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Foliar application of chitosan zinc oxide nanoparticles on wheat productivity and water use efficiency under deficit irrigation water

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ABSTRACT

The effectiveness of chitosan zinc oxide nanoparticles (CS-ZnO-NPs) on growth and yield of wheat (*Triticum aestivum* L., *Sakha-93*), zinc content and water use efficiency (WUE) under water stress were investigated. A pot experiment was conducted in a completely randomized design by foliar application of CS-ZnO-NPs. Wheat plants were sprayed four times at 15, 30, 45 and 60 days after sowing. The treatments were: control (treated with distilled water), 50, 100 and 150 ppm of CS-ZnO-NPs under 100, 80 and 60% of field capacity. Water shortage has a negative effect on growth parameters and productivity of wheat plants. While the foliar application of 150 ppm CS-ZnO-NPs significantly increased ($P \leq 0.05$) NPK content, growth parameters which in turn led to increase the productivity. The highest values of wheat yield were: 4990.55, 4453.50 and 4350.50 kg/ha under 100 80 and 60% of irrigation water, respectively at 150 ppm CS-ZnO-NPs. The highest values of N, P and K content in wheat grain were 1.95, 0.43 and 1.66, respectively at 100% FC under150 ppm CS-ZnO-NPs compared to control. Zn content in wheat grain significantly increased ($P \leq 0.05$) by application of CS-ZnO-NPs. The interaction of supplementary irrigation water and CS-ZnO-NPs treatments gave clear variation in water use efficiency. The highest relative increase of WUE (23.03%) was at the highest rate of CS-ZnO-NPs (150 ppm). Overall, the data suggested that the foliar application of CS-ZnO-NPs can be an efficient strategy for improving wheat yield, water use efficiency under deficit water and one of the solutions for Zn deficiency in wheat grains.

Keywords: wheat productivity, water stress, chitosan, zinc oxide nanoparticles

INTRODUCTION

Water stress is one of the most effective abiotic stresses on plant development. Many changes have been seen in plants due to water shortage, such as changes in the balance of mineral nutrients, bioactive compounds and antioxidant activity which reduces crop productivity (Farooq et al., 2017). Water deficit negatively affecting plant photosynthetic efficiency through impacts on disrupting membrane permeability, nutrient absorption, and chlorophyll synthesis (Awasthi et al., 2014). Water shortage is one of the main limiting factors to crop production. It slows down wheat growth and development, changing the crop's morphological, physiological, and biochemical characteristics (Rijal et al., 2021). Water stress significantly reduced the growth parameters of wheat crop (Mirbahar et al., 2009). Wheat (*Trilicum aestivum* L.) is one of the most cereal crops in the world (Adil et al., 2022). It contributes around 20% of the dietary calories consumed worldwide and in Egypt. There is an urgent need to increase wheat production per unit area from existing land under water scarcity and growing population. The ultimate goal must be high wheat production to fulfil the rising food demand and population growth. Wheat is among the crops whose yield is restricted by water shortage (Bameri et al., 2012).

Zinc deficiency is the most common micronutrient deficiency in agricultural areas worldwide, especially in cereal-cultivated soils. The desirable concentration to combat human Zn deficiency might be 50-70 mg/kg (Cakmak, 2008). Zinc deficiency causes chlorosis, limited growth, and inhibits photosynthesis (Zhao and Wu, 2017). While the high concentration of zinc can impair cell functioning and disrupt several critical processes in a plant organism due to the displacement of other elements of similar diameter and load (Andrejic et al., 2018). Also, Zinc deficiency in crops and humans remains a major health concern, particularly in poor nations, owing to insufficient nutritional intake and due to the widespread eating of Zn-deficient grains (Munir et al., 2018). Nano fertilizers are readily absorbed by the epidermis of leaves, facilitating the absorption of active molecules, and enhancing wheat growth and productivity (Abdel-Aziz et al., 2018).

The nanomaterial considers one of the succeeded technologies be used in agriculture production (Elizabath et al., 2017 and Abd El-Aziz et al., 2022). Generally, nanomaterials are known as modified particles at the atomic less than 1µm. They have size-related characteristics that differ greatly from bulk materials (Buzea et al., 2007). Nanomaterials are used to evaluate their potential in plant growth and mitigate the side effect the biotic and abiotic stresses (Raghvendra et al., 2016). Chitosan is a natural polycationic polymer made from chitin that has been deacetylated. Chitin is found in the shells of crustaceans such as crabs, shrimp, and lobsters, as well as insects, mollusks, and fungi. Because of its bioactivity, biocompatibility, biodegradability, high permeability, low cost, non-toxicity, and great film-forming ability, chitosan could be an ideal carrier for agrochemicals. Chitosan structure could be simply altered to better uptake and slow release of plant growth regulators, fertilizers, pesticides, herbicides (Mujtaba et al., 2020). Under both normal and stressed conditions, chitosan causes positive responses in plants. Its effectiveness, however, is dependent on the concentration, structure, application method, plant type, and growth stage (Hidangmayum et al., 2019 and Sadeghipour, 2021). The designed Zn-chitosan NPs are porous and have a spherical form thanks to their cross-linked chitosan sodium tripolyphosphate nano matrix, which has -NH2 and -OH functional groups to allow zinc ions to be enclosed. The primary motivation for encapsulating Zn in chitosan nano matrix is to control the gradual release of Zn ions by diffusion and chitosan nano matrix dissolution (Choudhary et al., 2019 and Guan et al., 2020). Zn-chitosan NPs had increased photosynthesis and cellular stability of wheat plant, which gave them elevated source activity. Additionally, because of the delayed release phenomena and long-lasting influence on plants, metals contained in chitosan are less harmful. Combining Zn with nano chitosan has the added benefit of giving plants nutrients and promoting vigorous plant growth to further protect them from biotic and abiotic stress (Kumar et al., 2021).

Zinc concentration affects the activity of some enzymes, such as carbonic anhydrase, which controls the CO_2 sensing pathway and is linked to drought tolerance (Tewari et al., 2019). Nano materials improve growth, nutrients and protect plants against abiotic stress due to small scale, structural features, and higher surface-to-volume ratios (Khan et al., 2014 and Qureshi et al., 2018). Nanoparticles (NPs) are having unique properties and special features (Irshad et al., 2020). Zinc oxide nanoparticles (ZnO-NPs) are one of the most significant metal oxides in biological applications due to their positive properties (Faizan et al., 2021). Zinc is an essential element that regulates a variety of physiological and molecular pathways to help crops tolerance drought stress (Hassan et al., 2020). Zinc also has an important role in helping the plants to combat drought stress (Cakmak, 2008). Zn has appositive role in the growth. ZnO-NPs can promote plant tolerance to drought stress by inducing drought-related gene expression. The utility of ZnO-NPs in coping with drought stress in soybean and other commercially important plant species at other plant growth stages warrants further investigation (Linh et al., 2020). The interaction between irrigation and foliar zinc application on wheat growth and productivity showed significant variance. Foliar zinc application under various water stress conditions has a significant impact on wheat growth and yield (Paul et al., 2016). The usage of ZnO NPs helps to improve the nutritional value of plants and lessen the negative impacts of drought conditions. The grain and shoot yield of wheat increased significantly. ZnO NPs may also enhance nutrient uptake and plant nutrient levels in addition to enhancing plant growth and physiological parameters (Abd El-Aziz et al., 2022). Also, it plays an important role for opening and closing the stomatal pore and regulating the mechanism of photosynthesis and altering the stomatal conductivity and transpiration (Pooja et al., 2020). Within three weeks of NP exposure, the ZnO-NP-treated lentil plants showed enhanced stress response, as evidenced by differences in stomatal conductance, crop water stress index, plant temperature, and temperature differential (Kolencik et al., 2022).

On the other hand, the use of nanomaterials at high concentrations causes oxidative stress and toxicity depending on the chemical structure, scale, surface area, reactivity and concentration used. Toxicity was seen in wheat plants at higher ZnO NPs treatment levels (150–200 mg/L), which may have been caused by Zn disturbed homeostasis as well as indirect effects on the uptake of other elements and interelement interactions (Srivastav et al., 2021). So, a wise and sustainable rate of nanomaterials in enhancing plant growth should be more studied to understand the physicochemical features of ZnO nanoparticles complexed with chitosan and their impact on plant physiology and seed quality. In general, nothing is known about the use and application of nanoparticles in conjunction with organic compounds like chitosan (Palacio-Marquez et al., 2021). Also, there is a scarcity of data regarding Zn nano -induced to address plant growth under drought tolerance in plants. So, this study relates to that hypothesize. Therefore, the aim is to evaluate and examine foliar application of chitosan zinc oxide nanoparticles (CS-ZnO-NPs) at proper rates on wheat growth, yield quality and water use efficiency under water stress.

MATERIALS AND METHODS

Experimental design

A pot experiment was conducted at the Faculty of Agriculture, Al- Azhar University, Nasr city, Cairo, Egypt, (30°03'19.49" N and 31°19'10.19" E) during the winter season of 2020 to assess the foliar application of chitosan zinc oxide nanoparticles (CS-ZnO-NPs) on water use efficiency, wheat (*Triticum aestivum* L., *Sakha-93*) growth, and productivity under deficit irrigation water. The pots were filled with 7 kg soil and mixed by chicken manure (10 ton/fed) and incubated 15 days at 60% of field capacity before planting, then wheat seeds were sown. The plants were sprayed by foliar application of CS-ZnO-NPs by hand sprayer after two weeks of germination. Then, the plants were sprayed every two weeks carefully to avoid the direct entry of CS-ZnO-NPs into the soil. Totally, four times of solution were applied (15, 30, 45 and 60 days) of sowing during the period of experiment. Each pot was sprayed with 25 ml at every time approximately.

Factorial experiments (4 concentrations of CS-ZnO-NPs × 3 levels of FC) were arranged in a completely randomized design with 12 treatments and three replicates per treatment. The treatments were: control (treated with distilled water), 50, 100 and 150 ppm of CS-ZnO-NPs at 7-8 am under 100%, 80% and 60% of field capacity. The moisture levels were maintained after 2 weeks of germination. The recommended doses of NPK were applied. Super phosphate was added at 200 kg/fed during soil preparation and potassium sulfate at 50 kg/fed. Nitrogen fertilizer rate was split into three doses as ammonium nitrate at rate of 360 kg/fed. Growth parameters such as plant height, dimeter and chlorophyll content were determined at 45 days of germination. At harvest (145 days after planting), grain and straw yield were recorded and converted to ton/ha. The total amount of water applied during the agricultural season were 4250, 3400 and 2550 m^3/ha, respectively which versus 100, 80 and 60% from field capacity, respectively.

Preparation of chitosan (CS)

Chitosan was prepared from shrimp shells with 110 kDa of molecular weight and 85% of degree of deacetylation according to Hussein et al., (2012) and Motawie et al., (2014). The shrimp shells were first deproteinized with 3.5% (w/w) NaOH solution for 2 hours at 65 °C, followed by demineralization for 1 day at room temperature with 1N HCl, followed by decolorization for 2 hours at 50 °C with acetone, and drying for 2 hours at room temperature. The removal of acetyl groups from the prepared chitin was achieved by mixing with NaOH (50%) with stirring for 2 hr at 115 °C in a solid to solvent ratio of 1: 10 (w/v). The resultant chitosan was rinsed with distilled water, filtered, and dried at 60 °C for 24 hours after being washed in running tap water until neutral.

Preparation of ZnO nanoparticles and CS-ZnO-NPs

Nanostructure ZnO was synthesized by using domestic microwave. 0.1 M Zinc nitrate solution was prepared, the pH was adjusted to 8 by adding NH_4OH solution. The precipitated product filtered and washed with deionized water and ethanol. The product was collected, dried at 130 °C and irradiated for 5 minutes in the domestic microwave (Prakash et al., 2013). CS-ZnO-NPs was prepared by dissolving 2.5 g of CS flake in 300 mL acetic acid (2.5 % aquas solution) and stirring for 5 hours until completely soluble. ZnO powder (1.25 g) was added into the previous CS solution, with adding 50 mL of acetic acid (0.1 M) until clear solution obtained (Salehi et al., 2010).

Characterization of ZnO and CS-ZnO nanoparticles size

The particle sizes of prepared samples were determined using dynamic light scattering (DLS) analytical technique and measured by using a *Zetasizer Nano instrument* supplied by *Malvern Instruments Ltd, United Kingdom. The ultraviolet–visible (UV–Vis) spectroscopy with the Shimadzu UV-2550 double beam system, Japan*, was used to conform the formation of CS-ZnO-Nps. Fourier transform infrared (FTIR) spectra was recorded on an ATI Mattson Infinity Series (USA) TM; Bench top 961 controlled by win first TM V2.01 software (Egyptian Petroleum Research Institute "EPRI") at 25 °C. All spectra were scanned against a blank KBr pellet back-ground in the range of 4000–400 cm^{-1} with resolution of 4.0 cm^{-1}.

Soil analysis

Soil article distribution was determined by using the Bouyoucous hydrometer method according to Gee and Bauder (1986). Bulk density, field capacity, wilting point and available water were determined as described by Blake and Hartge (1986). Soil pH was measured by using a glass electrode pH meter (JENWAY -3510). Total soluble salts were determined by conductivity meter (INE-DDSJ-318). Organic matter content in soil was estimated by dichromate oxidation method (Burt, 2004). The data are presented in Table 1. Available Zn in soil extract (Ammonium Bicarbonate-DTPA extract) according to Lindsay and Norvell (1978). Total porosity was calculated according to Blake and Hartage (1986) from the following equation:

$$\text{porosity} = 1 - \frac{\text{bulk density}}{\text{particle density}} \times 100$$

Monthly average agro-meteorological data at the studied area during the experimental period 2020/2021was illustrated in Figure1. The amount of irrigation water was calculated according to gravimetric methods by weight of a sown pots on field capacity and then subsequently reweighed at regular intervals (Dumroese et al., 2015). Water use efficiency (WUE) in k gm^{-3} was calculated from the relation between grain yield and water consumptive use (WCU) according to Ghane et al. (2010) as follows:

$$\text{WUE (kg/m}^3\text{)} = \frac{\text{Grain yield (kg/}ha\text{)}}{\text{WCU (m}^3\text{/ha)}}$$

Plant analysis

Dry wheat plant tissues were washed, dried at 70 °C and crushed. Half gram of dry matter from each sample was digested by a mixture of $HClO_4$ and H_2SO_4 acid (1: 3) (AOAC, 1995). Total N was calculated using the micro-Kjeldahl method, total P was determined using the ascorbic acid method Spectrophotometer (JENWAY-6105 Uv/v), total K was determined using the flame photometer (JENWAY-digital) and Zn in the plant digest as described by Cottenie et al. (1982). Growth parameters (plant height,

Table 1. Some physical and chemical characteristics of the studied soil and chicken manure

	Physical properties										
Soil	Soil water content %			BD Mg/m^3	Porosity %	Particle size distribution%			Texture class		
	FC	PWP	AW			Sand	Silt	Clay			
	9.50	3.10	6.40	1.59	40.0	79.00	14.50	6.50	Loamy sand		
	Chemical properties					Available nutrients mg/kg					
	pH	EC dS/m		OM%	CEC cmolc /kg	N	P	K	Zn		
	7.95	1.11		0.28	2.90	38.00	9.10	65.00	0.20		
Chicken manure	Characteristics										
	pH	OC%	C/N ratio	OM%	Total%			Total mg/kg			
					N	P	K	Fe	Zn	Mn	Cu
	6.61	34.0	14.47	58.48	2.35	0.55	1.28	41.50	28.50	12.00	5.50

FC: Field capacity: PWP: Permanent wilting point, AW: Available water, OM: Organic matter content, CEC: Cation exchange capacity, OC: Organic carbon, and EC: Electrical conductivity in 1:2.5 soil extract

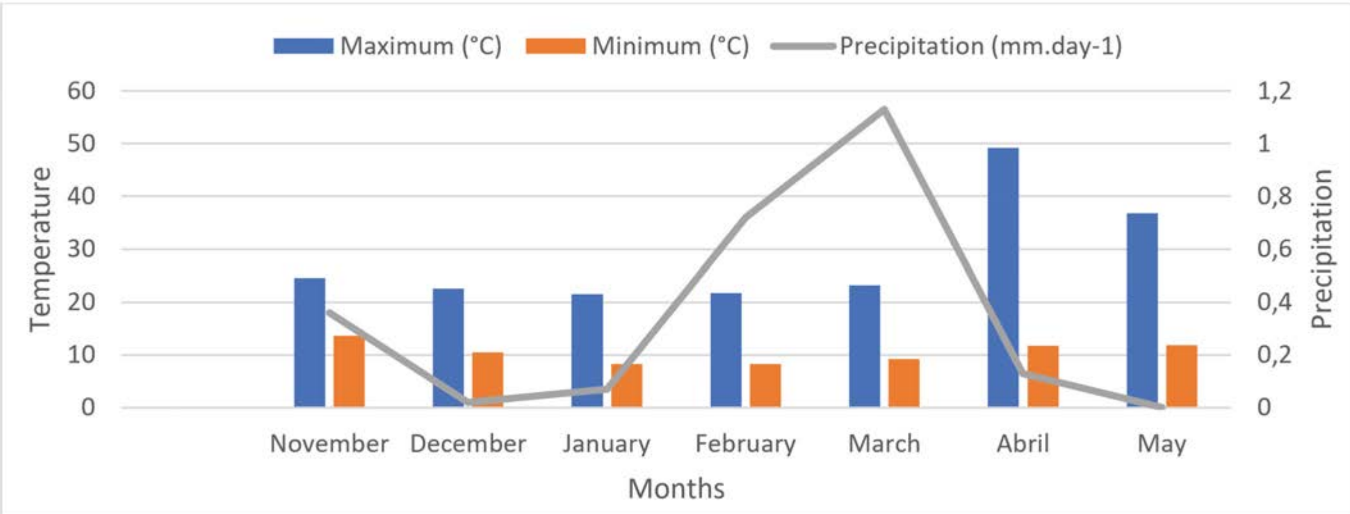

Figure 1. Mean monthly temperature and precipitation from November to May of the studied area

diameter, and chlorophyll content), grain and straw yield were determined. Chlorophyll content was measured at 60 days of planting by measured using a "SPAD 502" portable chlorophyll-meter instrument for fully expanded upper-canopy leaves.

Statistical analysis

The statistical analysis was analyzed by Statistical Package for Social Science version 20. Statistical differences between treatments were performed by using one way ANOVA. The least significant difference (LSD) method was used to test the differences between treatment at (P≤0.05) level of probability according to Levesque (2005).

RESULTS AND DISCUSSION

Characterization

FTIR Data

Figure 2 shows FTIR spectrum of CS^+ acetate. As can be seen from this figure the strong band at 1640 cm^{-1} is assigned to ($NH3^+$) groups combined with amide I group (Fouda et al., 2014). The shoulder at 1558 cm^{-1} and strong peak at 1408 cm^{-1} are owing to asymmetric and symmetric carboxylate anion stretching (Nunthanid et al., 2004). In addition of these, the bands of C3–OH- and C6–OH- groups of chitosan unit at 1080 and 1020 cm^{-1} are overlapped and appeared combined at 1074 cm^{-1} due to the presence of excess of H_2O (Ghaffari et al., 2020).

The spectrum of CS-ZnO-NPs in Figure 2 shows the shorter intensity of ($NH3^+$) band at 1640 cm^{-1} indicating the involvement and complexation of ($NH3^+$) groups with ZnO-NPs (Yazdani et al., 2018). The band at 1087 cm^{-1} representing the secondary -OH of C6 in chitosan unit is moved to 1070 cm^{-1} along with a lower intensity revealing a coordination of -OH with ZnO-NPs (Wang et al., 2004). AS well as the small band at 675 cm^{-1} corresponded to ZnO. The lower intensities of the bands at 1082 and 1016 cm^{-1} which related to both C3–OH- and C6–OH- groups in chitosan unit could be another evidence to complexation of these groups with ZnO-NPs (Aadnan et al., 2020).

UV data

As can be seen of Figure 3 the excitation peak was observed at the band-gap wavelength 268 nm is correspond to CS-ZnO-NPs which lies much below than the band-gap wavelength at 388 nm of ZnO (Dhillon et al., 2014).

Dynamic light scattering data

Figure 4 shows the size average of the CS-ZnO that has measured by undertaking DLS size distribution analysis. The average size of the CS-ZnO was 365 nm indicates the formation nano size of prepared compound.

Growth parameters of wheat plant

Table 2 shows the effect of foliar application of chitosan ZnO nanoparticles (CS-ZnO-NPs) under different levels of field capacity (FC) on growth parameters of wheat plant. Generally, all growth parameters (plant height, diameter and chlorophyll content) decreased significantly ($P \leq 0.05$) by decreasing the moisture content. Water stress typically inhibits photosynthesis, which is connected to the breakdown of chlorophyll (Rady et al., 2021).

These results are agreed with those obtained by Ali et al. (2018) who found that water stress reduces the height, biomass, and chlorophyll content on wheat crop by restricting photosynthesis. Also, water stress led to induce stomatal restriction, non-stomatal restriction, or

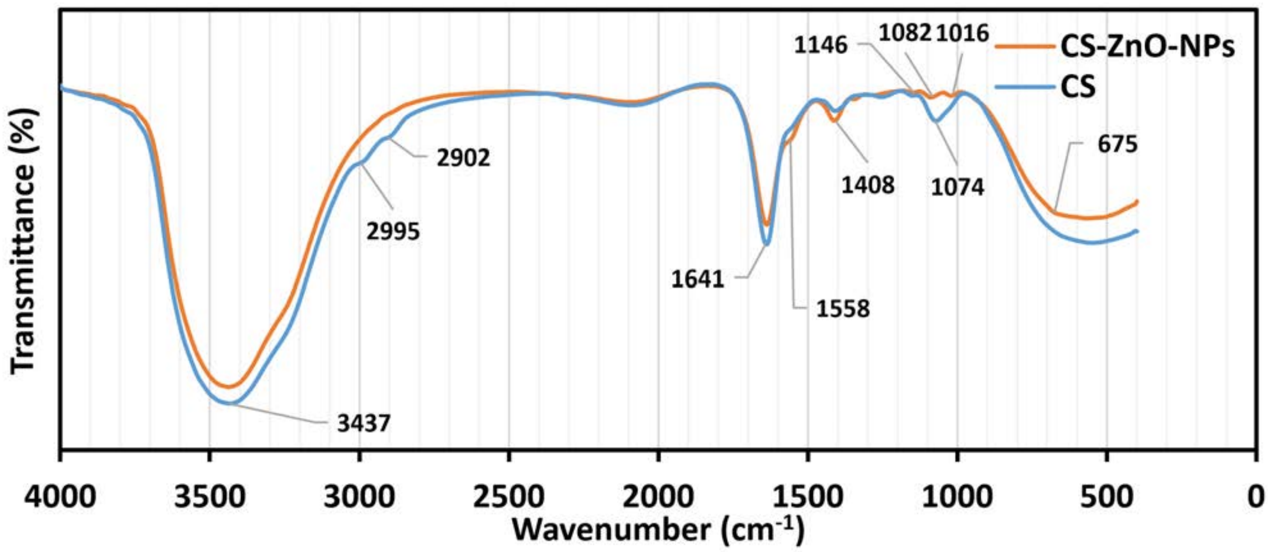

Figure 2. FTIR spectrum of CS^+ acetate and CS-ZnO-NPs

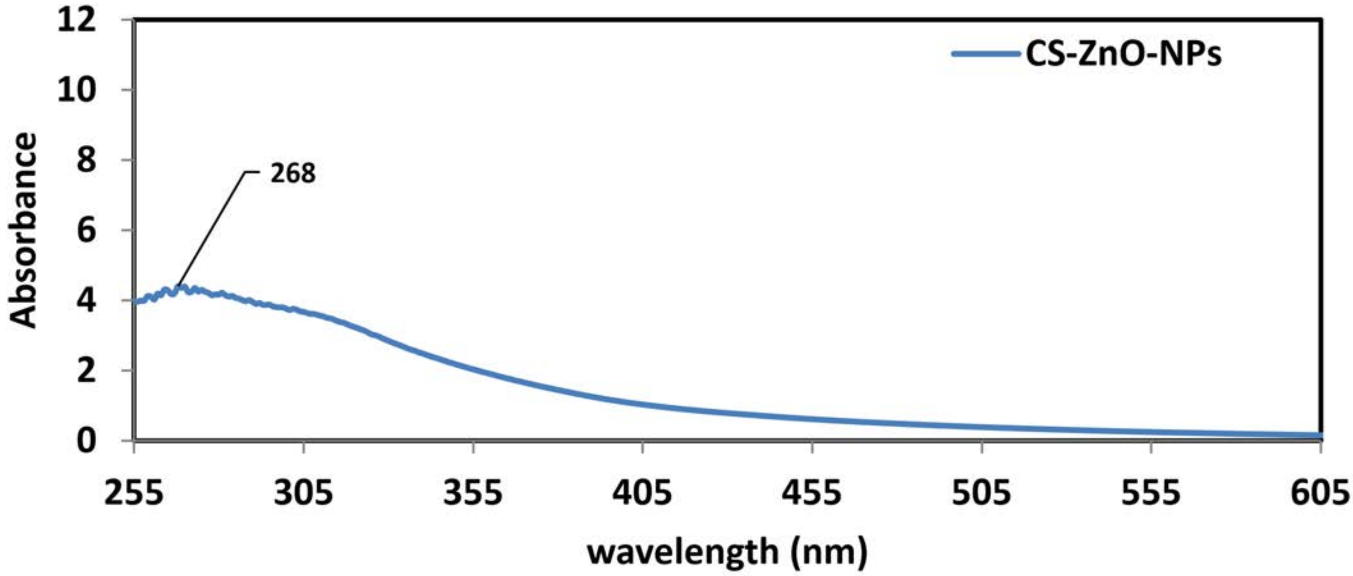

Figure 3. UV–Visible spectra of the different CS-ZnO-NPs synthesized by precipitation method

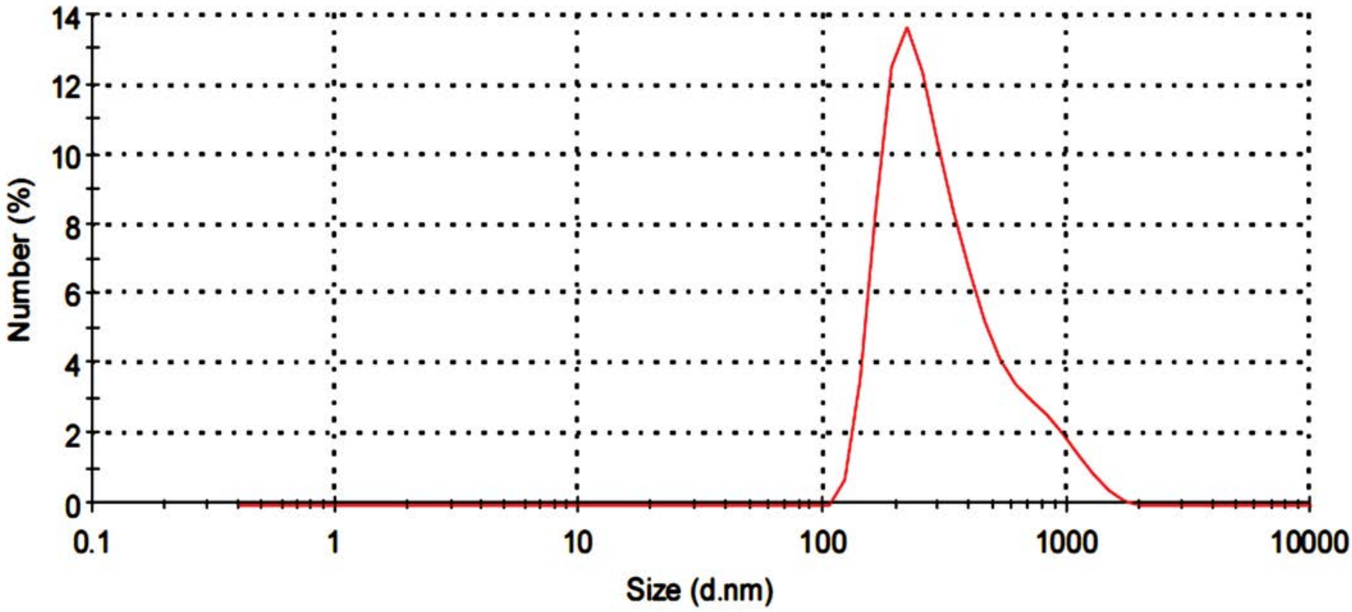

Figure 4. Size average of the CS-ZnO by DLS

both during photosynthesis (Elizabete Carmo-Silva et al., 2010).

On the other hand, the growth parameters are significantly increased by application of CS-ZnO-NPs under all levels of water content especially at 150 ppm CS-ZnO-NPs. Zinc addition supports chloroplast growth, protects sulfhydryl groups, among other actions that support chlorophyll biosynthesis (Sturikova et al., 2010). ZnO nanoparticles at lower concentrations could mitigate the effects caused by water stress (Upadhyaya et al., 2020), improved growth parameters of wheat plants (Srivastav et al., 2021).

This may be attributed to nano ZnO might be the reason for increased dry matter accumulation and might be due to the complementary effect of other inherent nutrients (Koti et al., 2009). The maximum plant height was 41.50, 38.52, and 30.25 cm under 100, 80 and 60% from FC, respectively. Also, the highest wheat diameters were 6.10, 5.23 and 3.20 mm under 100, 80 and 60% FC, respectively. Finally, the highest values of chlorophyll content were 51.50, 43.0 and 38.23 at 100, 80 and 60% FC, respectively at 150 ppm CS-ZnO-NPs. This trend agreement with that obtained by Kumar et al. (2021).

Macronutrients content in wheat straw and grain

The increasing of macronutrients content especially N content in grain is an indicator to wheat quality, as well as it is a critical value for human nutrition. The data in Table 3 indicated that there are highly decrease in NPK content by decreasing the moisture content. These findings are supported by Awasthi et al. (2014). Application of CS-ZnO-NPs significantly increased the content of N and K under all levels of moisture content as compared to control. But P was recorded a slightly increase in all treatments. The increasing in plant growth, N, P, and K concentrations in shoots and grains are attributed to involvement of nano Zn in boosting plant growth (Rietra et al., 2017), rapid nutrient uptake during the crop growth period, especially if the soil is poor in accessible nutrients (AlJuthery and Saadoun, 2018). These results are confirmed by Ponnmani et al. (2019) who obtained that the addition of various zinc sources during the crop growth significantly ($P \le 0.05$) increased N, P, and K concentrations. It could be seen from the previous results that the total nutrient content of wheat crop is strongly influenced by growth parameters, which is regulated by foliar application of CS-ZnO-NPs and moisture content. The increase could be attributable to a synergistic effect between recommended dose of macronutrients and Zn, which could be caused by an increase in enzymatic activity caused by Zn application (Potarzycki and Grzebisz, 2009). However, application of CS-ZnO-NPs at 150 ppm recorded the highest content of N, P and K (0.68, 0.25 and 1.41, respectively) in wheat straw under 100% of FC.

Table 2. Growth parameters of wheat plant as affected by chitosan ZnO nanoparticles (CS-ZnO-NPs) under different levels of moisture content

Treatments			Growth parameters		
CS-ZnO-NPs ppm	IW		Length cm	Diameter mm	Chlorophyll content (Spad)
	FC%	m^3/ha			
Control	100	4250	34.56	4.33	41.60
	80	3400	31.25	3.18	34.50
	60	2550	22.14	2.15	33.52
50	100	4250	37.12	4.88*	46.15*
	80	3400	34.30	3.65*	39.35*
	60	2550	25.20	2.80*	35.12*
100	100	4250	41.32*	5.16*	51.20*
	80	3400	37.42*	5.00*	42.15*
	60	2550	28.16*	3.11*	38.00*
150	100	4250	41.50*	6.10*	51.50*
	80	3400	38.52*	5.23*	43.00*
	60	2550	30.25*	3.20*	38.23*

* Significance at $P \le 0.05$

This may be due to zinc plays a crucial role in increasing protein synthesis, membrane function, cell elongation, and stimulating plant roots to actively exchange cations, which allows plants to absorb more nutrients (Ahmed et al., 2021). Also, the macronutrients content in grains were higher than their content in the straw. The highest values of N, P and K in wheat grain were 1.95, 0.43 and 1.66, respectively at 100% FC under 150 ppm CS-ZnO-NPs compared to control. ZnO NPs helps to reduce the negative impacts of drought, improving plant growth and physiological parameters and enhance the nutritional value of wheat plants (Abd El-Aziz et al., 2022).

Wheat yield

The overall increase in the growth and macronutrients uptake of the wheat plant has been reflected ultimately in wheat yield (Table 4). There is a significant variation among wheat treated by foliar applications of CS-ZnO-NPs along with control. These results are similar to those obtained by Sun et al. (2020) who found that nano zinc at 100 mg L^{-1} improved maize yield under water stress. While water shortage gave a clear decrease in wheat yield. This is confirmed by Mirbahar et al. (2009) and Abd El-Aziz et al. (2022). The highest values of straw yield were 5574.50, 5210.87 and 4822.56 kg/ha under 100, 80 and 60% of FC, respectively at 150 ppm CS-ZnO-NPs. While the lowest values were 4985.0, 4582.50 and 4269.90 kg/ha at 100, 80 and 60% of FC, respectively without application of CS-ZnO-NPs. Also, the highest relative increase in wheat grain and straw was 22.73% and 13.76%, respectively. These positive effects mostly result from enhanced macro- and micronutrient absorption, elevated relative water content and reduced cell membrane damage (Sedima et al., 2021). The results also obtained that; seed index of wheat (1000 grain) and total grain yield were increased significantly ($P \leq 0.05$) by increasing the foliar application of CS-ZnO-NPs under deficit irrigation water. The highest value of seed index and weight yield are recorded 44.7 g and 4990.55 kg/ha, respectively at 150 ppm nano ZnO under 100% FC,

Table 3. Macro nutrients content (%) in straw and grains as affected by application of chitosan ZnO nanoparticles (CS-ZnO-NPs)

Treatments			Straw			Grains		
CS-ZnO-NPs ppm	IW							
	FC%	m^3/ha	N	P	K	N	P	K
Control	100	4250	0.50	0.18	1.20	1.55	0.24	1.29
	80	3400	0.42	0.18	1.17	1.50	0.18	1.24
	60	2550	0.30	0.15	1.10	1.41	0.15	1.17
50	100	4250	0.55*	0.18	1.27	1.70*	0.31	1.37*
	80	3400	0.45	0.17	1.24	1.55	0.24	1.29*
	60	2550	0.34*	0.15	1.18*	1.46	0.20	1.22*
100	100	4250	0.58*	0.20*	1.36*	1.84*	0.36*	1.58*
	80	3400	0.50*	0.18	1.30*	1.63*	0.28*	1.38
	60	2550	0.37*	0.16	1.23*	1.50	0.26*	1.31*
150	100	4250	0.68*	0.25*	1.41*	1.95*	0.43*	1.66*
	80	3400	0.53*	0.20*	1.33*	1.67*	0.34*	1.43*
	60	2550	0.38*	0.20*	1.24*	1.53*	0.30*	1.35*

* Significance at $P \leq 0.05$

Table 4. Wheat yields as affected by foliar application of CS-ZnO-NPs and different levels of irrigation water (IW)

Treatments			Seed index (1000 grain g)	Straw		Grains	
CS-ZnO-NPs ppm	IW			Yield kg/ha	Relative increase %	Yield kg/ha	Relative increase %
	FC%	m^3/ha					
Control	100	4250	35.70	4985.00	-	3990.00	-
	80	3400	33.50	4580.50	-	3785.60	-
	60	2550	31.60	4260.90	-	3544.80	-
50	100	4250	39.60*	5189.87*	4.68	4250.90*	6.54
	80	3400	35.70*	4769.85*	4.13	3990.50	5.41
	60	2550	34.50*	4456.60*	4.59	3740.60	5.52
100	100	4250	42.30*	5340.60*	7.13	4630.58*	16.05
	80	3400	38.30*	4980.50*	8.73	4298.60*	13.55
	60	2550	37.60*	4655.50*	9.27	3990.70*	12.58
150	100	4250	44.70*	5574.50*	11.83	4890.55*	22.57
	80	3400	42.00*	5210.87*	13.76	4453.50*	17.64
	60	2550	37.50*	4822.56*	13.18	4350.50*	22.73

* Significance at $P \leq 0.05$. Relative increase = 100 x [1 - (treated parameter / control)]

as compared the lowest values which recorded 31.6 g and 3544.80 kg/ha under 60% FC. These changes are in line with those obtained by Sultana et al. (2016) and Adrees et al. (2021) found that application of ZnO-NPs counteracted the adverse effect of deficit water on wheat yield. One explanation could be that NPs have more surface reactivity, which enables them to open up new pores or enlarge existing ones in roots, enhancing water and nutrient circulation inside plants and promoting plant growth and development even in unfavorable environmental conditions (Raliya et al., 2015).

Zn content in wheat straw and grain

A higher Zn concentration in grain is a positive quality characteristic that can boost the nutritional value of grains. As shown in Table 5 Zn content in straw and grain increased significantly ($P \leq 0.05$) by application of chitosan ZnO nanoparticles (CS-ZnO-NPs) under all levels of moisture content. Therefore, the application of CS-ZnO-NPs was importance for improving the concentration of Zn in wheat grain. These findings are confirmed by Prasad et al. (2012) who found that foliar application of nano zinc oxide improved wheat yield and zinc content. All values of Zn were in permissible limits. In this respect, Srivastav et al. (2021) observed that wheat treated plants with ZnO NPs at high levels (150–200 mg/L) caused pant toxicity. The limits of Zn in wheat grain ranged between 25-40 mg/kg. While the desirable concentration to combat human Zn deficiency might be 50-70 mg/kg (Cakmak 2008). The values of Zn concentration were ranged between 12.5 to 23.9 mg/kg and 14.0 to 30.40 mg/kg in wheat straw and grain, respectively. The lowest values were observed at 60% moisture content, while the highest values were recorded at 150 CS-ZnO-NPs under 100% FC. Also, the highest relative increase in Zn content of wheat grain and straw was 88.57% and 61.79%, respectively. There is a significant increase in Zn content and uptake of wheat grain, and straw by application of nano Zn (Prajapati et al., 2018).

Water use efficiency (WUE)

It is critical to comprehend the relation between wheat yield and amount of water applied (Table 5). Water use efficiency (WUE) is the final performance of agricultural production and water consumption, and it defines agricultural water saving capability and water productivity. In general, WUE increased with decreased the amount of irrigation water, this is due to the plants consumed less water. This trend agreement with Zhao et al. (2020) who obtained that WUE was increased under water stress of various plant species. This due to that stomatal closure during water stress reduces leaf conductivity, photosynthesis, and transpiration and, due to leaf conductance responds sensitively to decreasing leaf water potential, more conservative water usage leads in increased WUE in water-stressed plants, which may be a strategy for enhancing resource usage efficiency. Among those who have contributed to this work are Liu et al. (2016). Interaction of different levels of irrigation and CS-ZnO-NPs treatments on seed yield and WUE were affected significantly ($P \leq 0.05$). The highest WUE was related to the increasing of CS-ZnO-NPs and decreasing in irrigation water. The highest value was observed (1.71 kg/m) at 150 ppm CS-ZnO-NPs under 60% of irrigation water. The data are confirmed by Semida, et al., (2021). Also, the highest relative increase in water use efficiency of the marketable yield (seed wheat yield) as kg seed m^{-3} of water was 23.03%.

Table 5. Zn content and water use efficiency as affected by foliar application of CS-ZnO -NPs and different levels of irrigation water (IW)

Treatments			Straw		Grains		Water use efficiency	
CS-ZnO-NPs ppm	IW		Zn mg/kg	Relative increase %	Zn mg/kg	Relative increase %	Value kg/m	% Increase
	FC%	m^3/ha						
Control	100	4250	15.10	-	18.75	-	0.94	-
	80	3400	14.00	-	17.20	-	1.11	-
	60	2550	12.50	-	14.00	-	1.39	-
50	100	4250	18.90*	25.17	26.44*	41.01	1.00	6.38
	80	3400	16.50*	17.86	25.33*	47.27	1.17	5.41
	60	2550	15.10*	20.80	24.22*	73.00	1.47	5.76
100	100	4250	21.00*	39.07	28.74*	53.28	1.09*	15.96
	80	3400	19.65*	40.36	27.65*	60.76	1.26*	13.51
	60	2550	17.45*	39.60	25.50*	82.14	1.56*	12.23
150	100	4250	23.90*	58.28	30.40*	62.13	1.15*	22.34
	80	3400	22.65*	61.79	28.50*	65.70	1.31*	18.01
	60	2550	19.25*	54.00	26.40*	88.57	1.71*	23.03

* Significance at $P \leq 0.05$. Relative increase = 100 x [1 - (treated parameter / control)]

CONCLUSION

It is necessary to create new methods that increase food production under water scarcity, while also supplying nutrients to plants at a rate that satisfies their requirements. As some manufactured nanoparticles (NPs) could be employed as fertilizer, nanotechnology is one approach for improving crop nutritional qualities especially, Zn content of wheat yield in the agricultural soils which suffer in deficient Zn. The current work sheds light on the potential role of chitosan zinc oxide nanoparticles (CS-ZnO-NPs) for enhancing wheat productivity under water stress. The findings of this study suggested that the foliar application of chitosan zinc oxide nanoparticles (150 ppm) at 15, 30, 45 and 60 days after sowing significantly increased wheat yield, zinc content and water use efficiency under water stress. Thus, foliar application of chitosan zinc oxide nanoparticles could assist in making the best use of limited water resources in water-stressed locations.

REFERENCES

Aadnan, I., Zegaoui, O., Daou, I., da Silva, J.C.E. (2020) Synthesis and physicochemical characterization of a ZnO-Chitosan hybrid-bio composite used as an environmentally friendly photocatalyst under UV-A and visible light irradiations. Journal of Environmental Chemical Engineering, 8 (5), 104260. DOI: https://doi.org/10.1016/j.jece.2020.104260

Abdel-Aziz, H.M.M., Mohammed, N.A.H., Aya, M.O. (2018) Effect of foliar application of nano chitosan NPK fertilizer on the chemical composition of wheat grains. Egyptian Journal of Botany, 58 (1), 87–95. DOI: https://doi.org/10.21608/EJBO.2018.1907.1137

Abd El-Aziz, G.H., Ahmed, S.S., Radwan, K.H., Fahmy, A.H. (2022) Positive and negative environmental effect of using zinc oxide nanoparticles on wheat under drought stress. Open Journal of Applied Sciences, 12, 1026-1044. DOI: https://doi.org/10.4236/ojapps.2022.126070

Adil, M., Zhang, S., Wang, J., Shah, A. N., Tanveer, M., Fiaz, S. (2022) Effects of fallow management practices on soil water, crop yield and water use efficiency in winter wheat monoculture system: a meta-analysis. Frontiers in Plant Science, 13, 825309. DOI: https://doi:10.3389/fpls.2022.825309

Adrees, M., Khan, Z.S., Hafeez, M., Rizwan, M., Hussain, Kh., Asrar, M., Alyemeni, M.N., Wijaya, L., Ali, Sh. (2021) Foliar exposure of zinc oxide nanoparticles improved the growth of wheat (*Triticum aestivum* L.) and decreased cadmium concentration in grains under simultaneous Cd and water deficient stress. Ecotoxicology and Environmental Safety, 208, 111627. DOI: https://doi.org/10.1016/j.ecoenv.2020.111627

Ahmed, A.M., Mostafa, M.R., Wael, M.S., Eman, E.B., Wail, M.O., Hatim, M.A., Esmat, F. (2021) Foliar Nourishment with Different Zinc-Containing Forms Effectively Sustains Carrot Performance in Zinc-Deficient Soil. Agronomy, 11, 1853. DOI: https://doi.org/10.3390/agronomy11091853

Ali, Sh., Xu, Y., Jia, Q., Ahmad, I., Wei, T., Ren, X., Zhang, P., Din, R., Cai, T., Jia, Z. (2018). Cultivation techniques combined with deficit irrigation improves winter wheat photosynthetic characteristics, dry matter translocation and water use efficiency under simulated rainfall conditions. Agricultural Water Management ,201, 207–218. DOI: https://doi.org/10.1016/j.agwat.2018.01.017

Al-Juthery, H. W. A., Saadoun, S. F. (2018) Impact of foliar application of micronutrients nano fertilizers on growth and yield of Jerusalem artichoke. Iraqi Journal of Agricultural Sciences, 49 (4), 755-787.

Andrejic, G., Gajic, G., Prica, M., Dzeletovic, Z., Rakic, T. (2018) Zinc accumulation, photosynthetic gas exchange, and chlorophyll a fluorescence in Zn-stressed Miscanthus x giganteus plants. Photosynthetica, 56, 1249–1258.

AOAC (1995) Association of Official Agricultural Chemists. Association of Official Analysis Chemists Official Methods of Analysis. 15th ed. Washington, DC, USA.

Awasthi, R., Kaushal, N., Vadez, V., Turne, N.C., Berger, J., Siddique, K.H.M., Nayyar, H. (2014) Individual and combined effects of transient drought and heat stress on carbon assimilation and seed filling in chickpea. Functional Plant Biology 41, 1148-1167. DOI: https://doi.org/10.1071/FP13340

Bameri, M., Abdolshahi, R., Nejad, G.M., Yousefi, K, Tabatabaie, S.M. (2012) Effect of different microelement treatment on wheat (*Triticum aestivum* L.) growth and yield. International Research Journal of Applied and Basic Sciences, 3 (1), 219-223.

Blake, G. R., Hartge K. H. (1986) Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. In: Klute A, Ed, Soil Science Society of America, 2nd Edition, Madison, 363-382. DOI: https://doi.org/10.2136/sssabookser5.1.2ed.c13

Burt, R. (2004) Soil survey laboratory methods manual. Soil Survey Investigations Report No. 42, Version 4.0, Natural Resources Conservation Service, United States Department of Agriculture.

Buzea, C., Pachec,o I.I., Robbie, K. (2007) Nanomaterials and nanoparticles: sources and toxicity. Biointerphases, 2 (4), MR17–71. PMID: 20419892. DOI: https://doi.org/10.1116/1.2815690.

Cakmak, I. (2008) Enrichment of cereal grains with zinc: agronomic or genetic biofortification? Plant Soil, 302 (1-2), 1-17. DOI: https://doi.org/10.1007/s11104-007-9466-3

Choudhary, R. C., Kumaraswamy, R. V., Kumari, S., Sharma, S. S., Pal, A., Raliya, R., Saharan, V. 2019 Zinc encapsulated chitosan nanoparticle to promote maize crop yield. International Journal of Biological Macromolecules, 127, 126-135. DOI: https://doi.org/10.1016/j.ijbiomac.2018.12.274

Cottenie A., Verloo, M., Kiekens, L., Velghe, G., Camerlynck, R. (1982) Chemical Analysis of Plant and Soil Laboratory of Analytical and Agrochemistry, State University Ghent, Belgium, pp. 100-129.

Dhillon, G.S., Kaur, S., Brar, S.K, (2014) Facile fabrication and characterization of chitosan-based zinc oxide nanoparticles and evaluation of their antimicrobial and antibiofilm activity. International Nano Letters, 4, 107. DOI: https://doi.org/10.1007/s40089-014-0107-6

Dumroese, R.K., Montville, M.E., Pinto, J.R. (2015) Using container weights to determine irrigation needs: a simple method. Native Plants Journal, 16 (1) ,67–71.

Elizabath, A., Bahadur, V., Misra, p., Prasad, V.M., Thomas, T. (2017) Effect of different concentrations of iron oxide and zinc oxide nanoparticles on growth and yield of carrot (*Daucus carota* L.) Journal of Pharmacognosy Phytochemistry, 6 (4), 1266-1269.

Elizabete Carmo-Silva, A.E., Keys, A.J, Andralojc, P.J., Powers, S.J., Arrabaça, M.C., Parry, M.A. (2010) Rubisco activities, properties, and regulation in three different C_4 grasses under drought. Journal of Experimental Botany, 61 (9), 2355-2366. DOI: https://doi.org/10.1093/jxb/erq071

Faizan, M., Faraz, A., Mir, A.R., Hayat, S. (2021) Role of zinc oxide nanoparticles in countering negative effects generated by cadmium in Lycopersicon esculentum. Journal of Plant Growth Regulation, 40, 101–115.

Farooq, M., Gogoi, N., Barthakur, S., Baroowa, B., Bharadwaj, N., Alghamdi, S.S., Siddique, K.H.M. (2017) Drought stress in grain legumes during reproduction and grain filling. Journal of Agronomy Crop Science, 203, 81–102. DOI: https://doi.org/10.1111/jac.12169

Fouda, A., Hussein, M.H.M., Mursy, M., Hazzaa, M.M., Shaban, A.F, Hefni, H.H.H. (2014) A Study on the effect of type of solvent on chitosan efficiency for treatment of drinking water contaminations. Egyptian Journal of Chemistry, 57 (4), 327-341.

Gee, G. W., Bauder, J. W. (1986) Particle Size Analysis. In: Methods of Soil Analysis, Part A. Klute (Ed) 2 ed Vol. 9nd American Society of Agronomy Madison. WI pp: 383-411. DOI: https://doi.org/10.2136/sssabookser5.1.2ed.c15

Ghaffari, S.B., Sarrafzadeh, M.H., Salami, M., Khorramizadeh, M.R. (2020) A pH-sensitive delivery system based on N-succinyl chitosan-ZnO nanoparticles for improving antibacterial and anticancer activities of curcumin. International Journal of Biological Macromolecules, 151, 428-440. DOI: https://doi.org/10.1016/j.ijbiomac.2020.02.141

Ghane, E., Feizi, M., Mostafazadeh-Fard, B., Landi, E. (2010) Water productivity of winter wheat in different irrigation planting methods using saline irrigation water. International Journal of Agriculture and Biology, 11, 131-137.

Guan, Z., Linsley, C. S., Pan, S., DeBenedetto, C., Liu, J., Wu, B. M., Li, X. (2020) Highly ductile Zn-2Fe-WC nanocomposite as biodegradable material. Metallurgical and Materials Transactions A, 51, 4406-4413. DOI: https://doi.org/10.1007/s11661-020-05878-y

Hassan, M.U., Aamer, M., Chattha, M.U., Haiying, T., Shahzad, B., Barbanti, L., Nawaz, M., Rasheed, A., Afzal, A., Liu, Y., Guoqin, H. (2020) The critical role of zinc in plants facing the drought stress. Agriculture, 10 (9), 396. DOI: https://doi.org/10.3390/agriculture10090396

Hidangmayum, A., Dwivedi, P., Katiyar, D., Hemantaranjan, A. (2019) Application of chitosan on 420 plant responses with special reference to abiotic stress. Physiology and Molecular Biology of Plants, 25 (2), 313–326. DOI: https://doi.org/10.1007/s12298-018-0633-1

Hussein, M.H.M., El-Hady, M.F., Sayed, W.M., Hefni, H. (2012) Preparation of some chitosan heavy metal complexes and study of its properties. Polymer Science serious A, 54 (2),113–124. DOI: https://doi.org/10.1134/S0965545X12020046

Irshad, M.A., Nawaz, R., Rehman, M.Z., Imran, M., Ahmad, M.J., Ahmad, S., Inaam, A., Razzaq, A., Rizwan, M., Ali, S., (2020) Synthesis and characterization of titanium dioxide nanoparticles by chemical and green methods and their antifungal activities against wheat rust. Chemosphere, 258, 1–10. DOI: https://doi.org/10.1016/j.chemosphere.2020.127352

Khan, M.R., Rizvi, T.F. (2014) Nanotechnology: Scope and application in plant disease management. Journal of Plant Pathology, 13, 214–231. DOI: https://doi.org/10.3923/ppj.2014.214.231

Kolencik, M., Ernst, D., Komar, M., Urik, M., Sebesta, M., Durisova, L., Bujdos, M., Cerny, I., Chlpik, J., Juriga, M., et al. (2022) Effects of foliar application of Zno-nanoparticles on lentil production, stress level and nutritional seed quality under field conditions. Nanomaterials, 12, 310. DOI: https://doi.org/10.3390/nano12030310

Koti, R.V., Mummigatti, U.V., Nawalgatti, C.M., Savita, F.H., Guled, M.B., Anand A. Complimenatry effect of zinc application on iron content in sorghum genotypes. Indian Journal of Plant Physiology 14(1),78-81.

Kumar, A., Prajapati, D., Devi, K. A., Pal, A., Choudhary, U., Dashora, A., Saharan, V. (2021) Slow-release Zn application through Zn-chitosan nanoparticles in wheat to intensify source activity and sink strength. Plant Physiology and Biochemistry, 168, 272-281. DOI: https://doi.org/10.1016/j.plaphy.2021.10.013

Levesque, R. (2005) SPSS programming and data management: A guide for SPSS and SAS users. Spss.

Lindsay, W.L., Norvell, W.A. (1978) Development of a DTPA micronutrient soil test for zinc, iron, manganese, and copper. Soil Science Society of American Journal, 42, 421–428.

Linh, T.M., Mai, N.C., Hoe, P.T., Lien, Q., Ban, N.K., Hien, L.T.T., Chau, N.H., Van, N.T. (2020) Metal-based nanoparticles enhance drought tolerance in soybean. Journal of Nanomaterials ID 4056563. DOI: https://doi.org/ 10.1155/ 2020/ 4056563

Liu, E.K., Mei, X.R., Yan, C.R., Gong, D.Z., Zhang, Y. Q. (2016) Effects of water stress on photosynthetic characteristics, dry matter translocation and WUE in two winter wheat genotypes. Agricultural Water Management, 167, 75–85.

Mirbahar, A. A., Markhand, G. S., Mahar, A. R., Abro, S. A., Kanhar, N. A. (2009) Effect of water stress on yield and yield components of wheat (*Triticum aestivum* L.) varieties. Pakistan Journal of Botany, 41 (3), 1303-1310.

Motawie, A.M., Mahmoud, K.F., El-Sawy, A.A., Kamal, H.M., Hefni, H., Ibrahiem, H.A. (2014) Preparation of chitosan from the shrimp shells and its application for pre-concentration of uranium after cross-linking with epichlorohydrin. Egyptian Journal of Petroleum, 23 (2), 221-228.

Mujtaba, M., Khawar, K.M., Camara, M.C., Carvalho, L.B., Fraceto, L.F., Morsi, R.E., Elsabee, M. Z., Kaya, M., Labidi, J., Ullah, H., Wang, D. (2020) Chitosan-based delivery systems for plants: A brief overview of recent advances and future directions. International Journal of Biological Macromolecules, 154, 683-697. DOI: https://doi.org/10.1016/j.ijbiomac.2020.03.128

Munir, T., Rizwan, M., Kashif, M., Shahzad, A., Ali, S., Amin, N., Zahid, R., Alam, M.F.E., Imran, M. (2018) Effect of zinc oxide nanoparticles on the growth and Zn uptake in wheat (*Triticumaestivum* L.) by seed priming method. Digest Journal of Nanomaterials Biostructures. ID 53596069, 13 (1), 315 – 323.

Nunthanid, J., Laungtana-Anan, M., Sriamornsak, P., Limmatvapirat, S., Puttipipatkhachorn, S., Yong, L., Khor, E. (2004) Characterization of chitosan acetate as a binder for sustained release tablets. Journal Control Release, 99 1, 15-26. DOI: https://doi.org/10.1016/j.jconrel.2004.06.008

Paul, A. K., Bala, T. K., Shahriar, S., Hira, H. R. (2016) Effect of foliar application of zinc on yield of wheat grown under water stress condition. International Journal of Bio-resource and Stress Management, 7 (5), 1025-1031. DOI: https://doi.org/10.23910/IJBSM/2016.7.5.1645b

Palacio-Márquez, A., Ramírez-Estrada, C. A., Gutiérrez-Ruelas, N. J., Sánchez, E., Ojeda-Barrios, D. L., Chávez-Mendoza, C., Sida-Arreola, J. P. (2021) Efficiency of foliar application of zinc oxide nanoparticles versus zinc nitrate complexed with chitosan on nitrogen assimilation, photosynthetic activity, and production of green beans (*Phaseolus vulgaris* L.). Scientia Horticulturae, 288, 110297. DOI: https://doi.org/10.1016/j.scienta.2021.110297

Ponnmani, P., Muthukumararaja, T., Sriramachandrasekharan, M.V. (2019) Effect of bio and nano zinc fertilization on nutrient content and yield of rice. International Journal of Scientific & Technology Research, 8 (12), 1170-1175

Pooja, R.M., Bhaumik, J., Kaur, R. (2020) Role of zinc oxide nanoparticles in mitigation of drought and salinity - A review. International Journal of Current Microbiology and Applied Sciences, 9 (11), 467-481. DOI: https://doi.org/10.20546/ijcmas.2020.911.058

Potarzycki, J., Grzebisz, W. (2009) Effect of zinc foliar application on grain yield of maize and its yielding components. Plant, Soil and Environment, 55 (12), 519-527. DOI: https://doi.org/10.17221/95/2009-PSE

Prajapati, B. J., Patel, S. B., Patel, R. P., Ramani, V. P. (2018) Effect of zinc nano-fertilizer on growth and yield of wheat (*Triticum aestivum* L.) under saline irrigation condition. Agropedology, 28 (1), 31-37.

Prakash, T., Jayaprakash, R., Neri, G., Kumar, S. (2013) Synthesis of ZnO nanostructures by microwave irradiation using albumen as a template. Journal of Nanoparticles. ID 274894. DOI: https://doi.org/10.1155/2013/274894

Prasad, T.N.V.K.V., Sudhakar, P., Sreenivasuki, Y., Latha, P., Munaswamy, V., Reddy, K.R., Sreeprsad, T.S., Sajanlal, P.R., Pradeep, T. (2012) Effect of nanoscale zinc oxide particles on the germination, growth and yield of Peanut. Journal of Plant Nutrition, 35, 905–927. DOI: https://doi.org/10.1080/01904167.2012.663443

Qureshi, A., Singh, D.K., Dwivedi, S. (2018) Nano fertilizers: A novel way for enhancing nutrient use efficiency and crop productivity. International Journal of Current Microbiology and Applied Sciences, 7 (2), 3325-3335. DOI: https://doi.org/10.20546/ijcmas.2018.702.398

Rady, M.O., Semida, W.M., Howladar, S., El-Mageed, T.A.A. (2021) Raised beds modulate physiological responses, yield and water use efficiency of wheat (*Triticum aestivum* L.) under deficit irrigation. Agricultural Water Management, 245, 610-629. DOI: https://doi.org/10.1016/j.agwat.2020.106629

Raliya, R., Nair, R., Chavalmane, S., Wang, W.N., Biswas, P. (2015) Mechanistic evaluation of translocation and physiological impact of titanium dioxide and zinc oxide nanoparticles on the tomato (*Solanum lycopersicum* L.) plant. Metall, 7, 1584–1594. DOI: https://doi.org/10.1039/c5mt00168d

Rietra, R.P.J., Marius, J. H., Chistian, O.D., Prem, S.B. (2017) Effects of nutrient antagonism and synergism on yield and fertilizer use efficiency. Communication in Soil Science and Plant Analysis, 48 (16), 1895–1920. DOI: https://doi.org/10.1080/00103624.2017.1407429

Rijal, B., Baduwal, P., Chaudhary, M., Chapagain, S., Khanal, S., Khanal, S., Poudel, P. B. (2021) Drought stress impacts on wheat and its resistance mechanisms. Malaysian Journal of Sustainable Agriculture, 5, 67-76.

Sadeghipour, O. (2021) Chitosan application improves nickel toxicity tolerance in soybean. Journal of Soil Science and Plant Nutrition, 21 (3), 2096-2104. DOI: https://doi.org/10.1007/s42729-021-00505-0

Salehi, R., Arami, M., Mahmoodi, N.M., Bahrami, H., Khorramfar, S. (2010) Novel biocompatible composite (chitosan–zinc oxide nanoparticle): preparation, characterization and dye adsorption properties. Colloids and Surface B: Bio interfaces, 80 (1), 86-93. DOI: https://doi.org/10.1016/j.colsurfb.2010.05.039

Semida, W. M., Abdelkhalik, A., Mohamed, G. F., Abd El-Mageed, T. A., Abd El-Mageed, S. A., Rady, M. M., Ali, E. F. (2021) Foliar application of zinc oxide nanoparticles promotes drought stress tolerance in eggplant (*Solanum melongena* L.). Plants, 10 (2), 421. DOI: https://doi.org/10.3390/plants10020421

Srivastav, A., Ganjewala, D., Singhal, R. K., Rajput, V. D., Minkina, T., Voloshina, M., Shrivastava, M. (2021) Effect of ZnO nanoparticles on growth and biochemical responses of wheat and maize. Plants, 10 (12), 2556. DOI: https://doi.org/10.3390/plants10122556

Sturikova, H., Krystofova, O., Huska, D. and Adam, V. (2010) Zinc, zinc nanoparticles and plants. Journal of Hazardous Materials, 349, 101-110. DOI: https://doi.org/10.1016/j.jhazmat.2018.01.040

Sultana, S., Naser, H., Shil, N., Akhter, S., Begum, R. (2016) Effect of foliar application of zinc on yield of wheat grown by avoiding irrigation at different growth stages. Bangladesh Journal of Agricultural Research, 41 (2), 323-334. DOI: https://doi.org/10.3329/bjar.v41i2.28234

Sun, L., Song, F., Zhu, X., Liu, Liu, F., Wang, Y., Li, Z. (2020) Nano-ZnO alleviates drought stress via modulating the plant water use and carbohydrate metabolism in maize. Achieve Agronomy and Soil Science, 67 (2), 245-259. DOI: https://doi.org/10.1080/03650340.2020.1723003

Tewari, R., Kumar, P., Sharma, P.N. (2019) An effective antioxidant defense provides protection against zinc deficiency-induced oxidative stress in Zn-efficient maize plants. Journal of plant Nutrition Soil Science, 182, 701–707. DOI: https://doi.org/10.1002/jpln.201800622

Upadhyaya, H., Shome, S., Tewari, S., Bhattacharya, M. K., Panda, S. K. (2020) Responses to ZnO-nanoparticles during water stress in Oryza sativa L. Journal of Stress Physiology and Biochemistry, 16 (2), 67-74.

Wang, X., Du, Y., Liu, H. (2004) Preparation, characterization and antimicrobial activity of chitosan–Zn complex. Carbohydrate polymers 56(1), 21-26.
DOI: https://doi.org/10.1016/j.carbpol.2003.11.007

Yazdani, M.R., Virolainen, E., Conley, K., Vahala, R. (2018) Chitosan–Zinc (II) complexes as a bio-sorbent for the adsorptive abatement of phosphate: mechanism of complexation and assessment of adsorption performance. Polymers, 10 (1), 25.
DOI: https://doi.org/10.3390/polym10010025

Zhao, K., Wu, Y. (2017) Effects of Zn deficiency and bicarbonate on the growth and photosynthetic characteristics of four plant species. PLoS ONE, 12 (1), e0169812.
DOI: https://doi.org/10.1371/journal.pone.0169812

Zhao, W., Liu, L., Shen, Q. Yang, J., Han, X., Tian, F., Wu, J. (2020) Effects of water stress on photosynthesis, yield, and water use efficiency in winter wheat. Water, 12 (8), 2127.
DOI: https://doi.org/doi:10.3390/w12082127

Zuverza-Mena, N., Martinez-Fernandez, D., Du, W., Hernandez-Viezcas, J.A., BonillaBird, N., Lopez-Moreno, M.L., Komarek, M., Peralta-Videa, J.R., Gardea-Torresdey, J.L. (2016) Exposure of engineered nanomaterials to plants: Insights into the physiological and biochemical responses-A review. Plant Physiology and Biochemistry, 110, 236-264. DOI: https://doi.org/10.1016/j.plaphy.2016.05.037