Journal of Soil Science and Plant Nutrition (2023) 23:2770–2785
https://doi.org/10.1007/s42729-023-01233-3

ORIGINAL PAPER

The Impacts of Applying Cobalt and Chitosan with Various Water Irrigation Schemes at Different Growth Stages of Corn on Macronutrient Uptake, Yield, and Water Use Efficiency

Ayman M. S. Elshamly[1] · **Saad M. A. Nassar**[2]

Received: 22 October 2022 / Accepted: 27 March 2023 / Published online: 12 April 2023

Abstract

While previous studies have demonstrated the positive effects of low cobalt (CB) levels and chitosan (CH) on yield and nutrient status, information about their individual and combined applications on plants under stress is still lacking. Therefore, we conducted a study to investigate CB and CH impacts on mitigating water stress during growth stages and their effects on corn macronutrient uptake and yield. Four irrigation schemes were employed, including (1) control (full irrigation), (2) 70% of irrigation water during the vegetative stage, (3) 70% of irrigation water during the flowering stage, and (4) 85% of irrigation water during both the vegetative and flowering stages. The plants were treated with (7.5 mg l^{-1}) CB injected into the irrigation water and CH foliar application (500 mg l^{-1}), while distilled water was used as the control. Plants that were exposed to water stress during the flowering stage and treated with CB, or those subjected to water stress during the vegetative stage and treated with CH, showed increased macronutrient uptake and growth, which had a positive effect on yield and water use efficiency. However, when CB and CH were applied in combination, their potential to enhance these features depended on the pattern of water stress adopted. Overall, the application of CB and CH was effective in mitigating water stress, and their combined application was particularly effective when 70% of irrigation water was applied during the flowering stage. This approach resulted in the highest yield, macronutrient uptake, water use efficiency, and tolerance index.

Keywords Corn · Cobalt · Chitosan · Water stress

1 Introduction

Despite the large consumption of available water for agricultural irrigation, only 5–10% of water uptake by plants is used for growth and development, with the remaining quantities lost through evaporation (Locke and Ort 2014; Shiferaw et al. 2021). As a result, there is an urgent need for innovative and unique methods to reduce water consumption, particularly in arid regions. To address this issue, there is growing interest in adopting certain applications that have additional roles, such as reducing the transpiration rate, increasing photosynthetic pigment, and positively impacting growth and physiological criteria. Ultimately, these measures can enhance yield components and improve water use efficiency (Abdallah et al. 2019; Mphande et al. 2020).

One pioneering approach that has gained traction is the adoption of chitosan (CH) as a nutrient substance that also reduces plant transpiration. CH is obtained by deacetylating chitin, and it is low in toxicity, easy to obtain, and an inexpensive compound that has been widely used in agriculture and pharmacy (Morin-Crini et al. 2019). Several studies have shown that foliar CH has numerous benefits, including reduced leaf transpiration (Attaran Dowom et al. 2022), improved plant growth and development under abiotic stresses (Coelho and Romano 2022), and the ability to counteract harmful effects on plants during unfavorable conditions. Moreover, CH has been found to enhance plant growth and yield by improving water uptake and essential nutrient absorption (Hidangmayum et al. 2019; Bibi et al. 2021; Makhlouf et al. 2022). However, the mechanisms

✉ Ayman M. S. Elshamly
ayman_saleh@nwrc.gov.eg

Saad M. A. Nassar
saad3a@drc.gov.eg

[1] Water Studies and Research Complex. National Water Research Center, Cairo, Egypt

[2] Department of Genetic Resources, Desert Research Center, El-Matareya, Cairo, Egypt

of CH in counteracting the harmful effects of unfavorable conditions are not well understood, although there is evidence that CH and its derivatives are effective in improving crop tolerance to water stress by alleviating the deleterious impacts of water stress on harvest index and yield (Rabêlo et al. 2019; Makhlouf et al. 2022).

On the other hand, CB is also used as an applied application. It is a transition element and a vital component of several enzymes and coenzymes. The interest in CB has arisen due to its multiple advantages, especially at low concentrations, such as increased percentage of stomatal closure, growth at par with yield parameters, and increased contents of macronutrients as well as micronutrients (Fang et al. 2017; Carvalho and Foulkes 2018; Hong et al. 2019). It is important to note the maximum allowable range for CB in plant parts due to health and environmental considerations. According to Codex Alimentarius (2001) and Ejaz et al. (2022), the maximum limit in grains is 50 mg kg^{-1}. Chen et al. (2021) and Lukin and Zhuikov (2022) mentioned that the maximum limit for cattle in forage crops, including grain, roughage, and succulent feed, is 1 mg kg^{-1}. Lukin and Zhuikov (2022) also indicated that corn has recorded the lowest CB contents in the grains amongst the studied crops, which include corn, barley, sunflower, winter wheat, soybean, pea, clover, sainfoin, alfalfa, and white lupine.

Based on the foregoing, it can be assumed that the application of CB or CH has the potential to reduce water loss by transpiration and increase crop productivity. However, the important goal of this research is to determine the impacts of the sole and combined applications of CB and CH on mitigating water stress conditions at the most sensitive growth stages.

To test the hypothesis, it is necessary to understand the impacts of water stress on plants. Knowledge of the effects of water deficiency on plant growth and the responses of plants to these stressful conditions can help develop technologies to improve crop performance in water-limited environments. This is particularly important given current climate change scenarios (Ávila et al. 2022). Plant responses to water stress can vary depending on several factors, such as stress intensity, duration, progression rate, and the stage of occurrence (Ma et al. 2020). Therefore, it is essential to identify the growth stages of corn in sequential stages to better understand the impacts of water stress on this crop. Wang et al. (2019) defined and divided the growth stages of corn into sequential stages, including the seedling stage (V1–V5), vegetative jointing stage (V6–V10), flowering stage, and maturation stage (milk to physiological maturity).

Several researchers have studied the sensitivity of corn to drought throughout the growing season, and their findings vary regarding the optimal timing for applying water stress. Ha (2017) suggested that corn crops are highly susceptible to water stress during the flowering stage, whereas applying water stress during the vegetative or maturation stages may have less impact on grain yield. Similarly, Na et al. (2018) reported that grain production significantly decreased with progressive water stress during either the vegetative or reproductive stage due to a decrease in kernels. Li et al. (2018) found that water deficit during the vegetative growth period negatively affected leaf development and assimilate flow, which ultimately retarded kernel development. Additionally, applying water deficit just before and during flowering reduced kernel sink. Comas et al. (2019) noted that approximately 17% of evapotranspiration could be saved if corn crops were exposed to water stress during the late vegetative growth stages and completed the rest of the growing season with regular or nearly full evapotranspiration.

Water stress during the pre-flowering and grain-filling stages significantly affects plant performance and reduces yield (Sah et al. 2020; Cheng et al. 2021). However, the optimal period for applying water stress to corn crops is not well defined, as previous studies have reported conflicting findings.

However, no previous studies have investigated the effects of sole and combined applications of (CB and CH) on corn plants in terms of their tolerance to water stress during the vegetative and flowering growth stages. Therefore, we conducted an experiment using plants from these stages to test the hypothesis that (CB and CH) applications would enhance macronutrient uptake, yield traits, and grain yield, thereby mitigating the deleterious effects of water stress and increasing the water use efficiency and irrigation water use efficiency of corn. In addition, we evaluated the combined effects of these applications on the multiplication of these benefits and monitored the environmental suitability resulting from the adoption of CB.

2 Materials and Methods

2.1 Study Site

The field experiment was carried out during the 2020 and 2021 growing seasons at the Water Studies and Research Complex station's experimental farm, which is situated in Toshka-Abu Simbel City, Egypt. The station is located at 22°, 2′. 11′ N longitude of 31°,35′0.43′E longitude, with an altitude of 188 m. The area is situated in the southern part of Egypt and is known for its hot, dry summers, moderate winters, and lack of rainfall.

2.2 Soil, Irrigation Water, and Meteorological Data

The experimental site had a soil texture of loamy sand, and its main physical and chemical properties are listed in Table 1. Well groundwater was the primary source of

Table 1 Some physicochemical properties and water status of soil at the experimental site during the 2020/2021 growing seasons

Parameter	Unit	Value	
		0–30	30–60
Mechanical analysis			
Sand	% by weight	86.76 ± 0.71	88.80 ± 0.70
Silt	% by weight	3.80 ± 0.74	4.00 ± 0.76
Clay	% by weight	9.44 ± 0.72	7.20 ± 0.75
Bulk density	g cm^{-1}	1.61 ± 0.71	1.55 ± 0.71
Texture	Loamy sand		
Chemical analysis			
pH (1:2.5 suspension)		7.93 ± 0.71	7.93 ± 0.71
EC	ds m^{-1}	1.71 ± 0.72	0.85 ± 0.98
$CaCO_3$	%	1.7 ± 0.72	1.6 ± 0.72
Calcium cations (Ca^{+2})	mg kg^{-1}	243.2 ± 0.74	121.6 ± 0.76
Magnesium cations (Mg^{+2})	mg kg^{-1}	108.8 ± 0.79	51.2 ± 0.74
Sodium cations (Na^+)	mg kg^{-1}	704.0 ± 0.72	345.6 ± 0.74
Potassium cations (K^+)	mg kg^{-1}	38.4 ± 0.73	19.0 ± 0.83
Chloride anions (Cl^-)	mg kg^{-1}	678.4 ± 0.72	339.2 ± 0.75
Bicarbonate anions (HCO_3^-)	mg kg^{-1}	172.8 ± 0.71	89.6 ± 0.75
Sulfate anions (SO_4^{-2})	mg kg^{-1}	236.8 ± 0.74	115.2 ± 0.73
Water status			
Field capacity	% by volume	12.5 ± 0.71	11.2 ± 0.72
Wilting point	% by volume	4.5 ± 0.74	3.5 ± 0.72
Saturation percent	% by volume	26.50 ± 0.71	25.25 ± 0.71

EC electrical conductivity. Each value represents the mean of replications ± standard errors

Table 2 Water chemical properties at the experimental site during the 2020/2021 growing seasons

Parameter	Unit	Value
pH		6.73 ± 0.71
TDS	mg l^{-1}	512.3 ± 0.76
HCO_3	mg l^{-1}	78.3 ± 5.26
Calcium cations (Ca^{+2})	mg l^{-1}	57.1 ± 0.72
Magnesium cations (Mg^{+2})	mg l^{-1}	16.8 ± 0.84
Sodium cations (Na^+)	mg l^{-1}	101.0 ± 0.72
Potassium cations (K^+)	mg l^{-1}	42.0 ± 5.71
Chloride anions (Cl^-)	mg l^{-1}	104.0 ± 0.71
Sulfate anions (SO_4^{-2})	mg l^{-1}	194.7 ± 0.96
SAR		3.1 ± 0.71
Rsc		− 4.4 ± 0.72
SSP	%	46.6 ± 0.71

Each value represents the mean of replications ± standard errors. *TDS* total dissolved solids, *RSC* residual sodium carbonate, *SAR* sodium adsorption ratio, *SSP* soluble sodium percent

irrigation water, and the chemical properties of the water during the growing seasons are presented in Table 2. Daily meteorological data from September to January in both growing seasons were collected from the nearby Toshka Agrometeorological Station, located approximately 100 m from the experiment site. Table 3 shows the monthly relative humidity, maximum and minimum temperature, precipitation, and wind speed during this period.

2.3 Experimental Design

The experiment was designed as a strip-split plot with five replications and conducted under a drip irrigation system. The vertical plots were assigned to irrigation regimes, while the horizontal plots were allocated to CB, CH treatments, and their combination. The irrigation treatments included full irrigation (100% of total calculated irrigation at all growth stages), short-term and moderate water stress conditions (70% of irrigation water during the vegetative stage and 100% in the remaining growth stages), long-term and moderate water stress conditions (70% of irrigation water during the flowering stage and 100% in the remaining growth stages), and prolonged and mild water stress conditions (85% of irrigation water during each of the vegetative and flowering stages and 100% in the remaining growth stages). The CB treatment (7.5 mg l^{-1}) was applied as an injection ground drench with irrigated water once after 30 days from emergence, while the CH treatment (500 mg l^{-1}) was applied as foliar applications, four times every 15 days, initiated after four weeks of emergence. The experiment consisted of four plots, each with five replications, and the plot size was 5 × 3.5 m (17.5 m^2), as shown in (Fig S1). All plots were irrigated equally after sowing, and then the irrigation treatments were applied.

2.4 Crop Management

The experimental location was properly prepared as per the guidelines for recently recovered soil provided by the Egyptian Ministry of Agriculture. Soil was amended with calcium superphosphate (15.5% P_2O_5) at a rate of 710 kg ha^{-1} during the tillage process. Three applications of potassium sulfate (48% K_2O) at a rate of 235 kg ha^{-1} were made at days 60, 75, and 90 of the cultivation. With the irrigation water, 950 kg N in the form of ammonium nitrate (33.5% N) was injected in the irrigation system. After 15 days of sowing, every 3–4 days up to the flowering growth stage, 50 kg of nitrogen was sprayed per portion. The initial planting of corn grains (Zea mays L., cv Triple Hybrid 352) was done in the hills during the first week of September 2020, and the second planting was done on September 8, 2021, at a rate of 35 kg ha^{-1}. The jet of a dripper was positioned to seed grains on only one side. The distance between plants was 20 cm, the distance between rows was 50 cm, and the depth of the sowing was 5 cm. After 2 weeks of emergence, the plants

Table 3 Weather data from the experimental site throughout the period of (September to December) during the 2017/2021 growing seasons

		Temperature (°C)		Relative humidity (%)		Wind speed (MS^{-1})	* Sunshine hours	Precipitation (mm)
		Max	Min	Max	Min			
September	2017	40.0±0.21	23.3±0.21	36.1±0.22	7.1± 0.25	3.1± 0.19	12.4± 0.19	0
	2018	37.6±0.20	22.7±0.20	38.5±0.23	9.6± 0.26	3.1± 0.19	12.4± 0.19	0
	2019	40.7±0.19	24.3±0.20	33.4±0.21	6.5± 0.24	2.8± 0.23	12.4± 0.19	0
	2020	39.5±0.20	22.2±0.20	35.1±0.22	9.3± 0.32	2.9± 0.24	12.4± 0.19	0
	2021	41.5±0.19	24.4±0.20	37.1±0.21	9.4± 0.31	3.2± 0.24	12.4± 0.19	0
October	2017	37.3±0.20	23.4±0.21	41.2±0.20	14.9± 0.30	2.9± 0.24	11.3± 0.18	0
	2018	35.9±0.20	20.3±0.20	42.0±0.21	10.6± 0.28	3.5± 0.22	11.3± 0.18	0
	2019	37.0±0.20	21.5±0.20	41.9±0.20	10.9± 0.30	3.0± 0.19	11.3± 0.18	0
	2020	34.0± 0.20	19.3± 0.20	41.0± 0.20	10.6± 0.28	3.2± 0.20	11.3± 0.18	0
	2021	36.5±0.20	21.0±0.21	43.0±0.21	12.6± 0.29	3.8± 0.20	11.3± 0.18	0
November	2017	27.8±0.20	12.8±0.19	56.8±0.23	18.3± 0.30	3.0± 0.21	10.3± 0.20	0
	2018	30.8±0.20	15.4±0.20	44.9±0.21	13.6± 0.31	3.9± 0.24	10.3± 0.20	0
	2019	28.9±0.20	13.2±0.20	56.8±0.22	17.3± 0.30	3.0± 0.21	10.3± 0.20	0
	2020	29.0±0.20	14.0±0.21	52.2±0.22	17.0± 0.29	2.0± 0.23	10.3± 0.20	0
	2021	31.8±0.20	16.0±0.20	35.0±0.22	19.3± 0.25	2.5± 0.24	10.3± 0.20	0
December	2017	23.3±0.18	9.4±0.22	62.3±0.19	24.6± 0.25	2.8± 0.23	10.0± 0.21	0
	2018	25.4±0.19	10.5±0.22	54.7±0.22	22.4± 0.28	3.5± 0.23	10.0± 0.21	0
	2019	27.6±0.21	11.8±0.19	52.3±0.21	20.6± 0.24	2.3± 0.22	10.0± 0.21	0
	2020	26.6± 0.20	10.8± 0.23	51.6± 0.21	19.6± 0.24	2.3± 0.22	10.0± 0.21	0
	2021	28.6±0.19	12.8±0.21	53.0±0.22	21.6± 0.24	2.3± 0.22	10.0± 0.21	0

*Sunshine hours were measured manually

Max maximum temperature, *Min* minimum temperature, MS^{-1} m $second^{-1}$, *mm* millimeter. The meteorological data were obtained from Toshka Agrometeorological Station, Egypt. Values are the mean of replicates ± standard errors

were trimmed to maintain a population density of 10 plants m^{-2} and ensure that just one plant would grow in each hill (100,000 plants ha^{-1}).

2.5 Calculations Related to Irrigation

2.5.1 The Soil Water Balance

The daily soil water balance was determined as the following equation of (El Namas 2020; Aydinsakir et al. 2021)

$$ETc = IW + P \pm \Delta S \pm R \pm D \qquad (1)$$

where:

ETc	crop evapotranspiration (mm).
IW	amount of irrigation water (mm).
P	effective rainfall (mm). (According to the measured data from Toshka agrometeorological station, P = zero).
ΔS	change in soil water storage (mm).
R	surface runoff (mm).
D	amount of drainage water (mm).

Since the quantity of irrigation water was controlled, surface runoff was neglected, whereas the experimental site has a flat topography. Likewise, the amounts of drainage water were considered negligible (zero) as there was no high ground water problem in the experimental site (the groundwater table was 25–30 m).

2.5.2 The Actual Irrigation Water Applied

Actual irrigation water applied (100% IW) was calculated according to the equation of Zotarelli et al. (2022) as follows:

$$\mathrm{IW} = \frac{\mathrm{ETc} \times \mathrm{Kr}}{\mathrm{ER}} + \mathrm{Lf} \qquad (2)$$

where

IW	irrigation water applied (mm).
ETc	crop evapotranspiration (mm).
Kr	reduction factor which depends on ground cover, this is equivalent to 0.7 for mature plants.
Lf	leaching factor 10% (since the electrical conductivity of soil solution is low, Lf was neglected).
ER	irrigation system efficiency% (the efficiency for drip irrigation = 85%).

Furthermore, to apply the targeted water amounts the (mm) units were converted to (m^3 ha $^{-1}$) by multiplying (mm day^{-1}) values with a coefficient of 10, as mentioned by (Allen et al. 1998; Danielescu et al. 2022). The irrigation amounts for the other treatments were proportionally obtained from the (100% IWc) treatment. The ETc and IW which are applied to corn crops at the different growth stages during the seasons of 2020 and 2021 are presented in Table 4.

2.5.3 Water Use Efficiency

Mathematically water use efficiency (WUE) can be represented as:

$$\mathrm{WUE} = \left(\frac{\mathrm{GY}}{\mathrm{ETc}}\right) \tag{3}$$

where

WUE water use efficiency (kg m^{-3}).

GY yield (kg ha^{-1}) and.

ETc equals seasonal actual evapotranspiration (mm).

2.5.4 Irrigation Water Use Efficiency

Mathematically irrigation water use efficiency (IWUE) can be represented as:

$$\mathrm{IWUE} = \left(\frac{\mathrm{GY}}{\mathrm{IW}}\right) \tag{4}$$

where

IWUE irrigation water use efficiency (kg m^{-3}).

GY yield (kg ha^{-1}) and.

IW irrigation water applied (m^3 ha^{-1}).

2.6 Measurements

Ten plants were randomly selected from each plot and collected after the corn plants had reached full maturity (about 16 weeks). The average of ten plants' worth of information was collected, including ear count, ear weight in grams, 1000-grain index weight in grams after adjusting for moisture content of 15.5%, and grain yield. Each plot's data was calculated, and then the findings were transformed into kilograms per hectare.

2.7 Macronutrient Analysis

2.7.1 Measurements of nitrogen, Phosphorus, and Potassium

The maize kernels were weighed and then ground into a powder. Using Micro-equipment, Kjeldahl's as described in (Ray et al. 2020). In contrast to the measurement of phosphorus (P) using a UV–VIS spectrophotometer and the determination of potassium (K) with a flame photometer, as outlined by (Abdallah et al. 2019; Mohammed et al. 2021).

Table 4 The actual irrigation water applied for corn at different growth stages at the experimental site during the 2020/2021 growing seasons

		Growth stages				Total
		Seedling	Vegetative	Flowering	Maturation	
ETC (mm)		112.5	243.5	365.2	99.0	820.2
Irrigation system efficiency%		0.85				
IW (mm)		132.4	286.5	430.0	116.5	965.4
Leaching factor		13.2	29.0	43.0	12.0	97.2
The total of IW (m3 ha -1)	Non-water stress- 100% IWc at (Gs,Gv,Gf, Gm)	1456.0	3155.0	4730.0	1285.0	10626.0
	Short-term and moderate water stress - 70% IW (Gv) & 100% IW at (Gs,Gf,Gm)	1456.0	2208.5	4730.0	1285.0	9680.0
	Long-term and moderate water stress – 70% IW at (Gf) & 100% IW at (Gs,Gv,Gm)	1456.0	3155.0	3311.0	1285.0	9207.0
	Prolonged and mild water stress – 85% IW at (Gv,Gf) & 100% IW at (Gs,Gm)	1456.0	2682.0	4021.0	1285.0	9444.0

ETC crop evapotranspiration, *IW* irrigation water applied, *mm* millimeter, m^3 h^{-1} cubic meter per hectare, 100,85, and 70% IW (applying 100,85, and 70% of irrigation requirements), *Gs* seedling growth stage, *Gv* vegetative growth stage, *Gf* flowering growth stage, *Gm* maturity growth stage.

2.7.2 Measurements of CB

At harvest time, kernels of maize were collected from each ear in each CB-treated plot. For metal analysis, the dried, prepared samples of grains and soil were crushed into a powder and kept. Afterwards, it was figured out using flame atomic absorption spectroscopy in an acetylene-air flame, as stated by (Wojcieszek and Ruzik 2020). After determining the CB content in both the corn grain and the treated soil, the bioconcentration coefficient was computed using the following formula (Ali et al. 2013; Mleczek et al. 2013):

$$\text{BCF} = \text{ CB content in grain }/\text{CB content in soil expressed as mg kg. }^{-1}$$

In this concern, BCF values greater than one means that a plant is a hyperaccumulator (Usman et al. 2019).

Moreover, from the following formula the tolerance index (TI) was computed:

$$\text{TI} = \text{ biomass yield based on a CB} - \text{treated object}/\text{ biomass yield based on the control object}$$

The tolerance index greater than 1 indicates a positive influence, whereas TI less than 1 indicates a negative influence of CB on plant growth and development (Kosiorek and Wyszkowski 2019a, b).

2.8 Statistical Analysis

The analysis of variance (two way-ANOVA) was used to estimate the statistical differences between the treatments by using SAS software version 9.1 (SAS Institute, Cary, NC, USA). The means were separated through a revised least significant difference (LSD) test at the 0.05 level.

3 Results

3.1 The Effect of Water Stress Schemes, CB, and CH on Corn Yield Traits

ANOVA findings showed that in both growing seasons, the water stress scheme and application treatments had significant individual impacts ($p < 0.05$) and interactive effects on the weight of corn ears. According to the data shown in (Fig. 1a), the weight of the ears was greater in the first and second seasons under separated CH application than under control CH, with the exception of the long-term and mild water stress schemes. As compared to the control (CB and CH) treatment, the ears' weight rose in both the first and second growing seasons when a combination of CB and CH was applied alongside diverse water stress schemes, with the exception of the short-term and moderate water stress schemes. A substantial reduction in corn ear weight was seen between the first and second growing seasons after adopting a short-term and moderate water stress scheme and using a single application of CB (Fig. 1a).

On the contrary, a negative significant difference in the corn grain index was seen when the tap water treatment (100% IWc) was compared between the first and second growing seasons (Fig. 1c). Nevertheless, this unfavorable effect diminished when long-term, mild water stress was implemented in addition to the single administration of (CB and CH). To get the best corn grain index in the first and second seasons, it is just as effective to adopt a long-term and moderate water stress scheme and apply combined applications of (CB and CH) as it is to implement a non-water stress scheme and apply the combined application of (CB and CH).

To maximize corn plant height in the first growing season, either CB alone or CB with CH was applied to provide a protracted, moderate water stress scheme (Fig. 2a). Nevertheless, in the second season, a lengthy and moderate water stress scheme with the application of tap water was considerably matched by the application of either CB or CH alone, regardless of whether the two were applied separately or together, for achieving the largest corn plant height.

As can be seen in (Fig. 2b), adopting a long-term and moderate water stress scheme or a prolonged and mild water stress scheme and applying combined applications of (CB and CH) significantly matched either adopting a non-water stress scheme and applying the combined application of (CB and CH) or adopting a short-term and moderate water stress scheme and applying separate applications of CH to achieve the longest corn ear length in the first and second seasons.

Corn production was significantly affected in both the first and second growing seasons by water stress scheme, application treatment, and their interactions (all $p < 0.05$). Long-term and moderate water stress schemes in the first and second growing seasons resulted in reduced maize yields when compared to the tap water treatment (as shown in Fig. 2c). The adoption of a short-term and moderate scheme resulted in a decreased corn yield in the first and second growing seasons when compared to the adoption of a non-water stress scheme or the adoption of a long-term and moderate water stress scheme with the combined applications of (CB and CH). In the same vein, the combination application of (CB

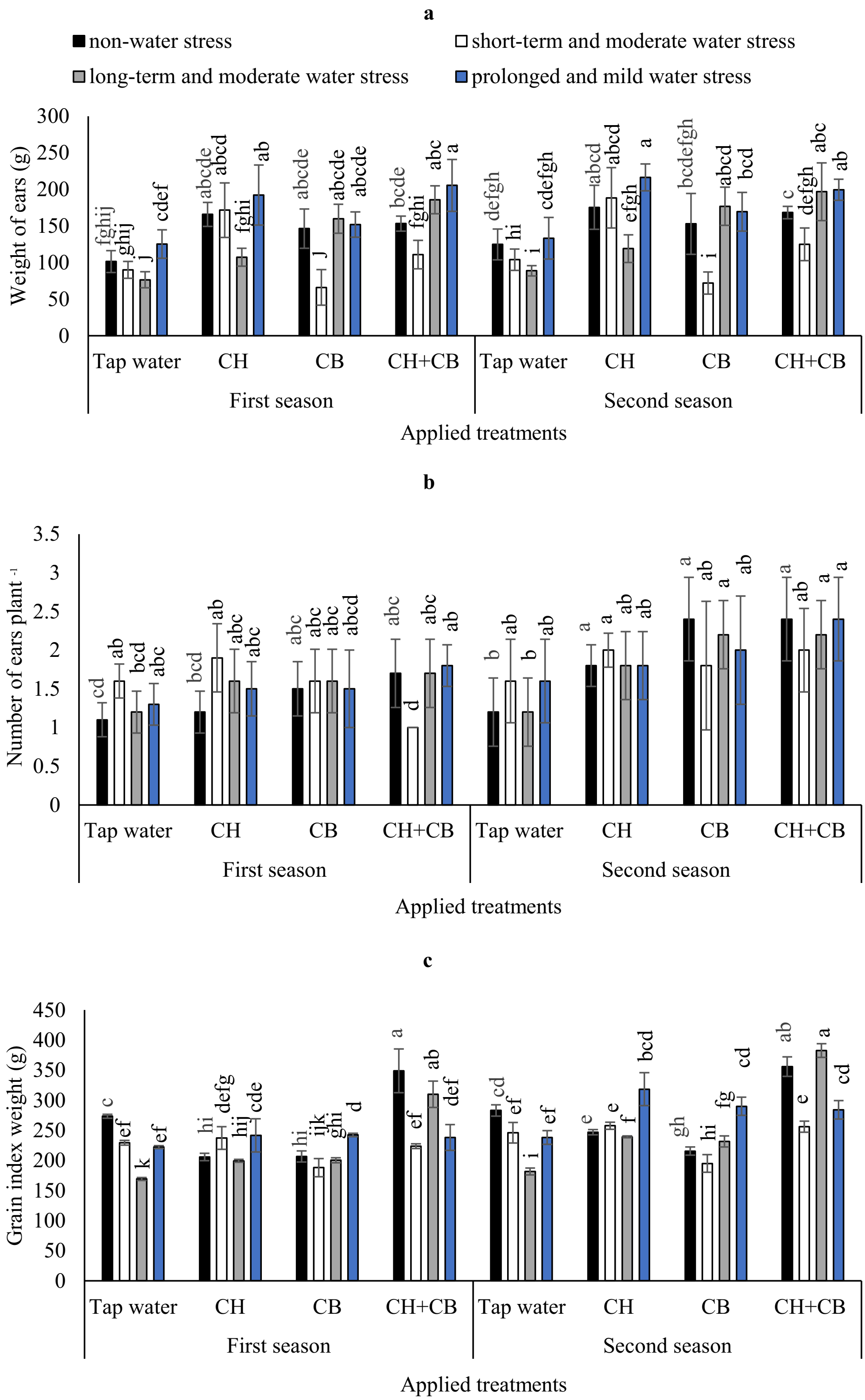

Fig. 1 The interactive influence of implementing (non water stress and water stress schemes at different growth stages) with adding individual or combined applications of cobalt and chitosan on **a** the weight of ears, **b** the number of ears per plant, and **c)** grain index weight in two growing seasons of 2020/2021. Error bars indicate standard errors from the mean. Bars with different letters are statistically significant at $p \leq 0.05$. Abbreviations: Tap water (control, spray with pure water); CH (spray with 500 mg l^{-1} chitosan); and CB (7.5 mg $l^{-}.^{1}$ cobalt was applied injection in the irrigation water)

and CH) remains clearly better in maximizing corn production (Fig. 2c). Adopting a non-water-stress scheme and applying a combined application of (CB and CH) were equivalent to adopting a short-term and moderate water-stress scheme and applying sole applications of CH, and to adopting a long-term and moderate water-stress scheme and applying a combined application of (CB and CH), respectively, in the first season (CB and

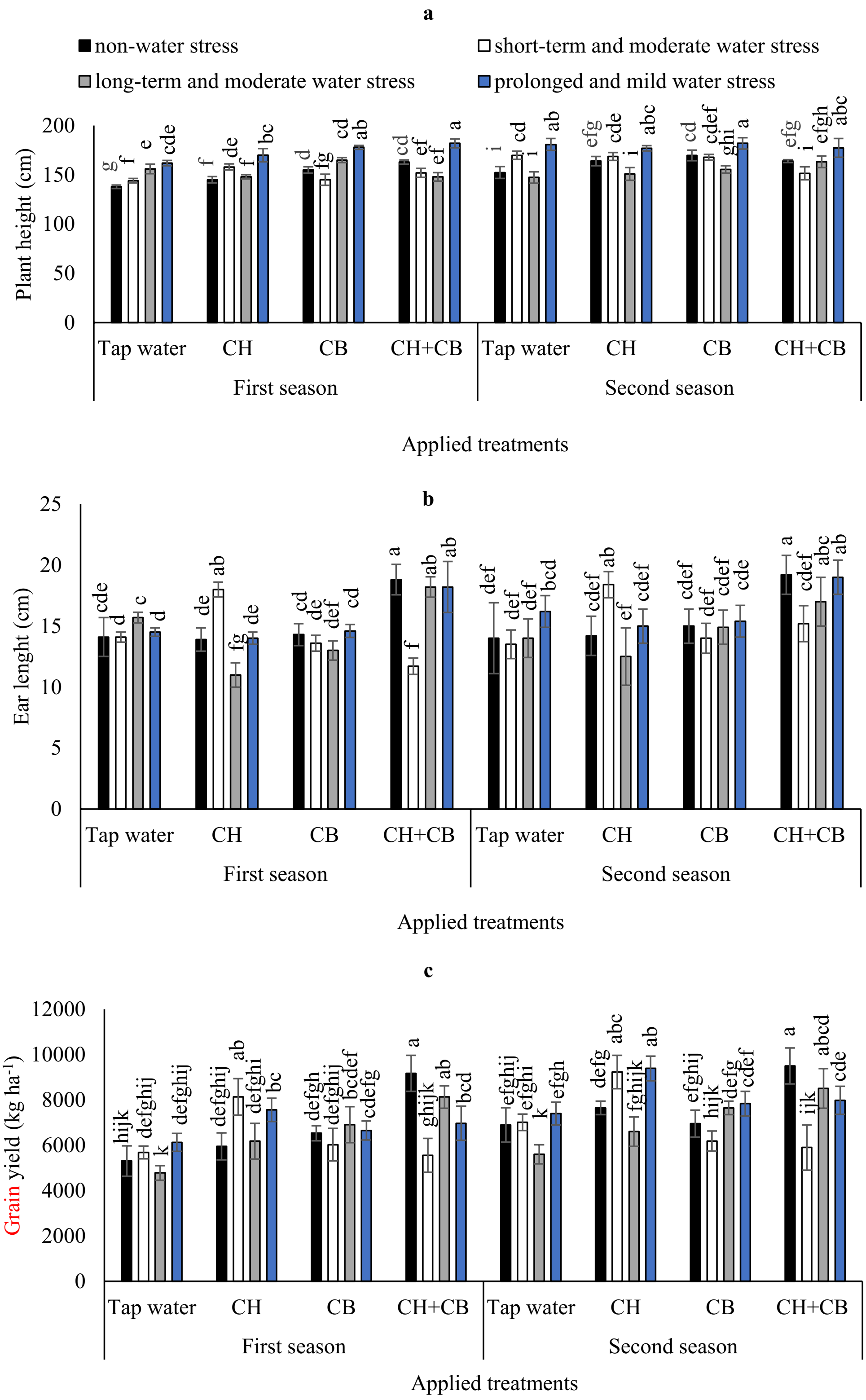

Fig. 2 The interactive influence of implementing (non water stress and water stress schemes at different growth stages) with adding individual or combined applications of cobalt and chitosan on **a** plant height, **b** ear length, and **c** corn grain yield in two growing seasons of 2020/2021. Error bars indicate standard errors from the mean. Bars with different letters are statistically significant at $p \leq 0.05$. Abbreviations: Tap water (control, spray with pure water); CH (spray with 500 mg l^{-1} chitosan); and CB (7.5 mg $l^{-}.^{1}$ cobalt was applied injection in the irrigation water)

CH). And in the second season, there was no discernible difference between using a non-water stress scheme or a long-term and moderate water stress scheme with a combined application of CH and using a short-term and moderate water stress scheme with separate applications of CH (CB and CH).

3.2 The Effects of Adopting Various Irrigation Schemes and Applying CB and CH on Macronutrient Uptake

By comparing tap water treatment from the first and second seasons (Fig. 3a), we see that choosing a long-term and moderate water stress scheme or a prolonged and mild water stress scheme results in a significantly different N content than using a non-water stress scheme. Adopting a long-term and moderate water stress scheme x applying separated or combined applications of (CB and CH) resulted in the highest N content after the first season, while adopting a short-term and moderate water stress scheme × sole applications of CH or adopting a short-term and moderate water stress scheme × combined application of (CB and CH) were significantly equal. Similarly, in the second season, there was no discernible difference between using a long-term and moderate water stress scheme and either applying separated or combined applications or using a short-term and moderate water stress scheme and either applying sole applications of CH or by the combined application of (CB and CH) (sole applications of CB or with the combined applications). Results also showed that the long-term and mild water stress scheme resulted in the lowest N concentration in the first and second growing seasons when compared to the tap water treatment.

The ANOVA findings showed that in the first and second seasons, the influence of water stress scheme and application treatments ($p < 0.05$) on P content was significant, whereas the interaction effects were not. According to the data in (Fig. 3b), executing a long-term and moderate water stress scheme and applying the combined application of (CB and CH) were statistically equivalent in terms of yielding the greatest P content in the first season (CB and CH). In the second season, however, there was no discernible difference between the effects of adopting a long-term and mild water stress scheme × (sole or combined applications of CB and CH) and those of adopting a long-term and moderate water stress scheme × (adopting a non-water stress scheme) or a short-term and moderate scheme × separated applications of CB.

Non-water stress scheme × solo applications of CH in the first season and non-water stress scheme x separated applications of CB or CH in the second season resulted in lower K levels, as shown in (Fig. 3c). The maximum first-season K content was achieved by combining applications with either a long-term and moderate water stress scheme x solo applications of CB or a short-term and moderate water stress scheme × sole applications of CH. Similarly, in the second season, the highest K content was achieved through the adoption of the long-term and moderate water stress scheme × sole applications of CH, which was statistically equivalent to the application of the combined applications of (CB and CH) × (the long-term and moderate water stress scheme or the prolonged and mild water stress scheme).

3.3 The Effects of Implementing Various Schemes at Different Growth Stages and Applying (CB and CH) on WUE and IWUE

As can be observed in (Fig. 4a), the maximum WUE was achieved in the first season through a combination of (CB and CH) applications × (adopting non-water stress scheme or long-term and moderate water stress scheme) × (adopting short-term and moderate water stress scheme). It was shown that the maximum WUE could be achieved in the second season by using combination applications of (CB and CH) × (adopting non-water stress scheme or by adopting long-term and moderate stress) × (adopting short-term and moderate water stress).

Yet, when it comes to maximizing corn's IWUE, a solitary application of CH or a combination of CB and CH remains preferable (Fig. 4b). In this regard, applying sole applications of CB × adopting long-term and moderate water stress scheme was significantly equal to applying sole applications of CH × adopting short-term and moderate water stress scheme, for attaining the highest IWUE in the first season. Similarly, in the second season, the highest IWUE was achieved by adopting (the short-term and moderate scheme or adopting the prolonged and mild scheme) × applying sole applications of CH, which was statistically equivalent to adopting (the short-term and moderate scheme or adopting the prolonged and mild scheme) × applying combined applications of (CB and CH).

3.4 The Effects of Implementing Various Schemes at Different Growth Stages and Applying (CB and CH) on Cobalt Content (Soil – Grains), BCF, and TI

The ANOVA findings showed that in the first and second seasons, the individual effect of application treatments ($p < 0.05$) on CB content in soil was significant, whereas the individual effect of water stress scheme was not. Nevertheless, in the first and second seasons, the CB content in soil was significantly affected by the interaction effects of water stress scheme and application treatments ($p < 0.05$). In the first two seasons, applying a combined application of CB and CH using a short-term and moderate scheme improved the soil's CB content, as shown in (Fig. 5a). Nevertheless, using a non-water-stress method and a combined application of CB and CH during the first and second growing seasons resulted in the lowest CB level in the soil. Nevertheless, data shown in (Fig. 5b) showed that solitary applications of CB or the combination application

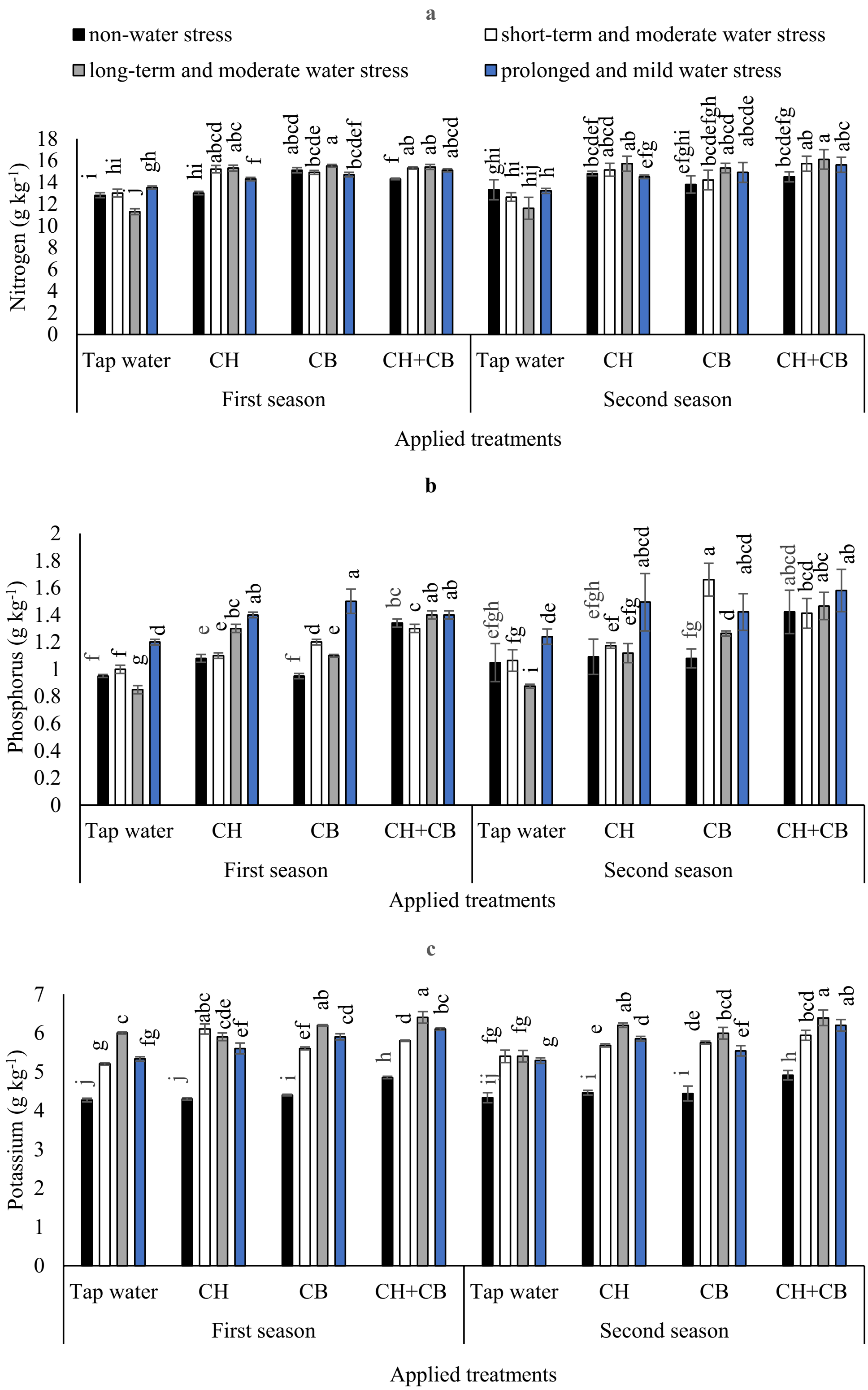

Fig. 3 The interactive influence of implementing (non water stress and water stress schemes at different growth stages) with adding individual or combined applications of cobalt and chitosan on **a** nitrogen content, **b** phosphorus content, and **c** potassium content in corn grains in two growing seasons of 2020/2021. Error bars indicate standard errors from the mean. Bars with different letters are statistically significant at $p \leq 0.05$. Abbreviations: Tap water (control, spray with pure water); CH (spray with 500 mg l^{-1} chitosan); and CB (7.5 mg $l^{-}.^{1}$ cobalt was applied injection in the irrigation water)

of (CB and CH) when adopting a protracted and moderate water stress scheme enhanced CB content in corn grains compared to the non-water stress scheme in the first and second growing seasons. Yet, the long-term and moderate water stress × using (the solitary CB or the combination application of (CB and CH) scheme yielded the lowest CB content value in the grains across the first and second growing seasons.

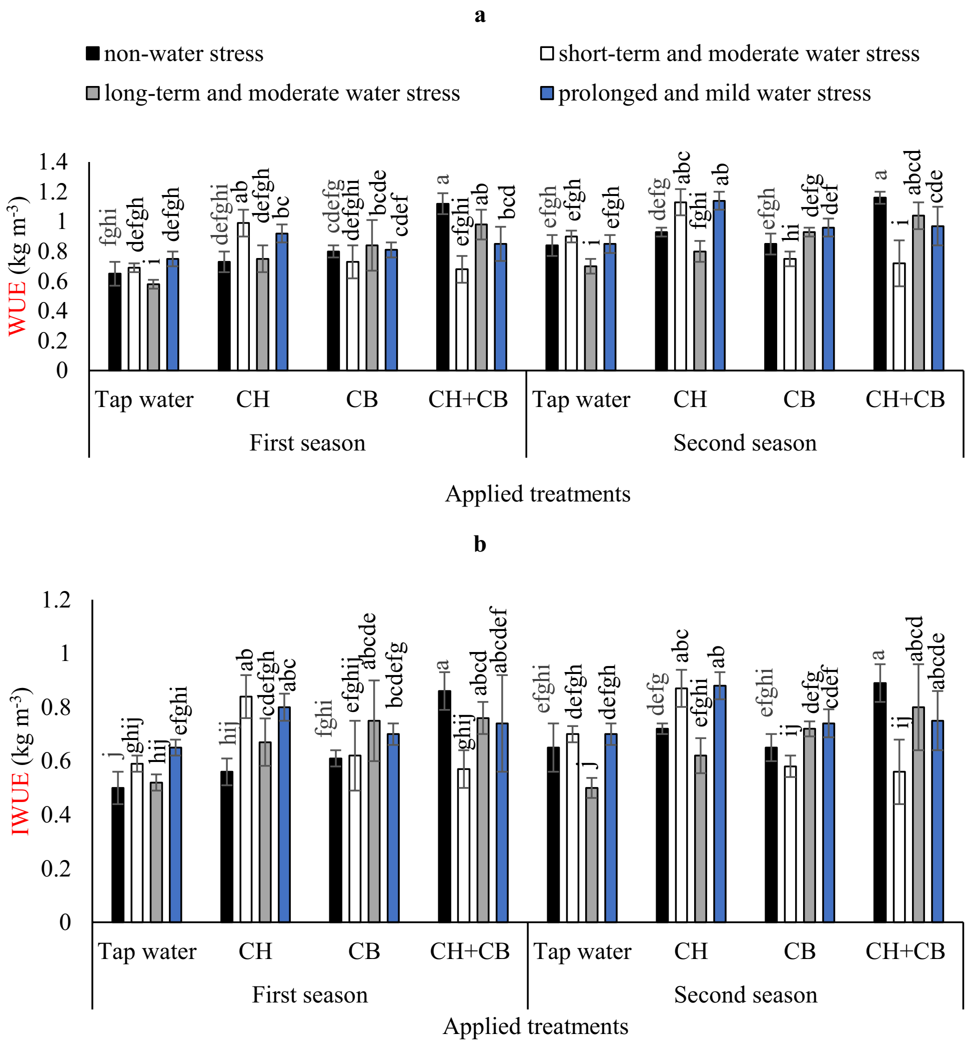

Fig. 4 The interactive influence of implementing (non water stress and water stress schemes at different growth stages) with adding individual or combined applications of cobalt and chitosan on **a** water use efficiency (WUE), and **b** irrigation water use efficiency (IWUE) of corn in two growing seasons of 2020/2021. Error bars indicate standard errors from the mean. Bars with different letters are statistically significant at $p \leq 0.05$. Abbreviations: Tap water (control, spray with pure water); CH (spray with 500 mg l^{-1} chitosan); and CB (7.5 mg $l^{-}.^{1}$ cobalt was applied injection in the irrigation water)

For the best BCF values in the first season, the adoption of either the non-water stress scheme or the prolonged and mild water stress scheme × the application of sole applications of CB were statistically equivalent to the adoption of either the combined application of (CB and CH) x the application of sole applications of CB (Fig. 5c). Although in the second season, the best BCF values may be attained by the use of scheme x (either solitary applications of CB or combination applications) and extended, mild water stress.

Nevertheless, as noted in, the lowest amounts of TI were achieved by using a short-term and moderate scheme during the first season (Fig. 6). Adopting (non-water stress scheme or a long-term and mild water stress scheme) × applying the sole applications of CB were significantly equal to (the non-water stress scheme or a long-term and moderate water stress scheme) × applying the combined application of (CB and CH), for achieving the highest TI content in the first season. By using a non-water stress scheme × applying the combined application of (CB and CH) produced the greatest TI concentration in the second season.

4 Discussion

In dry environments, yield is affected by a number of variables, although drought duration is often cited as the primary limiting factor. While corn can tolerate brief periods of water stress, the crop's reaction to extended water stress relies on the severity of the stress, the length of time the plant is under stress, and the stage the plant is in its growth. As this research has shown, using a long-term and moderate water stress scheme results in a decreased corn yield. We conclude that under the long-term and moderate water stress scheme, plants are subjected to a critical reduction of the soil moisture around the roots, resulting in a decrease in grain index weight and in the uptake of nutrients from the rhizosphere (N and P), in particular, that P promotes root growth (Heydari et al. 2019; Bechtaoui et al. 2021). This is because P is also responsible in the determination of root architecture, so lateral root growth has increased over primary root growth as a result of the decrease in P uptake and the decrease in the penetration of the root system within the soil due to the decrease in root cell

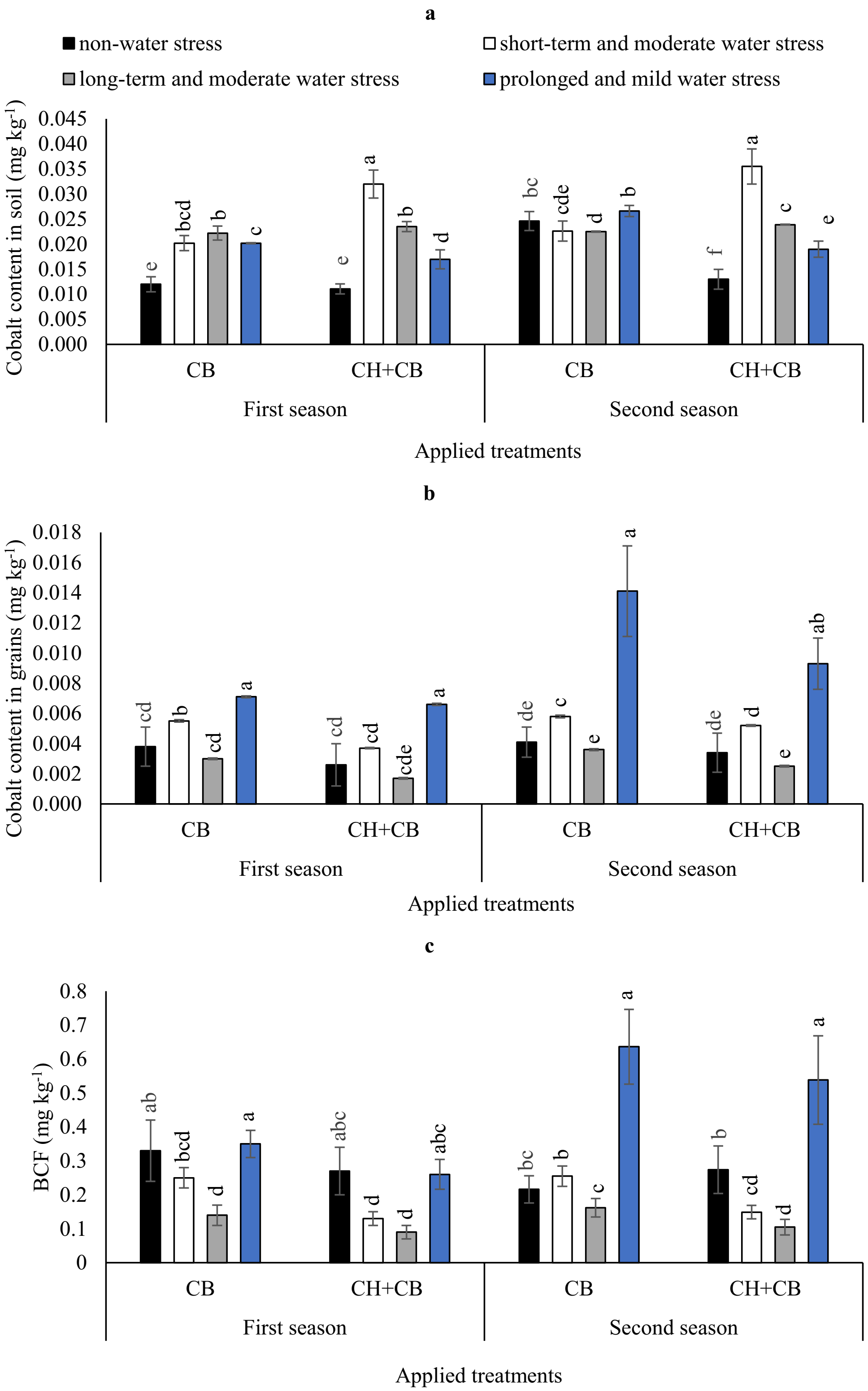

Fig. 5 The interactive influence of implementing (non water stress and water stress schemes with adding individual or combined applications of cobalt and chitosan on **a** cobalt content in soil, **b** cobalt content in corn grains, and **c** bioconcentration coefficient (BCF) in two growing seasons of 2020/2021. Error bars indicate standard errors from the mean. Bars with different letters are statistically significant at $p \leq 0.05$. Abbreviations: Tap water (control, spray with pure water); CH (spray with 500 mg l^{-1} chitosan); and CB (7.5 mg l$^{-.1}$ cobalt was applied injection in the irrigation water)

elongation (Huang et al. 2019). Our results corroborated the findings of other research showing that the flowering growth stage of corn is more vulnerable to water stress than the vegetative stage (Ha 2017; Na et al. 2018).

The effects of water stress on corn plants were evident in the decrease of nutrient absorption and several yield attributes during the flowering growth stage, as described above. Because of this, this study hypothesized that giving plants

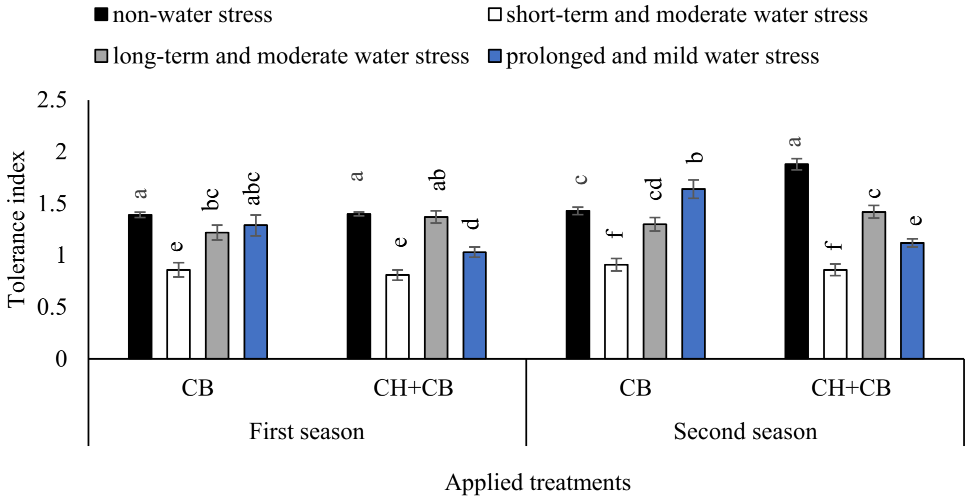

Fig. 6 The interactive influence of implementing (non water stress and water stress schemes with adding individual or combined applications of cobalt and chitosan on tolerance index of corn in two growing seasons of 2020/2021. Error bars indicate standard errors from the mean. Bars with different letters are statistically significant at $p \leq 0.05$. Abbreviations: Tap water (control, spray with pure water); CH (spray with 500 mg l^{-1} chitosan); and CB (7.5 mg $l^{-}.^{1}$ cobalt was applied injection in the irrigation water)

(CB and CH) would increase their nutrient absorption across a variety of irrigation regimes and their tolerance against the detrimental effects of water stress.

Results gained confirm this theory by demonstrating that the adoption of the combined application of (CB and CH) under the non-water stress scheme led to improvements in corn yield, WUE, IWUE, and Ti, and that these effects persisted throughout both growing seasons. In this light, we hypothesized that the combined applications worked to enhance root development and diffusion; whereas (CB and CH) worked to expand the roots' total length and surface area, particularly the thinner ones (Zhang et al. 2021; De Lima et al. 2022), which, in turn, promoted the nutrient absorption slightly as evidenced by the higher number of ears, grain index weight, ear length, and yield (Farouk and El-Metwally 2019; Hidangmayum et al. 2019; Bibi et al. 2021). Corn crop hyperaccumulator under these conditions (higher BCF values) and the plant was able to tolerate CB at this treatment concentration (7.5 mg l^{-1}), and that it was very effective in extracting CB from the soil. In this regard, we assumed that due to the existence of a strong antioxidant defense system (Jayakumar 2019), that helps corn plant deal with the higher concentrations of CB accumulated in their tissues (Kosiorek and Wyszkowski 2019a, b). While the combined additions of (CB and CH) under the non-water stress scheme improved TI, which represents the influence on the relative growth of plants and their roots (Diwan et al. 2010; Awasthi et al. 2017). Moreover, combining the treatment with supplemental foliar sprays of CH appears to be acting on accelerating the plant's tolerance, a finding that is consistent with that achieved by (Rahman et al. 2018).

It is crucial to remember that the beneficial effects of TI varied with the water stress pattern used. In contrast, using either CB alone or a combination of (CB and CH) in a moderate and short-term, the plant yielded the lowest TI content.

We found that when using a short-term and moderate scheme, plants' roots experience water stress during the peak of root development; nevertheless, this did not have an unfavorable effect on grain nutritional content. Moreover, it is usual for soil pH to increase when soil moisture decreases, thus reducing nutrient availability and CB mobility. Yet, although the short-term and moderate scheme resulted in a higher CB concentration in the soil, the long-term and mild scheme resulted in a greater CB absorption concentration in the grains. Thus, and based on the preceding, we infer that the following effects resulted from the solo or combined application of CB to stressed plants under these conditions: Reduced soil moisture appears to make roots more sensitive to changes in water availability and CB concentrations (Kulczycki et al. 2022). By raising rhizosphere CB concentration, we were able to boost microbial activity, which in turn boosted nutrient uptake and CB bioavailability (Kosiorek and Wyszkowski 2019a, b; Singh et al. 2022). As a result of a steeper decrease in microbial activity, the adoption of the short-term and moderate scheme led to a decrease in soil moisture and the absorption of CB in the grains in the meanwhile. Furthermore, increasing the bioavailable molecules of CB around the sensitive roots; together with lower soil moisture and an unestablished root system or even antioxidant defense system, had a negative impact on some agronomic traits of the corn, reflected in the obtained yield. The results are consistent with those of (Hong et al. 2019), who demonstrated that plant development and metabolism change depending on the level and condition of CB in the rhizosphere and soil.

The results confirmed the need of avoiding short-term and moderate scheme exposure to corn during the vegetative stage when CB was used. Moreover the results showed that under the same scenario, WUE, IWUE, and corn yield were all maximized by switching from CB to CH in the prior water stress scheme (short-term and moderate scheme). Under these conditions, the ear length, grain index weight, and yield all increased, which is consistent with our hypothesis that short-term and moderate irrigation during the vegetative stage increased root penetration within the soil to ensure water and nutrient supply, which are in agreement with (Kang et al. 2022). This, in turn, improved the plant's strength and the absorption of the macronutrients, which was reflected in the increased ear length, grain index weight, and yield (Hu et al. 2021). In this regard, (Kang et al. 2022) noted that improved crop tolerance to water stress, which in turn increased crop production and quality, achieved through a well-developed root system architecture.

Hence, once CH is incorporated into plant tissues, it helps to enhance the antioxidant defense system against the detrimental effects of water stress (Villa et al. 2022). As CH molecules include an amino proton group, they boost photosynthesis (Rizzi et al. 2016; Jiménez-Gómez and Cecilia 2020). More than that, CH labored to extend the root system deeper into the soil profile. It strengthened the roots and sped up their ability to uptake the macronutrients, which in turn boosted ear weight, ear number per plant, ear length, and eventually yield, WUE, and IWUE; these results are consistent with those reported by (Suarez-Fernandez et al. 2020; Makhlouf et al. 2022; Elshamly 2023).

But, when applied together, CB and CH were found to increase corn yield, WUE, and IWUE, and TI. In this light, we hypothesized that although the roots are exposed to a critical reduction in soil moisture through the adoption of the long-term and moderate water stress scheme, the CH applications formed a transparent layer reducing transpiration, which in turn worked on maintaining water within plant tissues and mitigating the deleterious impact of the reduction in soil moisture. In addition, CH applications improved the root system's penetration deeper in the soil, which in turn enhanced the absorption of the macronutrients, and all agronomic parameters of corn, with the exception of plant height, led to an increase in production. It is also interesting to observe that the low BCF value matched the high TI. Specifically, we hypothesized that boosting the efficiency of the antioxidant defense system would need beginning CH treatments prior to adopting the water stress scheme (begun after 4 weeks of emergence). Furthermore, it appears the plants may adapt their defensive technique to their present situation. These results are consistent with those obtained by showing that the plant defense strategy reduces CB absorption and accumulation in the grains (Viehweger 2014; Angulo-Bejarano et al. 2021). As a result, plant growth enhanced, which in turn increased WUE and IWUE. Nevertheless, if you apply CB 30 days after planting and begin reducing soil moisture during the flowering growth, the molecules will be at a greater distance from the roots during the sensitive period (the vegetative stage) and therefore less effective. Moreover, as a result of the many benefits mentioned earlier of applying CB on the microorganism activity, plants work on increasing the uptake of (N and P) nutrients, which is considered a guide for improving roots strength and diffusion. Furthermore, accompanied the foliar applications of CH by CB soil applications contributes to a greatly increased absorption of K, whereas K is an important nutrient in the process of plant resistance to water stress, these findings are consistent with (Gad et al. 2019).

5 Conclusion

In the current investigation, cobalt and chitosan were employed to reduce the negative effects of water stress on corn at different growth stages. Using varied irrigation schemes during different stages of growth, the effects of treating corn plants with cobalt and chitosan alone or in combination were clearly demonstrated. The current study found that these applications increased nutrient absorption and yield, but only if the right pattern was used. Negative effects on yield, water use efficiency, and tolerance index were seen after cobalt was applied to corn plants during the vegetative growth stage and applied 70% of the irrigation water requirements. Combining cobalt and chitosan treatments or increasing irrigation water levels both led to benefits under similar conditions. More research is needed to examine these effects on the other crops, but our results contradict the concept that modest rates of cobalt treatment always have the potential to boost yields. We suggest adopting the combination of (cobalt and chitosan) and irrigating corn plants with 70% of the irrigation water requirements during the flowering stage. Cobalt and chitosan applied together improved yield, macronutrient absorption, water use efficiency, and tolerance index in corn that had been exposed to water stress. Cobalt and chitosan applied together can reduce the negative effects of water stress and the need for extensive irrigation in dry regions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42729-023-01233-3.

Acknowledgements The authors would like to thank the Water Studies and Research Complex (WSRC) Station and National Water Research Center (NWRC) for their financial support to conduct this work.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Declarations

Ethics Approval and Consent to Participate This manuscript is an original paper and has not been published in other journals. The authors agreed to keep the copyright rule.

Conflict of Interest The authors declare no competing interests.

References

Abdallah MMS, El-Bassiouny HMS, AbouSeeda MA (2019) Potential role of kaolin or potassium sulfate as antitranspirant on improving physiological, biochemical aspects and yield of wheat plants under different watering regimes. Bull Natl Res Cent 43:1–12. https://doi.org/10.1186/s42269-019-0177-8

Ali H, Khan E, Sajad MA (2013) Phytoremediation of heavy metals concepts and applications. Chemosphere 91:869–881. https://doi.org/10.1016/j.chemosphere.2013.01.075

Allen R G, Pereira L S, Raes D, Smith M (1998) Crop evapotranspiration-guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56

Angulo-Bejarano PI, Puente-Rivera J, Cruz-Ortega R (2021) Metal and metalloid toxicity in plants: an overview on molecular aspects. Plants 10:635. https://doi.org/10.3390/plants10040635

Attaran Dowom S, Karimian Z, Mostafaei Dehnavi M, Samiei L (2022) Chitosan nanoparticles improve physiological and biochemical responses of *Salvia abrotanoides (Kar.)* under drought stress. BMC Plant Biol 22:1–17. https://doi.org/10.1186/s12870-022-03689-4

Ávila RG, Magalhães PC, Vitorino LC, Bessa LA, de Souza KRD, Queiroz RB, Jakelaitis A, Teixeira MB (2022) Chitosan induces sorghum tolerance to water deficits by positively regulating photosynthesis and the production of primary metabolites, osmoregulators, and antioxidants. J Soil Sci Plant Nutr. https://doi.org/10.1007/s42729-022-01111-4

Awasthi JP, Saha B, Regon P, Sahoo S, Chowra U, Pradhan A, Roy A, Panda SK (2017) Morpho-physiological analysis of tolerance to aluminum toxicity in rice varieties of North East India. PLoS One 12:e0176357. https://doi.org/10.1371/journal.pone.0176357

Aydinsakir K, Dinc N, Buyuktas D, Kocaturk M, Ozkan CF, Karaca C (2021) Water productivity of soybeans under regulated surface and subsurface drip irrigation conditions. Irrig Sci. https://doi.org/10.1007/s00271-021-00744-0

Bechtaoui N, Rabiu M K, Raklami A, Oufdou K, Hafidi M, Jemo M (2021) Phosphate-dependent regulation of growth and stresses management in plants. Front Plant Sci 2357 https://doi.org/10.3389/fpls.2021.679916

Bibi A, Ibrar M, Shalmani A, Rehan T (2021) A review on recent advances in chitosan applications. Pure Appl Biol 10:1217–1229. https://doi.org/10.19045/bspab.2021.100128

Carvalho P, Foulkes M J (2018). Roots and uptake of water and nutrients. In: Meyers R (ed) Encyclopedia of sustainability science and technology. Springer pp:1–24. https://doi.org/10.1007/978-1-4939-2493-6_195-3

Chen F, Khan ZI, Zafar A, Ma J, Nadeem M, Ahmad K, Shehzadi M, Wajid K, Bashir H, Munir M, Malik IS, Ashfaq A, Ugulu I, Dogan Y, Yang Y (2021) Evaluation of toxicity potential of cobalt in wheat irrigated with wastewater: health risk implications for public. Environ Sci Pollut Res 28:21119–21131. https://doi.org/10.1007/s11356-020-11815-8

Cheng M, Wang H, Fan J, Zhang F, Wang X (2021) Effects of soil water deficit at different growth stages on maize growth, yield, and water use efficiency under alternate partial root-zone irrigation. Water 13:148–167. https://doi.org/10.3390/w13020148

Codex Alimentarius (FAO/WHO) (2001) Food additive and contaminants. In Joint FAO/ WHO Food Standards Programme pp:1–289.

Coelho N, Romano A (2022) Impact of chitosan on plant tissue culture: recent applications. Plant Cell Tissue Organ Cult 148:1–13. https://doi.org/10.1007/s11240-021-02156-6

Comas LH, Trout TJ, DeJonge KC, Zhang H, Gleason SM (2019) Water productivity under strategic growth stage-based deficit irrigation in maize. Agric Water Manag 212:433–440. https://doi.org/10.1016/j.agwat.2018.07.015

Danielescu S, MacQuarrie KTB, Zebarth B, Nyiraneza J, Grimmett M, Levesque M (2022) Crop water deficit and supplemental irrigation requirements for potato production in a temperate humid region (Prince Edward Island, Canada). Water 14:2748. https://doi.org/10.3390/w14172748

De Lima SVAM, Marques DM, Silva MFS, Bressanin LA, Magalhães PC, de Souza TC (2022) Applications of chitosan to the roots and shoots change the accumulation pattern of cadmium in Talinum patens (*Talinaceae*) cuttings. Environ Sci Pollut Res 29:67787–67800. https://doi.org/10.1007/s11356-022-20620-4

Diwan H, Ahmad A, Iqbal M (2010) Uptake-related parameters as indices of phytoremediation potential. Biologia 65:1004–1011. https://doi.org/10.2478/s11756-010-0106-7

Ejaz A, Ahmad K, Khan ZI, Akhtar S, Sultana R, Nadeem M, Hussain MI, Elshikh MS (2022) Assessment of cobalt in wheat grains as affected by diverse fertilizers: implications for public health. Environ Sci Pollut Res 29:34558–34574. https://doi.org/10.1007/s11356-022-18528-0

El Namas AE (2020) Effect of deficit irrigation and biochar application on growth, yield components, water use efficiency and water productivity of banana (*Musa sapientum*) grown in sandy soil under drip irrigation. J Soil Sci Agric Eng 11:163–175

Elshamly AMS (2023) Minimizing the adverse impact of drought on corn by applying foliar potassium humate combined with chitosan. J Soil Sci Plant Nutr. https://doi.org/10.1007/s42729-023-01146-1

Fang Y, Du Y, Wang J, Wu A, Qiao S, Xu B, Zheng S, Siddique KHM, Chen Y (2017) Moderate drought stress affected root growth and grain yield in old, modern and newly released cultivars of winter wheat. Front Plant Sci 8:672. https://doi.org/10.3389/fpls.2017.00672

Farouk S, El-Metwally IM (2019) Synergistic responses of drip-irrigated wheat crop to chitosan and/or silicon under different irrigation regimes. Agric Water Manag 226:105807. https://doi.org/10.1016/j.agwat.2019.105807

Gad N, Sekara A, Abdelhamid MT (2019) The potential role of cobalt and/or organic fertilizers in improving the growth, yield, and nutritional composition of *Moringa oleifera*. Agronomy 9:862. https://doi.org/10.3390/agronomy9120862

Ha BM (2017) A reviews of growth stage deficit irrigation effecting sticky maize production. De Gruyter Open 63:13–18

Heydari MM, Brook RM, Jones DL (2019) The role of phosphorus sources on root diameter, root length and root dry matter of barley (*Hordeum vulgare L.*). J Plant Nutr 42:1–15. https://doi.org/10.1080/01904167.2018.1509996

Hidangmayum A, Dwivedi P, Katiyar D, Hemantaranjan A (2019) Application of chitosan on plant responses with special reference to abiotic stress. Physiol Mol Biol Plants 25:313–326. https://doi.org/10.1007/s12298-018-0633-1

Hong DD, Anh HTL, Tam LT, Show PL, Leong HY (2019) Effects of nanoscale zerovalent cobalt on growth and photosynthetic parameters of soybean *Glycine max (L.) Merr. DT26* at different stages. BMC Energy 1:1–9. https://doi.org/10.1186/s42500-019-0007-4

Hu X, Wei X, Ling J, Chen J (2021) Cobalt: An essential micronutrient for plant growth? Front Plant Sci 12:1–24. https://doi.org/10.3389/fpls.2021.768523

Huang W, Zhao X, Liang N, He L, Yu L, Zhan Y (2019) Phosphorus deficiency promotes the lateral root growth of *Fraxinus mandshurica* seedlings. J Soil Sci Plant Nutr 182:552–559. https://doi.org/10.1002/jpln.201800465

Jayakumar K (2019) Antioxidant enzyme mechanism of cluster bean (*Cyamopsis tetragonaloba (L.) Taub*). under cobalt stress. World News Nat Sci 24:64–70

Jiménez-Gómez CP, Cecilia JA (2020) Chitosan: a natural biopolymer with a wide and varied range of applications. Molecules 25:3981. https://doi.org/10.3390/molecules25173981

Kang J, Peng Y, Xu W (2022) Crop root responses to drought stress: molecular mechanisms, nutrient regulations, and interactions with microorganisms in the rhizosphere. Int J Mol Sci 23:9310. https://doi.org/10.3390/ijms23169310

Kosiorek M, Wyszkowski M (2019a) a) Remediation of cobalt-polluted soil after application of selected substances and using oat (*Avena sativa L.*). Environ Sci Pollut Res 26:16762–16780. https://doi.org/10.1007/s11356-019-05052-x

Kosiorek M, Wyszkowski M (2019b) Effect of cobalt on the environment and living organisms- a review. Appl Ecol Environ Res 17:11419–11449

Kulczycki G, Sacała E, Chohura P, Załuska J (2022) Maize and wheat response to drought stress under varied sulphur fertilisation. Agronomy 12:1076. https://doi.org/10.3390/agronomy12051076

Li Y, Tao H, Zhang B, Huang S, Wang P (2018) Timing of water deficit limits maize kernel setting in association with changes in the source-flow-sink relationship. Front Plant Sci 9:1326–1327. https://doi.org/10.3389/fpls.2018.01326

Locke AM, Ort DR (2014) Leaf hydraulic conductance declines in coordination with photosynthesis, transpiration and leaf water status as soybean leaves age regardless of soil moisture. J Exp Bot 65:6617–6627. https://doi.org/10.1093/jxb/eru380

Lukin SV, Zhuikov DV (2022) Content and balance of trace elements (Co, Mn, Zn) in agroecosystems of the central chernozemic region of Russia. Agriculture 12:154–172. https://doi.org/10.3390/agriculture12020154

Ma Y, Dias M C, Freitas H (2020) Drought and salinity stress responses and microbe-induced tolerance in plants. Front Plant Sci 1750. https://doi.org/10.3389/fpls.2020.591911

Makhlouf BSI, Khalil SRAE, Saudy HS (2022) Efficacy of humic acids and chitosan for enhancing yield and sugar quality of sugar beet under moderate and severe drought. J Soil Sci Plant Nutr 22:1676–1691. https://doi.org/10.1007/s42729-022-00762-7

Mleczek M, Gąsecka M, Drzewiecka K, Goliński P, Magdziak Z, Chadzinikolau T (2013) Copper phytoextraction with willow (*Salix viminalis L.*) under various Ca/Mg ratios. Part 1. Copper accumulation and plant morphology changes. Acta Physiol Plant 35:3251–3259. https://doi.org/10.1007/s11738-013-1360-4

Mohammed SB, Dzidzienyo DK, Yahaya AL, Umar M, Ishiyaku MF, Tongoona PB, Gracen V (2021) High soil phosphorus application significantly increased grain yield, phosphorus content but not zinc content of cowpea grains. Agronomy 11:802. https://doi.org/10.3390/agronomy11040802

Morin-Crini N, Lichtfouse É, Torri G, Crini G (2019) Fundamentals and applications of chitosan. In: Crini G, Lichtfouse É (eds) Chitin and chitosan—history, fundamentals & innovations. Sustainable agriculture reviews. Springer pp.338–407. https://doi.org/10.1007/978-3-030-16538-3_2

Mphande W, Kettlewell PS, Grove IG, Farrell AD (2020) The potential of antitranspirants in drought management of arable crops: a review. Agric Water Manag 236:106143. https://doi.org/10.1016/j.agwat.2020.106143

Na M, Cai F, Zhang Y, Ruipeng J, Zhang S, Wang Y (2018) Differential responses of maize yield to drought at vegetative and reproductive stages. Plant Soil Environ 64:260–267. https://doi.org/10.17221/141/2018-PSE

Rabêlo V M, Magalhães P C, Bressanin L A, Carvalho D T, Reis C O, Karam D, Doriguetto A C, Santos M H, Filho P R S S, Souza T C (2019) The foliar application of a mixture of semisynthetic chitosan derivatives induces tolerance to water deficit in maize, improving the antioxidant system and increasing photosynthesis and grain yield. Sci Rep 1–13. https://doi.org/10.1038/s41598-019-44649-7

Rahman M, Mukta JA, Sabir AA, Gupta DR, Mohi-Ud-Din M, Hasanuzzaman M, Miah MG, Rahman M, Islam MT (2018) Chitosan biopolymer promotes yield and stimulates accumulation of antioxidants in strawberry fruit. PLoS ONE 13:1–14. https://doi.org/10.1371/journal.pone.0203769

Ray K, Banerjee H, Dutta S, Sarkar S, Murrell TS, Singh VK, Majumdar K (2020) Macronutrient management effects on nutrient accumulation, partitioning, remobilization, and yield of hybrid maize cultivars. Front Plant Sci 11:1–19. https://doi.org/10.3389/fpls.2020.01307

Rizzi V, Fini P, Semeraro P, Cosma P (2016) Detailed investigation of ROS arisen from chlorophyll a/chitosan based-biofilm. Colloids Surf, B 142:239–247. https://doi.org/10.1016/j.colsurfb.2016.02.062

Sah RP, Chakraborty M, Prasad K, Pandit M, Tudu VK, Chakravarty MK et al (2020) Impact of water deficit stress in maize: Phenology and yield components. Sci Rep 10:1–15. https://doi.org/10.1038/s41598-020-59689-7

Shiferaw H, Alamirew T, Dzikiti S, Bewket W, Zeleke G, Schaffner U (2021) Water use of *Prosopis juliflora* and its impacts on catchment water budget and rural livelihoods in Afar Region, Ethiopia. Sci Rep 11:1–14. https://doi.org/10.1038/s41598-021-81776-6

Singh SK, Wu X, Shao C, Zhang H (2022) Microbial enhancement of plant nutrient acquisition. Stress Biol 2:1–14. https://doi.org/10.1007/s44154-021-00027-w

Suarez-Fernandez M, Marhuenda-Egea F C, Lopez-Moya F, Arnao M B, Cabrera-Escribano F, Nueda M J, et al (2020) Chitosan induces plant hormones and defenses in tomato root exudates. Front Plant Sci 11. https://doi.org/10.3389/fpls.2020.572087

Usman K, Al-Ghouti MA, Abu-Dieyeh MH (2019) The assessment of cadmium, chromium, copper, and nickel tolerance and bioaccumulation by shrub plant *Tetraena qataranse*. Sci Rep 9:1–11. https://doi.org/10.1038/s41598-019-42029-9

Viehweger K (2014) How plants cope with heavy metals. Bot Stud 55:35. https://doi.org/10.1186/1999-3110-55-35

Wang X, Zhang R, Song W, Han L, Liu X, Sun X et al (2019) Dynamic plant height QTL revealed in maize through remote sensing phenotyping using a high-throughput unmanned aerial vehicle (UAV). Sci Rep 9:1–10. https://doi.org/10.1038/s41598-019-39448-z

Wojcieszek J, Ruzik L (2020) Study of bioaccessibility of cobalt species in berries and seeds by mass spectrometry techniques. J Analytical Sci Tech 11:26. https://doi.org/10.1186/s40543-020-00225-7

Zhang H, Wang N, Zheng S, Chen M, Ma X, Wu P (2021) Effects of exogenous ethylene and cobalt chloride on root growth of Chinese fir seedlings under phosphorus-deficient conditions. Forests 12:1585. https://doi.org/10.3390/f12111585

Zotarelli L, Dukes MD, Liu GD, Simonne EH (2022) Principles and practices of irrigation management for vegetables. Univ Florida Instit Food Agri Sci. https://doi.org/10.32473/edis-cv297-2022