Egyptian Sugar Journal (2025), 24: 1 - 12
https://doi.org/10.21608/esugj.2025.402221.1081

RESEARCH ARTICLE

Impact of calcium and cobalt foliar application on sugar beet quality under different irrigation levels

Teama EA[1], Dawood RA[1], Ahmed AZ[2]. and Youssef AMM[2*].

Received: 9 July 2025\ Revised: 12 Aug 2025\ Accepted: 17 Aug 2025\ Published online: 21 Aug 2025

Abstract

Two field experiments were conducted during the 2021/2022 and 2022/2023 seasons at Mallawi Research Station, El-Minia Governorate, Egypt, to investigate the effects of calcium and cobalt foliar application on sugar beet quality under varying irrigation regimes.
A split-plot design with three irrigation levels (full, moderate stress, and severe stress) was used as the main plots, while combinations of calcium (0, 4, and 8 kg/fed $CaCl_2$) and cobalt (0, 10, 20, and 30 ppm $CoCl_2$) treatments were assigned to subplots.
Results indicated that moderate water stress enhanced sugar quality traits without compromising yield.
Calcium and cobalt significantly improved sucrose content and sugar recovery, with optimal effects at moderate rates. Interaction effects among irrigation, calcium, and cobalt treatments were significant for most traits.
The combination of moderate stress, 8 kg/fed calcium, and 20 ppm cobalt produced the best overall quality.
20 ppm of cobalt chloride showed the greatest sugar yield (5.14, and 5.11 ton/fed. for 1st and 2nd respectively).
These findings highlight the potential of nutrient management to mitigate water stress effects on sugar beet quality.

Keywords: Sugar beet, calcium chloride, cobalt chloride, irrigation stress, sugar recovery, quality index.

[1]Department of Agronomy, Faculty of Agriculture, Assiut University, Egypt
[2]Sugar Crops Institute, Agriculture Research Center, Giza, Egypt
*Corresponding author: ahmedmedhaty78@gmail.com

Introduction

Sugar beet (*Beta vulgaris L.*) is a relatively new crop in the Arab Republic of Egypt, introduced as a sugar source in the mid-1990s. Since then, its cultivated area has expanded rapidly, surpassing that of sugarcane and reaching approximately 700,000 feddans in 2024.

About 65% of the total cultivation area (390,000 feddans) was concentrated in fertile old lands. El-Minya Governorate alone cultivated 36,000 feddans on old lands under flood irrigation, where sowing takes place from mid-August to late December, with an average yield of around 28.0 tons per feddan.

This system of irrigation poses several challenges, including poor water control and an increased risk of diseases. Soils in sugar beet-growing regions vary widely in their water-holding capacity, making it difficult to precisely determine seasonal water requirements. Both over- and under-irrigation can cause significant yield and quality losses. Additionally, flood irrigation increases production costs, as more than 80% of the irrigated area relies on diesel- or electricity-powered pumps for water lifting. Consequently, irrigation management plays a critical role in the net profit of sugar beet farming in these regions.

Calcium, which constitutes approximately 3.64% of the Earth's crust (Lide, 2005), is an essential nutrient for plant growth, with its soil content varying according to soil type, parent material, and climatic conditions. It occurs in different soil forms that vary in their characteristics and plant availability. Within plants, calcium plays vital roles, including contributing to cell wall structure and enhancing cohesion (Hepler, 2005; White and Broadley, 2003), stimulating enzymes, and promoting meristematic cell development (Hirschi, 2004). It is crucial for cell division, elongation, and photosynthesis, contributing up to 60% of chloroplast composition (Hochmal et al., 2015).

Calcium also supports root system growth, while its deficiency leads to weak, short-lived roots susceptible to rot (Marschner, 2012). Furthermore, it mitigates the toxic effects of certain inorganic elements such as sodium, cobalt, copper, and zinc (White, 2001). Cobalt

(Co, atomic number 27) is a relatively rare transition metal, comprising about 0.004% of the Earth's crust. Biologically, cobalt is essential for systems requiring vitamin B12 (cobalamin), notably for Rhizobium bacteria in legume root nodules to facilitate nitrogen fixation (Dart and Day, 1971; Riley and Dilworth, 1985). While its necessity for most plant species remains unconfirmed and deficiency symptoms are rare, recent recognition by the European Parliament's Scientific Committee has classified cobalt as a plant micronutrient, with studies highlighting its role in enhancing physiological processes, yield, and quality (Rady, 2011; Souri and Hatamian, 2019). Cobalt is also an important major component of many enzymes, and it also acts as an enzyme cofactor and it is safe to use for humans, as the daily dose reaches 8.0 mg without any health risks.

This study aims to evaluate an applied approach for conserving irrigation water in sugar beet cultivation through the combined influence of calcium and cobalt supplementation.

Materials and Methods

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

	Sand	Silt	Clay	pH	ECe	$CaCo^3$	O. M
1st season	8.47	36.82	54.71	7.80	1.52	1.93	1.60
2nd season	10.11	40.57	49.32	7.75	1.59	1.81	1.72

The experiment was conducted using a randomized complete block design (RCBD) with three replicates, adopting a strip-plot arrangement within a split-plot structure. Three irrigation regimes were applied vertically: full irrigation (I1: 8.0 irrigations, 4320 m³/fed.), one irrigation omitted (I2: 7.0 irrigations, 3860 m³/fed.), and two irrigations omitted (I3: 6.0 irrigations, 3130 m³/fed.). Calcium chloride treatments were applied horizontally as foliar sprays at three levels: Ca_1 (0.0 kg/fed.), Ca_2 (4.0 kg/fed.), and Ca_3 (8.0 kg/fed.). Within each combination of irrigation and calcium treatments, four cobalt levels were applied as foliar sprays in the sub-plots: Co1 (0.0 ppm/fed.), Co_2 (10.0 ppm/fed.), Co_3 (20.0 ppm/fed.), and Co_4 (30.0 ppm/fed.). Each plot occupied an area of 18 m², consisting of five rows spaced 0.6 meters apart, with each row measuring 6.0 meters in length.

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.

The first three irrigations were done to all of the experimental plots. The irrigation schedule was gradually reduced according to the treatment plan. At 105 days after sowing, only the plots receiving full irrigation were watered. Subsequently, two additional irrigations were applied uniformly across all plots. In mid-April, irrigation was limited to treatments I1 and I2. Twenty days later, a final irrigation was applied to all plots, after which no further irrigation occurred until harvest.

Measured Traits and Calculations

1- POL %: was determined by the ICUMSA method (1994).
2- Potassium (K. meq/L)
3- Sodium (Na. meq/L)
4- Alfa amino nitrogen (α-N) was determined according to Brown and Lilliand (1964) using Auto-Analyzer (type Zig Verems Automation) by Abou-Korkas Sugar Company.
5- Sugar recovery: determined according to the procedure of Abou-Korkas Sugar Company described by Saparonova, et al.; 1979 by the following equation: -

(pol – 0.29) – 0.343 (K + Na) – alpha amino N (0.094)

6- Quality index (Qz): was calculated according to Cook and Scott (1993) by the following equation: -

(Sugar recovery % x 100) / Pol %).

7- Sugar yield (ton/fed.)

Statistical analysis was performed using ANOVA, and mean differences were tested using LSD at the 5% level.

Results and Discussion

Sucrose Content (POL %)

Irrigation levels significantly impacted POL% in both seasons. In the first season, the highest POL% was recorded under moderate stress (I2), followed by full irrigation (I1), while severe stress (I3) was the lowest. In the second season, I1 and I2 were statistically similar but significantly higher than I3. This aligns with Pidgeon et al. (2000), who reported enhanced sugar content under moderate water stress due to better partitioning of assimilates to roots.

Conversely, severe drought likely reduced sugar accumulation via inhibited photosynthesis, enzyme activity, and sugar transport (Ober and LeBrocq, 2002).

Calcium significantly enhanced POL% in both seasons. The increase was proportional to $CaCl_2$ concentration, with Ca_3 giving the highest values. Differences between Ca_1 and Ca_2 were not significant in the first season. These improvements are attributed to calcium's role in membrane stability, enzyme activity, and sugar translocation (Awasthi and Lal, 2009; Artyszak et al., 2014).

Moreover, calcium enhances cellular function under stress by regulating calmodulin activity and maintaining membrane permeability (White and Broadley, 2003).

Cobalt chloride also significantly influenced POL%, with 20 ppm (Co_3) giving the highest values across both seasons. 10 ppm (Co_2) was comparable to Co_3 in the first season. Higher concentrations (30 ppm) and the control (0 ppm) gave lower values, aligning with Gad (2005). Cobalt at optimal concentrations enhances chlorophyll content and nitrogen metabolism, improving assimilate formation and allocation.

Table 2. Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on POL % 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)	15.31	16.41	14.42	14.51	15.16	14.90	14.60	14.50	14.60	14.65
	4.0 (Ca_2)	16.79	17.55	16.47	16.66	16.87	14.80	14.60	15.35	14.65	14.85
	8.0 (Ca_3)	15.25	15.69	17.04	13.39	15.34	14.41	16.15	16.95	15.95	16.05
	Mean	15.78	16.55	15.98	14.85	15.79	14.95	15.12	15.60	15.07	15.18
Drop one (I_2)	0.0 (Ca_1)	15.40	17.05	15.92	13.78	15.54	15.60	14.75	14.95	15.25	15.14
	4.0 (Ca_2)	15.44	16.65	16.74	16.51	16.33	15.65	14.75	15.65	15.90	15.49
	8.0 (Ca_3)	17.47	15.23	17.47	16.82	16.75	14.85	15.20	15.55	15.75	15.34
	Mean	16.10	16.31	16.71	15.70	16.21	15.37	14.90	15.38	15.63	15.32
Drop two (I_3)	0.0 (Ca_1)	13.12	14.46	14.44	14.72	14.18	12.78	14.03	13.23	13.78	13.45
	4.0 (Ca_2)	14.95	14.76	16.08	16.30	15.52	14.73	13.83	14.78	14.13	14.37
	8.0 (Ca_3)	15.14	16.21	15.67	16.02	15.76	12.98	14.58	14.83	13.87	14.07
	Mean	14.40	15.14	15.40	15.68	15.15	13.50	14.15	14.28	13.93	13.96
Means of Ca	0.0 (Ca_1)	14.61	15.97	14.93	14.34	14.96	14.43	14.46	14.23	14.54	14.41
	4.0 (Ca_2)	15.72	16.32	16.43	16.49	16.24	15.06	14.39	15.26	14.89	14.90
	8.0 (Ca_3)	15.95	15.71	16.73	15.41	15.95	14.33	15.31	15.78	15.19	15.15
	Mean	15.43	16.00	16.03	15.41		14.60	14.72	15.09	14.88	
				F.test	$LSD_{0.05}$				F.test	$LSD_{0.05}$	
	I			*	0.36				*	0.26	
	Ca			*	0.30				*	0.23	
	I x Ca			*	0.52				*	0.41	
	Co			*	0.35				*	0.27	
	I x Co			*	0.60				*	0.47	
	Ca x Co			*	0.60				*	0.47	
I x Ca x Co				*	1.04				ns	--	

Significant interactions (I × Ca, I × Co, Ca × Co) occurred in both seasons, with the best performance under Ca_3Co_3. A second-order interaction (I × Ca × Co) was significant in the first season only, with $I1Ca_3Co_3$ and $I2Ca_3Co_3$ among the highest performers, confirming the synergistic effects of micronutrient and water management.

Sodium Content (meq/L)

Sodium levels in sugar beet showed minimal variation across irrigation treatments in both seasons, indicating a limited effect of irrigation on sodium accumulation. However, calcium chloride application had a clear influence. In the first season, higher calcium levels significantly reduced sodium content, suggesting an antagonistic relationship between Ca^{2+} and Na^{+}. This trend aligns with previous studies highlighting calcium's role in limiting sodium uptake by stabilizing cell membranes and competing at the root level. In the second season, the pattern shifted slightly, with moderate calcium application (Ca_2) leading to the highest sodium content, possibly due to improved root activity, while excessive calcium (Ca_3) may have disrupted ionic balance.

Table 3. Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on sodium (meq.L^{-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)	2.51	2.11	2.69	2.02	2.33	5.20	5.49	5.30	4.44	5.11
	4.0 (Ca_2)	2.53	2.10	3.50	2.43	2.64	4.98	5.86	4.87	4.85	5.14
	8.0 (Ca_3)	2.26	2.27	1.81	2.55	2.22	5.03	5.83	4.76	4.61	4.99
	Mean	2.43	2.16	2.66	2.33	2.40	4.98	5.73	4.98	4.63	5.08
Drop one (I_2)	0.0 (Ca_1)	2.75	2.64	1.97	3.12	2.62	4.89	4.64	5.50	4.56	4.90
	4.0 (Ca_2)	2.50	1.41	1.89	1.68	1.87	5.10	5.17	5.10	6.13	5.37
	8.0 (Ca_3)	1.46	2.47	1.46	1.49	1.72	4.91	4.95	5.15	4.67	4.92
	Mean	2.23	2.17	1.77	2.10	2.07	4.97	4.92	5.25	5.12	5.06
Drop two (I_3)	0.0 (Ca_1)	3.16	2.16	2.66	1.85	2.45	4.39	5.11	5.68	5.13	5.08
	4.0 (Ca_2)	2.86	2.78	1.67	1.51	2.20	5.32	5.54	4.65	4.86	5.09
	8.0 (Ca_3)	1.97	1.50	2.64	2.36	2.12	5.53	4.85	4.89	4.42	4.92
	Mean	2.66	2.15	2.32	1.90	2.26	5.08	5.16	5.07	4.80	5.03
Means of Ca	0.0 (Ca_1)	2.80	2.30	2.44	2.33	2.47	4.83	5.08	5.49	4.71	5.03
	4.0 (Ca_2)	2.63	2.10	2.35	1.87	2.24	5.13	5.52	4.87	5.28	5.20
	8.0 (Ca_3)	1.89	2.08	1.97	2.13	2.02	5.06	5.21	4.93	4.57	4.94
	Mean	2.44	2.16	2.25	2.11		5.01	5.27	5.10	4.85	
				F.test	$LSD_{0.05}$				F.test	$LSD_{0.05}$	
	I			ns	--				ns	--	
	Ca			*	0.26				*	0.16	
	I x Ca			*	0.45				ns	--	
	Co			ns	--				ns	--	
	I x Co			ns	--				ns	--	
	Ca x Co			ns	--				*	0.33	
I x Ca x Co				ns	--				ns	--	

A significant calcium × irrigation interaction was observed in the first season, where calcium was most effective in reducing sodium content under moderate irrigation (I2). Cobalt alone and its interaction with irrigation had no significant effect on sodium levels. However, in the second season, a calcium × cobalt interaction emerged: spraying 20 ppm cobalt increased sodium under no calcium, but significantly reduced it when combined with moderate calcium levels, suggesting a synergistic effect. No significant three-way interactions (irrigation × calcium × cobalt) were found in either season.

Potassium content (meq/L)

None of the studied factors, either individually or in combination, had a significant effect on potassium content.

Table 4. Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on potassium (meq.L^{-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)	3.46	3.96	4.37	3.82	3.90	3.08	2.71	3.50	3.25	3.13
	4.0 (Ca_2)	3.67	3.05	3.41	4.26	3.60	2.89	3.50	2.45	3.50	3.08
	8.0 (Ca_3)	3.88	3.42	3.67	3.89	3.71	3.16	3.17	2.77	2.61	2.86
	Mean	3.67	3.47	3.81	3.99	3.74	2.96	3.13	2.91	3.12	3.03
Drop one (I_2)	0.0 (Ca_1)	4.32	4.34	3.57	3.63	3.96	3.45	2.78	3.75	2.80	3.19
	4.0 (Ca_2)	3.91	4.29	4.16	4.01	4.09	3.66	3.47	3.66	3.46	3.56
	8.0 (Ca_3)	4.62	3.69	4.62	4.36	4.32	2.99	2.97	3.47	3.07	3.12
	Mean	4.28	4.10	4.12	4.00	4.13	3.37	3.07	3.63	3.11	3.29
Drop two (I_3)	0.0 (Ca_1)	3.53	2.91	3.35	3.72	3.38	3.03	3.33	2.77	3.43	3.14
	4.0 (Ca_2)	3.04	3.54	4.03	4.38	3.75	3.26	3.00	2.92	2.96	3.04
	8.0 (Ca_3)	4.45	4.26	3.51	3.89	4.03	2.82	3.23	3.18	2.87	3.02
	Mean	3.67	3.57	3.63	3.99	3.72	3.04	3.19	2.95	3.09	3.07
Means of Ca	0.0 (Ca_1)	3.77	3.73	3.76	3.72	3.75	3.19	2.94	3.34	3.16	3.16
	4.0 (Ca_2)	3.54	3.62	3.87	4.21	3.81	3.27	3.32	3.01	3.31	3.23
	8.0 (Ca_3)	4.31	3.79	3.93	4.04	4.02	2.90	3.12	3.14	2.85	3.00
	Mean	3.87	3.72	3.85	3.99		3.12	3.13	3.16	3.10	
				F.test	$LSD_{0.05}$				F.test	$LSD_{0.05}$	
	I			ns	--				ns	--	
	Ca			ns	--				ns	--	
	I x Ca			ns	--				ns	--	
	Co			ns	--				ns	--	
	I x Co			ns	--				ns	--	
	Ca x Co			ns	--				ns	--	
I x Ca x Co				ns	--				ns	--	

Alfa amino nitrogen (meq.L-1)

Irrigation significantly affected α-N. Both I1 and I3 recorded higher values than I2 in both seasons, suggesting stress-induced accumulation of amino compounds (Bethke et al., 2007; Kenter and Hoffmann, 2006). Under full irrigation, enhanced metabolic activity may lead to greater nitrogen assimilation, while under severe stress, plants accumulate amino acids as osmo-protectants. Calcium had a significant effect only in the first season. α-N content decreased with increasing $CaCl_2$, with Ca_1 > Ca_2 > Ca_3. This may be due to reduced amino acid transport under high calcium levels (White and Broadley, 2003) or reduced ethylene-mediated stress signaling (Bangerth, 1979).

Table 5. Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on alpha amino nitrogen (meq.L^{-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)	5.50	3.68	4.71	5.29	4.79	2.51	1.52	2.05	2.39	2.12
	4.0 (Ca_2)	4.40	3.64	5.01	5.12	4.54	2.09	2.33	1.80	2.10	2.08
	8.0 (Ca_3)	5.13	4.21	4.65	4.61	4.65	1.98	1.84	2.35	2.11	2.14
	Mean	5.01	3.84	4.79	5.00	4.66	2.29	1.90	2.07	2.20	2.11
Drop one (I_2)	0.0 (Ca_1)	3.98	3.61	4.78	5.56	4.48	2.11	1.89	1.80	1.74	1.88
	4.0 (Ca_2)	4.40	3.85	3.82	3.90	3.99	1.87	1.92	1.87	2.12	1.94
	8.0 (Ca_3)	3.12	5.03	3.12	3.63	3.72	2.17	1.86	2.00	1.85	1.97
	Mean	3.83	4.16	3.90	4.36	4.07	2.05	1.89	1.89	1.90	1.93
Drop two (I_3)	0.0 (Ca_1)	5.75	5.08	4.90	4.52	5.06	2.15	1.60	2.03	2.02	1.95
	4.0 (Ca_2)	4.45	5.32	4.44	4.63	4.71	2.21	1.93	2.47	2.06	2.17
	8.0 (Ca_3)	2.98	4.07	4.72	4.07	3.96	1.89	2.03	2.13	2.08	2.03
	Mean	4.39	4.82	4.69	4.41	4.58	2.08	1.85	2.21	2.05	2.05
Means of Ca	0.0 (Ca_1)	5.08	4.12	4.79	5.12	4.78	2.25	1.67	1.96	2.05	1.98
	4.0 (Ca_2)	4.42	4.27	4.42	4.55	4.41	2.05	2.06	2.05	2.09	2.06
	8.0 (Ca_3)	3.74	4.44	4.16	4.10	4.11	2.11	1.91	2.16	2.01	2.05
	Mean	4.41	4.28	4.46	4.59		2.14	1.88	2.05	2.05	
				F.test	$LSD_{0.05}$				F.test	$LSD_{0.05}$	
	I			*	0.12				*	0.07	
	Ca			*	0.26				ns	--	
	I x Ca			*	0.45				ns	--	
	Co			ns	--				*	0.15	
	I x Co			ns	--				ns	--	
	Ca x Co			ns	--				ns	--	
I x Ca x Co				ns	--				ns	--	

Cobalt had no significant effect in the first season, but in the second season, Co_2 reduced α-N, while Co_3 and Co_4 had higher, comparable values. This indicates a non-linear response and aligns with Gad (2005), who noted cobalt's dual role in enhancing or inhibiting nitrogen metabolism based on dose.Interactions (I × Co, Ca × Co, I × Ca × Co) were not significant in either season.

Sugar Recovery (%)

Irrigation significantly influenced sugar recovery. I2 gave the highest values in the first season. In the second, I1 and I2 were similar and superior to I3. These findings support Hoffmann and Kluge-Severin (2010) and Bassirirad (2000), who noted that moderate stress enhances sugar concentration by reducing dilution and improving source-sink relationships.

Table 6. Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on sugar recovery % 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)	12.46	13.69	11.26	11.72	12.28	11.53	11.35	11.00	11.45	11.33
	4.0 (Ca_2)	13.96	15.15	13.34	13.59	14.01	11.62	10.88	12.38	11.30	11.54
	8.0 (Ca_3)	12.37	13.06	14.43	10.45	12.58	11.13	12.60	13.86	12.99	12.87
	Mean	12.93	13.97	13.01	11.92	12.96	11.72	11.61	12.41	11.91	11.91
Drop one (I_2)	0.0 (Ca_1)	12.31	14.03	13.28	10.65	12.57	12.25	11.74	11.32	12.27	11.90
	4.0 (Ca_2)	12.53	14.04	14.01	13.90	13.62	12.18	11.32	12.18	12.12	11.95
	8.0 (Ca_3)	14.80	12.36	14.80	14.18	14.04	11.65	12.02	12.12	12.63	12.11
	Mean	13.22	13.47	14.03	12.91	13.41	12.03	11.69	11.87	12.34	11.98
Drop two (I_3)	0.0 (Ca_1)	10.00	11.95	11.63	12.10	11.42	9.74	10.69	9.85	10.36	10.16
	4.0 (Ca_2)	12.21	11.80	13.42	13.56	12.75	11.29	10.42	11.66	10.96	11.08
	8.0 (Ca_3)	12.37	13.56	12.83	13.20	12.99	9.65	11.32	11.58	10.89	10.86
	Mean	11.53	12.44	12.62	12.95	12.39	10.23	10.81	11.03	10.74	10.70
Means of Ca	0.0 (Ca_1)	11.59	13.22	12.06	11.49	12.09	11.17	11.26	10.72	11.36	11.13
	4.0 (Ca_2)	12.90	13.66	13.59	13.68	13.46	11.70	10.87	12.07	11.46	11.53
	8.0 (Ca_3)	13.18	12.99	14.02	12.61	13.20	11.11	11.98	12.52	12.17	11.94
	Mean	12.56	13.29	13.22	12.60		11.33	11.37	11.77	11.66	
				F.test	$LSD_{0.05}$				F.test	$LSD_{0.05}$	
	I			*	0.40				*	0.33	
	Ca			*	0.34				*	0.25	
	I x Ca			*	0.59				*	0.44	
	Co			ns	--				ns	--	
	I x Co			*	0.68				ns	--	
	Ca x Co			*	0.68				ns	--	
I x Ca x Co				1.17	1.17				ns	--	

EKB

Calcium significantly improved sugar recovery in both seasons. Ca_2 and Ca_3 were superior to Ca_1 in season one, with Ca_3 being best in season two.

Calcium enhances phloem loading, membrane integrity, and enzymatic function (Marschner, 2012; White and Broadley, 2003).

Cobalt effects were not statistically significant, but Co_2 and Co_3 showed numerical improvements. These may relate to increased antioxidative capacity and improved metabolic stability under stress (Kiran et al., 2010).

Significant interactions were found for I × Ca and I × Co, particularly under I2. Ca × Co was significant in season one. The second-order interaction showed that $I1Ca_2Co_2$ and $I2Ca_3Co_3$ were among the best combinations.

Quality Index (Qz)

No significant differences in Qz were recorded among irrigation treatments in season one. In season two, I1 and I2 outperformed I3. This indicates tolerance to moderate stress, consistent with Ober and Luterbacher (2002) and Tarkalson et al. (2014).

Table 7. Effect of irrigation regimes (I), calcium chloride (Ca), cobalt chloride (Co), and their interactions on quality index (Qz) 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)	81.31	83.42	77.79	80.77	80.82	77.41	77.73	75.83	78.41	77.35
	4.0 (Ca_2)	83.19	86.21	80.97	81.54	82.97	78.50	74.52	80.62	77.02	77.67
	8.0 (Ca_3)	81.02	83.22	84.70	78.11	81.76	77.14	78.01	81.72	81.46	80.13
	Mean	81.84	84.28	81.15	80.14	81.85	78.42	76.75	79.39	78.96	78.38
Drop one (I_2)	0.0 (Ca_1)	79.94	82.14	83.42	77.26	80.69	78.36	79.58	75.71	80.48	78.53
	4.0 (Ca_2)	81.21	84.34	83.73	84.22	83.38	77.84	76.74	77.84	76.24	77.17
	8.0 (Ca_3)	84.72	81.13	84.71	84.34	83.72	78.45	79.02	77.92	80.23	78.90
	Mean	81.96	82.53	83.95	81.94	82.60	78.22	78.45	77.16	78.98	78.20
Drop two (I_3)	0.0 (Ca_1)	75.77	82.66	80.50	82.15	80.27	76.23	76.21	74.46	75.21	75.53
	4.0 (Ca_2)	81.73	79.97	83.37	83.11	82.04	76.63	75.40	78.90	77.59	77.13
	8.0 (Ca_3)	81.67	83.65	81.86	82.41	82.40	74.34	77.70	78.01	78.43	77.12
	Mean	79.72	82.10	81.91	82.56	81.57	75.73	76.44	77.12	77.08	76.59
Means of Ca	0.0 (Ca_1)	79.01	82.74	80.57	80.06	80.60	77.33	77.84	75.33	78.04	77.14
	4.0 (Ca_2)	82.04	83.51	82.69	82.95	82.80	77.66	75.55	79.12	76.95	77.32
	8.0 (Ca_3)	82.47	82.67	83.76	81.62	82.63	77.38	78.24	79.22	80.04	78.72
	Mean	81.17	82.97	82.34	81.55		77.46	77.21	77.89	78.34	
				F.test	$LSD_{0.05}$				F.test	$LSD_{0.05}$	
	I			ns	--				*	0.91	
	Ca			*	0.81				*	0.73	
	I x Ca			ns	--				*	1.27	
	Co			ns	--				ns	--	
	I x Co			*	1.63				ns	--	
	Ca x Co			ns	--				ns	--	
	I x Ca xCo			*	2.82				ns	--	

Calcium significantly improved Qz in both seasons, with Ca_3 giving the highest values, especially in the second season (Hepler, 2005). The beneficial effect is due to calcium's structural role and its effect on reducing sugar losses.

Cobalt had no significant effects, but moderate doses (Co_2, Co_3) showed numerical increases, possibly due to improved enzyme activity and stress mitigation (Palit et al., 1994).

Interaction I × Ca was significant only in the second season. I × Co was significant in season one, with $I1Co_2$ and $I2Co_3$ performing best. The three-way interaction (I × Ca × Co) was significant only in season one, with $I1Ca_2Co_2$ and $I2Ca_3Co_3$ among the best combinations.

Sugar Yield (tons/fed)

Sugar yield is a key economic trait in sugar beet production, representing the amount of extractable sugar per unit area. It is a function of both root yield and sucrose concentration. Enhancing sugar yield is essential to maximize land productivity and sugar industry profitability.

Agronomic interventions, including optimized irrigation, calcium, and cobalt applications, play a crucial role in modulating physiological and biochemical pathways that influence sugar accumulation and partitioning.

According to Ober and Luterbacher (2002), sugar yield reflects the integration of genetic potential and environmental adaptation, particularly under abiotic stress conditions.

Sugar yield was significantly influenced by irrigation. Full irrigation (I1) and moderate water stress (I2) produced the highest sugar yields, with no significant difference between them in the second season. Severe stress (I3) significantly reduced yield in both seasons.

These results corroborate Jaggard et al. (2010) and Hergert et al. (2015), emphasizing sugar beet's tolerance to moderate stress and its susceptibility to severe drought. Water deficit reduces leaf area, photosynthetic activity, and assimilate transport to roots (Gzik, 1996; Zhang et al., 2013).

Calcium application significantly increased sugar yield. Ca_3 showed superior performance in both seasons, likely due to enhanced cell wall strength, root elongation, and sugar translocation (Marschner, 2012; Cakmak, 2005).

Calcium also improves nutrient uptake and root growth, especially under water stress (Shaaban et al., 2011).

Cobalt chloride had a marked positive effect on sugar yield. The 20 ppm treatment (Co_3) produced the highest values, supporting the idea that cobalt at moderate levels boosts chlorophyll synthesis, nitrogen metabolism, and stress resilience (Gad and Ismail, 2011; Yadav et al., 2011; Rao and Rao, 1981).

However, excessive levels can induce oxidative stress and diminish returns (Palit et al., 1994).

Irrigation × Cobalt interaction was significant. Under moderate stress (I2), 20 ppm cobalt ($I2Co_3$) gave the best sugar yield (5.96 t/fed in the first season).

Severe stress diminished cobalt's effectiveness, reflecting cobalt's role in mitigating stress up to a physiological threshold (Nair and Kuttan, 2004).

Calcium × Cobalt interaction showed that combinations such as Ca_2Co_3 and Ca_3Co_3 yielded the highest outputs, confirming synergism between structural stability (Ca) and metabolic enhancement (Co).

The three-way interaction (I × Ca × Co) was significant in both seasons. $I2Ca_3Co_3$ gave the highest yield (6.70 t/fed), illustrating the buffering capacity of optimal nutrition under moderate water stress.

These combinations optimized photosynthesis, assimilate partitioning, and root performance. Similar benefits of micronutrient synergy under stress were reported by Ali et al. (2016) and El-Sayed et al. (2015).

These findings underline the importance of integrated water and nutrient management in sugar beet cultivation, where fine-tuning calcium and cobalt under controlled irrigation can sustain high sugar productivity even under suboptimal environmental conditions.

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	
				F.test	$LSD_{0.05}$				F.test	$LSD_{0.05}$	
	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	

Conclusion

Moderate irrigation stress combined with foliar applications of calcium and cobalt significantly improved sugar beet quality traits. The best results were achieved under $I2Ca_3Co_3$ treatment. These results suggest that proper nutrient supplementation can partially offset the negative impacts of water stress.

Recommendation

To improve sugar beet quality under limited water availability, foliar application of 8 kg/fed calcium chloride and 20 ppm cobalt chloride is recommended, particularly under moderate irrigation conditions.

References

Ali AM; El-Sayed, AA, and Ibrahim, ME. (2016). Role of micronutrients in alleviating drought stress in crops. Journal of Agronomy and Crop Science, 202(4), 327–336.

Artyszak A, Gozdowski D, Kucińska K. (2014). The effect of foliar application of calcium and boron on the technological quality of sugar beet roots. Plant, Soil and Environment, 60(5), 205–211.

Awasthi R, Lal M. (2009). Role of calcium in plant responses to abiotic stresses. Current Science, 96(11), 1535–1542.

Bangerth F. (1979). Calcium-related physiological disorders of plants. Annual Review of Phytopathology, 17(1), 97–122.

Bassirirad H. (2000). Kinetics of nutrient uptake by roots: responses to global change. New Phytologist, 147(1), 155–169.

Bethke PC, Libourel, IG, Jones, RL. (2007). Nitric oxide reduces seed dormancy in barley by enhancing the expression of genes related to germination. Plant Physiology, 145(4), 145–155.

Brown, RJ, Lilliand, RH. (1964). Determination of alpha-amino nitrogen in sugar beet juice using auto-analyzer technique. Journal of the American Society of Sugar Beet Technologists, 12, 133–137.

Cakmak I. (2005). The role of potassium in alleviating detrimental effects of abiotic stresses in plants. Journal of Plant Nutrition and Soil Science, 168(4), 521–530.

Cook DA, Scott RK. (1993). The sugar beet crop: Science into practice. Chapman and Hall, London, 571–617.

Dart PJ, Day JM. (1971). Role of cobalt in nitrogen fixation by Rhizobium. Plant and Soil, 34(1): 245-254.

El-Sayed HM, El-Metwally IM. (2015). Effect of Calcium Chloride and Some Micronutrients on Growth and Productivity of Sugar Beet (Beta vulgaris L.). Middle East Journal of Agriculture Research 4 (4): 910–17.

Gad N. (2005). Interactive effect of cobalt and salinity on tomato plants. Egyptian Journal of Horticulture, 32(1), 123–138.

Gad N, Ismail AM. (2011). Response of sunflower plants to cobalt and nickel treatments. Research Journal of Agriculture and Biological Sciences, 7(2), 163–174.

Gzik A. (1996). Accumulation of proline and pattern of α-amino acids in sugar beet plants in response to osmotic, water and salt stress. Environmental and Experimental Botany, 36(1), 29–38.

Hepler PK. (2005). Calcium: A central regulator of plant growth and development. The Plant Cell, 17(8), 2142–2155.

Hergert GW, Schneekloth JP, Martin, DL. (2015). Sugar beet response to deficit irrigation. Irrigation Science, 33(6), 477–491.

Hirschi KD. (2004). The calcium conundrum. Both versatile nutrient and specific signal. Plant Physiology, 136(1): 2438-2442.

https://doi.org/10.1104/pp.104.046490.

Hochmal AK, Schulze S, Trompelt K, Hippler M. (2015). Calciumdependent regulation of photosynthesis. Biochim Biophys Acta.

Sep;1847(9):993-1003. doi: 10.1016/j.bbabio.2015.02.010.

Hoffmann, CM, Kluge-Severin, S. (2010). Relationships between photosynthesis and quality parameters of sugar beet under drought stress. Journal of Agronomy and Crop Science, 196(4), 247–256.

ICUMSA (1994). Methods of Sugar Analysis. International Commission for Uniform Methods of Sugar Analysis, Oxford University Press.

Jaggard KW, QiA, Ober ES. (2010). Possible changes to arable crop yields by 2050. Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1554), 2835–2851.

Kenter C, Hoffmann C. (2006). Sugar beet as affected by drought stress: Tolerance, storage and nitrogen metabolism. European Journal of Agronomy, 24(2), 101–112.

Kiran R, Singh A, Kumar V. (2010). Influence of cobalt on growth and metabolism of plants. Indian Journal of Plant Physiology, 15(3-4), 237–245.

Lide, DR. (2005). CRC Handbook of Chemistry and Physics (86th Ed.).

Marschner, H. (2012). Mineral nutrition of higher plants. 3rd Edition, Academic Press, London.

Nair MG, Kuttan R. (2004). Role of antioxidants and trace elements in enhancing stress tolerance. Plant Biology, 6(3), 235–242.

Ober ES, Luterbacher, MC. (2002). Genotypic variation for drought tolerance in sugar beet. Annals of Botany, 89(1), 9–18.

Palit S, Sharma A, Talukder G. (1994). Effects of cobalt on plants. The Botanical Review, 60(2), 149–181.

Pidgeon JD, Rickard JF, Jaggard KW. (2000). Water use and crop development in sugar beet grown under drought stress. Journal of Agricultural Science, 134(3), 343–352.

Rady MM. (2011). Effect of cobalt on growth, yield, and leaf anatomy of wheat under salinity stress. Plant Archives, 11(2): 705-712. https://www.plantarchives.org.

Rao MM, Rao AS. (1981). Effect of cobalt on plant growth and productivity. Plant and Soil, 63(2), 283–291.

Riley IT, Dilworth MJ. (1985). Cobalt status affects nitrogenase activity in Rhizobium lupini." New Phytologist, 100(3): 463-472.

Shaaban MM, El-Ghamry AM, Hassan MA. (2011). Role of calcium in ameliorating salt and drought stress in plants. Australian Journal of Basic and Applied Sciences, 5(11), 460–466.

Sapronova IA, Kochetkova AA, and Kurbatova, TA. (1979). Technological evaluation of sugar beet quality. Sakhar Promyshlennost (Sugar Industry), 3, 20–22. (As adopted by Abou-Korkas Sugar Company protocol).

Souri MK, Hatamian M. (2019). Biochemical functions of cobalt in plants: An overview. Plant Physiology Reports, 24, 137-146. https://doi.org/10.1007/s40502-019-00444-8.

Tarkalson DD, Eghball B, Schlegel, AJ. (2014). Impact of irrigation and tillage practices on sugar beet quality. Agricultural Water Management, 132, 115–123.

White, P.J. (2001). The pathways of calcium movement to the xylem. Journal of Experimental Botany, 52 (358): 891-899. https://doi.org/10.1093/jexbot/52.358.891.

White, PJ, Broadley, MR. (2003). Calcium in plants. Annals of Botany, 92(4), 487–511.

Yadav RK, Singh P, Kumaibrahimr S. (2011). Influence of cobalt and molybdenum on growth and yield of sunflower. International Journal of Agricultural Sciences, 7(2), 312–315.

Zhang Y, Wang X, Liu J. (2013). Water stress effects on growth, photosynthesis and carbohydrate metabolism in sugar beet. Plant Physiology and Biochemistry, 71, 123–130.