Ca	*	0.65	*	0.47
I x Ca	*	1.13	*	0.81
Co	*	0.75	*	0.54
I x Co	*	1.30	*	0.93
Ca x Co	*	1.30	*	0.93
I x Ca x Co	*	2.26	*	1.62

The application of calcium chloride significantly improved root yield across both seasons. Yield consistently increased with higher calcium rates, peaking at 8.0 kg $CaCl_2$ (Ca3). This can be attributed to calcium's essential role in cell wall structure,

membrane integrity, and osmotic regulation. According to **White and Broadley (2003) and**

Waraich *et al*. (2012), calcium enhances drought resistance by promoting ion homeostasis and improving water use efficiency, particularly under stress. The interaction between calcium and irrigation was especially evident under I_3, where calcium alleviated the adverse effects of water shortage,

indicating its protective function during osmotic stress (**Geilfus *et al*., 2015**).

Regarding cobalt, significant improvements in root yield were recorded up to 20 ppm (Co3), beyond which yield decreased, indicating a threshold of tolerance. However, excess cobalt (>20 ppm) may lead to toxicity, as observed by **Pendias and Pendias (2001).** Notably, under moderate water stress (I_2), the I_2Co_3 treatment resulted in yields of 42.27 and 43.09 tons.fed^{-1} in the first and second seasons, comparable to full irrigation, emphasizing cobalt's stress-buffering capacity (**Palit *et al*., 1994**). Under severe drought (I_3), Co_3 also led to substantial yield gains, nearly doubling yield compared to Co_1.

Interestingly, calcium and cobalt showed synergistic interaction. In the absence of calcium, cobalt effects were inconsistent. However, when calcium was applied at moderate to high levels, cobalt's benefits were maximized, particularly at 20 ppm. According to **Marschner (2012)**, calcium enhances structural stability, while cobalt supports nitrogen metabolism and enzyme activation, enhancing stress tolerance and yield.

The three-way interaction (Irrigation × Calcium × Cobalt) was significant in both seasons. Under I_2, a combination of Ca_3 and Co_3 in the first season and $Ca_3 \times Co_3$ consistently resulted in the highest root yields, suggesting an optimal combination for enhancing productivity under mild water stress. These results align with **Reddy *et al*. (2011),** who emphasized that optimal micronutrient management supports physiological adaptation and nutrient use efficiency under drought.

6) Sugar Yield

Sugar yield in sugar beet was significantly influenced by irrigation, calcium, and cobalt treatments (Table 8). Full irrigation (I_1) and mild water stress (I_2) produced the highest yields across both seasons, with no significant difference between them in the second season, indicating the crop's ability to tolerate moderate water deficit without major yield loss. In contrast, severe stress (I_3) led to a marked reduction in sugar yield. **Jaggard *et al*. (2010)** reported that moderate irrigation deficits in sugar beet can sustain sugar yield by promoting root development and sugar accumulation, whereas severe stress significantly limits both growth and productivity.

Calcium chloride application significantly enhanced sugar yield, especially at higher doses (Ca_2 and Ca_3). Calcium's role in improving root growth, cell wall strength, and nutrient uptake likely contributed to this effect, particularly under water-limited conditions. **Marschner (2012)** reported that calcium chloride enhances sugar beet yield by improving sucrose translocation. Similarly, **El-Sayed and El-Metwally (2015)** observed increased sugar yields following calcium chloride supplementation.

Cobalt chloride also improved sugar yield, with the 20-ppm treatment (Co_3) achieving the highest values. This is attributed to cobalt's role in enzymatic activity, nutrient absorption, and stress tolerance. However, excessive cobalt (30 ppm) slightly reduced yields, likely due to toxicity effects. **Gad and Ismail (2011)** and **Yadav *et al*. (2011)** highlighted cobalt's positive influence on photosynthesis and chlorophyll stability under stressful environments. However, excessively high cobalt concentrations can induce oxidative stress and inhibit plant growth.

Table 8: Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on sugar yield ($tons.fed^{-1}$) of sugar beet during 2021/2022, and 2022/2023 seasons.

Irrigation regimes (I)	Calcium chloride (Ca) ($kg.fed^{-1}$)	2021-2022 season					2022-2023 season				
		Cobalt chloride ($ppm.fed^{-1}$)				Mean	Cobalt chloride ($ppm.fed^{-1}$)				Mean
		0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)		0.0 (Co_1)	10.0 (Co_2)	20.0 (Co_3)	30.0 (Co_4)	
Full (I_1)	0.0 (Ca_1)	4.99	5.54	4.53	4.37	4.86	5.25	5.19	5.39	3.67	4.88
	4.0 (Ca_2)	5.32	6.01	5.40	5.42	5.53	4.28	4.77	4.93	5.75	4.93
	8.0 (Ca_3)	5.30	5.22	6.06	5.03	5.40	4.12	5.34	5.56	5.53	5.60
	Mean	5.20	5.59	5.33	4.94	5.26	5.17	5.10	5.30	4.98	5.14
Drop one (I_2)	0.0 (Ca_1)	4.33	5.23	4.57	3.66	4.45	3.43	4.13	4.08	4.14	3.94
	4.0 (Ca_2)	4.17	5.18	6.61	6.12	5.52	5.06	5.26	6.11	6.44	5.72
	8.0 (Ca_3)	4.90	5.18	6.70	4.66	5.36	4.71	6.29	5.22	5.25	5.37
	Mean	4.46	5.20	5.96	4.81	5.11	4.40	5.23	5.14	5.28	5.01
Drop two (I_3)	0.0 (Ca_1)	2.90	3.54	3.12	3.19	3.19	2.62	3.86	4.11	3.60	3.55
	4.0 (Ca_2)	3.45	3.89	4.67	3.91	3.98	2.68	2.58	5.44	3.37	3.52
	8.0 (Ca_3)	3.47	4.35	4.63	4.91	4.34	2.88	4.21	5.11	4.31	4.13
	Mean	3.27	3.93	4.14	4.00	3.84	2.73	3.55	4.89	3.76	3.73
Means of Ca	0.0 (Ca_1)	4.07	4.77	4.07	3.74	4.16	3.77	4.39	4.53	3.80	4.12
	4.0 (Ca_2)	4.31	5.03	5.56	5.15	5.01	4.01	4.20	5.49	5.19	4.72
	8.0 (Ca_3)	4.55	4.92	5.80	4.87	5.03	4.53	5.28	5.30	5.03	5.03
	Mean	4.31	4.90	5.14	4.58		4.10	4.63	5.11	4.67	

	2021-2022 F.test	2021-2022 $LSD_{0.05}$	2022-2023 F.test	2022-2023 $LSD_{0.05}$
I	*	0.10	*	0.13
Ca	*	0.06	*	0.12
I x Ca	*	0.11	*	0.21
Co	*	0.07	*	0.14
I x Co	*	0.12	*	0.24
Ca x Co	*	0.12	*	0.24
I x Ca x Co	*	0.21	*	0.42

Significant interactions were observed between irrigation, calcium, and cobalt. Under mild stress (I_2), combining high calcium (Ca_3) and 20 ppm cobalt (Co_3) resulted in the highest sugar yield (6.70 $tons.fed^{-1}$). These results highlight the synergistic benefits of proper nutrient management under moderate water stress. However, under severe stress (I_3), even optimal nutrient application could not fully restore yields, emphasizing the critical role of adequate water availability during sensitive growth stages.

Conclusion

The present study demonstrated that root development and productivity of sugar beet are significantly influenced by the interaction between irrigation regimes and foliar application of calcium and cobalt chloride. Moderate water stress (I_2) was found to enhance root morphological traits such as root length and weight, especially when combined with appropriate micronutrient supplementation.

Calcium chloride application, particularly at 8 kg $fed.^{-1}$, played a crucial role in improving root traits under both optimal and water-limited conditions. Its influence was attributed to its regulatory effects on cell structure, membrane stability, and osmotic balance. Likewise, cobalt chloride applied at 10–20 ppm improved root length, weight, and root/shoot ratio by enhancing stress tolerance, antioxidant activity, and nitrogen metabolism.

Significant two-way and three-way interactions revealed that the combination of moderate irrigation with 8.0 kg $CaCl_2$ and 20 ppm $CoCl_2$ resulted in the most favorable root yield. These findings underscore the synergistic effect of calcium and cobalt in enhancing sugar beet resilience under water stress conditions.

Recommendations

Adopt moderate irrigation regimes (I) in sugar beet cultivation to optimize water use efficiency without compromising root development, especially in semi-arid regions.

Apply calcium chloride at a rate of 8 kg fed.$^{-1}$ as a foliar spray during active vegetative growth stages to improve root architecture and enhance stress tolerance.

Supplement cobalt chloride at 10–20 ppm to support root biomass development, particularly under water-deficient conditions. Care should be taken to avoid higher concentrations (e.g., 30 ppm) to prevent potential toxicity.

Utilize combined calcium and cobalt foliar treatments under moderate water stress (IxCaxCo) to achieve the highest root yield, improve root/shoot balance, and promote overall plant vigor.

Further research is encouraged to investigate the **physiological and molecular mechanisms** underlying the calcium–cobalt interaction in sugar beet, especially under different environmental conditions.

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