

Contents lists available at [Egyptian Knowledge Bank](https://www.egyptianknowledgebank.com)

Labyrinth: Fayoum Journal of Science and Interdisciplinary Studies

Journal homepage: <https://ifsis.journals.ekb.eg/>Labyrinth
Journal

Effect of foliar application of zinc nanoparticles on growth and yield of grain sorghum (*Sorghum bicolor* L Moench) under drought conditions

Salah.M. Emam ^a, Ali. A.A. Mekdad ^{a, *}, K. M. Mahmoud ^b, Kefah M. Mansour ^a

^a Department of Agronomy, Faculty of Agriculture, Fayoum University, Fayoum, 63514, Egypt.

^b Sorghum Res. Dept., Field Crops Research Institute, Agricultural Research Center, Giza 12112, Egypt.

ARTICLE INFO

Keywords:

Irrigation intervals,
Zinc nanoparticles,
Varieties,
Sorghum bicolor L

ABSTRACT

Water stress, can negatively impact the productivity of sorghum. To study the effects of foliar use of zinc nanoparticles on sorghum (*Sorghum bicolor* L Moench) varieties production under different water regimes, were studied during the 2022 and 2023 seasons at Tamiya Experiment Station, Fayoum Governorate, Agricultural Research Center, Egypt. The results showed that exposure to increasing irrigations intervals resulted significant reduction in SPAD and Fv/fm values, performance index, 50% flowering and leaf area index, yield and yield characteristics traits across all sorghum varieties tested. Increasing the irrigation period from 10 to 15 and twenty day reduces grain yield by 28.48 & 56.29 and 37.58 and 57.05 %, in both seasons. However, the use of Zn nanoparticles was significantly enhance grain yield, leaf area index, ear length and diameter, weight of 1000 grains and grains ear weight in the sorghum varieties under normal irrigations and increasing water periods. In both seasons, irrigated sorghum plants every 10 days and planted Shandawil 1 variety and sprayed at a level 100 PPM of zinc oxide nanoparticles fertilizer gave significantly the highest grain sorghum yield (2.07 and 1.93 ton/fed.). According to using the relative drought index, with values ranging from 1.13 to 1.23 for Shandawil 1 variety, 0.75 to 0.84 for the Dorado variety under 15 day irrigation intervals, and the values ranging from 0.82 to 0.78 for Shandawil 1 variety, 0.42 to 0.44 for the Dorado variety under 20 day irrigation intervals.

1. Introduction

Sorghum (*Sorghum bicolor* L. Moench) considers is an important food of the most food-insecure people, living essentially in the semi-arid environment [1]. The most important countries in the world for sorghum yielding are USA, Nigeria, Sudan, Mexico, India and Ethiopia, while Egyptian production has ranked 19th [2]. In addition, Egyptian cultivated area from grain sorghum was about 150 thousand hectare, which yielding about 790 thousand tons by productivity 5.27 ton hectare⁻¹ [3]. Grains sorghum are used to make many types of breads that form the major food of more than 500 million people in different countries [4]. It is rich in antioxidants that help reduce the crises of diabetes and cancer [5]. Sorghum has a difference of uses including feed grain for livestock, which give dairy products, meat, eggs and food for human consumption, besides industrial use such as ethanol production. Although sorghum can grow under many types of stresses conditions, including drought and salinity compared to maize or sugar cane, it can be used as a good source for making ethanol fuel. Scarcity of water will affect a large part of the world's population through the next fifty years also, limit agricultural production [6]. Sorghum is a water efficient crop that makes it a major cereal in the semi-arid environment, where water is the essential limiting factor of yielding. However, sorghum must compete in economic and agricultural with other cereal crops, also to meet this challenges productivity of grain sorghum must be increase significantly. Water stress is an important limitation crop production in the worldwide also, possible climate change indicators suggest a future raise in the risk of drought. Drought is certainly major significance in the semi-arid environment. In cereal crops included sorghum that are important carbohydrate staples for humans, water deficient at seedling, tillering and reproduction stages might result in significant production reduction and may lead to lethal of the plants [7]. Moreover, water deficit at the reproduction stage causes the major decline in production as compared to stress at any other growth stages. Irrigation period at ten days gave the maximum values of yield [8]. Selection of proper varieties and proper soil significantly affect soil sustainability and crop productivity [9]. Productivity of grain sorghum is affected severely by many factors, such as variety selection, that is one of the most major decisions to produce the grain sorghum.

Zinc (Zn) is a major micronutrient for plants, animals and humans. Semi-arid environment soil including Egyptian soils are deficient in the zinc element and food crops which grown on these soils. It acts as an essential catalyst for many metabolic enzymes, especially RuBisCO during photosynthesis [10]. It also plays an effective role in the growth regulation (through IAA, gibberellin and tryptophan biosynthesis), carbohydrate

* Corresponding author.

E-mail address: aam07@fayoum.edu.eg (A. Mekdad); Tel.: +201005033128

DOI: 10.21608/ifsis.2025.405976.1121

Received 20 July 2025; Received in revised form 14 September 2025; Accepted 14 September 2025

Available online 26 September 2025

All rights reserved

metabolism, and protein synthesis [11]. Besides, it also helps with ionic equilibria to avoid osmotic stress in the phyto-system induced by stressful conditions, including water stress and salinity [12]. In particular, Zn in plants is activates metabolic processes regulating water dynamics. Under water shortage condition, water stressed plants produce more quantities of abscisic acid to improve stomatal closure to maintain water [13]. Cereals production is affected due to decrease soil zinc. To overcome this micronutrient problem and crop production, ZnSO_4 is spired to foliage, but Zinc applied to the soil are going to be fixed and making it not available to the rhizosphere, also becomes toxic to microorganisms in the soil and plants.

In Egypt, the soils are suffer from a shortage of water resources and deficient in the zinc element for agriculture, which prevents the agricultural sector from meeting the food needs of a growing population. Therefore, solutions to this problem must be found. Finding drought-tolerant varieties and using the new nanotechnology strategy for micronutrient that produce high yields under the conditions of these regions is essential to meeting these food needs and achieving sustainable agriculture. Therefore, the study was carried out to investigate the effects of irrigation intervals, varieties and different levels of Zinc oxide NPs on yield and yield attributes in grain sorghum.

2. MATERIALS AND METHODS

Two field experiments were conducted at the Tamiya experiment station, at Fayoum, Agricultural Research center (A.R.C), Egypt, during the two successive growing seasons of 2022 and 2023.

2.1. Treatments:

2.1.1. Irrigation intervals (I)

Three irrigation intervals (irrigation every ten (I_1), fifteen (I_2) and twenty (I_3) days) were studied. These irrigation intervals were applied after 30 days from the sowing date.

2.1.2. Varieties (V)

Two commonly used Egyptian varieties of *Sorghum bicolor* L Moench were used in this study namely, Shandawil 1 (V_1) and Dorado (V_2). The grain sorghum varieties were obtained from the Agricultural Research Center. Giza, Egypt.

2.1.3. Zinc oxide nanoparticles levels (ZnO NPs = Z)

- 1- Control plants (without ZnO NPs (Z_1)).
- 2- Plants sprayed by 50 PPM level of ZnO NPs (Z_2).
- 3- Plants sprayed by 100 PPM level of ZnO NPs (Z_3).

2.2. Soil Characteristics

The soil type of the experimental site was clay loom in the two seasons with the physical and chemical properties shown in Table 1.

Table (1): Some physical and chemical analysis of the experimental site" Tamiya experimental station" in 2022 and 2023 seasons.

Soil analysis	2022	2023
A: Mechanical analysis		
Sandy %	38.00	34.92
Silt %	21.20	22.50
clay%	40.80	42.58
Textural grade	Clay loom	Clay loom
B: chemical analysis		
pH	8.12	8.20
E.C(ds/m) at 25°C	4.00	3.96
Organic matter %	1.68	1.72
CaCo3%	11.18	11.14
N (mg kg ⁻¹ soil)	67.41	78.23
Available P (meq 100 ⁻¹ g soil)	7.24	7.67
Available Zn (meq 100 ⁻¹ g soil)	0.92	0.98

2.3. Experimental design

The trials were laid out in a split-split plot in randomized complete blocks (RCBD) design arrangements with 3 replications. Where, irrigation intervals every 10 (I_1), 15 (I_2) and 20 (I_3) days were arranged for the main plots, two grain sorghum varieties Shandawil 1 (V_1) and Dorado (V_2) were distributed in the subplots and foliar spraying of zinc nanoparticles (0, 50 and 100 ppm) were arranged in the sub- subplots. The sub-sub plot area was 10.5 m² and consisted of five ridges of 3.5 m² in length and 60 cm in width. Sorghum grains were hand- planted in hills 15 cm on a part at the rate of two grains/hill using the dry sowing method on one side of the ridge.

2.4. Cultural practices

The dates of sowing were 8 June in the 2022 and 23 May in the 2023 seasons, respectively. Super-phosphate was added before sowing. Hand hoeing twice was applied after 20 and 35days from planting. Thinning was done at 20 days after planting to secure 2 plants per hill before the first irrigation. The first irrigation was used after 21 days after sowing and the following irrigation was used at periods during the growing seasons. Nitrogen fertilizer was used as 225 kg /fed from of urea (46.5 % N) in an equal two doses with the 2nd and 4th irrigations.

2.5. Data Recorded:

2.5.1. Physiological measurements:

- 1-SPAD values (Soil Plant Analysis Development) was measured by chlorophyll meter (SPAD-502; Minolta, Osaka, Japan).
- 2-Chlorophyll fluorescence (F_v/F_m and F_v/F_0 = maximum quantum efficiency of photosystem) was measured by (Handy PEA, Hansatech, Instruments Ltd, Kings Lynn, UK).
- 3-Performance index
- 4-50 % flowering (day).
- 5-Leaf area index.

2.5.2. Growth parameters:

Plants were harvested at the maturity stage, a five guarded plants in each sub-subplot were taken to record the data which included.

- 1-Ear length (in cm).
- 2-Ear diameter (in cm).
- 3-Grains ear weight per plant (g).
- 4-Weight of 1000 Grain (g).

2.5.3. Yield:

At harvest crop were taken two rows, the data recorded to calculate the yield, these measurements include steam yield, leaves yield, grain yield and biological yield.

2.5.4. Relative Drought Index (RDI):

RDI was calculated according to [14], as follows: $RDI = (YS/Y_p) / (\bar{y}_s/\bar{y}_p)$, Where: YS = grain yield of variety under water deficient, Y_p = grain yield of a variety under control treatment, $\bar{y}_s$ = average grain yield of all varieties under water deficient, $\bar{y}_p$ = average grain yield of all varieties under control treatment. When relative drought index ≥ 1 , (T) refer to the variety tolerant to water deficient; if $0.5 \leq$ relative drought index < 1 , (M) refer to the variety is moderately tolerant; and if relative drought index < 0.5 , (S) refer to the variety is sensitive.

All collected data were statistically analyzed according to technique of analysis of variance for split- split plot design by means of "M STAT- C " computer software Package. The differences among treatment means were detected by LSD test at 5% level of probability [15].

3. Results and discussion

3.1. Characterization of ZnO NPs

ZnO-NPs including the shape and size were examined by High resolution transmission electron microscopy (HR-TEM) as shown in Figure 1. The average size was 13.39 nm. The zeta potential was determined as shown in Figure 2.

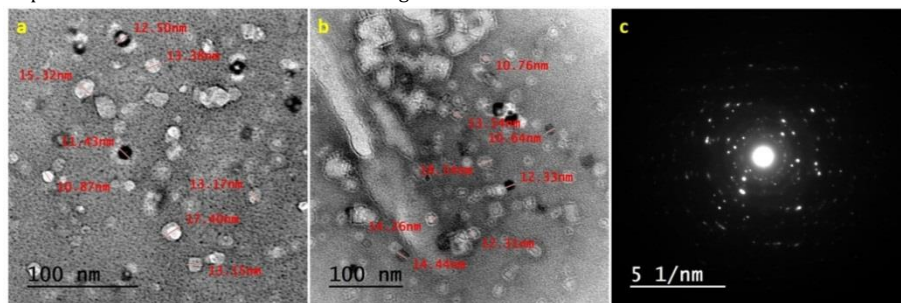


Fig. 1. (a and b) HR-TEM images of synthesized ZnO NPs, (c) Selected Area Electron Diffraction pattern (SAED) pattern.

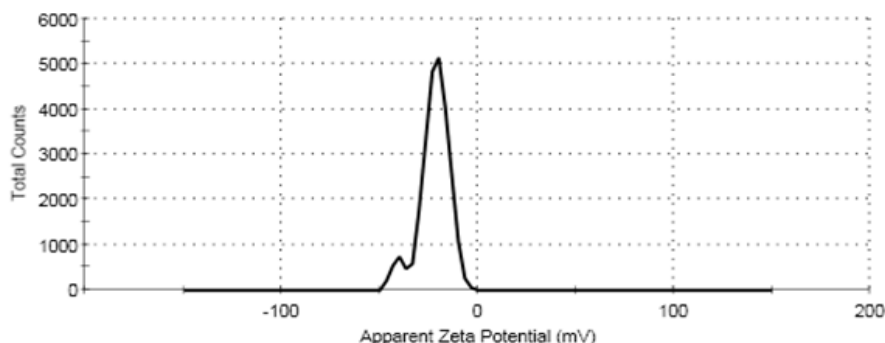


Fig. 2. Zeta potential distribution, the zeta potential values were determined by Zetasizer (Malvern ZS, UK).

3.2. Physiological parameters:

Data in Table 2 presented show the effect of irrigation intervals exerted significant effects on all traits under study such as, SPAD values, Fv/Fm values, performance index (PI), 50 % flowering (day) and leaf area index in both seasons. According to the LSD test prolonging irrigation times (drought stress), produced significantly decreased SPAD values, Fv/Fm values, performance index (PI), 50 % flowering (day) and leaf area index. Based on the results presented above, it is clear that, increasing the irrigation period (water deficit) from ten (I₁) to twenty (I₃) days reduces SPAD values by 31.15 and 16.22 %, Fv/Fm values by 22.98 and 21.18 %, performance index (PI) by 44.86 and 38.45 %, 50 % flowering (day) by 6.44 and 6.73 % and leaf area index by 20.61 and 27.60 %, in the 2022 and 2023 seasons, respectively. The reduction in physiological parameters of sorghum plants caused by increasing irrigation periods may be attributed to the retardation of enzymatic processes those concerned with photosynthesis and water decrease influenced the cell divisions which led to decreasing length and width of leaves which in turn was reflected in the reduction leaf area index. These results are in agreement with those of [16,17].

Sorghum varieties exhibited significant differences in SPAD values, Fv/Fm values, 50% flowering and leaf area index in both seasons, but performance index differed significantly only in the first season. Shandawil 1 variety (V₁) produced the higher SPAD values (48.17 and 50.85), and Fv/Fm (0.77 and 0.77), compared to Dorado variety (V₂) which recorded (44.65 and 48.52) and (0.74 and 0.73) in both 1st and 2nd seasons, respectively. As well as, Shandawil 1 produced the higher performance index (5.51) than Dorado (V₂) variety which produced (5.14) in the first season. On the contrary, Dorado (V₂) variety produced the higher 50% flowering (82.52 and 81.98 day) than Shandawil 1 variety (V₁) which produced (87.26 and 86.81) in both 1st and 2nd seasons. The superiority of Shandawil 1 (V₁) variety might have been due to increased photosynthetic efficiency. The variation between sorghum varieties in physiological parameters of sorghum plants was reported by many investigators among them [18,19].

The data presented in Table (2) indicate that the zinc oxide nanoparticles fertilizer levels significant effect on SPAD values, Fv/Fm values, performance index (PI), 50% flowering and leaf area index in both seasons of the experimental, respectively. The sorghum plants which sprayed with the higher level at 100 PPM (Z₃) of zinc oxide nanoparticles fertilizer (ZnO NPs) gave the maximum SPAD values (48.11 and 51.50), performance index (5.51 and 5.62), Fv/Fm values (0.77 and 0.77), 50% flowering (86.78 and 85.89 day) and of leaf area index (4.15 and 4.11), as against 0 PPM (Z₁ in control plants) which produced the lower values in both 1st and 2nd seasons, respectively. Zinc addition helps chloroplast growth and development, protects sulfhydryl groups, this leads to help chlorophyll biosynthesis. Zinc deficiency inhibits photosynthesis and causes chlorosis. These findings are in line with those obtained by [19,20,21].

Irrigation intervals and sorghum varieties interaction had significant effect on SPAD values, Fv/Fm values, performance index (PI) and leaf area index, while insignificant with respect to on 50% flowering in both seasons of the experiential. It is obvious that the highest values of SPAD (58.40 and 54.90), Fv/Fm values (0.88 and 0.87), performance index (6.83 and 6.70), leaf area index (4.79 and 4.93), were obtained by shorten the irrigation period to 10 days (I₁) when planted Shandawil 1 variety (V₁), in the two respective seasons, Table (2). Similar trend was observed [16].

Table 2 Mean SPAD values, Fv/Fm values, performance index, 50% flowering (day) and Leaf area index as affected by sorghum irrigation intervals, varieties, zinc nanoparticles fertilizer and their interactions in 2022 and 2023 seasons.

Treatments	SPAD values	Fv/Fm values	Performance index	50% flowering	Leaf area index	SPAD values	Fv/Fm values	Performance index	50% flowering	Leaf area index
	2022					2023				
Irrigation (I)	*	*	*	*	*	*	*	*	*	*
10 days (I ₁)	55.60	0.86	6.71	87.94	4.61	53.88	0.85	6.58	87.50	4.71
15 days (I ₂)	45.34	0.75	5.53	84.44	3.98	50.03	0.73	5.72	84.06	3.82
20 days (I ₃)	38.28	0.65	3.73	82.28	3.66	45.14	0.67	4.05	81.61	3.41
Varieties (V)	*	*	*	*	*	*	*	N.S	*	*
Shandawil 1 (V ₁)	48.17	0.77	5.51	82.52	4.28	50.85	0.77	5.60	81.96	4.13
Dorado (V ₂)	44.65	0.74	5.14	87.26	3.88	48.52	0.73	5.30	86.81	3.83
Zinc nanoparticles (Z)	*	*	*	*	*	*	*	*	*	*
0 PPM (Z ₁)	44.74	0.74	5.16	83.17	3.91	48.71	0.75	5.31	82.94	3.87
50 PPM (Z ₂)	46.37	0.76	5.30	84.72	4.19	48.84	0.73	5.42	84.33	3.97
100 PPM (Z ₃)	48.11	0.77	5.51	86.78	4.15	51.50	0.77	5.62	85.89	4.11
F test for interaction	*	*	*	N.S	*	*	*	*	N.S	*
IxV	*	*	*	*	*	*	*	*	*	*
IxZ	*	*	*	*	*	*	*	*	*	*
VxZ	*	*	*	*	*	*	*	*	*	*
IxVxZ	*	*	*	N.S	*	*	*	*	N.S	*

*and N.S refer to significant at 5% and not significant

Irrigation intervals (I) X zinc oxide nanoparticles fertilizer levels (Z) had significant effect on SPAD values, Fv/Fm values, performance index, 50% flowering and leaf area index in both seasons of experimentation. According to LSD test, significantly the highest values of SPAD (57.63 and 57.56), Fv/Fm values (0.87 and 0.86), performance index (6.94 and 6.89), 50% flowering (90.50 and 89.33 day) and leaf area index (4.78 and 4.89) was obtained from shorten the irrigation period to 10 days (I₁) when sprayed sorghum plants with ZnO NPs level at 100 ppm (Z₃), but the minimum values of the abovementioned traits was obtained from prolonging irrigations times (under water stress) to 20 days (I₃) when sprayed sorghum plants with ZnO NPs level at 0 PPM (Z₁ in control plants), in both seasons. It has been noted that, the zinc oxide nanoparticles fertilizer levels improved SPAD values under prolonging irrigations times (drought stress).

The interaction between sorghum varieties and ZnO NPs levels V x Z had significant effect on SPAD values, Fv/Fm values, performance index (PI),

50% flowering and leaf area index in the 1st and 2nd seasons, respectively. The highest value of SPAD (50.50 and 53.44), Fv/Fm values (0.78 and 0.79), performance index (5.68 and 5.83) and leaf area index (4.32 and 4.31) were obtained from Shandawil 1 (V₁) sorghum plants variety which were sprayed by ZnO NPs concentration at a level 100 ppm (Z₃) in the two respective seasons Table 2. On the contrary, The maximum of 50% flowering (89.44 and 88.33 day), were produced from Dorado (V₂) variety which were sprayed by ZnO NPs level at 100 ppm (Z₃) in the two respective seasons. Generally, foliar application with ZnO NPs level at a level 100 PPM makes sorghum plants tolerant to water stress. These findings are in line with those obtained by [21].

Irrigation intervals X sorghum varieties X and ZnO NPs levels interaction had a significant effect on SPAD values, Fv/Fm values, performance index and leaf area index, while insignificant with respect to on 50% flowering in both seasons of the experiential, respectively. The data in Table (x) show that when irrigated sorghum plants every 10 days and planted Shandawil 1 (V₁) variety and sprayed at a level 100 PPM (Z₃) of zinc oxide nanoparticles fertilizer (ZnO NPs) gave significantly the highest SPAD values (61.64 and 61.45), Fv/Fm values (0.89 and 0.88), performance index (6.94 and 6.89) and leaf area index (5.00 and 5.20), in both seasons of the experiential, respectively.

3.3. Yield components:

The differences in ear length and diameter (cm), grain ear weight (g) and weight of 1000 grains (g) due to irrigation intervals (I) were significant in 2022 and 2023 seasons. Increasing irrigation period (water deficit) from ten (I₁) to twenty (I₃) days reduces ear length by 13.69 and 18.50 %, ear diameter by 9.49 & 17.62, grains ear weight per plant (g) by 25.26 and 20.75 % and weight of 1000 grains (g) by 30.95 and 28.03 % in 2022 and 2023 seasons, respectively.

Table 3 Mean Ear length, ear diameter (cm), weight of 1000 grains and grain ear weight per plant as affected by sorghum irrigation intervals, varieties, zinc nanoparticles fertilizer and their interactions in 2022 and 2023 seasons.

Treatments	Ear length	Ear diameter	Weight of 1000 grains	Grain ear weight per plant	Ear length	Ear diameter	Weight of 1000 grains	Grain ear weight per plant
	(cm)	(cm)	(g)	(g)	(cm)	(cm)	(g)	(g)
	2022				2023			
Irrigation (I)	*	*	*	*	*	*	*	*
10 days (I ₁)	23.25	12.54	38.22	54.47	23.03	12.53	36.67	55.91
15 days (I ₂)	20.71	11.35	28.78	49.55	20.13	11.24	28.44	50.58
20 days (I ₃)	19.37	10.33	26.39	40.71	18.77	9.90	26.39	44.31
Varities (V)	*	*	*	*	*	*	*	*
Shandawil 1 (V ₁)	21.71	11.70	35.11	50.11	21.40	11.70	34.33	52.30
Dorado (V ₂)	20.51	11.09	27.15	46.38	19.92	10.77	26.70	48.44
Zinc nanoparticles (Z)	*	*	*	*	*	*	*	*
0 PPM (Z ₁)	20.33	10.87	28.33	46.65	19.71	10.72	27.78	48.59
50 PPM (Z ₂)	21.03	11.47	31.27	48.11	20.73	11.24	30.72	50.42
100 PPM (Z ₃)	21.97	11.88	33.89	49.97	21.49	11.71	33.00	52.05
F test for interaction								
I x V	N.S	N.S	*	*	N.S	N.S	*	*
I x Z	*	*	*	*	*	*	*	*
V x Z	N.S	N.S	*	*	N.S	N.S	*	*
I x V x Z	*	*	*	*	*	*	*	*

*and N.S refer to significant at 5% and not significant

The decreased on the abovementioned under water deficient can be attributed to different physiological mechanisms such as decreased in SPAD values, Fv/Fm values and performance index. Water stress reduces biomass accumulation, inhibits cell expansion, impairs osmotic adjustment, affects cell membrane stability, and negatively impacts metabolic activities; this is reflected in the decreased yield components. These results are agreed with those obtained by [22].

Regarding the varieties *i.e.*, Shandawil-1 (V₁) and Dorado (V₂) variety, the results in the Table (3) demonstrated that varieties exerted significant influence on ear length and diameter (cm), ear weight per plant (g) and weight of 1000 grains (g) in both seasons. Results showed that Shandawil 1 (V₁) variety produced significantly tallest ear length (21.71 and 21.40 cm), thickest ear diameter (11.70 and 11.70 cm), heaviest grains ear weight per plant (50.11 and 52.30 g) and heaviest weight of 1000 grains (35.11 and 34.33 g), than Dorado (V₂) variety which produced values on the above mentioned in both 1st and 2nd seasons, respectively. The superiority of Shandawil 1 (V₁) variety in weight of yield components might have been due to increased photosynthetic efficiency, heaviest grains ear weight and the maximum leaf area index, which led to increasing weight of 1000 grains. The variation between sorghum varieties sorghum yield components was reported by many investigators among them [9,23,22].

The presented results in Table (3) showed that the zinc oxide nanoparticles fertilizer levels significant effect on ear length and diameter (cm), ear weight per plant (g) and weight of 1000 grains (g) in both seasons, respectively. The sorghum plants which sprayed at a level 100 PPM (Z₃) of zinc oxide nanoparticles fertilizer (ZnO NPs) gave significantly the tallest ear length (21.97 and 21.49), as against 0 PPM (Z₁ in control plants), thickest ear diameter (11.88 and 11.71), the heaviest grains ear weight per plant (49.97 and 52.05 g) and highest weight of 1000 grains (33.89 and 33.00 g), as against 0 PPM (Z₁ in control plants) which produced the lower values in both 1st and 2nd seasons, respectively. Zinc addition helps chloroplast growth and development, this leads to help chlorophyll biosynthesis, plays a major role in increasing protein synthesis and cell elongation. So zinc oxide nanoparticles fertilizer may be attributed to increase the values of leaf area index, and heaviest grains ear weight of sorghum leaves which in turn was reflected to increasing

sorghum yield components. This finding are in line with those obtained by [22].

Irrigation intervals and sorghum varieties interaction had a significant effect on grains ear weight and weight of 1000 grains per plant Table (3), while insignificant with respect to on ear length and diameter (cm) in both seasons of the experiential, respectively. It is obvious that the maximum values of grains ear weight (57.70 and 58.93 g), and weight of 1000 grains (42.00 and 40.33 g), were obtained by shorten the irrigation period to 10 days (I_1) when planted Shandawil 1 variety (V_1). Irrigation intervals (I) X zinc oxide nanoparticles levels (Z) had significant effect on ear length and diameter (cm), grains ear weight per plant and weight of 1000 grains in both seasons of experimentation. According to LSD test, significantly the tallest values of ear length (57.71 and 58.27 cm), thickest values of ear diameter (13.23 and 13.04 cm), heaviest values of grains ear weight per plant (57.71 and 58.27 g) and the highest values of weight of 1000 grains (42.83 and 41.00 g) were obtained from shorten the irrigation period to 10 days (I_1) when sprayed sorghum plants with ZnO NPs at a level 100 ppm (Z_3) in the two respective seasons.

The interaction between sorghum varieties and ZnO NPs levels V x Z had significant effect on grains ear weight and weight of 1000 grains per, but insignificant with respect to ear length and diameter (cm) in both seasons of the experiential, respectively. The heaviest value of grains ear weight per plant (52.31 and 54.65 g) and weight of 1000 grains (38.67 and 37.33 g), were obtained from Shandawil 1 (V_1) variety which were sprayed by ZnO NPs at a level 100 ppm (Z_3) in the two respective seasons, Table (3). Irrigation intervals X sorghum varieties X and ZnO NPs levels interaction was significant effect on ear length and diameter (cm), grains ear weight (g) and weight of 1000 grains (g) in both seasons, respectively, Table (3) indicating that when irrigated sorghum plants every 10 days and planted Shandawil 1 (V_1) variety and sprayed with at a level 100 PPM (Z_3) of zinc oxide nanoparticles fertilizer (ZnO NPs) gave significantly the tallest ear length (26.71 and 26.11 cm), thickest ear diameter (13.80 and 13.88 cm), the heaviest grains ear weight (62.26 and 63.10 g) and weight of 1000 grains (48.33 and 45.67 g).

3.4. Yield

Table 4 demonstrate that significant differences were observed among the irrigation intervals for sorghum grain, stalk, leaves and biological yield (ton/fed.) in 2022 and 2023 seasons of the experimental. Increasing irrigation period from ten to fifteen and twenty day reduces grain yield (ton/fed.) by 28.48 & 56.29 and 37.58 and 57.05 %, reduces stalk yield (ton/fed.) by 16.06 & 30.76 and 16.11 and 29.92 % and reduces leaves yield (ton/fed.) by 21.94 & 37.89 and 20.49 and 38.80 %, in 2022 and 2023 seasons, respectively. Drought stress resulted in significantly decline in grain yield and yield components of all the tested sorghum varieties. Prolonging irrigation times major impacted the physiological traits, vegetative growth and yielding of the tested sorghum varieties. The reduction in the yielding performance of sorghum under water deficient can be attributed to different physiological traits like SPAD values, performance index and Fv/fm. Where, prolonging irrigation times reduce cell expansion, alter cell membrane stability reduces, biomass accumulation, impairs osmotic adjustment, as well as negatively impacts metabolic activities. So, this led to a decrease leaf area index, ear length and diameter, weight of 1000 grains, grains ear weight per plant, and reflected to a decrease in the grain sorghum yield (ton/fed.). These results are in agreement with some previous papers [16.17.22].

Table 4 Mean leaves yield, stalk yield, grain yield and biological yield (ton/fed.) as affected by sorghum irrigation intervals, varieties, zinc nanoparticles fertilizer and their interactions in 2022 and 2023 seasons.

Treatments	leaves yield	Stalk yield	Grain yield	Biological yield	leaves yield	Stalk yield	Grain yield	Biological yield
	(ton/fed.)							
	2022				2023			
Irrigation (I)	*	*	*	*	*	*	*	*
10 days (I_1)	3.51	22.17	1.51	27.19	3.66	22.66	1.49	27.81
15 days (I_2)	2.74	18.61	1.08	22.43	2.91	19.01	0.92	22.84
20 days (I_3)	2.18	15.35	0.66	18.20	2.24	15.88	0.64	18.75
Varities (V)	*	*	*	*	*	*	*	*
Shandawil 1 (V_1)	3.00	19.55	1.24	23.78	3.14	20.16	1.17	24.50
Dorado (V_2)	2.63	17.87	0.92	21.42	2.73	18.20	0.86	21.80
Zinc nanoparticles (Z)	*	*	*	*	*	*	*	*
0 PPM (Z_1)	2.68	17.92	0.97	21.57	2.82	18.49	0.89	22.20
50 PPM (Z_2)	2.81	18.79	1.07	22.67	2.93	19.22	1.02	23.17
100 PPM (Z_3)	2.94	19.42	1.20	23.57	3.06	19.83	1.13	24.02
F test for interaction	*	*	*	*	*	*	*	*
I x V								
I x Z	*	*	*	*	*	*	*	*
V x Z	N.S	*	*	*	N.S	*	*	*
I x V x Z	*	*	*	*	*	*	*	*

*, N.S and fed refer to significant at 5%, not significant and feddan=4200 m²

Data tabulated in (Tables 4) denote that sorghum varieties significantly differed in sorghum grain, stalk, leaves, and biological yield in both seasons. Sorghum Shandawil 1 (V_1) variety surpassed Dorado (V_2) variety in sorghum grain yield by 25.80 and 26.50 %, stalk yield by 8.59 and 9.72 % and leaves yield by 12.33 and 18.68 %, in 2022 and 2023 seasons, respectively. The superiority of variety Shandawil 1 in grain yield (ton/fed.) may be attributed to this variety which has the best values of leaf area index, ear length and diameter, weight of 1000 grains and grains ear weight per plant which reflected to increasing grain yield. These results are in agreement with those of [16.17.9.23.22].

The presented results in Table (4) illustrate that the zinc oxide nanoparticles fertilizer levels significant effect on sorghum grain, stalk, leaves and

biological yield in the first and second seasons, respectively. LSD test explained that, the sorghum plants which sprayed with at a level 100 PPM (Z_3) of zinc oxide nanoparticles fertilizer (ZnO NPs) gave significantly the heaviest grain yield (1.20 and 1.13 ton/fed.), stalk yield (19.42 and 19.83 ton/fed.) and leaves yield (2.94 and 3.06 ton/fed.), as against 0 PPM (Z_1 in control plants), which produced the lower values of the above-mentioned traits. Zinc additions helps chloroplast growth and development, plays a major role in increasing protein synthesis and cell elongation. So zinc oxide nanoparticles fertilizer may be attributed to increase the values of leaf area index, ear length and diameter, and weight of 1000 grains, as well as grains ear weight per plant which reflected to increasing grain yield. These findings are in line with those obtained by Abbas et al., [22].

Irrigation intervals and sorghum varieties interaction had significant effect on sorghum grain, stalk, leaves and biological yield in both seasons, respectively. It is obvious that the heaviest grain yield (1.73 and 1.70 ton/fed.), stalk yield (23.53 and 23.98 ton/fed.) and leaves yield (3.76 and 3.88 ton/fed.), were obtained by shorten the irrigation period to 10 days (I_1) when planted sorghum Shandawil 1 variety (V_1), in the two respective seasons Table (4). According to the data in the Table (4), it is clear that Shandawil 1 (V_1) was the most droughts tolerant and Dorado (V_2) the least drought tolerant varieties as determined by calculation of the relative drought index (RDI). The extent of grain sorghum yield (ton/fed.) reduction under prolonging irrigation times (drought stress) varied among the varieties. For the Shandawil 1 (V_1) variety, grain yield (ton/fed.) decreased by 27.75%, 56.65% in the first season and 39.41, 55.29% in the second season, under 15 and 20 day interval, respectively. Similar trend was observed by Abbas et al., [22].

Irrigation intervals (I) X zinc oxide nanoparticles fertilizer levels (Z) had significant effect on sorghum grain, stalk, leaves and biological yield (ton/fed.) in both seasons of experimentation. According to LSD test, significantly the heaviest values of grain yield (1.72 and 1.66 ton/fed.), stalk yield (23.22 and 22.66 ton/fed.) and leaves yield (3.68 and 3.85 ton/fed.), were obtained from shorten the irrigation period to 10 days (I_1) when sprayed sorghum plants with ZnO NPs at a level 100 ppm (Z_3) in the two respective seasons. Generally, foliar using zinc oxide nanoparticles at a level of 100 ppm makes plants tolerant to water stress. It has been noted that, the zinc oxide nanoparticles fertilizer levels improved grain yield (ton/fed.) under prolonging irrigations times (drought stress). The foliar application of zinc nanoparticles, however, significantly enhanced most agronomic traits in the different tested varieties, under both the well-watered and prolonging irrigation period conditions. Furthermore, zinc nanoparticles included enhancements in the leaf area index, ear length, and weight of 1000 grains, as well as grains ear weight per plant, compared to the control and reflected to increase in the grain sorghum yield (ton/fed.). These findings are in line with those obtained by Abbas et al., [22]. The improved growth and yielding can be attributed to the physiological and yield components roles of Zn in plant cells during prolonging irrigation period. ZnO NPs concentration has been noted to increase the yielding of abscisic acid in sorghum, which can improve stomatal regulation and enhance water use efficiency under water stress [24]. The data of the present research highlight the potential of the foliar using of zinc nanoparticles as a strategy to reduce the harmful effects of prolonging irrigation interval on sorghum grain production. The findings emphasize the significance of managing Zn nanoparticles in order to improving the productivity of sorghum under prolonging irrigation interval. This could be attributed to the ability of these zinc nanoparticles to enhance different physiological and biochemical responses in sorghum plants, thereby improving their productivity under prolonging irrigation interval.

The interaction between sorghum varieties and ZnO NPs levels V x Z had significant effect on sorghum grain, stalk and biological yield, while insignificant with respect to leaves yield (ton/fed.) in both seasons of the experiential, respectively. The heaviest value of grain yield (1.41 and 1.32 ton/fed.) and stalk yield (20.32 and 20.79 ton/fed.) were obtained from Shandawil 1 (V_1) variety which were used by ZnO NPs concentration at 100 ppm (Z_3) in the two respective seasons, Table (4). This findings are in line with those obtained by Abbas et al., [22].

Irrigation intervals X sorghum varieties X and ZnO NPs levels interactions was significant effect on sorghum grain, stalk, leaves, and biological yield in the first and second seasons, respectively. Table (4) indicating that, when irrigated sorghum plants every 10 days and planted Shandawil 1 (V_1) variety and sprayed at a level 100 PPM (Z_3) of zinc oxide nanoparticles fertilizer (ZnO NPs) gave significantly the heaviest grain sorghum yield (2.07 and 1.93 ton/fed.), stalk sorghum yield (24.93 and 25.00 ton/fed.) and leaves sorghum yield (4.00 and 4.17 ton/fed.). These results confirmed with those obtained by Abbas et al., [22].

3.5. Relative Drought Index (RDI):

The current research study evaluated the drought tolerance of two sorghum varieties, Shandawil 1 and Dorado, under different levels of irrigation intervals (Table 5). The RDI was used as an index of water deficient, with values ranging from 1.13 to 1.23 for Shandawil 1 variety, 0.75 to 0.84 for the Dorado variety under 15 day irrigation intervals, and the values ranging from 0.82 to 0.78 for Shandawil 1 variety, 0.42 to 0.44 for the Dorado variety under 20 day irrigation intervals (water stress conditions). These results confirmed with those obtained by [22]. Based on the RDI values, the Shandawil 1 variety was classified as tolerant to water deficient in 15 day period and moderately tolerant (M) under 20 day period, the Dorado variety was moderately tolerant (M) at 15 day period, but was sensitive tolerant (S) at 20 day period.

Table (5.): Mean grain yield (ton/fed.) and relative drought index (RDI) for sorghum varieties under irrigation intervals in 2022 and 2023 seasons.

Varieties	Irrigation intervals	15 days		20 days	
		2023 season	2022 season	2023 season	2022 season
Shandawil 1 (V_1)		1.13 (T)	1.23 (T)	0.82 (M)	0.78 (M)
Dorado (V_2)		0.75 (M)	0.84 (M)	0.42 (S)	0.44 (S)

T, M, and S refer to tolerant, moderately and sensitive, respectively.

4. Conclusions

Zn nanoparticles at a level 100 PPM effectively reduced the negative effects of water deficient on sorghum. This type can be recommended in Egypt conditions, to enhance sorghum productivity under water stress conditions.

Acknowledgment

The authors would like to thank Agronomy Department, Fayoum University for encouraging and supporting the publication of this study.

Author Contributions

Conceptualization, S.M. Emam and A. A.A. Mekdad; Methodology, S.M. Emam, A. A.A. Mekdad and K. M. Mahmoud; Formal analysis, A. A.A. Mekdad, K. M. Mahmoud and Kefah M. Mansour; Writing original draft preparation, S.M. Emam and A. A.A. Mekdad; Writing review and editing, S.M. Emam, A. A.A. Mekdad and K. M. Mahmoud; Supervision, S.M. Emam, A. A.A. Mekdad and K. M. Mahmoud. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no competing interests that could have appeared to influence the work reported in this paper.

References

- [1] A. Bibi, H. A Sadaqat, H.M. Akram, M.I. Mohammed, Physiological markers for screening sorghum (*Sorghum bicolor*) germplasm under water stress condition. *Int. J. Agric. Biol.* 12: (2010) 451–455.
- [2] F A O " Food and Agriculture Organization of the United Nations " (2019). Nations, Food and Agriculture Organization of the United /FAOSTAT Statistics Division.
- [3] United State Development Agriculture: <https://ipad.fas.usda.gov/country-summary/Default.aspx?id=US&crop=Sorghum>
- [4] ICRISAT: Sorghum. Patancheru (AP): International crops research institute for the semi-arid tropics. 2009.
- [5] W. Dy Kes and Lloyd, Rooney. Sorghum and millet phenols and antioxidants. *Journal of cereal science.* (2006) 236- 251.
- [6] C.J. Vörösmarty, P. Green, J. Salisburly, R.B. Lammers, Global water resources: Vulnerability from climate change and population growth. *Sci.* 289: (2000) 284-288.
- [7] M. M. Ludlow, R.C. Muchow, A critical evaluation of traits for improving crop yields in water-limited environments. *Adv Agron* 43: (1990) 107-153
- [8] Taha, Nour El-Hoda M, Laila M. Saif, F. A. Abd El-Latef, M.K. Aly, Response of sweet sorghum to irrigation intervals and nitrogen fertilization. *Assiut J. of Agric. Sci.* 30 (3): (1999) 65-80.
- [9] A.A.A. Mekdad, M.M. Rady, Productivity response to plant density in five *sorghum bicolor* varieties in dry environments. *Ann. Agric. Crop Sci.* 1(2): (2016) 1-7.
- [10] A.U. Jan, F. Hadi, M. A. Nawaz, K. Rahman, Potassium and zinc increase tolerance to salt stress in wheat (*Triticum aestivum* L.). *Plant Physiol. Biochem.* 116, (2017) 139–149.
- [11] B. Afeez, Y. M. Khanif, M. Saleem, Role of zinc in plant nutrition A review. *Am. J. Exp. Agric.* 2013, 3, (2013) 374–391.
- [12] M.Y. Ashraf, S. Tariq, S. Saleem, M.A. Khan, S.W.U. Hassan, Y. Sadeef, Calcium and zinc mediated growth and physio-biochemical changes in mungbean grown under saline conditions. *J. Plant Nutr.* 43, (2020) 512–525.
- [13] M. Lamaoui, M. Jemo, R. Datla, F. Bekkaoui, Heat and drought stresses in crops and 632 approaches for their mitigation. *Front. Chem.* 6, (2018) 26.
- [14] R. A. Fischer, J. T. Wood, Drought resistance in spring wheat cultivars. III. Yield associations with morpho-physiological traits. *Aust. J. Agric. Res.*, 30, (1979) 1001–1020.
- [15] K. A Gomez, A. A. Gomez, Statistical procedures for agriculture research. 2nd ed. John Wiley and Sons. New York, USA. (1984) 680.
- [16] F.K. Younis, O A El Shahaby, S A Abo-Hamed, A. H. Ibrahim, Effects of water stress on growth pigments and O3C01 assimilation in three sorghum cultivars. *J. Agronomy and Crop Science.* 185, (2000) 73-82.
- [17] M. A. El - Hawary, M. A. Hager, A. M. Abd - Elkader and Y.Z. KHALF Alla, Effect of irrigation intervals and nitrogen fertilizer on growth and yield of two sweet sorghum varieties. *J. Plant Production, Mansoura Univ.*, 3 (5): (2012) 819 – 833.
- [18] J. Sékou, B. Dembele, B. Gano, M Vaksman, M. Kouressy, L. L. Dembele, M. Doumba, N. Teme, D. Diouf, A. Audebert, Response of eight sorghum varieties to plant density and nitrogen fertilization in the Sudano-Sahelian zone in Mali. *African Journal of Agricultural Research*, 16(10): (2020) 1401-1410.
- [19] A. R. Adebayo, M. Mazibuko, E.T. Sebetha, Effect of zinc fertilizer rates on growth and panicle yield of grain sorghum cultivars. *Egypt. J. Agron.* 45(3): (2023) 259 – 269.
- [20] K. Zhao, Y. Wu, Effects of Zn deficiency and bicarbonate on the growth and photosynthetic characteristics of four plant species. *PLoS ONE*, 12 (1), (2017) e0169812.
- [21] Tag El-Din, Aml A, Response of two sorghum genotypes to foliar spray by different zinc oxide nanoparticles concentrations. *SVU-International Journal of Agricultural Sciences*, 3 (3): (2021) 170-176.
- [22] M. Abbas, C. Tian, M. K. I., Nagy, Al-Metwally, Maryam S., X Chen, H. M. Abdel-Lattif, Synergistic effect of iron and zinc nanoparticles with recommended nitrogen dose on production and grain quality of maize (*Zea mays* L.) cultivars under drought stress. *Nitrogen*, 5(4): (2024). 1156–1180.
- [23] A. A.A. Mekdad, S.M. Emam, Biofuel sugar content, grain Yields and Qualities of Two Sorghum bicolor in Responses to Levels and Timing of Nitrogen Applications. *Egypt. J. Agron.* 41(2): (2019) 105 – 117.
- [24] F.K. Zengin, The effects of Co2+ and Zn2+ on the contents of protein, abscisic acid, proline and chlorophyll in bean (*Phaseolus vulgaris* cv. Strike) seedlings. *J. Environ. Biol.* 27, (2006) 441–448.