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Physiological performance and herbage yield of coriander affected by carbon quantum dots and titanium dioxide nanoparticles (Coriandrum sativum) under water deficit stress

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Article

Keywords: Carbon quantum dots, catalase, leaf proline, malondialdehyde, nanoparticle, peroxidase

Posted Date: December 3rd, 2025

DOI: https://doi.org/10.21203/rs.3.rs-7830240/v1

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Additional Declarations: No competing interests reported.

Abstract

Under water deficit stress condition, using nanoparticles could increase the growth and yield of medicinal plants. Under water deficit stress, the effects of carbon quantum dots (CQDs) and TiO_2 nanoparticles (TiO_2-NPs) were investigated on physiological parameters and yield of coriander (*Coriandrum sativum* L.). The experiment was arranged as factorial with randomized complete block design and three replicates in greenhouse. The first factor was different water deficit stress levels as control (no water deficit stress,100% FC), mild (50% FC) and high (25% FC) water deficit stress. The second factor was spraying nanoparticles at four levels consisted of control (distilled water), CQDs (10 mg L^{-1}), TiO_2-NPs (50 mg L^{-1}), and CQDs (10 mg L^{-1}) + TiO_2-NPs (50 mg L^{-1}). The relative water content (RWC), chlorophyll a (Chl a) and b (Chl b), plant height, dry herbage yield, EO content and yield of coriander decreased under water deficit stress, while, increases in malondialdehyde (MDA) and leaf proline (LP) contents, catalase (CAT), peroxidase (POD) and polyphenol oxidase (PPO) activities were observed. Under high water deficit stress, using CQDs + TiO_2-NPs increased the RWC (21%), Chl a (96%), Chl b (46%) and LP (45%) contents, CAT (53%), POD (11%) and PPO (16%) activities, dry herbage yield (49%), EO content (38%) and yield (105%) of coriander compared with control, while the MDA content decreased by 83%. Generally, we can conclude that CQDs + TiO_2-NPs improved the physiological performance, antioxidant enzymes activity, and dry herbage and EO yield of coriander under water deficit stress. This nanoparticle treatment could be recommended in cropping systems of coriander with water limitation.

Introduction

Coriander (*Coriandrum sativum* L.), an herbaceous medicinal plant in Apiaceae family with great importance in the food (leaves), pharmaceutical (essential oil of seed), health and cosmetic industries[1]. In Iran, the coriander is used as an edible vegetable (leaves and stems) and the seed is used for spicy fragrance and cooking[2]. The main constituents in EO of coriander include limonene, geraniol, camphor, linalool, γ-terpinene and α-pinene[3]. The antioxidant, antibacterial, antidiabetic, anticancer and anti-mutation properties of this plant have also been proven[2].

Water deficit decreases the crop growth and yield and is the main abiotic stress throughout the world[4]. It causes changes in plant physiological parameters and ultimately affecting some metabolic processes. Reduced turgor pressure can be the first effect of water limitation that affects cell growth and crop performance[5]. Changes in photosynthesis pigments, antioxidant enzymes activity and plant growth lead to improve in adaptation of crops to water deficit[6]. Exogenous application of stimulants could improve the crop growth and yield under drought stress condition. Foliar spraying of brassinosteroids and salicylic acid, increased the proline content and antioxidant enzymes activity, reduced the effects of water deficit, which in turn increased the coriander seed and oil yield[7].

In recent years, nanotechnology has been used in agricultural industry and is considered as a strategy that improve the tolerance of plants to environmental stresses[8]. In recent decades, different types of nanoparticles have been used in agriculture, which improve the crop development and growth, increasing fertilizer use efficiency and yield, reducing environmental pressure[9]. Application of nanoparticles is an efficient strategy that could be used in order to improve the plant resistance to water deficit stress[10].

Carbon quantum dots (CQDs) with quasi-spherical structures and less than 10 nm size are carbon-based nanomaterials[11]. The effects of CQDs on the growth of monocots (wheat, rice, and corn) and dicots (beans, soybeans and coriander) has been reported[12]. In agriculture CQDs are widely used as photosynthetic enhancers, abiotic stress modifiers and seed primers[13]. CQDs could improve plant growth especially under abiotic stresses, so they could be used for enhancing plant resistance to this condition[11]. The main factor that affect crop growth and yield under water deficit stress, is oxidative damage to lipids, carbohydrates and proteins, because of increasing the reactive oxygen species (ROS)[14,15]. For improving the crop resistance to abiotic stress, the mechanism of CQDs is scavenging free radicals, through a hydrogen transfer mechanism[16,17]. CQDs decreased the malondialdehyde (MDA) and ROS contents and improved the peroxidase (POD) and catalase (CAT) activities[18]. CQDs increase the scavenging the free radical activity of antioxidant enzymes to reduce the abiotic stress outcomes in crops, justifying their application in water-limited condition. Application of carbon quantum dots under drought stress, reduced the accumulation of ROS and oxidative stress in maize, increased the proline content[19].

TiO_2-NPs (Titanium dioxide nanoparticles) exhibit photocatalytic properties, oxidation, and reduction activities, and therefore inactivate oxygen-derived free radicals[20]. This nanoparticle reduces the destructive effects of abiotic stress by reducing oxygen free radicals and malondialdehyde, increasing antioxidant enzymes and photosynthetic carbon assimilation and subsequently improve the plant growth[21]. Foliar spray and root nutrition of TiO_2-NPs, enhanced the photosynthetic rate and nitrate reductase activity that caused improve in nitrogen uptake that finally led to increase in proteins synthesis[22]. Generally, the efficient antioxidant defense systems is employed to mediate stress tolerance through these nanoparticles[23]. Sharghi and Khalilvand Behrouzyar[24] observed that under water deficit stress, foliar application of TiO_2-NPs, decreased malondialdehyde content of corn (*Zea mays* L.) and increased the proline and soluble sugars content and peroxidase enzyme activity.

Under water deficit stress, using nanoparticles such as titanium dioxide and carbon quantum dots could increase drought resistance and improve physiological performance and yield of coriander. So, the study aimed to investigate the effect of CQDs and TiO_2-NPs on physiological performance, activities of antioxidant enzymes, dry herbage and EO yield of coriander under water deficit stress.

Results

Leaf temperature

ANOVA results (Table 1) showed that the effects of nanoparticle, water deficit stress, treatment and interaction of nanoparticle × water deficit stress treatment were significant on leaf temperature ($p \leq 0.01$). The results of mean comparison (Fig. 1, A) indicated that the leaf temperatures increased with water deficit stress level.

Table 1. The ANOVA results for effects of water deficit stress and nanoparticles on physiological traits of coriander (ns, * and **: non -significant and significant at p ≤ 0.05 and p ≤ 0.01, respectively).

Source of variation	df	Leaf temperature	RWC	Chl a	Chl b	Carotenoids	MDA	Leaf proline (LP)
Block	2	n.s	n.s	n.s	n.s	n.s	n.s	n.s
Water deficit stress (WD)	2	**	**	**	**	**	**	**
Nanoparticle (NP)	3	**	**	**	**	**	**	**
WD × NP	6	**	**	**	**	**	**	**
Error	22	-	-	-	-	-	-	-
CV (%)	-	5.52	11.32	6.25	7.86	10.62	9.71	13.51

Relative water content (RWC)

The effects of nanoparticle treatment, water deficit stress and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on RWC (Table 1). Comparison of means (Fig. 1,B) indicated that the highest values of RWC were observed in no water deficit stress and decreased by increase in water deficit stress level.

Chl a, b and carotenoid contents

The effects of water deficit stress, nanoparticle treatment and interaction of nanoparticle treatment ×water deficit stress were significant (p ≤ 0.01) on Chl a content (Table 1). Results (Fig. 2,A) showed that the highest Chl a contents were obtained in no water deficit stress and the lowest values were obtained under high water deficit stress. At all water deficit stress levels, using the CQDs and CQDs + TiO_2-NPs treatments, increased the Chl a content compared with control treatments and the highest contents of Chl a were obtained in CQDs + TiO_2-NPs treatments. Under high water deficit stress, CQDs + TiO_2-NPs treatment increased the Chl a content by 95% compared with control treatment.

The effects of water deficit stress, nanoparticle treatment and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on Chl b content (Table 1). The comparison of means (Fig. 2, B) indicated that the greatest Chl b content were obtained in no water deficit stress and decreased

under mild and high water deficit stress levels. At all water deficit stress levels, the highest Chl b contents were observed in CQDs + TiO_2-NPs treatment. At high water deficit stress and CQDs + TiO_2-NPs treatment, the Chl b content increased by 46% compared with control treatment.

The effects of nanoparticle treatment, water deficit stress and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on carotenoid content (Table 1). Means comparison (Fig. 2, C) indicated that the greatest and lowest carotenoid contents were observed in no and high water deficit stress, respectively. At all water deficit stress levels, using all nanoparticle treatments, increased the carotenoid content compared with control treatments and the highest carotenoid contents were observed in CQDs + TiO_2-NPs treatment. Under mild and high water deficit stress levels, the carotenoid contents in CQDs treatments were higher than those in TiO_2-NPs treatments, while in no stress water deficit stress level, the carotenoid content in TiO_2-NPs treatments was higher than that in CQDs treatment.

Leaf proline (LP) content

The effects of nanoparticle treatment, water deficit stress and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on LP content (Table 1). The LP contents enhanced by water deficit stress and the highest values were observed under high water deficit stress (Fig. 3, A). At all water deficit stress levels, using all nanoparticles increased the LP contents than control treatment. In control treatment (no water deficit stress), the LP contents in CQDs and CQDs + TiO_2-NPs treatments were higher than TiO_2-NPs treatment, while in mild water deficit stress, the LP contents were not significantly different among the nanoparticle treatments. Under high water deficit stress, in CQDs + TiO_2-NPs, the LP content was higher than those in CQDs and TiO_2-NPs treatments and increased the LP content by 46% compared with control treatment.

Malondialdehyde (MDA) content

The effects of nanoparticle treatment, water deficit stress and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on MDA (Table 1). Comparison of means (Fig. 3,B) indicated that the lowest and highest contents of MDA were obtained in no and high water deficit stress, respectively. Under no water deficit stress, there was no significant differences in MDA contents among the nanoparticle treatments. Under mild water deficit stress level, using CQDs + TiO_2-NPs treatment reduced the MDA content compared with other treatments, while under high water deficit stress level, all nanoparticle treatments (CQDs, TiO_2-NPs and CQDs + TiO_2-NPs) significantly decreased the MDA contents. The highest reduction in MDA content (83%) was observed under high water deficit stress and CQDs + TiO_2-NPs treatment.

Table 2. The analysis of variance for effects of water deficit stress and nanoparticles on antioxidant enzymes activity, dry herbage and EO yield of coriander (ns, * and **: non -significant and significant at $p \leq 0.05$ and $p \leq 0.01$, respectively).

Source of variation	df	Catalase (CAT) activity	Peroxidase (POD) activity	Polyphenol oxidase (PPO) activity	Plant height	Dry herbage yield	EO content	EO yield
Block	2	**	n.s	n.s	n.s	n.s	n.s	n.s
Water deficit stress (WD)	2	**	**	**	**	**	**	**
Nanoparticle (NP)	3	**	**	**	**	**	**	**
WD × NP	6	**	**	**	**	**	**	**
Error	22	-	-	-	-	-	-	-
CV (%)	-	8.38	13.07	9.25	8.92	11.42	8.95	12.77

Catalase (CAT) activity

The effects of nanoparticle treatment, water deficit stress and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on CAT activity (Table 2). The results (Fig. 4, A) indicated that the lowest and highest CAT activities were obtained in no and high water deficit stress levels, respectively. Under no water deficit stress, there was no significant difference among the nanoparticle treatments for CAT activity, while under mild and high drought stress levels, using nanoparticle treatments increased that compared with control. The CAT activities in CQDs and CQDs + TiO_2-NPs treatments were higher than those in TiO_2-NPs treatments. Under mild and high water deficit stress, the CAT activities in CQDs + TiO_2-NPs treatments increased by 124 and 53%, respectively, compared with control treatments (Fig. 4A). Previous studies have shown that there is a correlation between water deficit (drought) tolerance in crops and catalase activity[65, 67].

Peroxidase (POD) activity

The effects of nanoparticle treatment, water deficit stress and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on POD activity (Table 2). The results (Fig. 4,B) indicated that at all water deficit stress levels, POD activity increased by using nanoparticles, compared with control treatment. Also, POD activity enhanced by increasing the water deficit stress. Under mild water deficit stress, the POD activities in TiO_2-NPs and CQDs + TiO_2-NPs treatments were higher than CQDs treatment, while in high water deficit stress, the POD activities in CQDs and CQDs + TiO_2-NPs treatments were the highest (Fig. 4,B).

CQDs scavenge free radicals which improve the crop resistance to abiotic stress such as water deficit. Also, these nanoparticles can enhance the activities of POD, CAT and SOD and decrease the contents of MDA and ROS[12, 10]. Under drought stress, application of CQDs to maize plants reduced the accumulation of ROS and attenuates the oxidative stress caused by drought stress[51].

Polyphenol oxidase (PPO) activity

The effects of nanoparticle treatment, water deficit stress and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on PPO activity (Table 2). The results (Fig. 4,C) indicated that PPO activity increased by water deficit stress. Using nanoparticles increased the PPO activity compared to control treatment, at all water deficit stress levels. At no water deficit stress, the PPO activities were not significantly different among the nanoparticle treatments, but under mild and high water deficit stress levels, the PPO activities in CQDs + TiO_2-NPs treatments were higher than CQDs and TiO_2-NPs. Under high water deficit stress, the greatest reduction in PPO activity compared with control treatment (16.3%), was observed in CQDs + TiO_2-NPs (Fig. 4,C).

Plant height

The effects of nanoparticle treatment, water deficit stress and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on plant height (Table 2). Comparison of means (Fig. 5,A) revealed that the greatest and lowest plant heights were observed in no and high water deficit stress levels, respectively. At no water deficit stress, using TiO_2-NP_S and CQDs + TiO_2-NP_S increased the plant height significantly compared with control treatment, while in high water deficit stress, using CQDs, TiO_2-NP_S and CQDs + TiO_2-NP_S, increased the plant height significantly (Fig. 5,A).

Dry herbage yield

The effects of nanoparticle treatment, water deficit stress and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on dry herbage yield (Table 2). The results (Fig. 5,B) indicated that the highest and lowest dry herbage yields were obtained in no and high water deficit stress levels, respectively.

At all water deficit stress levels, the dry herbage yield of coriander increased by using all nanoparticle treatments compared with control treatment; also, the CQDs + TiO_2-NPs treatment had the greatest dry herbage yield. Under high water deficit stress, the highest increase in dry herbage yield (49% compared with control) was observed in CQDs + TiO_2-NPs treatment (Fig. 5,B).

EO content

The effects of nanoparticle treatment, water deficit stress and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on EO content (Table 2). Comparison of means (Fig. 6,A) indicated that the highest and lowest EO contents were obtained in no and high stress levels, respectively. At all stress levels, the EO contents in CQDs +TiO_2-NPs treatments were higher than those in in CQDs and TiO_2-NPs treatments. Under no and mild stress levels, the EO contents in CQDs and TiO_2-NPs treatments were not significantly different.

EO yield

The effects of nanoparticle treatment, water deficit stress and interaction of nanoparticle treatment × water deficit stress were significant ($p \leq 0.01$) on EO yield (Table 2). The results of mean comparison (Fig. 6,B) indicated that the highest EO yields were observed in no water deficit stress (26 mg pot^{-1} in CQDs +TiO_2-NPs treatment) and the lowest values were obtained under high water deficit stress level. Using all nanoparticle treatments enhanced the EO yield compared with control. At all water deficit stress levels, the EO yields in CQDs +TiO_2-NPs treatments were higher than those in CQDs and TiO_2-NPs treatments. Under no and mild stress levels, the EO yields in CQDs and TiO_2-NPs treatments were not significantly different, while in high water deficit stress, the EO yield in CQDs was significantly higher than TiO_2-NPs treatment.

Discussion

Leaf temperature

Increasing the leaf temperature under high water deficit stress could be explained by decrease in transpiration because of limitation in available water[37]. Under no water deficit stress, there was no significant deference among the leaf temperatures of different nanoparticle treatments. Under high water deficit stress, using nanoparticle treatments reduced the leaf temperature compared with control treatment and the lowest leaf temperature (14.8 ^{o}C) was observed in CQDs + TiO2-NPs treatment.

Relative water content (RWC)

The imbalance between the rate of water absorption and consumption in the plant is one of the reasons for reduction in RWC of leaves under water deficit stress. In such conditions, the roots are unable to supply the water lost through leaf transpiration, and as a result, the leaf water potential decreases[6]. Under no water deficit stress, there is no significant differences among the RWCs of nanoparticles treatments, while under high water deficit stress levels, the CQDs + TiO_2-NPs treatment had the highest RWC and increased it by 21% compared with control treatment (Fig. 1). Cevik[8] reported that application of TiO_2 nanoparticles in tomato (*Lycopersicon esculentum* L.) without drought stress, had no significant effect on RWC, while in drought stress treatment, TiO_2 treatment increased that compared to control (non-TiO_2 treatment). Sutulienė et al., [38] also reported that in green pea (*Pisum sativum* L.), better water retention by TiO_2 nanoparticles treatment, increased the drought stress resistance.

Chl a, b and carotenoid contents

Chl a and Chl b contents decreased under high water deficit stress (Fig. 2, A and 2, B). The reason for reduction of chlorophyll contents could be explained by production of oxygen free radicals (oxidative stress) under water stress conditions, which causes damage to chloroplasts[39]. Under high water deficit stress, CQDs + TiO2-NPs treatment increased Chl a and Chl b contents compared to the control treatment, that could be related to decrease in activity of chlorophyllase enzyme that led to maintain chlorophyll and leaf greenness. The increase in photosynthetic pigments in TiO2-NPs treatments were

also observed at different stress treatments[22]. Photosynthesis is determined by the activity of the Rubisco enzyme. Rubisco 15 activase is a component of Rubisco that is responsible for CO2 uptake in plants. CQDs increased the activity of the Rubisco enzyme in mung bean plants[40]. Schutzz and Fangmeier[41] reported that under water deficit stress the decline in chlorophyll content is due to its decomposition. Ashraf[42] also reported that, the decrease in chlorophyll concentration under drought stress, could be attributed to the chlorophyllase enzyme activity, peroxidase, phenolic compounds, and ultimately chlorophyll decomposition. Therefore, water deficit stress causes the breakdown of chloroplasts and a decrease in chlorophyll content 279 which is in agreement with the findings of this research. At all water deficit stress levels, the carotenoid contents increased in CQDs + TiO2-NPs treatment, compared to the control. Carotenoids improve the plant resistance to water deficit stress condition[43]. Under water deficit stress conditions, the balance between the two stages of the carbon dioxide 283 assimilation and electron transport chain is disrupted; consequently, reactive oxygen species will be formed[44]. To combat these reactive species, the plant has non-enzymatic and 285 enzymatic antioxidant systems. One of the non-enzymatic components of the plant 286 antioxidant system, is carotenoid that can protect chlorophylls and other components of the photosynthetic apparatus against oxidative stress caused by reactive oxygen species[45]. With application of CQDs + TiO2-NPs at all water deficit stress levels, the content of carotenoid was improved.

Leaf proline (LP) content

Accumulation of glycine, proline, alanine and valine is one of the strategies of the plants to mitigate the destructive effects of water deficit stress[46]. Adaptation to water deficit stress condition has high correlation with accumulation of proline, which is also observed in this experiment. In addition, when the plant is under water deficit conditions, the proline concentration may increase up to 100 times compared to normal conditions, because plant cells begin to synthesize and accumulate some amino acids such as proline in response to drought and salinity stress[47]. Using CQDs reduced the water deficit effects by changes such as an increase in proline and amino acids contents[46]. In *Catharanthus roseus*, proline content increased by chitosan NPs treatment under drought stress[48]. Ramadan et al.[49] observed that under drought stress, proline content was not significantly affected by TiO2-NPs, while Karvar et al.,[20] reported that using 50 mg/L of TiO2-NPs, increased the leaf proline content *Dracocephalum moldavica* L. By increasing the salinity level, seed priming with TiO2-NPs improved the content of proline in maize[50]. Also, synthesis of proline and abscisic acid in leaves and their transport to the roots, increased with application of CQDs[51]. Also, high positive correlation between proline content in wheat cultivars and drought stress tolerance, reported by El-Bassiouny et al.[52]. In this study all nanoparticle treatments, especially CQDs + TiO2-NPs, increased the LP content and presumably improved water deficit stress tolerance in of coriander.

Malondialdehyde (MDA) content

Under water deficit stress conditions, the first plant cell structures to be damaged are the cell membrane lipids[53]. Under water deficit stress condition, with application of TiO2-NPs and CQDs, the accumulation of MDA was significantly reduced, which can be attributed to the higher enzymatic activity of these plants due to the use of this nanoparticles, because there have been numerous reports that CQDs and TiO2-NPs reduce the destructive effects of water deficit stress. These nanoparticles decrease the effects of drought stress by reducing the oxygen free radicals and MDA and increasing the antioxidant enzymes activity[54]. Our results are in agreement with findings of Aghdam[55] on *Linum usitatissimum*.

Activity of antioxidant enzymes

It was found that increase in water deficit stress leads to increases in CAT, POD and PPO enzyme activities. Catalase (one of the enzymes of the antioxidant system), the activity of which increases with increased oxidative stress. In peroxisomes, catalase converts H2O2 to molecular oxygen and water and detoxify the hydrogen peroxide[6]. Therefore, increased activity of catalase can be attributed to increased H2O2 content. In this study, under high water deficit stress conditions, CQDs and TiO2-NPs increased the activity of antioxidant enzyme activities. In addition, these nanoparticles are able to increase the activity of these enzymes under stress and non-stress conditions. Research has shown that TiO2-NPs are able to prevent the destructive effects of oxidative stress and plant cell death by strengthening the antioxidant system[21]. In addition, TiO2-NPs improve the morphological and physiological traits of plants[58]. Under water deficit stress, using CQDs increased the POD, CAT and SOD activities and photosynthetic rate and decreased the MDA content [51]. In this study, it can be concluded that the improve in antioxidant enzymes activity, declined the outcomes of water deficit stress. Using TiO2-NPS enhanced the peroxidase, catalase and ascorbate peroxidase activities in lentil under water deficit stress[59]. In non-stress conditions, the use of these substances has also increased the activity of these enzymes. Therefore, it can be concluded that the increase in enzymatic activity in coriander occurs under water deficit stress conditions, but the use of CQDs and CQDs + TiO2-NPS has further enhanced this activity in order to enhance the resistance of coriander to water deficit stress. The results of El-Bassiouny et al.[52] are also completely consistent with the findings of this study.

Plant height

Water deficit stress reduces the plant height and leaf area[4, 60]. The RWC decreases under water deficit stress and turgor pressure falls rapidly that cause reduction in plant height and growth[61]. Also, under water deficit conditions, cytokinin production in the root decreases, which affects plant height through reduction in cell division[62]. CQDs + TiO2-NPs increased the plant height and this increase was significant at all three water deficit levels. The plant height in maize[65] and rice[63, 64, 65, 66] increased by application of carbon dots compared to the control. Under water deficit stress, cytokinin production decreases in the roots, and plant height is affected through reduced cell division[62]. Carbon dots mitigate this effect and could increase the plant growth and height under water deficit stress[65]. Saikia et al.[67] also reported that using CQDs in *Stevia rebaudiana* increased the plant height and biomass yield.

Dry herbage yield

The results in (Fig. 5, B) showed that dry herbage yield decreased with increasing drought stress. Under severe drought stress, treatment with CQDs + TiO2-NPs increased dry herbage yield. The increase in RWC, which itself indicates the leaf water status, is also another evidence of the positive role of CQDs + TiO2-NPs in increasing photosynthesis and production of assimilates and ultimately increasing dry matter production[63]. Other studies also confirmed the positive role of CQDs and TiO2-NPs in improving plant growth[65, 66]. Using CQDs in Rome lettuce plants, increased the biomass by 48.1% compared to the control plant[10]. Using CQDs under drought stress condition, increased the maize[68] and peanut[18] growth and yield. Soltani et al.[59] also observed that the foliar spraying of TiO2-NPS enhanced the biological and grain yield of lentil. Carbon dots increased the photosynthetic pigments in rice[66] and CO2 assimilate rate of rice and corn[63] that led to increase in plant growth and biomass.

EO content and yield

The EO content of coriander decreased under drought stress condition and foliar-applied of folic acid improved this trait[3]. The EO content in leaf of coriander decreased under salinity stress[69]. Also, in Moldavian balm, the EO content decreased under drought stress treatment[4]. Gohari[22] observed that TiO2-NPs, increased the EO content of Moldavian balm under salinity stress. The EO production as secondary metabolites, is affected by availability of nutrients that affect photosynthesis rate[70]. Increase in EO content in CQDs + TiO2-NPs treatment could be explained by increase in nutrients availability in this treatment that leads to increase in growth rate and essential oil- forming glands[4, 58].

The EO yield of coriander decreased under drought stress condition and foliar-applied of folic acid improved this trait by 250% compared with control[3]. The EO yield in coriander decreased under salinity stress and improved by application of cobalt[69]. Norzad[71] observed that the EO yield of coriander increased under mild water deficit stress and decreased under high water deficit stress. Also, in previous studies observed that the photosynthetic efficiency and yield of rice and corn[65, 68, 72] increased by application of CQDs. Using the TiO2-NPs increased the yield of corn[20] and wheat[73]. In this study using CQDs, TiO2-NPs and CQDs + TiO2-NPs improved the physiological performance and antioxidant enzymes activities of coriander compared with control treatment under water deficit condition which caused an improve in dry herbage and EO yield. Among these nanoparticle treatments, the CQDs + TiO2-NPs had the highest values for all growth and yield traits and mitigated the water deficit stress in coriander.

Conclusions

The results indicated that water deficit stress decreased the RWC, chlorophyll content, plant height and dry herbage and EO yield of coriander and using all nanoparticle treatments (CQDs, TiO_2-NPs and CQDs

+ TiO_2-NPs) improved the physiological parameters, dry herbage and EO yield. Among the nanoparticle treatments, the greatest increases in physiological traits, dry herbage and EO yield of coriander were obtained in CQDs + TiO_2-NPs treatment. The highest increases in Chl a, Chl b, carotenoids, LP and antioxidant enzymes activities (CAT, POD and PPO) were observed in this treatment. Also, the highest decrease in MDA content under high water deficit stress, was observed in CQDs + TiO_2-NPs treatment. When the CQDs is combined with TiO_2-NPs, the efficacy of nanoparticles improved in mitigating the effect of water deficit stress in coriander. Therefore, the CQDs + TiO_2-NPs treatment could be used by coriander growers in agroecosystems with water deficit stress.

Materials and methods

Experimental design and treatments

In order to assess the effects of CQDs and TiO_2-NPs on physiological response and dry herbage yield of coriander under water deficit stress, a factorial experiment was arranged with three replications based on randomized complete block design in 2025 in greenhouse of the Faculty of Agriculture, University of Tabriz, Iran. The first factor was water deficit stress with levels of control without water deficit stress (100% of field capacity (FC)), mild water deficit stress (50% FC), and high water deficit stress (25% FC). The second factor was application of nanoparticles at four levels, including control (distilled water), using CQDs (10 mg/L), TiO_2-NPs (50 mg/L), and CQDs (10 mg/L) + TiO_2-NPs (50 mg/L). 25 cm-diameter pots with 25 cm height (containing 6 kg of soil) were used as experimental plots. The soil was prepared from field soil + leaf soil in a ratio of 80/20 and the soil properties are shown in Table 3. Based on soil-to-soil tests, the chemical fertilizers were added to the pots. In all pots, 1.5 g urea, 0.2 g triple superphosphate and 0.2 g potassium sulphate were added in order to compensate the nutrients deficiencies of coriander plants.

Table 3. Soil analysis of the soil used in the pots of the experiment

Soil texture	K (mg/kg)	P (mg/kg)	EC (dS/m)	OC (%)	pH	Field Capacity (%)	Silt (%)	Clay (%)	N (%)	Sand (%)
Sandy loam	326.0	13.0	2.10	0.91	7.80	19.0	26	15.0	0.30	59

Providing nanoparticles

TiO_2-NPs

TiO_2-NPs (Titanium (IV) oxide, Nano ArcTM, anatase, nano powder, 99.9%, 20 nm, metals basis) were provided from Thermo Fisher Scientific and used to prepare TiO_2-NPs solution for spray.

CQDs

Green synthesis of CQDs using orange peel waste

In this study, carbon dots (CQDs) were synthesized via a green and sustainable approach using orange peel as a biomass precursor. Initially, four oranges were peeled, and in order to remove any surface impurities the collected peels were thoroughly washed with distilled water. The clean peels were then chopped into small pieces and in order to remove moisture, they were dried in an oven (60 °C) for 24 hours. Then, the peels were ground into a fine powder using a mortar and pestle. Subsequently, 4 grams of the obtained orange peel powder were dispersed in 60 mL of an ethanol–water solution containing 60% ethanol by volume. In order to allow for sufficient extraction and pre-reaction processes, the resulting mixture was stirred continuously for 24 hours at room temperature. The mixture was then transferred to a furnace and subjected to pyrolysis at 600 °C for 6 hours to induce carbonization and formation of carbon dots. After cooling to room temperature, the solid product was filtered using filter paper to remove large particulates. The filtrate was further centrifuged to separate any remaining impurities, and the supernatant containing the synthesized carbon dots was collected for further characterization.

Characterization of CQDs

Average hydrodynamic size of synthesized CQDs (as about 72 nm) measured by Dynamic Light Scattering (DLS) technique (Fig. 7).

Experimental procedure

The seeds of coriander (*Coriandrum sativum* L.) were provided commercially from Pakan Bazr Company (Esfahan, Iran). Coriander seeds were sown on 13 November 2024 at 10 seeds per pot at a depth of 2 cm and thinned to 5 plants per pot after emergence. Two weeks after the establishment of the seedlings, (from 4-5-leaf stage) water deficit stress treatments were imposed to the end of the growth period based on field capacity (FC). The pressure plate apparatus was used to determine the FC[4]. Based on water deficit stress levels, the pot irrigation was done by the weighing method to obtain the desired FC level. Two weeks after imposing the water deficit stress treatments, the CQDs and TiO_2-NPs were sprayed by 2-week intervals up to flowering stage of coriander (60 days after planting).

Physiological and biochemical traits

Leaf temperature

In order to record the leaf temperature, an infrared thermometer (TES-1327) was used. At flowering stage (60 days after planting), two plants from each pot were selected, leaf temperatures were measured from the top, middle and bottom three leaves of the same plant and their average was recorded as the leaf temperature.

Relative Water Content (RWC)

The leaves fresh weight for coriander was measured with an accurate scale. Then all samples were kept in a cold room at 4°C for 24 hours in distilled water[25]. After 24 hours, the turgid weight of the leaves was measured and for another 24 hours the leaves were oven dried at 70°C and the dry weight was recorded for each sample. For calculation of RWC the following equation was used[26].

$$RWC\% = [(FW-DW) / (TW-DW)] \times 100$$

Where DW was the dry leaf weight, FW the fresh leaf weight, and TW was the leaf weight in the turgid state after 21 hours of waterlogging at 21°C. The average of the obtained results was reported as the relative leaf water content in each treatment.

Leaf photosynthetic pigments

The chlorophyll a (Chl*a*), chlorophyll b (Chl*b*) and carotenoids (*Cart*) contents were measured spectrophotometrically as described by Jeffery and Humphrey[27] and Jaspers[28].

$$Chla = 12.25(A_{663}) - 2.79(A_{646})$$

$$Chlb = 21.50(A_{646}) - 5.10(A_{663})$$

$$Cart = (1000A_{470} - 1.82Chla - 85.02Chlb) /198$$

A = Light absorption in wavelengths 663, 644 and 470 nm.

Malondialdehyde (MDA), leaf proline (LP) content and antioxidant enzymes activity

At flowering stage of coriander (60 days after planting), in each pot the plants were taken to measure these traits. MDA content was measured as explained by Li[29] and leaf proline (LP) content based on Bates[30] method. The method of Ghanati[31] was employed for peroxidase activity (POD) measurement. The method of Cakmak and Marschner[32] was used to measure the catalase (CAT) activity and the activity of polyphenol oxidase (PPO) was measured by method of Kumar and Khan[33].

Growth traits, EO content and yield

Plant height was measured at flowering stage (60 days after planting) from the crown to the end of the stem using a metal meter. The average height of 5 plants in each experimental plot, which were randomly selected, was considered as plant height. In order to measure dry herbage yield, the plants were harvested at flowering stage and placed in paper bags and oven dried for 72 hours at 75°C until they reached constant weight, and then weighed and were recorded. At flowering stage, the coriander shoot was harvested. Then 30 g of dried and powdered herbage was hydrodistilled by a Clevenger device[34] for 3.5 h. The EO content was measured as fallows[35]:

EO content (%) = {EO (g) / Dry herbage yield (g)} ×100

Also, the EO yield (mg pot^{-1}) was calculated as follows[36]:

EO yield (mg pot $^{-1}$) = EO content (%) × Dry herbage yield (g pot $^{-1}$ × 1000)

Statistical analysis

After passing the homogeneity of variances the normality tests of the data, the analysis of variance was performed as a factorial experiment with three replications. The whole experiment was carried out two times in greenhouse condition. The time × treatments interactions were not significant, so for data analysis, the data of both experiments were pooled. SAS software version 9.0.3 was employed for analysis of variance (ANOVA) and Duncan's multiple range test at a probability level of 5% was used for means comparison.

Declarations

Acknowledgements

This research is supported by the research grant of the University of Tabriz (number 2527), Iran. Parikhani, F and Amini, R. appreciate University of Tabriz (Iran) for technical and financial support.

Author Contributions

All authors conceived and planned the project. F.P. performed the experiments and wrote the draft. R.A. supervised the experiment, analyzed the data and finalized the latest version of the manuscript.

Funding

This project financially supported by the University of Tabriz.

Data Availability

The datasets used during the current study are available from the corresponding author on reasonable request.

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Figures

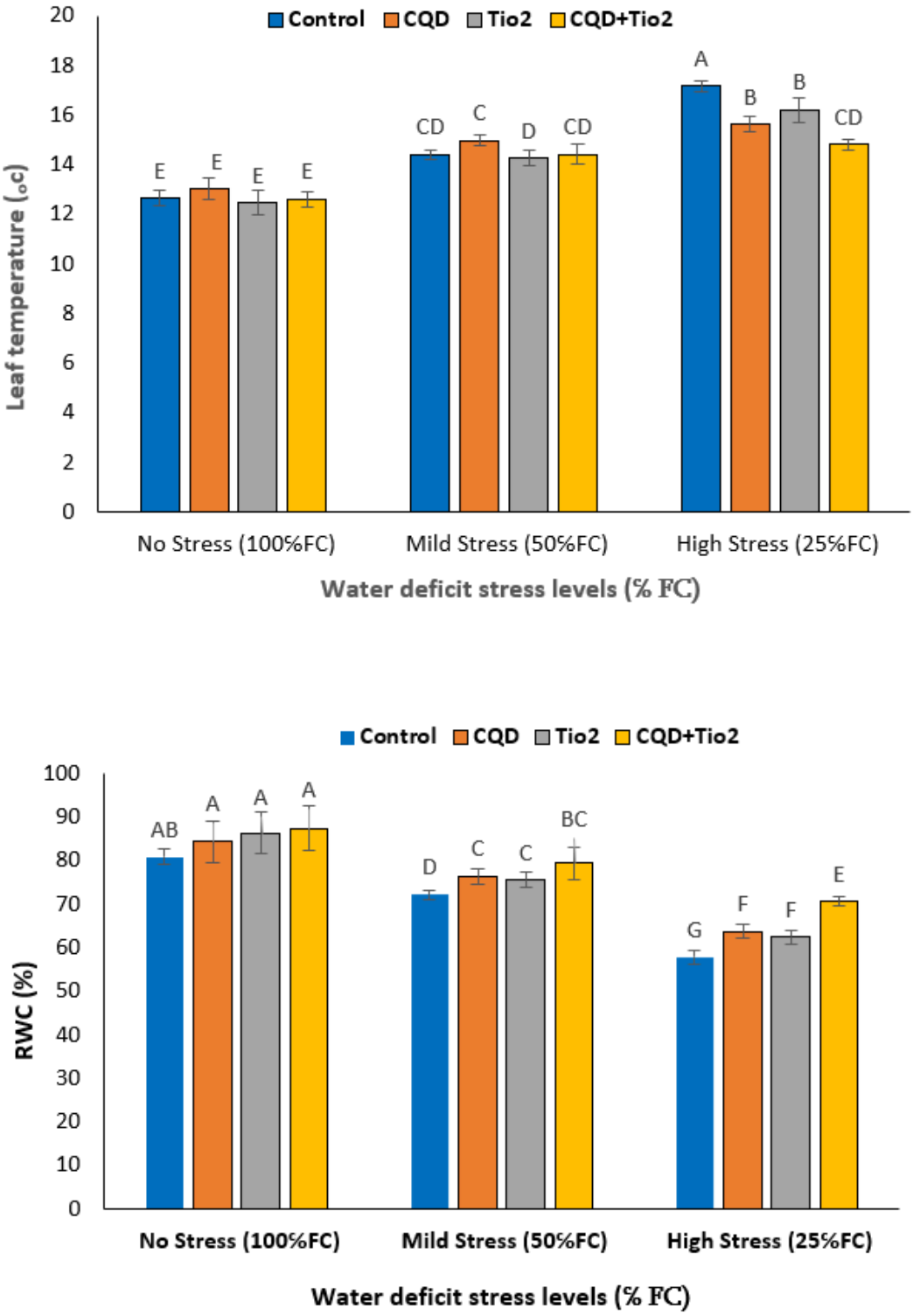


Figure 1

The interaction effect of water deficit stress × nanoparticle treatment on leaf temperature (**A**) and RWC (**B**) of coriander. The means with similar letters are not significantly different at $p \leq 0.05$.

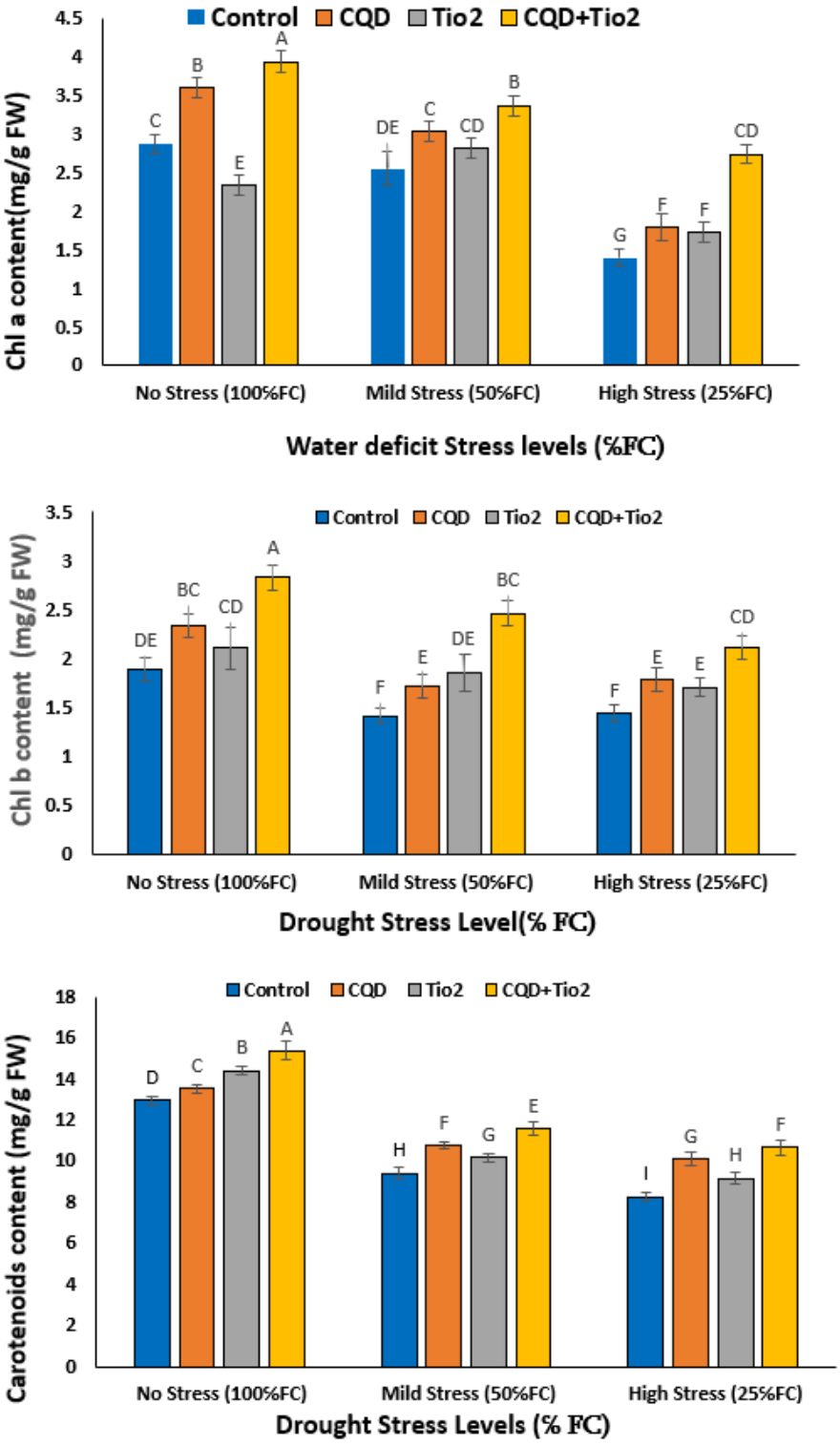


Figure 2

The interaction effect of water deficit stress × nanoparticle treatment on Chl a (**A**), Chl b (**B**) and carotenoid (**C**) contents of coriander. The means with similar letters are not significantly different at $p \leq 0.05$. No stress (100%FC).

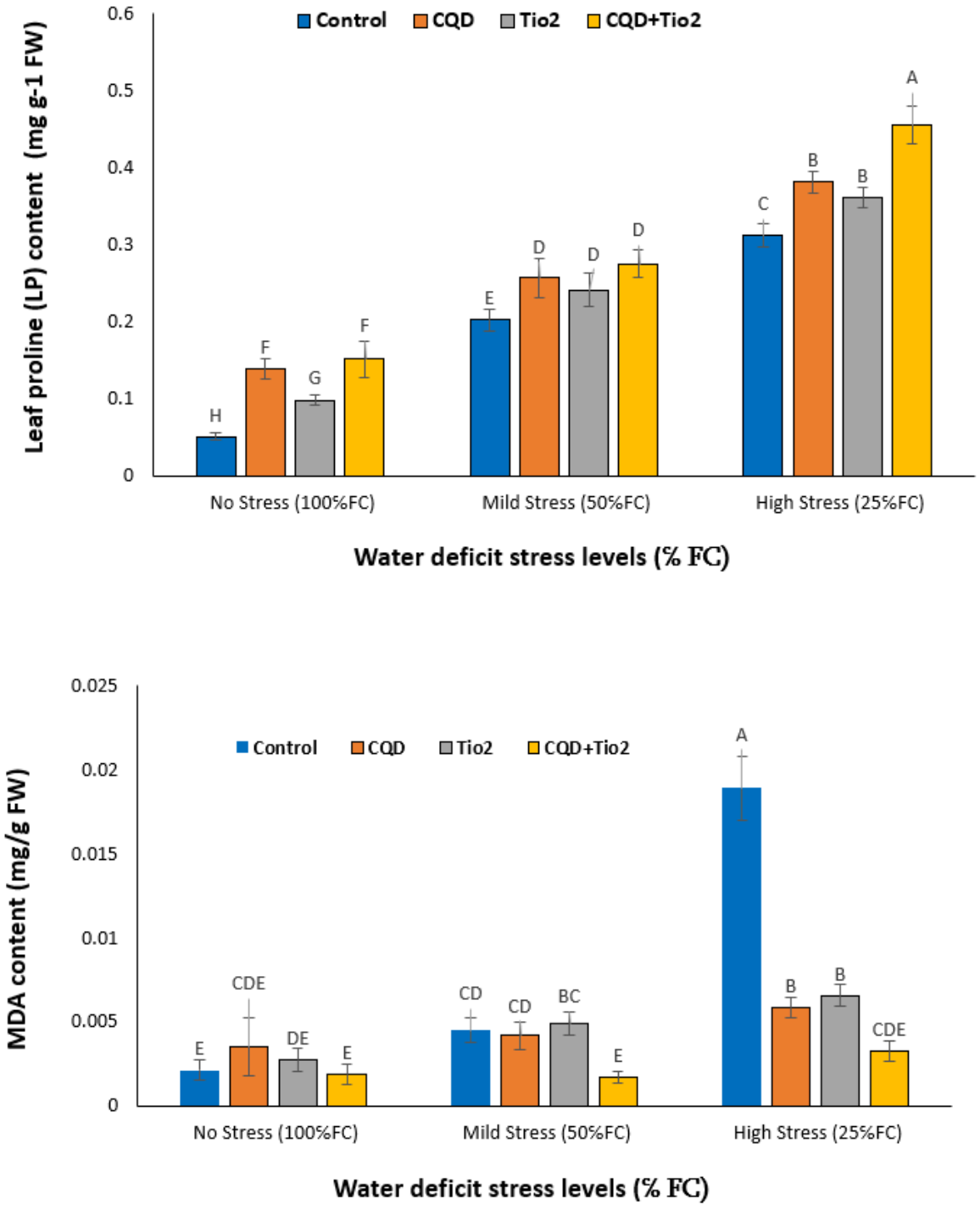


Figure 3

the interaction effect of water deficit stress × nanoparticle treatment on leaf proline (**A**) and MDA (**B**) contents of coriander. The means with similar letters are not significantly different at $p \leq 0.05$.

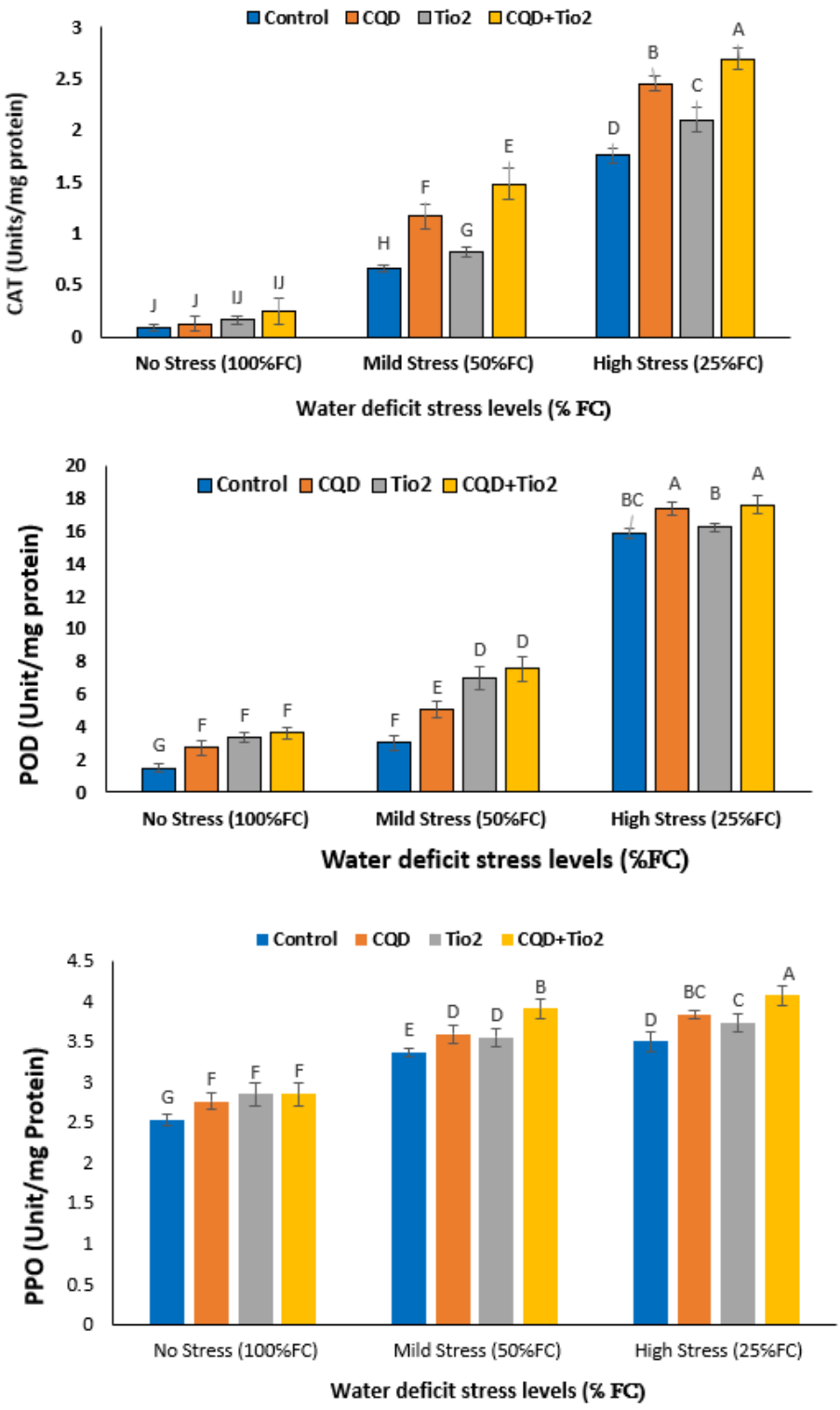


Figure 4

The interaction effect of water deficit stress × nanoparticle treatment on CAT (**A**), POD (**B**) and PPO (**C**) activities in coriander. The means with similar letters are not significantly different at $p \leq 0.05$.

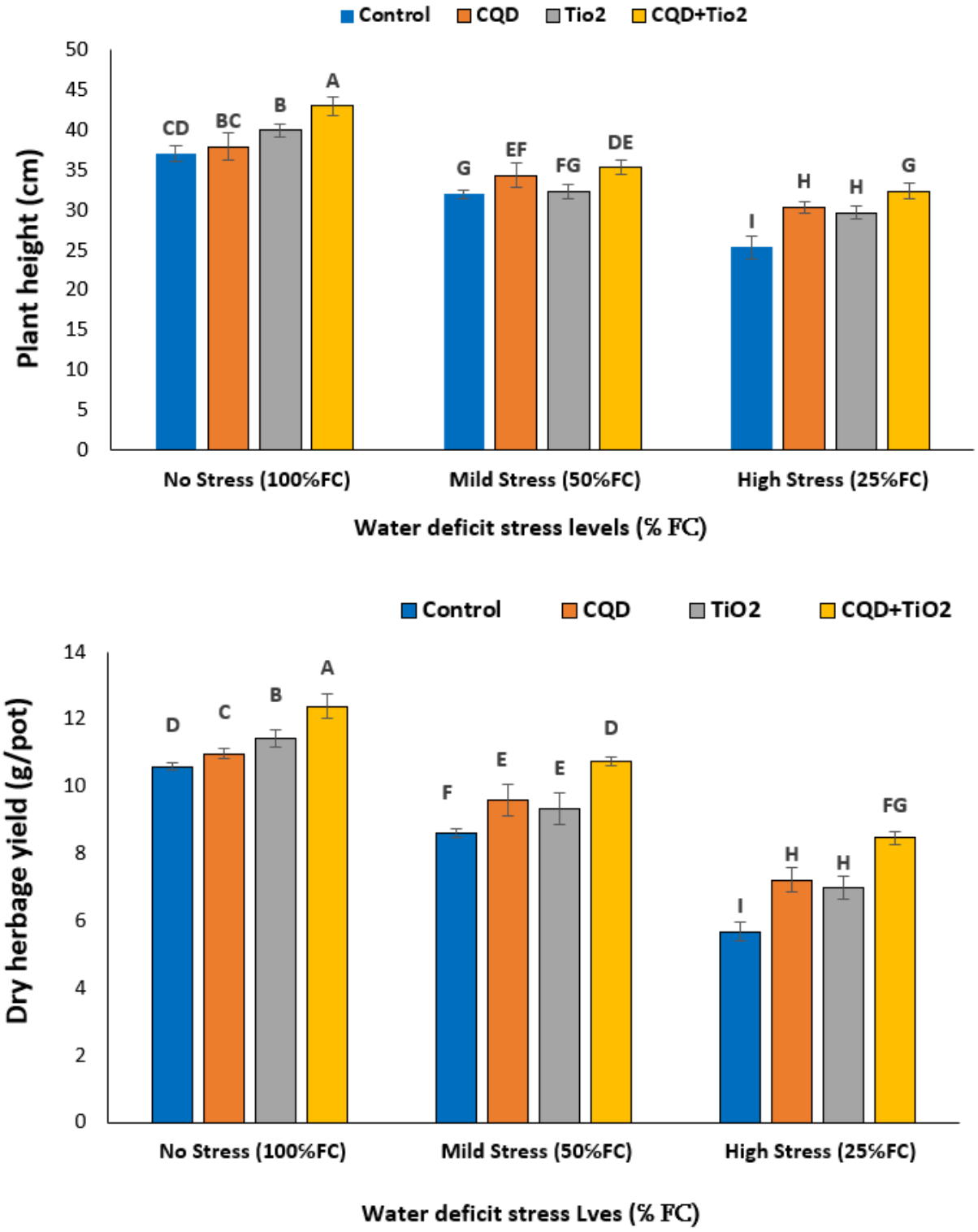


Figure 5

The interaction effect of water deficit stress × nanoparticle treatment on plant height (**A**) and dry herbage yield (**B**) of coriander. The means with similar letters are not significantly different at $p \leq 0.05$.

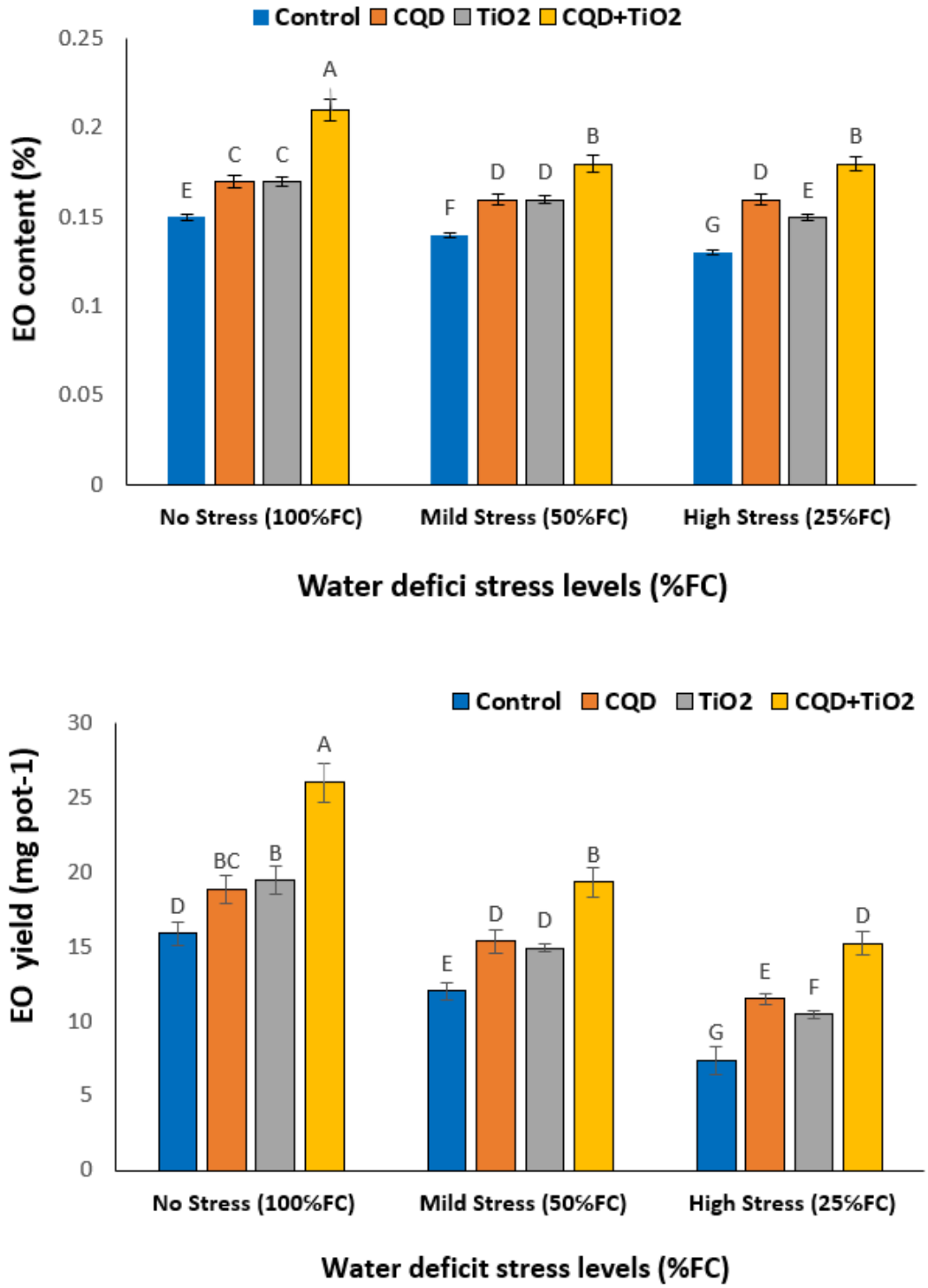


Figure 6

The interaction effect of water deficit stress × nanoparticle treatment on EO content (**A**) and EO yield (**B**) of coriander. The means with similar letters are not significantly different at $p \leq 0.05$