RESEARCH ARTICLE

SABRAO Journal of Breeding and Genetics
56 (2) 823-837, 2024
http://doi.org/10.54910/sabrao2024.56.2.33
http://sabraojournal.org/
pISSN 1029-7073; eISSN 2224-8978

IMPACT OF TITANIUM-DIOXIDE AND ZINC-OXIDE NANOPARTICLES IN IMPROVING WHEAT PRODUCTIVITY UNDER WATER STRESS CONDITIONS

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SUMMARY

Agricultural areas worldwide suffer immensely due to the rapid depletion of irrigation water. Applying the proper nutrients can alleviate the harmful effects of water stress. This field study transpired to evaluate the influence of both titanium-dioxide (TiO_2) and zinc-oxide (ZnO) nanoparticles on two wheat (*Triticum aestivum* L.) cultivars (Gimeza-12 and Sids-13) under water irrigation requirements (WIR) of 100% and 75% WIR. Water stress reduced yield attributes and mineral contents but increased protein, gluten, Zeleny sedimentation index, flavonoids, antioxidant activities, and WP. All used concentrations of TiO_2-NPs and ZnO-NPs induced positive responses for all tested parameters compared with non-treated corresponding controls under well-watered and drought-stress conditions. Treatment with 10 mg L^{-1} of ZnO-NPs followed by 10 mg L^{-1} TiO_2-NPs gave the highest values of all studied yield parameters in plants subjected to 75% WIR for both cultivars compared to other controls. The results showed that the Gimeza-12 cultivar, which had the highest grain yield, was more tolerant to drought than the Sids-13 cultivar.

Keywords: Wheat (*Triticum aestivum* L.), water stress condition, nanoparticles, grain yield, biochemical composition, nutritional values

Key findings: All used concentrations of TiO_2 and ZnO-NPs induced positive responses for all tested parameters compared with non-treated corresponding controls under well-watered or drought-stress conditions in wheat (*T. aestivum* L.). Treatment with 10 mg L^{-1} of ZnO-NPs followed by 10 mg L^{-1}

Communicating Editor: Prof. Dr. Clara R. Azzam

Manuscript received: October 19, 2023; Accepted: December 5, 2023.

Citation: Bakry AB, Abd-El-Monem AA, Abdallah MMS, Al-Ashkar NM, El-Bassiouny HMS (2024). Impact of titanium-dioxide and zinc-oxide nanoparticles in improving wheat productivity under water stress conditions. *SABRAO J. Breed. Genet.* 56(2): 823-837. http://doi.org/10.54910/sabrao2024.56.2.33.

TiO2-NPs resulted in higher yield parameters in plants under 75% WIR for both cultivars than the control. The Gimeza-12 cultivar was more tolerant to water stress than the Sids-13 cultivar, which produced excellent grain yield.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is an essential cereal crop, which is vital, grown on over 213.9–219.0 million hectares of land and donates approximately one-fifth of the total calorie requirement in human nutrition worldwide (Mitura *et al.*, 2023). Hence, wheat is necessary in human food, particularly in developing countries. It is an energy source and includes other crucial nutrients, including fiber, proteins, and secondary components, such as lipids, minerals, phytochemicals, and vitamins. The discriminative characteristics of the wheat flour dough obtained from the gluten protein complex permit it to be processed into bread, pasta, noodles, and other food-feeding forms worldwide (Sabença *et al.,* 2021).

Modifications in the precipitation quantities, intensity, and patterns retard wheat growth and productivity under such conditions. Thus, evaluating water shortage outcomes through different wheat growth developmental stages for grain yield and quality attributes has real value (Rao *et al*., 2021). With the predicted climate variation, reductions and impacts on food security will increase water resource competition between different categories (Rady *et al.*, 2020). Research is continuous to improve water productivity (WP) to enhance wheat production and ensure food safety by keeping water by decreasing its amount under the irrigation water requirements (Semida *et al*., 2021).

Seleiman *et al.* (2021) reported that water deficit altering physiological and biochemical processes in plants would consequently diminish growth and yield, leading to a severe reduction in crop productivity. When it comes to dealing with abiotic stress in plants, nutrient management is a cost-effective and eco-friendly technique (Tripathi *et al*., 2017). Applying the proper nutrients can significantly improve plant tolerance against various abiotic stresses. Calcium (Ca), iron (Fe), magnesium (Mg), sulfur (S), titanium (Ti), and zinc (Zn) are some of the nutrients that have proven to be effective in water shortage conditions (Adnan *et al*., 2020). In addition, applying these nutrients can help plants absorb them quickly, reducing nutrient losses and making them an essential part of crop management. Also, the seed priming process allows seed germination and seedling evolution to gain upgrades under several hostile circumstances containing drought stress (Tasan, 2023).

Nanotechnology as a "smart fertilizer technique" produced new facilities to promote nutrient use efficiency under different environmental conditions via other mechanisms involving antioxidant defense systems (Rafique *et al.,* 2018). TiO_2-NP promotes the plant, struggles against environmental hassles, and decreases free radicals (El-Bassiouny *et al.,* 2022). Nano-TiO_2 affects an increase in plants' meiosis and size. Its suggestion as a growth regulator acts like gibberellin and cytokinin, consequently stimulating the seed yield of cowpeas (*Vigna unguiculata* L.) due to a promoted photosynthetic rate (Owolade and Ogunleti, 2008). Nano-TiO_2 caused increases in the total carbohydrate, starch, protein, gluten, and Zeleny sedimentation index of the grains produced under water shortage (Jaberzadeh *et al.,* 2013).

Past studies reported that soaking seeds in ZnO-NPs gradually increased growth attributes, photosynthesis, and biomass of wheat (Munir *et al*., 2018). El-Bassiouny *et al.* (2022) concluded that wheat plants treated with ZnO-NPs maximized all the studied growth parameters, biochemical direction, and yield. Kolenˇcík *et al.* (2022) proved that treatment with nano ZnO promoted yield, 1000-seed weight, and the pod number per plant. Hussain *et al.* (2019) revealed that treatment with different Zn sources induced maximum values of wheat plants' dry matter, crude protein, fiber, gluten, and mineral contents. Hence, its use is a promising tool in maximizing crop production under applied states, proving it is an achievable strategy for sustainable agriculture. The presented study provides a practical approach using TiO_2-NPs and ZnO-NPs to increase wheat cultivars' yield quantity and quality and minimize the drought stress' negative impacts on this vital cereal crop.

Materials and Methods

The grains of the two wheat cultivars (Gimeza-12 and Sids-13) came from the Agricultural Research Center in Egypt. Obtaining titanium-dioxide and zinc-oxide nanoparticles (NPs) commenced from the Sigma–Aldrich Company.

Experimental site

Two field trials management throughout the winter of 2019–2020 and 2020–2021 transpired at the experimental farm of the National Research Center (NRC), Al Nubaryia district, El-Behaira Governorate, Egypt (30_86'67" N 31_16'67" E, with a mean altitude of 21 masl). The zone of the farm may either have an arid or semi-arid climate. Table 1 shows the climatic data of the experimental site during the growing seasons. Samples of soil examined used the documented methods described by Carter and Gregorich (2006) and are available in Tables 2a and b.

Experimental design

Wheat grains were laved, sterilized, and laved again using distilled water. Then, grain immersion occurred for 12 h in different concentrations (5 mg L^{-1} and 10 mg L^{-1}) of TiO_2-NPs or ZnO-NPs. The experiment proceeded in a completely randomized block design in a split-split plot system with four replicates, in which the water irrigation requirements (WIR) of 100% and 75% occupied the main plots, and wheat cultivars (Gimeza-12 and Sids-13) had random assigning to subplots. Similarly, intermittent allocations of the treatments (with TiO_2-NPs or ZnO-NPs) continued in sub-sub plots. In two seasons, on November 26, wheat grains cultivation commenced in rows 3.5 m long; the space between rows was 20 cm apart, and the plot area was 10.5 m^2 (3.0 m in width and 3.5 m in length).

The agricultural operations started as advised by sowing wheat under sandy soil conditions, with a 140 kg ha^{-1} seeding rate. Adding 360 kg ha^{-1} of calcium superphosphate (15.5% P_2O_5) to the soil ensued before sowing. Nitrogen fertilizer addition as ammonium nitrate at 33.5% continued after the plant rose to 180 Kg ha^{-1}, divided into five equal amounts before the 1st, 2nd, 3rd, 4th, and 5th irrigations. Potassium sulfate (48.52% K_2O) distribution in two equal parts of 120 kg ha^{-1} proceeded before the 1st and 3rd irrigations. The irrigation occurred using a new sprinkler technique, with water provided every five days by the timetable shown in Table 3 for water requirements ha^{-1}.

Irrigation water requirements

The requirements computation used the Penman Monteith-equation and crop coefficient described by Allen *et al.* (1989). The regular irrigation water employed was 5950 and 4462.5 m^3 ha^{-1} $season^{-1}$, respectively, for 100% and 75% WIR for both studied seasons (Table 3).

The water quantities computations were as follows:

$$IWR= [ET0 \times Kc \times Kr \times I + LR]/ Ea \times 4.2$$

Where:
IWR = water irrigation quantities m^3 ha^{-1},
ET0 = Evapotranspiration (mm day^{-1}),
Kc = Crop coefficient,
Kr = Reduction factor,
I = the period between two irrigations, a day,
Ea = Irrigation water efficiency, 90%, and
LR = Leaching requirement = 10% of the total water requirement applied to the treatment.

Plant sampling

Random samples of 10 bounds of plants from each plot incurred their harvesting, recording the following criteria: Plant height (cm), no. of spikelets $spike^{-1}$, the weight of 1000 grains (g), and grain yield $spike^{-1}$ (g). All the area of each

Table 1. The data of maximum, minimum, average temperature, and relative humidity came from the weather station installed at the experimental station of the National Research Centre, Nubaria region, Egypt.

Month	Temperature (°C)			Humidity (%)		
	Max	Avg	Min	Max	Avg	Min
November 2019	25.93	20.04	15.56	86.08	69.81	48.23
December 2019	19.86	15.52	12.03	85.97	69.41	50.06
January 2020	16.34	12.71	9.66	89.26	74.53	57.42
February 2020	18.01	13.77	8.83	91.62	73.66	52.55
March 2020	20.84	15.61	9.66	88.94	70.72	44.65
April 2020	23.18	17.83	13.18	90.40	69.23	44.50
May 2020	28.03	22.04	15.50	86.19	62.55	35.74
November 2020	22.74	18.55	14.09	88.93	73.90	53.30
December 2020	20.16	15.62	10.95	89.16	70.05	46.16
January 2021	19.93	14.60	7.65	90.23	72.35	45.48
February 2021	19.27	14.64	10.93	90.79	72.26	47.57
March 2021	20.72	15.55	7.47	83.65	64.37	36.35
April 2021	26.09	18.78	12.18	85.47	60.88	32.30
May 2021	29.84	23.41	17.44	84.32	59.75	34.00

Table 2a. Soil physical properties of the experimental site.

Season	Constant Depth (cm)	Sand%	Silt%	Clay%
2019/2020	00 – 30	85.3	10.5	4.2
	30 – 60	81.2	13.6	5.2
2020/2021	00 – 30	81.3	13.4	5.3
	30 – 60	74.6	17.6	7.8

Table 2b. Soil chemical and nutritional properties of the experimental site.

Seasons	Constant Depth (cm)	pH	Electrical conductivity (ds/m)	Saturation Percentage	Anions (milliequivalents/liter)				Cations (milliequivalents/liter)				$CaCo_3$ %	Organic Matter %
					CO_3^{--}	CO_3-	Cl	SO_4^{--}	Ca^{++}	Mg^{++}	Na^+	K^+		
2019/ 2020	00 – 30	7.84	1.17	32	--	0.50	8.40	1.11	1.80	0.90	7.10	0.20	1.00	0.40
	30 – 60	7.89	1.79	27	--	0.60	8.00	1.40	2.10	1.50	6.20	0.20	6.00	0.07
2020/ 2021	00– 30	7.95	1.59	23	--	0.32	12.70	1.98	4.00	1.80	9.00	0.20	1.90	0.38
	30 – 60	7.85	1.81	25	--	0.45	15.40	2.15	5.60	2.00	10.20	0.20	1.30	0.32

plot harvested helps estimate the straw yield (t ha^{-1}), biological yield (t ha^{-1}), and grain yield (t ha^{-1}). The nutritional assay of grains and crop water productivity (WP) in kg mm^3 ha^{-1} plants bore measuring at the harvest stage.

Biochemical analysis

Analysis of total carbohydrates was according to AOAC (1990). The establishment of percentages of grain protein, gluten, starch, and Zeleny sedimentation index based on the methods of the American Association of Cereal Chemists (AACC, 2000) used the non-destructive grain analyzer, Model Infratec TM 1241 Grain Analyzer, ISW 5.00 valid from S/N 12414500, 1002 5017/Rev.1, manufactured by Foss Analytical AB, Hoganas, Sweden. The total flavonoid content measurement employed the approach described by Dewanto *et al.* (2002). Antioxidant activities (DPPH radical scavenging) determination used the technique of Liyana-Pathiranan and Shahidi (2005). Determining the nitrogen content utilized the micro-Kjeldahl method described by AOAC (1990). Measuring the produced grains' Ca, P, and K contents engaged a method by Ohyama *et al*. (1991).

Water-productivity (WP)

WP calculation proceeded as illustrated by Howell *et al.* (1990), recognized as the relevance between yielded grains and the water quantity for irrigation. WP in kg mm^3 ha^{-1} computation used the following formula:

$$WP = Ey / Et$$

Where WP is the water productivity (kg/m^3); Ey is the economical yield (kg ha^{-1}); and Et is the total irrigation water used, m^3 ha^{-1} $season^{-1}$.

Statistical analysis

The trial in the experiment had a completely randomized block design in a split-split plot system with four replicates. Given that the tendency was similar between the two seasons, the homogeneity test using Bartlet's equation aided in integrating the analyses of the two seasons. All data underwent the analysis of variance according to the MSTAT-C (1988) statistical analysis program version 14. The means comparison used Duncan's multiple range test at a 5% probability level, with the results expressed as mean ± standard errors (SE).

RESULTS

Yield components

The data presented in Table 4 explored the interaction effect of irrigation with two levels (100% and 75%) of WIR. They received 5 and 10 mg L^{-1} treatments of both TiO_2-NPs and ZnO-NPs on yield components of two wheat cultivars (Gimeza-12 and Sids-13). Exposure of plants to water stress (75% WIR) in the field conditions significantly reduced all studied criteria (plant height, spike length, number of spikelets $spike^{-1}$, spike weight, grain weight $spike^{-1}$, 1000 grain weight, straw, grain, and biological yield [t ha^{-1}]) of wheat yield compared with total water irrigation requirements (100% WIR) in both wheat cultivars. Treatment with both nanoparticles significantly increased all studied parameters under normal (100% WIR) or stressed (75% WIR) conditions compared with corresponding controls. Treatment with 10 mg L^1 TiO_2-NPs induced the maximum values in all studied parameters in the Gimeza-12 cultivar rinsed with 100% WIR compared with the controls.
Noteworthy here that the application of 10 mg L^{-1} ZnO-NPs on the Gimeza-12 cultivar gave the maximum values in plants subjected to 75% WIR by 16.75%, 18.33%, 28.32%, and 28.35% in 1000 grain weight, straw, grain, and biological yield (t ha^{-1}), respectively, compared with the corresponding control. The same trend surfaced with 10 mg L^{-1} ZnO-NPs on the Sids-13 cultivar in plants subjected to 100% or 75% WIR. The percentage increase reached 17.30%, 20.56%, 26.09%, and 25.43% in 1000 grain weight, straw, grain, and biological yield (t ha^{-1}), respectively, of plants irrigated with 75% WIR.

Table 3. Water regime for growth stages of the wheat crop at the Nubaria station during two successive winter seasons 2019/2020 and 2020/2021.

Growth stages	No. of Days	The applied water to the growth stages (m_3 ha^{-1})	
		100%	75%
Initial	20	326.04	244.5
Develop.	30	1086.76	815.06
Mid	65	3260.27	2445.21
Late	40	1141.08	855.57
Harvest	27	135.85	101.64
Total	182	5950	4462

Table 4. Yield and yield attributes of two wheat cultivars (Gimeza-12 and Sids-13) subjected to different water irrigation requirements and treated with different concentrations of both TiO_2-NPs and ZnO-NPs (5 and 10 mg L^{-1}l) (mean of two seasons).

Cultivars	Water irrigation quantities (m_3 ha^{-1}.)	Nano treatments (mg/l)		Plant height (cm)	Spike length (cm)	Spikelet no/spike	Spike wt (g)	Grain wt/ spike (g)	1000 grain wt (g)	Straw wt (t ha^{-1})	Grain yield (t ha^{-1})	Biological yield (t ha^{-1})
Gimeza-12	100%	Control		59.67±1.345^{b-e}	9.00±0.333^{d}	13.67±0.313^{e}	3.09±0.045^{d}	2.76±0.029^{de}	40.10±0.072^{k}	7.54±0.038^{f}	5.39±0.038^{g}	12.93±0.060^{h}
		TiO2	5	62.58±1.674^{ab}	10.00±0.332^{b-d}	16.00±0.333^{c}	3.25±0.055^{c}	2.82±0.015^{b-d}	46.45±0.040^{c}	8.36±0.069^{c}	6.17±0.020^{bc}	14.53±0.074^{c}
			10	65.23±1.534^{a}	11.67±0.577^{a}	19.67±0.323^{a}	3.39±0.023^{ab}	2.98±0.017^{a}	47.55±0.023^{a}	9.11±0.026^{a}	6.40±0.029^{a}	15.51±0.092^{a}
		Zn O	5	61.50±0.289^{a-c}	10.33±0.343^{b-d}	16.33±0.577^{c}	3.46±0.062^{a}	2.84±0.061^{b-d}	43.94±0.083^{f}	8.85±0.095^{b}	6.14±0.060^{bc}	14.99±0.130^{b}
			10	64.63±0.984^{a}	11.00±0.333^{a-b}	19.33±0.333^{a}	3.33±0.0125^{a-c}	2.93±0.012^{ab}	46.66±0.084^{c}	8.67±0.085^{b}	6.29±0.021^{ab}	14.96±0.078^{b}
	75%	Control		56.33±0.882^{d-g}	7.67±0.002^{f}	11.27±0.577^{fg}	2.71±0.017^{fg}	2.19±0.018^{hi}	35.70±0.023^{p}	6.98±0.089^{h}	4.59±0.023^{i}	11.57±0.033^{k}
		TiO2	5	59.38±1.199^{b-f}	8.67±0.313^{e}	12.33±0.955^{f}	2.59±0.058^{g-i}	2.36±0.025^{g}	37.69±0.035^{n}	7.68±0.038^{f}	5.63±0.079^{f}	13.31±0.043^{fg}
			10	57.67±1.013^{b-g}	9.50±0.332^{cd}	13.67±0.333^{e}	2.98±0.085^{de}	2.44±0.csss^{fg}	40.67±0.030^{i}	8.17±0.081^{d}	5.84±0.049^{de}	14.01±0.043^{de}
		Zn O	5	58.33±2.603^{b-f}	9.33±0.323^{d}	13.67±0.313^{e}	2.84±0.090^{ef}	2.39±0.023^{g}	38.99±0.058^{m}	7.61±0.027^{f}	5.42±0.033^{g}	13.03±0.078^{h}
			10	59.93±2.906^{b-d}	10.00±0.333^{b-c}	14.67±0.333^{de}	2.97±0.015^{de}	2.53±0.021^{f}	41.33±0.032^{h}	7.56±0.078^{f}	5.99±0.092^{de}	13.55±0.151^{ef}
Sids-13	100%	Control		57.44±1.382^{c-g}	9.17±0.563^{d}	14.00±0.002^{e}	3.07±0.074^{d}	2.41±0.026^{g}	40.47±0.010^{j}	7.17±0.022^{g}	4.94±0.042^{h}	12.11±0.046^{j}
		TiO2	5	59.56±0.342^{b-e}	10.33±0.313^{b-d}	16.50±0.289^{c}	3.31±0.038^{a-c}	2.82±0.022^{b-d}	45.51±0.017^{d}	7.53±0.025^{f}	5.78±0.083^{ef}	13.31±0.064^{fg}
			10	58.99±1.596^{b-f}	11.00±0.333^{ab}	18.67±0.882^{ab}	3.41±0.036^{ab}	2.92±0.017^{ab}	46.98±0.047^{b}	8.01±0.96^{de}	6.09±0.080^{c}	14.10±0.070^{de}
		Zn O	5	59.68±1.865^{b-e}	10.67±0.001^{a-c}	18.50±0.333^{ab}	3.11±0.058^{d}	2.70±0.052^{de}	44.76±0.043^{e}	8.49±0.024^{c}	5.68±0.021^{ef}	14.17±0.069^{d}
			10	59.74±0.332^{b-e}	11.67±0.333^{a}	19.33±0.331^{a}	3.51±0.052^{a}	3.01±0.015^{a}	47.51±0.035^{a}	8.56±0.023^{b}	6.110.064^{c}	14.57±0.033^{c}
	75%	Control		53.47±1.919^{g}	8.33±0.323^{e}	12.00±0.001^{f}	2.31±0.035^{j}	2.11±0.078^{i}	36.47±0.030^{o}	6.76±0.061^{i}	4.37±0.036^{j}	11.13±0.052^{l}
		TiO2	5	55.21±0.409^{e-g}	9.87±0.289^{b-d}	13.17±0.332^{e}	2.55±0.027^{hi}	2.39±0.015^{g}	39.99±0.026^{k}	7.40±0.059^{f}	5.10±0.039^{h}	12.50±0.093^{i}
			10	55.36±0.808^{d-g}	10.50±0.186^{b-d}	13.83±0.333^{e}	2.49±0.015^{i}	2.24±0.022^{h}	41.33±0.024^{h}	7.68±0.038^{f}	5.39±0.021^{g}	13.07±0.104^{gh}
		Zn O	5	55.33±0.617^{d-g}	9.67±0.333^{cd}	13.83±0.313^{e}	2.51±0.024^{hi}	2.40±0.012^{g}	39.15±0.031^{l}	7.92±0.017^{e}	5.39±0.037^{h}	13.31±0.094^{fg}
			10	54.67±0.667^{fg}	10.67±0.313^{a-c}	14.83±0.333^{d}	2.66±0.029^{gh}	2.48±0.012^{f}	42.78±0.021^{g}	7.95±0.045^{d}	5.41±0.042^{g}	13.66±0.043^{e}

Nutritional values of yielded grain

The results further explored the mentioned treatments' effect on the grain nutritional values of two wheat cultivars (Figure 1). The outcomes indicated that the 75% WIR reduced carbohydrates and starch contents (%) and increased protein, gluten (%), and Zeleny sedimentation index in both cultivars compared with a well-watered treatment (100% WIR). The Sids-13 cultivar surpassed the Gimeza-12 cultivar in the most studied nutritional values of wheat grain irrigated with both WIR. Treatment with TiO_2-NPs or ZnO-NPs significantly alleviates all earlier declared parameters in both cultivars with 100% or 75% WIR versus the corresponding control. Treatment with 10 mg L^{-1} TiO_2-NPs induced the maximum values in carbohydrate and starch contents in both cultivars with 100% or 75% WIR, followed by treatment with 10 mg L^{-1} ZnO-NPs compared with corresponding the control or other treatments (Figure 1). The nutritional contents (protein, gluten, and Zeleny sedimentation index) recorded higher values using 10 mg L^{-1} ZnO-NPs, followed by 10 mg L^{-1} TiO_2-NPs, than the corresponding control or other treatments in both cultivars (Figure 1).

Flavonoids and antioxidant activities (%) in yielded grains

The interaction effects of all the factors mentioned for drought, cultivars, and their treatments are visible in Figure 2. It shows that 75% WIR triggers significant increases in flavonoids and antioxidant activities in a percentage of wheat-yielded grains compared with corresponding controls (100% WIR). The Gimeza-12 cultivar outperformed the Sids-13 significantly on their flavonoid content and antioxidant activities compared with plants grown under both WIR conditions. Moreover, all applied treatments (5 and 10 mg L^{-1} nano titanium or nano zinc) increased the flavonoids and antioxidant activities % of wheat-yielded grains in plants grown under 100% or 75% WIR. The lower concentration (5 mg L^{-1}) of TiO_2-NPs or ZnO-NPs recorded the maximum values of flavonoids in plants subjected to both WIR treatments. The results clearly show that the 10 mg L^{-1} ZnO-NPs exceeded other treatments significantly and recorded the highest values of antioxidant activities in cultivars grown under both WIRs.

Mineral contents in yielded grains

The results in Figure 3 exhibited the effects of irrigation of both studied cultivars with 100% and 75% WIR and treated with 5 and 10 mg L^{-1} TiO_2-NPs or ZnO-NPs on the mineral contents of wheat grain yields. Decreasing WIR to 75% caused a reduction in most mineral ions (N, K, and Ca) contents of yielded grains of two wheat cultivars (Gimeza-12 and Sids-13), compared with corresponding controls. The Sids-13 cultivar gave the maximum N, P, and Ca values under 100% and 75% WIR versus the Gimeza-12 cultivar. However, the Gimeza-12 cultivar exceeded the Sids-13 in their K content of grains rinsed with 100% or 75% WIR. It also records that all applied treatments significantly increased all studied mineral contents of wheat grain yield grown under both irrigation levels compared with corresponding controls. ZnO-NPs surpassed TiO_2-NPs in all the above-studied criteria of both cultivars. The lower level (5 mg L^{-1}) of ZnO-NPs gave the maximum values in all studied parameters of both cultivars under 75% WIR. The uppermost values came from 10 mg L^{-1} ZnO-NPs in plants of two cultivars subjected to 75% WIR.

Water productivity

Irrigation of wheat plants with 75% WIR leads to a marked increase in water productivity compared with unstressed plants (100% WIR) of both cultivars (Figure 4). Treatment of plants with TiO_2-NPs and ZnO-NPs (5 and 10 mg L^{-1}) increased water productivity under different water levels versus the corresponding controls. The Gimeza-12 outperformed the Sids-13 cultivar significantly on WP content in plants grown under either well-watered or stressed conditions. The higher concentration used 10 mgL^{-1} of TiO_2-NPs, followed by 10 mgL^{-1} ZnO-NPs, recorded the highest values of WP in plants subjected to 75% and 100% WIR, respectively, compared with other treatments.

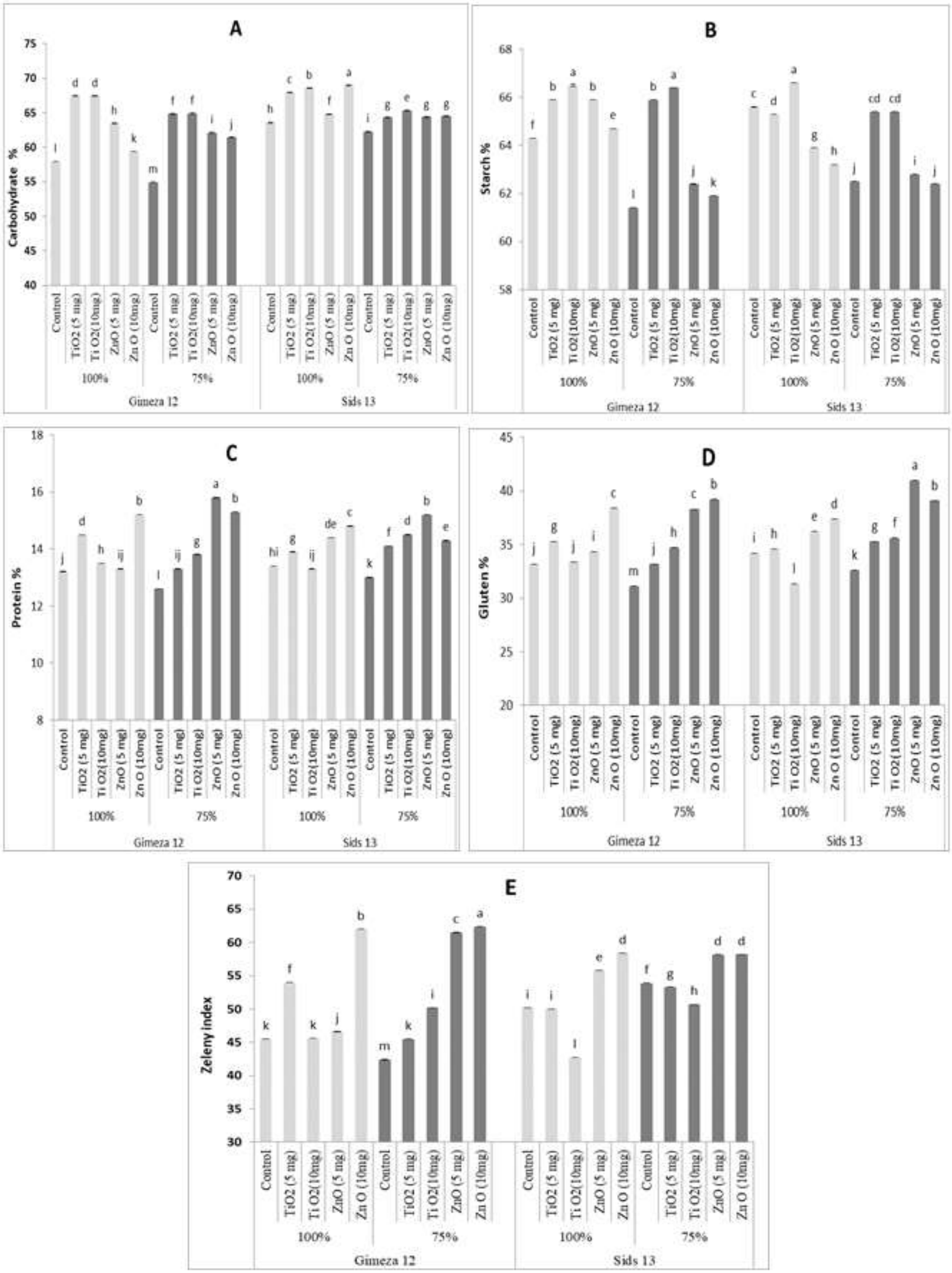

Figure 1. Nutritional values (A-carbohydrates, B-starch, C-protein, D-gluten, and E-Zeleny sedimentation index) %, in the yielded grains of two wheat cultivars (Gimeza-12 and Sids-13) exposed to water irrigation requirement (100% and 75%) and treated with different concentrations of both TiO_2-NPs and ZnO-NPs (5 and 10 mg L^{-1}).

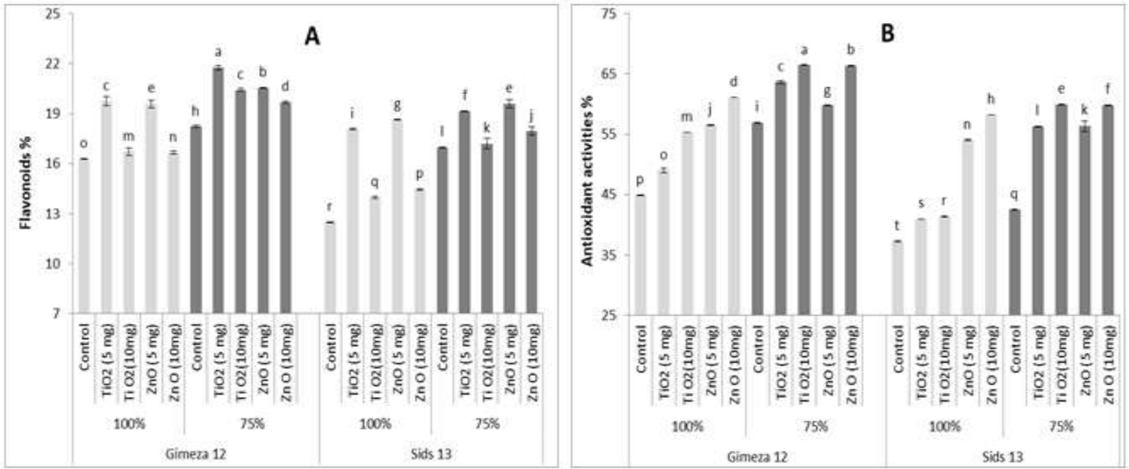

Figure 2. A**-** Flavonoids and B- Antioxidant activities (%) in the yielded grains of two wheat cultivars (Gimeza-12 and Sids-13) exposed to water irrigation requirement (100% and 75%) and treated with different concentrations of both TiO_2-NPs and ZnO-NPs (5 and 10 mg L^{-1}).

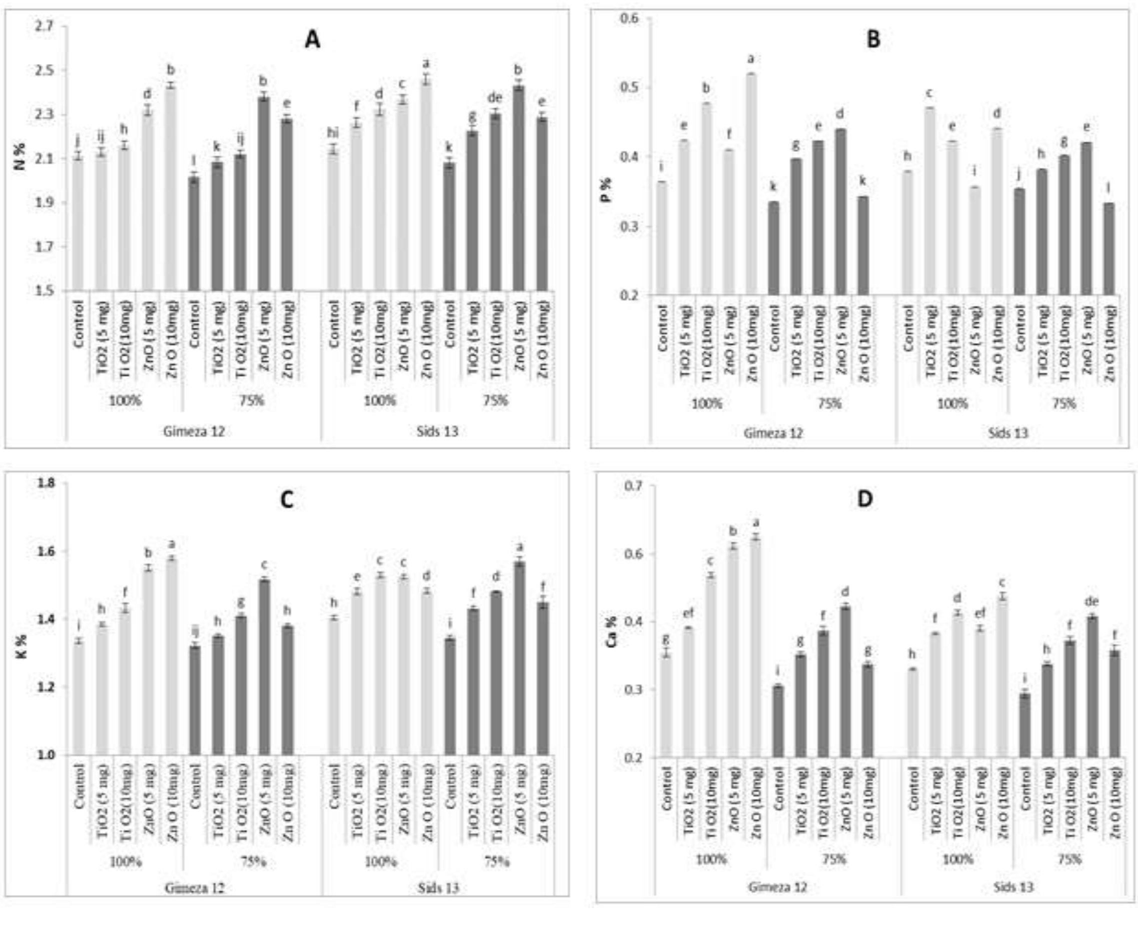

Figure 3. Mineral contents (A- N, B- P, C- K, and D- Ca) % in the yielded grains of two wheat cultivars (Gimeza-12 and Sids-13) exposed to water irrigation requirement (100% and 75%) and treated with different concentrations of both nano- TiO_2-NPs and ZnO-NPs (5 and 10 mg L^{-1}).

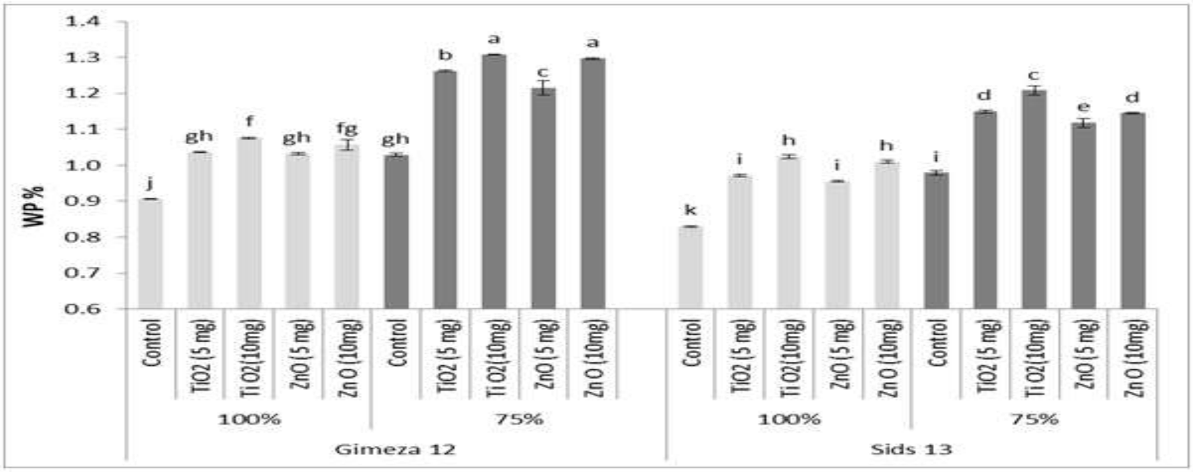

Figure 4. Water productivity (%) in the yielded grains of two wheat cultivars (Gimeza-12 and Sids-13) exposed to water irrigation requirement (100% and 75%) and treated with different concentrations of both TiO_2-NPs and ZnO-NPs (5 and 10 mg L-1).

DISCUSSION

Drought stress emerged as an environmental problem affecting plant productivity. Water deficit decreases different growth and yield parameters. The reductions may refer to the reduction in the available nutrients or the physiological disturbance caused by the increase in osmotic stress, which has a linkage with a decline in cell enlargement, turgor, volume, and, eventually, cell growth. Water shortage at any specific stage significantly lowered the yield and components of yield in sunflower crops (Abdallah *et al.,* 2020).

Furthermore, the higher yield in a 100% WIR might result from a long grain-filling period and a high number of wheat grains per spike. Hence, under unfavorable conditions, a progressive correspondence was likely to occur among grain yield, grain-filling rate, grain-filling duration, plant height, grains for each spike, the number of productive tillers for each plant, and spikelet numbers for each spike. Thus, the last grain weight as a yield component acquires influence from the rate and duration of grain filling (Sattar *et al.,* 2020). The reduction in the total carbohydrates and starch contents of wheat grains due to drought stress may be owing to the alteration of metabolites, the harmful effect of drought on photosynthetic pigment contents, and the conversion of metabolites from source to sink in unfavorable environments. These outcomes align with the results of Rekowski *et al.* (2021).

Bartels and Sunkar (2005) suggested that water shortage can cause a decline in starch content due to a reduced transfer of compounds from the leaves and slower consumption resulting from starch hydrolysis. The rate of starch hydrolysis depends on the activity of hydrolytic enzymes that convert sucrose to starch. In addition, the interference of physiological and biochemical processes in starch biosynthesis and water deficit hastens the onset and filling time of the grain and decreases the gathering of starch, which alters wheat productivity (Golfam *et al.,* 2021; Babar *et al*., 2022; Farhood *et al*., 2022).

Several authors recommended that the increase in grain protein percentage due to drought stress in wheat grains may ascribe to reduced starch accumulation (Rao *et al*., 2021). These effects had a decline in the grain yield and the thousand-kernel weight accompanying them. Haji *et al.* (2020) documented a progressive correlation between grain protein content and dry and wet gluten content. Generally, significant increases in Zeleny sedimentation index, wet and dry gluten contents, and gluten index showed following stress (Rao *et al.,* 2021).

Water deficit interrupts mineral nutrient relations, decreasing plant growth and development, impacting directly the final crop yield. This disturbance lowers mass flow-dependent mineral nutrient uptake and the translocation of these nutrients from the roots to the shoot, affecting all metabolic processes in plant physiology. These results agreed with Dimkpa *et al.* (2020). Asghar and Bashir (2021) demonstrated that reducing soil moisture decreases plant roots' capability to absorb adequate moisture, consequently lessening its NPK uptake, transport, and translocation.

The severity of the water shortage remarkably stimulated flavonoids and antioxidant activities (%). Sarker and Oba (2018) concluded that water shortages promoted the quantitative and qualitative stimulation of nutritional and bioactive compounds, phenolic acids, flavonoids, and antioxidants.

The results indicated that WP significantly increased when plants underwent water shortages. El-Bassiouny *et al.* (2022) concluded that crop water productivity was higher under irrigation water deficiency than under well-watered conditions because, under water stress, the plants consumed water more efficiently and reduced water loss. In drought, stomatal closure causes a reduction in leaf conductance, photosynthesis, and transpiration, which consequently leads to the more conventional practice of watering too much, resulting in excessive WP in water-lacking plants, which might be a tool for increasing reserve use value.

Substantial variations exist between the two cultivars under study in their responses to all the mentioned parameters. These variations may be due to genotype differences, which affect the plant's response to various stressful conditions. Bonfil *et al.* (2015) postulated that the genetic background of different cultivars could be why they have diverse reactions when growing under the same environmental conditions. These outcomes gained support from the highest grain yield of the Gimeza-12 cultivar compared with the Sids-13 cultivar. The same findings came from El-Bassiouny *et al.* (2022).

This study exhibited that applying TiO_2-NPs and ZnO-NPs at different concentrations improved all studied parameters. The stimulatory results from TiO_2-NPs under this study may be due to their function in stabilizing chloroplasts under regular conditions or in scavenging the ROS produced in plants under stress conditions. TiO_2-NPs have gained acceptance to stimulate crop performance by improving the agitation of definite enzymes, promoting chlorophyll content and photosynthesis, improving nutrient uptake, reinforcing stress tolerance, and encouraging crop yield and quality (Šebesta *et al.,* 2021). The promotive effect of TiO_2-NPs in this study on yield production and its attributes may be a conclusion resulting from their protective role on all plant cells, induction of defense phenolic compounds, promotion of the total antioxidant system (Figure 1), and crop water productivity (Figure 4), which reflected on the quantity and quality of grain yield as described by El-Bassiouny *et al*. (2022).

The recorded results approved that treating wheat plants under water shortage with nano-TiO_2 caused increases in the total carbohydrate, starch, protein, gluten, and Zeleny sedimentation index of the grains produced. These results are in harmony with those reported by Jaberzadeh *et al.* (2013), who suggested that TiO_2-NPs stimulated all agronomic traits, including gluten and starch contents in wheat, under water shortage conditions. Connectively, the higher contents of carbohydrates in grains with TiO_2-NPs-mediated plants showed a very active transportation system of carbohydrate content, which transfers the carbohydrate contents of the shoot to the grain. Moreover, Kandhol *et al.* (2022) proved that TiO_2-NPs improved crop yield and quality via substantially enhancing gluten, starch, and Zeleny sedimentation index under normal or stress conditions on several plants.

The stimulatory effect of TiO_2-NPs on the nutritional ion (N, P, K, and Ca) values of produced grains under this study may be attributable to increasing the uptake and translocation of minerals that affect several physiological processes inside the plant and consequently reflect on the rise of such minerals in the produced grains. These findings agree with Šebesta *et al.* (2021). They concluded that TiO_2-NP application promoted the plant's N, P, K, and Ca uptake.

The promotive role of ZnO-NPs on plants under normal or stressed conditions in this research may refer to the stimulatory role of ZnO-NPs on plant growth, photosynthetic pigment, and the uptake and translocation of mineral contents that promote the yield parameters and its components. Zn is a co-enzyme for the manufacture of tryptophane, a precursor to the establishment of auxins that enhance root growth and drought tolerance in plants (Waraich *et al.,* 2011). ZnO-NP treatments also induced better plant physiological responses and, consequently, superior yield components. Kolenˇcík *et al.* (2022) demonstrated that ZnO-NP exposure of lentils positively affected yield.

In addition, Zn fertilizers in nanocomponents increased total soluble carbohydrate, starch, and total carbohydrate concentrations, accelerating carbohydrate formation. It is included in carbohydrate, protein, and plant hormone metabolism, particularly indole acetic acid (IAA), which aids in forming starch, total carbohydrates, and seed maturity (Dimkpa *et al.,* 2020). The treatment with different Zn sources induced the maximum values of dry matter, crude protein, fiber, gluten, and mineral contents compared with the other treatments and the corresponding control (Hussain *et al.,* 2019). Moreover, the application of Zn is beneficial in increasing crop yield and quality by working in conjunction with plant hormones, enhancing the expression of stress proteins, and promoting antioxidant enzymes. It helps to mitigate the effects of water shortage and improve quality indicators (Naeem *et al*., 2018; Sallam *et al*., 2022). Semida *et al.* (2021) proved that foliar application of ZnO-NPs alleviates the harmful impacts of water deficit via increased macro- and micronutrients.

Salih *et al.* (2021) indicated that the treatment of wheat plants with ZnO-NPs induced crucial boosts in the flavonoids and antioxidant activities of yielded grains under normal or stressed conditions. These results may refer to the antioxidant scavenger role of nanoparticles and the co-action of ZnO as a cofactor in several enzyme formations that positively alleviate the harmful effects of water shortage conditions. ZnO-NP treatments stimulated the content of anthocyanins, flavonoids, total phenol content, and the radical scavenging activity toward antioxidant activities % (Sallam *et al*., 2022).

Water productivity exhibited relevant enhancements in plants treated with ZnO-NPs under normal or stressed conditions. It may be owing to the stabilizing role of ZnO-NPs in maintaining membrane integrity, consequently increasing water contents and saving water in wheat grains. Seghatoleslami and Forutani (2015) reported that the WP of seed and biomass yield of sunflower plants increased by using ZnO-NPs in 50% WHC. Also, Semida *et al.* (2021) concluded that the highest water productivity (WP) was notable in eggplants rinsed with 60% WIR and treated with ZnO-NPs compared with non-treated fully irrigated plants.

CONCLUSIONS

In the existing research, the yield characteristics of two studied wheat cultivars decreased due to drought stress. Both wheat cultivars underwent water shortage stress, receiving treatments with TiO_2-NPs and ZnO-NPs. Using these nanomaterials helped in mitigating the harmful effects of water scarcity. The application of nanomaterials resulted in an increase in yield characteristics, total carbohydrate, starch, protein, gluten, Zeleny sedimentation index, mineral nutrition values (N, P, K, and Ca), flavonoids, total antioxidant capacity, and water productivity in both wheat cultivars compared with the corresponding control plants. Thus, the improvement of phenolic compounds by NPs has been successful as a new strategy for alleviating abiotic stress. Both types of nanoparticles have the potential to lessen stresses, such as drought. They play a vital role in adapting different mechanisms involved in recognizing and responding to unfavorable conditions in plants. These outcomes attained support from the highest grain yield of the Gimeza-12 cultivar compared with the Sids-13 cultivar.

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