Egypt. J. Plant Breed. 23(1):119– 145 (2019)

EFFECT OF NANO ZINC-OXIDE FOLIAR APPLICATION ON SOME FLAX CULTIVARS UNDER DIFFERENT IRRIGATION TREATMENTS

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ABSTRACT

Two field experiments were carried out at an agricultural extension field, El-Mahalla El-Kobra City, Gharbiua Governorate, Egypt during the two successive winter seasons of 2015/16 and 2016/17. The objective of this work was to study the effect of foliar application of zinc-oxide nanoparticles on some physiological characters and yield components as well as quality attributes of four flax cultivars under different irrigation treatments. Three irrigation treatments were applied through three separated irrigation experiments each season (irrigate only life irrigation (IT_1), irrigate one irrigation after life irrigation (IT_2) and Irrigate two irrigations after life irrigation (IT_3). Each irrigation experiment was carried out using a split-plot design with three replications. The four cultivars were plotted in the main plots (Sakha 3, Sakha 5, Giza 11 and Giza 12). However, nano-zinc oxide treatments (control, Nano-ZnO_1 (50 ppm) and Nano-ZnO_2 (100 ppm) were arranged in the sub-plots. Irrigation treatment (IT_3) had superiority and ranked the first for all straw yield traits, no. of capsules per plant, seed and oil yields per hectare, fiber length and fiber yield per hectare. However, irrigation treatment (IT_2) recorded the highest total fiber percentage. On contrast, there was no significant variation among the three irrigation treatments for oil percentage trait. The data showed that, Sakha 3 gave the highest values for plant height, technical stem length, fiber length, fiber fineness, total fiber percentage and fiber yield per hectare, while, Giza 11 and Giza 12 recorded the highest values of main stem diameter and straw yield per hectare. Besides, Sakha 5 scored the highest number of capsules per plant, seed and oil yields per hectare and oil percentage. One irrigation treatment (IT_1) gave the lowest concentrations of chlorophyll a and b, while, the highest levels of proline, CAT and POX were recorded. With respect to nano –zinc oxide application, foliar spray of Zinc oxide nanoparticles induced a significant increment in all straw, oil and fiber traits except fiber fineness. Application of the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the highest values of the previous mentioned traits.

Key words: ***Flax, Linum usitatissimum* L., *Nano Zinc oxide, Irrigation, chlorophyll, Antioxidant enzymes.***

INTRODUCTION

Flax is an industrially important crop cultivated all over the world, it is an annual winter crop, cultivated in Egypt for its phloem fiber, and it usually produced by a few number of tradesmen concentrated in Gharbiua governorate, in the middle Delta region, who export its fibers to Europe and China in its raw form. Oil produced from its seeds considered an important secondary product that exploit locally in human nutrition in form of raw oil. Also, it is used in some industries such as a drying agent for paints, varnishes, lacquer, and printing ink. Beside its valuable oil, seed meal which contains a high percent of protein 42-46 % used as an animal feed. In Egypt, the cultivated area of flax is so limited compared to other common crops, but despite hard competition with other winter crops, flax cultivated area in Egypt increased in the last five years due to renting more farmlands by tradesmen involved in flax cultivation. These rented farmlands mostly located in various areas due to failure of recurrent flax cultivation in the same farmland that forces tradesmen to rent farmlands in distant and scattered areas. This case forces tradesmen to apply different irrigation regimes based on source, distance and quantity of available irrigation water. Water deficit irrigation significantly reduced growth parameters such as stem length, fresh and dry weights, yield and photosynthetic pigments (Abdelaal *et al* 2017 and Abdelaal *et al* 2018) in corn and barley plants. Therefore, studying different irrigation treatments to cope with that case is essential.

Significant clear differences in straw, seed, oil and fiber yields and their components among different flax types were reported by many researchers. Bauer *et al* (2015), El-Refaey *et al* (2015) and Rashwan *et al* (2016), concluded that, oil type cultivars were superior in main stem diameter, biological and straw yields, seed index, seed and oil yields and oil percentage. Meanwhile, fiber types cultivars highly significantly out-yielded dual purpose and oil type cultivars in plant height, fiber fineness, fiber length, total fiber percentage and fiber yield.

Zinc is an essential micro-element for crop production, it plays a key role as a structural constituent or regulatory co-factor of a wide range of different enzymes and proteins in many important biochemical pathways and these are mainly concerned with: carbohydrate metabolism, both in photosynthesis and in the conversion of sugars to starch, protein metabolism, auxin (growth regulator) metabolism, pollen formation, the maintenance of the integrity of biological membranes, the resistance to infection by certain pathogens (Alloway 2008). In that respect, flax is classified as one of the highly sensitivity crops to zinc deficiency (Alloway 2008). Zinc deficiency can limit flax yield, and symptoms may include stunting, yellowing out, and terminal die-back. Deficiency of zinc occurs in many areas a cross the world on a wide range of soil types. Semi-arid areas - such as Egypt- tends to be the most seriously affected as a result of the low absorption of micronutrients due to a high pH level of the soil (Akay 2011).

Nanoparticles (NPs) interact with plants causing many morphological and physiological changes, depending on the properties of NPs. Efficacy of NPs is determined by their chemical composition, size, surface covering, reactivity, and most importantly the dose at which they are effective (Khodakovskaya *et al* 2012). Recently, many new strategies have been created depending on application of NPs as a new approach to improve crop production and tolerance to biotic and abiotic stresses in crop plants (Jaberzadeh *et al* 2013).

In accordance with the previous strategies, the aim of this study was to investigate the effects of foliar application of zinc –oxide nanoparticles on four flax cultivars under different irrigation treatments, and their impacts on yield and yield components.

MATERIALS AND METHODS

Plant material and Procedures

The present experiments were carried out at an agricultural extension field, El-Mahalla El-Kobra City, Gharbiua Governorate , the laboratory studies were conducted at Plant Pathology and Biotechnology Laboratory (PPBL) and Excellence Center (EPCRS) (certified according to ISO 17025 and ISO 9001, ISO 14001, OHSAS 18001) Department of Agricultural Botany, Kafrelsheikh University, Egypt during the two successive winter seasons of 2015/16 and 2016/17 to study the effect of foliar application of zinc-oxide nanoparticles on morpho-physiological characters and yield components as well as quality attributes of four flax cultivars under different irrigation treatments. The preceding crop was maize (*Zea mays*) and rice (*Oryza sativa*) in the first and second seasons, respectively. The properties of experimental soli were presented in Table (1).

Table 1.The mechanical and chemical analysis of the experimental soil.

Seasons	Piratical size distribution							Soluble cations $meqL^{-1}$				Soluble anions $meqL^{-1}$				Trace elements (ppm)		
	Sand %	Silt %	Clay %	Texture class	pH	Ec_e	OM %	Ca^{++}	Mg^{++}	K^{+}	Na^{+}	Co_3^{--}	Hco_3^{-}	Cl^{-}	So_4^{--}	Fe^{++}	Zn^{++}	Mn^{++}
2015/16	12.6	31.3	56.1	clayey	7.9	0.96	2.49	5.3	2.0	0.5	3.8	0.0	2.8	9.2	1.3	6.1	0.76	2.22
2016/17	12.57	31.68	55.57	clayey	8.05	1.14	2.64	4.4	2.6	0.35	4.5	0.0	2.2	8.4	1.15	5.4	0.92	1.83

The Meteorological data of the experimental location according to NASA POWER Data Access Viewer-Prediction of Worldwide Energy Resource (https://power.larc.nasa.gov/data-access-viewer) are presented in Table (2).

Table 2. The Meteorological data of the experimental location

Meteorological data	Season	November	December	January	February	March	April
Precipitation (mm day^{-1})	2015/16	0.66	0.27	0.61	0.08	0.26	0.07
	2016/17	1.3	1.21	0.1	0.19	0.0	1.39
Relative Humidity at 2 Meters (%)	2015/16	63.92	64.61	63.15	56.53	48.47	39.26
	2016/17	57.55	67.82	67.11	63.04	53.15	49.30
Maximum Temperature at 2 Meters (C°)	2015/16	26.36	21.49	18.72	24.45	26.57	33.79
	2016/17	26.91	19.24	18.38	20.95	25.22	29.00
Minimum Temperature at 2 Meters (C°)	2015/16	15.73	11.21	7.91	9.79	11.58	14.96
	2016/17	14.87	9.00	6.67	7.69	10.88	12.52

Three irrigation treatments were applied through three separated irrigation experiments each season, these irrigation treatments were as follows:

1- Irrigate only life irrigation (IT_1): sowing irrigation then life irrigation after 30 days from sowing. Physiologically, under this treatment, plants have exposed to water deficit stress during all growth stages (stem elongation, apical branching, flowering and seed filling.), starting from the late period of the stem elongation stage.
2- Irrigate one irrigation after life irrigation (IT_2): sowing irrigation, life irrigation after 30 days from sowing then the first irrigation after 75 days from sowing, and under this treatment, plants have exposed to water deficit stress during the late period of the stem elongation stage and the whole seed filling stage.
3- Irrigate two irrigations after life irrigation (IT_3): sowing irrigation, life irrigation after 30 days from sowing, first irrigation after 65 days from sowing then the second irrigation after 100 days from sowing. Physiologically, under this treatment, plants didn't expose to any water deficit stress at any of the previous mentioned growth stages.

Surface irrigation was applied using a hose with a flow rate of 105 liter per minute and the irrigation period was approximately 7 minutes and 9 seconds for each sub-plot sized 10.5 m^2 (3 m × 3.5 m). This period permitted to flow about 750 liter (0.75 m^3) which considered equal to 300 m^3 per faddan (An Egyptian area unit equal to 4200 m^2) or 714.3 m^3 per hectare in each irrigation time.

Each irrigation experiment was carried out using a split-plot design in a randomized complete plot arrangement with three replications. The four cultivars were plotted in the main plots (Sakha 3, Sakha 5, Giza 11 and Giza 12). And, nano-zinc oxide treatments were arranged in the sub-plots as follows:

- Control, foliar application with distilled water without Nano-zinc oxide.
- Nano-ZnO_1, foliar application with a solution of Nano- Zinc oxide at concentration of 50 ppm.
- Nano-ZnO_2, foliar application with solution of Nano- Zinc oxide at concentration of 100 ppm.

Foliar applications were applied three times at the morning after dew evaporation from surfaces of plant leaves; at 30, 45 and 60 days from sowing; Zinc oxide nanoparticles were diluted with water at the rate of 200 liter per faddan (476.2 liter per hectare) which is equal to 0.5 liter per each sub-plot; and sprayed using a backpack sprayer (16 liter Motorized backpack atomizer and sprayer MONSONE DK200) fitted with one nozzle. Worthy to mention that, Tween 80 (Polysorbate 80 at the rate of 0.1% or 1 ml/liter) was added to prevent nanoparticles conglomerate during application.

Zinc oxide nanoparticles were purchased from Sigma-Aldrich Co. (USA) and Product Specifications were as follows:

Zinc oxide, dispersion –nanoparticles, <100 nm particle size (TEM), ≤40 nm avg. part. Size (APS), 20 wt. % in H_2O, Size < 100 nm, pH 6.0 - 9.0 Product Number: 721077, CAS Number: 1314-13-2.

The two experiments were sown on the 1^{st} and the 3^{rd} of November in the first and second season, respectively. Calcium super phosphate was added at the rate of 100 kg/faddan or 238 kg/hectare (15.5% P_2O_5) before sowing and potassium sulphate (48% K_2O) was applied in one dose at the rate of 50 kg/faddan or 119 kg/hectare before sowing in both seasons. Nitrogen was added to the sub-plots at the rate of 60 kg N/faddan or 142.85 kg N/ hectare in the form of urea (46% N) in two doses, the first one was about one-third of the whole dose and added before the sowing irrigation and the second one was about two-third of the whole dose and added before the life irrigation. Other recommended cultural practices for growing flax were done as usual in the area.

Sampling and Measurements

Physiological characters

Chlorophyll and Proline concentrations

Chlorophyll a and b concentrations were determined as mg-1g fresh leaves. Flax leaves 0.5g were homogenized with acetone (90%) filtered and make up to a final volume of 50 mL. Chlorophyll concentration was measured spectrophotometerically of extract at 663 and 648 nm according to Lichtenthaler (1987). Proline was extracted from dried leaves from treatments by ethanol 70% and determined colorimetrically in the extraction by the methods described by Bates *et al* (1973).

Activity of antioxidant enzymes

Antioxidant enzymes activity were measured in flax leaves as follows: 0.5 g fresh leaves were homogenized at 0-4 °C in 3 ml of 50 mM TRIS buffer (pH 7.8), containing 1 mM EDTA-Na2, and 7.5% polyvinylpyrrolidone and centrifuged (12,000 rpm, 20 min, 4 °C). The total soluble enzyme activity was measured in the supernatant spectrophotometrically (Hafez *et al* 2012). Activity of catalase (CAT) was determined according to Aebi (1983). The activity was expressed as the increase in absorbance min-1 g-1 fresh weight. Peroxidase (POX) activity was directly determined in the crude enzyme extract according to a typical procedure proposed by *Hammerschmidt et al* (1982). The absorbance was recorded at 470 nm at every 30 s interval for 3 min.

Yield and quality traits:

Ten individual plants were chosen randomly at full maturity for each sub-plot to record plant height (cm), technical stem length (cm), main stem diameter (mm), straw yield per plant (gm) and no. of capsules per plant, while other traits were taken from whole plants of the sub-plot.

Straw yield and its related characters

Plant height (cm): the distance from the cotyledonary node to the top of plant, technical stem length (cm): the distance from the cotyledonary node to the first apical branch of the main stem, main stem diameter (mm): at the middle region to the nearest 0.1 mm by using biocles, straw yield per plant (gm): as the total weight of the air dried straw per plant after removing the capsules and straw yield per hectare (ton): estimated from the sub-plots and converted to record straw yield per hectare after removing the capsules.

Seed yield and its related characters

No. of capsules per plant: was counted in each plant, seed yield per hectare (kg): seed yield of an area of each plot (10.5 m^2) was estimated and transformed to kg per hectare, oil percentage (%): was determined as described by the (AOAC 1990) methods, using petroleum ether (40-60 °C) in Soxhlet apparatus and oil yield per hectare: was calculated from the following formula: Oil yield per hectare = oil percentage × seed yield per hectare.

Fiber yield and its technological characters

Fiber length (cm): Ten fiber ribbons from each treatment were spreaded out and each ribbon was measured then the average fiber length was recorded. Fiber Fineness (N.m) determined using Radwan and Momtaz (1966) method according to the following equation:

$$N.m = (N \times L)/W \qquad (1)$$

Where, N.m = Metrical number, N = Number of fibers (20 fibers and the length for each one = 10 cm), L = Length of fibers in mm (10 cm), and W = Weight of fibers in mg.

Total fiber percentage: It was calculated from the following formula:

$$\text{Total fiber percentage} = \frac{\text{Fiber yield}}{\text{Straw yield after retting}} x100 \qquad (2)$$

Fiber yield per hectare (Kg): calculated from the fiber yield of the whole plot.

Statistical analysis

Using Michigan State University Computer Statistical Package (MSTAT-C), the analysis of variance was used for the three irrigation experiments according to Snedecor and Cochran (1994) each season. The homogeneity of experimental error for the three irrigation experiments was tested each season, and then the combined analysis of data was performed for these three irrigation experiments (Le Clerg *et al* 1962) to present the main factors and its first and second order interactions each season.

Different Means were compared using (Duncan 1955), when the ANOVA showed significant differences ($P<0.05$) or highly significant differences ($P<0.01$).

RESULTS AND DISCUSSIONS

Physiological characters

Exposing flax plants to various irrigation treatments caused different responses in chlorophyll and proline concentrations as well as antioxidant enzymes activities. Our results showed that application of one irrigation treatment (IT1) (water deficit stress) led to significant reduction in chlorophyll a and b concentrations compared with two and three irrigation treatments in both seasons (Table 3), while there were no significant differences among cultivars.

Table 3. Effect of various irrigation treatments and flax cultivars on chlorophyll and proline concentrations as well as antioxidant enzymes activities in the two seasons.

Factors	Clorophyll A		Clorophyll B		Proline		CAT		POX	
	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17
Irrigation treatments(I) (I)										
IT_1	1.197^b	1.217^c	0.6458^b	0.6650^b	42.40^a	41.13^a	81.91^a	82.29^a	0.7900^a	0.8325^a
IT_2	1.697^a	1.692^a	0.7658^a	0.7600^a	33.60^b	32.93^b	68.14^b	68.46^b	0.6363^b	0.6637^b
IT_3	1.515^a	1.518^b	0.6983^{ab}	0.7208^{ab}	26.11^c	26.67^c	48.22^c	44.88^c	0.4237^c	0.4425^c
Cultivars (C)										
Sakha 3	1.496	1.507	0.713	0.718	34.811	33.82	66.833	66.88^a	0.6267^a	0.6580
Sakha 5	1.456	1.510	0.690	0.712	34.533	34.49	66.617	65.73^a	0.6300^a	0.6320
Giza 11	1.461	1.466	0.688	0.710	33.811	32.84	65.850	65.05^{ab}	0.6017^c	0.6470
Giza 12	1.466	1.421	0.722	0.721	32.989	33.14	65.067	63.17^b	0.6083^b	0.6480
I	**	**	**	**	**	**	**	**	**	**
C	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	*	**	N.S.
I x C	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	*	**	**	**

IT_1= only life irrigation, IT_2= irrigate one irrigation after life irrigation and IT_3= Irrigate two irrigations after life irrigation.

Means designated by the same letter in the same column are not significantly different a according to Duncan's Test.

***, ** and N.S.indicate $P < 0.05$, $P < 0.01$ and not significant, respectively.**

The harmful effect of water deficit (one irrigation treatment) may be due to the decrease in photo-assimilation level of the chloroplasts, chlorophyll degradation and dehydration of protoplasm. These results are in agreement with (Siddiqui *et al* 2015 and Abdelaal *et al* 2017) in faba bean and corn plants. Regarding the effect of one irrigation treatment, the proline concentration and antioxidant enzymes activities (CAT and POX) were significantly increased in both seasons compared with other irrigation treatments. These results may be due to the role of proline and antioxidant enzymes in improving plant growth and reduce oxidative damages under water deficit irrigation. The increment of proline concentration and antioxidant enzymes activities are in accordance with many researchers in various plants (Ekinci *et al* 2015, El Sabagh *et al* 2017 and Helaly *et al* 2017).

Straw yield and its related characters

The analysis of variance for the combined data (among the three irrigation treatments) with regard to plant height, technical stem length, main stem diameter, straw yields per plant and per hectare showed highly significant differences among the three tested irrigation treatments in both seasons, as presented in (Table 4). It was observed that, two irrigations after life irrigation treatment had a positive effect and increased plant height, technical stem length, main stem diameter, straw yields per plant and per hectare and recorded the highest values for these traits followed by one irrigation after life irrigation treatment which ranked the second with insignificant difference with two irrigations after life irrigation treatment for main stem diameter in the second season only. While the lowest values for all above mentioned traits were recorded by only life irrigation treatment. These results may be attributed to the shallow root system of flax plants which demands adequate water in the highest ten centimeters of soil layer (Wood 1997). This poor root development makes flax one of the most crops affected by water stress (Hocking *et al* 1997). From physiological perspective, the reduction in straw yield components under water stress condition occurs due to metabolic regulation of adaptation to water stress as reduction in the synthesis of proteins and inhibition of cell expansion, elongation and division, as a result to decrease in the photochemical activity of photosynthesis, rubisco enzyme activity, the accumulation of secondary metabolites and stomatal conductance (Chavarria and dos Santos 2012). Also, relative water content decline and reduction in dry weight have a direct contribution to reduce biomass and straw yield (Lilian *et al* (2014)). These results are in accordance with those obtained by Gabiana (2005), who reported that, there were significant straw yield responses to irrigation, and the plants under the recommended irrigation treatment gave the highest straw yield as result to producing the highest total dry matter and partitioning biomass in favour of stems. Also, Kariuki *et al* (2016), noted that well irrigated plants significantly produced taller plant height, higher number of tillers and leaves and heavier plant dry weight in comparison to water stressed plants. Further, (Rashwan *et al* 2016), found that, the highest plant height, biological yield and straw yield per faddan were obtained from applying four irrigations during the growth season including sowing and life irrigations.

Table 4. Means of straw yield and its related characters as affected by irrigation treatments, flax cultivars and nano-ZnO treatments in the two seasons

Factors	Plant height (cm)		technical stem length (cm)		Main stem diameter(mm)		Straw yield per plant (g)		Straw yield per hectare (ton)	
	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17
Irrigation treatments (I)										
IT1	83.78 c	79.52c	68.09 c	65.34c	1.481 c	1.376b	0.857 c	0.824c	3.48 c	3.435c
IT2	89.16 b	92.47b	73.27 b	74.68b	1.755 b	1.648 a	1.172 b	1.198 b	6.40 b	6.394 b
IT3	92.09 a	95.34a	77.35 a	80.29a	1.954 a	1.752 a	1.344 a	1.403 a	8.34a	8.336 a
Cultivars (C)										
Sakha 3	96.93a	97.08a	84.56a	84.98 a	1.723 b	1.575 b	1.153 ab	1.174ab	6.20b	5.883 b
Sakha 5	78.57 c	79.14c	61.03d	61.27 d	1.215 c	1.059 c	1.059 c	1.070 c	4.73c	4.492 c
Giza 11	88.86b	89.92b	71.26c	71.91 c	2.034 a	1.939 a	1.090 bc	1.110bc	6.60ab	7.008 a
Giza 12	89.03b	90.30b	74.76b	75.59 b	1.948 a	1.796 a	1.196 a	1.211a	6.78a	6.837 a
Nano-ZnO treatments (N)										
Control	85.82c	86.27c	71.13c	71.61c	1.557 c	1.415c	0.999 c	1.013 c	5.88c	5.852 c
Nano-ZnO1	89.08b	89.85b	73.34b	73.87b	1.734 b	1.597 b	1.114 b	1.131 b	6.08b	6.064 b
Nano-ZnO2	90.13a	91.21a	74.23a	74.82a	1.899 a	1.764 a	1.261 a	1.281 a	6.27a	6.248 a
I	**	**	**	**	**	**	**	**	**	**
C	**	**	**	**	**	**	**	**	**	**
N	**	**	**	**	**	**	**	**	**	**
I x C	**	**	**	**	N.S.	N.S.	**	**	**	**
I x N	N.S.	N.S.	**	**	N.S.	N.S.	*	**	N.S.	N.S.
C x N	**	**	*	*	**	**	**	**	**	**
I x C x N	N.S.	N.S.	**	**	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

IT_1= only life irrigation, IT_2= irrigate one irrigation after life irrigation and IT_3= Irrigate two irrigations after life irrigation.

Means designated by the same letter in the same column are not significantly different a according to Duncan's Test.

***, ** and N.S.indicate $P < 0.05$, $P < 0.01$ and not significant, respectively.**

Concerning to differences among the four tested flax cultivars (Sakha 3, Sakha 5, Giza 11 and Giza 12), the analysis of variance showed highly significant differences among these cultivars in both seasons as shown in Table (4). The results cleared that, Sakha 3 (fiber type) was the best and recorded the tallest plant height and technical stem length, followed by Giza 12 then Giza 11 (dual purpose types). On the other hand, Giza 11 and Giza 12 ranked the first and recorded the highest values of main stem diameter and straw yield per hectare with insignificant differences between them. Also, Giza 12 ranked the first with insignificant differences with

Sakha 3 for straw yield per plant. However, Sakha 5 (oil type) recorded the lowest values for all straw yield and its related characters. These results are mainly due to differences in the genetical factors of the four tested cultivars and potentiality among the fiber, oil and dual-purpose types of flax. These results are in accordance with those obtained by Leilah *et al* 2010, El-Refaey *et al* (2015), Rashwan *et al* (2016) and El-Refaey *et al* (2017) where they noted that, fiber types cvs. were highly significantly out yielded dual-purpose and oil types in plant height and technical length. Whereas, dual purpose types were superior in main stem diameter, straw yields per plant and per faddan.

Comparison of means for nano-zinc oxide treatments (Table 4) showed that, foliar application of zinc-oxide NPs led to highly significant effect on all straw yield characters compared to control plants, and application of the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the highest values, followed by the lowest concentration (50 mg/ Litre). On the other hand, control treatment recorded the lowest values. This may be due to the role of zinc in the cell division, cell enlargement and synthesis of protein, regulation the membrane function, protection of membranes from oxidative injury by detoxification of reactive oxygen species and providing resistance to environmental stress in crop plants (Tahir *et al* 2014). In addition, zinc is an essential element for plants, it increases photosynthesis rate, plant metabolism and plays an important role in the production of biomass (Cakmak 2008). Furthermore, zinc may be required for the activity of enzymes that are involved in chlorophyll biosynthesis, pollen function and fertilization (Pandey *et al* 2010 and Mohsenzadeh and Moosavian 2017). From nanoscience perspective, using zinc-oxide NPs performs better due to its wider specific surface area compared to other forms which leads to better contact between zinc-oxide and plant surface, consequently absorbed more efficiently and increases plant growth (Taheri *et al* 2015). These results are in accordance with those obtained by (Raliya *et al* 2015) where they noted that ZnO nanoparticles promoted the highest plant height and biomass. Also, it enhances physiological and biochemical response due to its dual role as an essential nutrient and a cofactor in increasing activity of phosphorous mobilizing enzymes such as phosphatase and phytase.

In both seasons, the interaction between irrigation treatments and flax cultivars had highly significant effect on plant height, technical stem length, straw yields per plant and per hectare (Fig.1). Under the irrigation treatment (two irrigations after life irrigation), Sakha 3 cultivar recorded the tallest plant height and technical stem length. However, Giza 12 and Giza 11 cultivars recorded the highest straw yield per plant and per hectare, respectively.

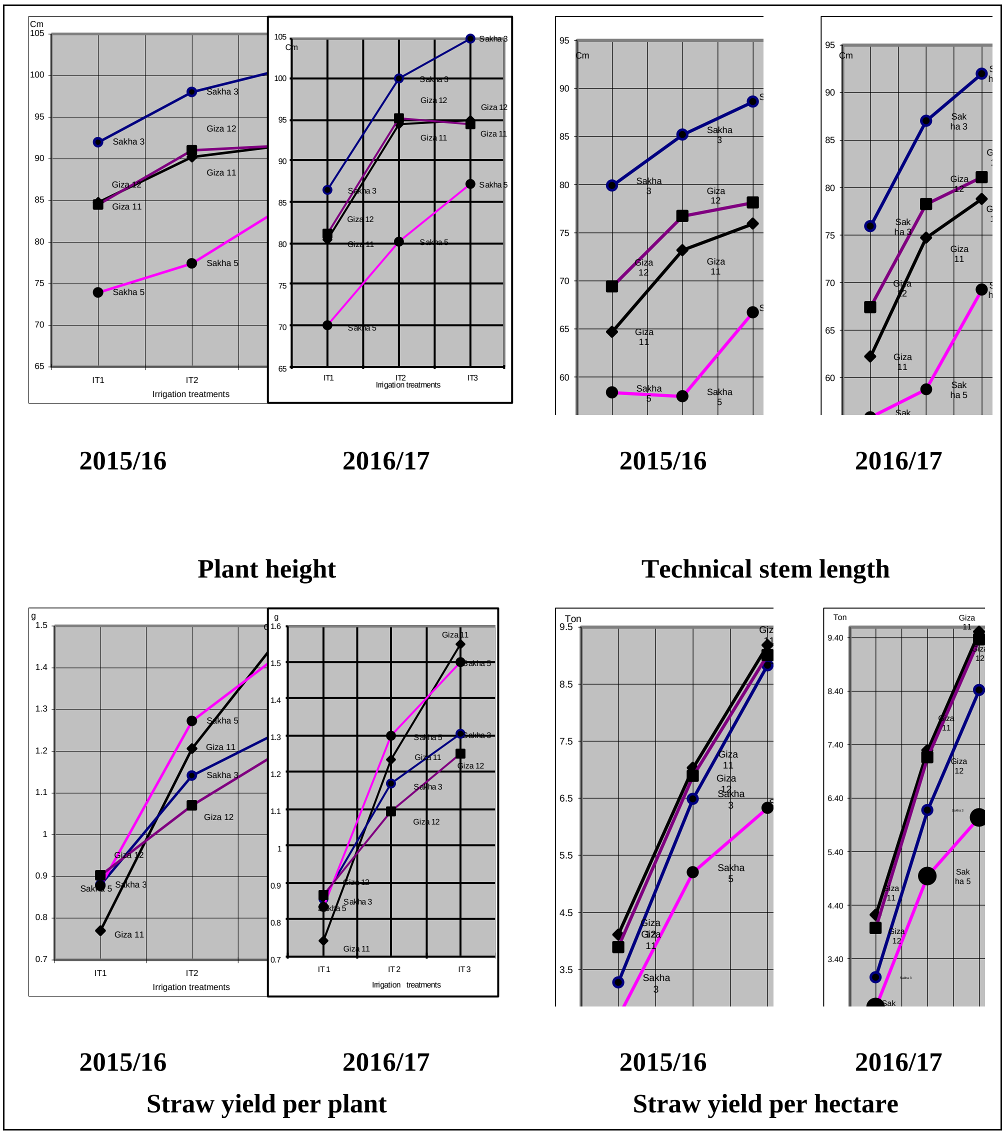
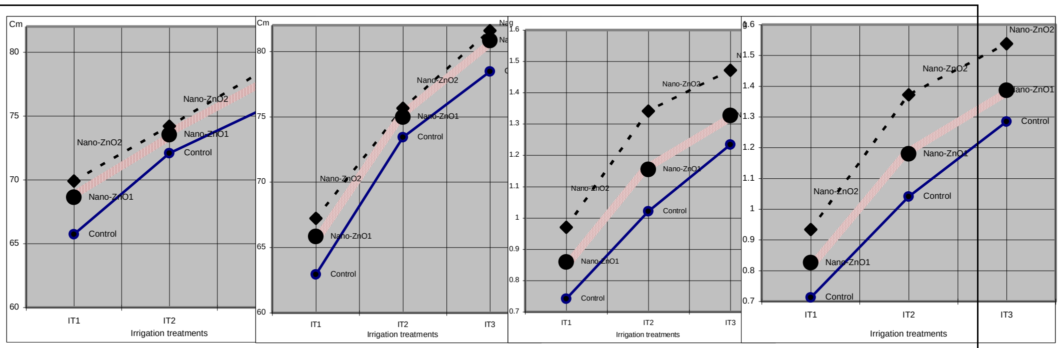


Fig. 1. Interaction between irrigation treatments and flax cultivars on plant height, technical stem length, straw yield per plant and per hectare

The interaction between irrigation treatments and nano-zno treatments had highly significant effect on technical stem length and straw yield per plant (Fig. 2). Nevertheless, application of the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the highest values of these traits under two irrigations after life irrigation treatment in both seasons.



2015/16 **2016/17** **2015/16** **2016/17**

Technical stem length **Straw yield per plant**

Fig. 2. Interaction between irrigation treatments and nano-zno treatments on technical stem length and straw yield per plant.

The interaction between flax cultivars and nano-zno treatments had highly significant effect for all straw yield and its related traits except technical stem length, where it was only significant in both seasons (Fig. 3). Application of the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the highest plant height and technical stem length under Sakha 3. Also, this application recorded the highest values of main stem diameter in both seasons and straw yield per hectare only in the first one under Giza 11, while it recorded the highest straw yield per plant in both seasons and straw yield per hectare only in the second one

The effect of the second order interaction (irrigation treatments x cultivars x nano-zno treatments) was highly significant only for technical stem length, (Fig. 4), where the application of the highest concentration of zinc-oxide NPs (100 mg/Litre) on Sakha 3 cultivar under two irrigations after life irrigation treatment recorded the tallest technical stem length, in both seasons.

The analysis of variance for the combined data (among the three irrigation treatments) with regard to number of capsules per plant, seed yield per hectare, oil percentage and oil yield per hectare showed highly significant differences among the three tested irrigation treatments for all traits except oil percentage trait, where there were no significant differences in both seasons (Table 5).

Treatment of two irrigations after life irrigation achieved the highest values for number of capsules per plant, seed yield per hectare and oil yield per hectare traits. In addition, treatment of one irrigation after life irrigation ranked the second, while treatment of only life irrigation recorded the lowest values and ranked the last for these traits.

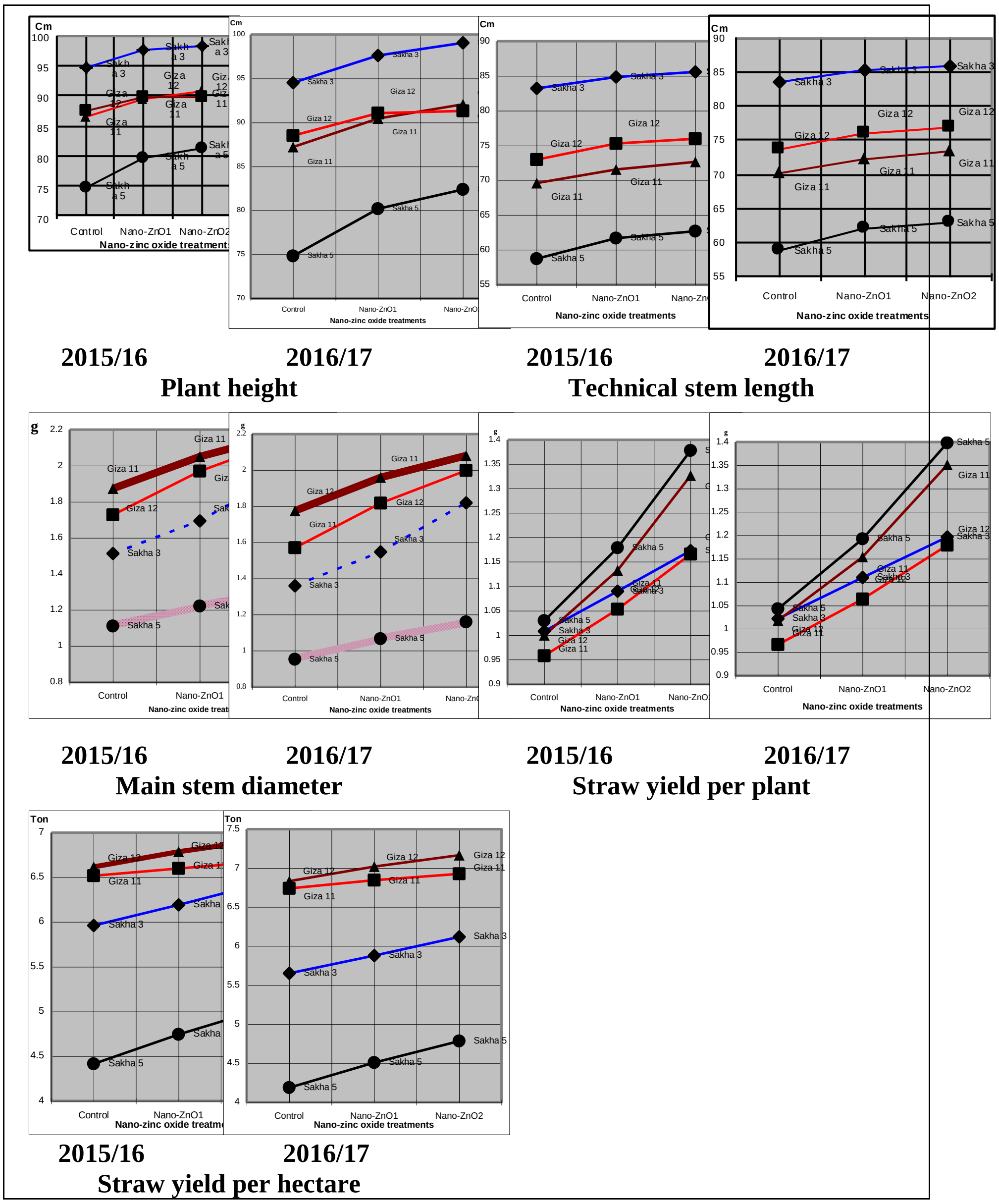


Fig. 3. Interaction between flax cultivars and nano-zno treatments on plant height, technical stem length, main stem diameter, straw yield per plant and per hectare

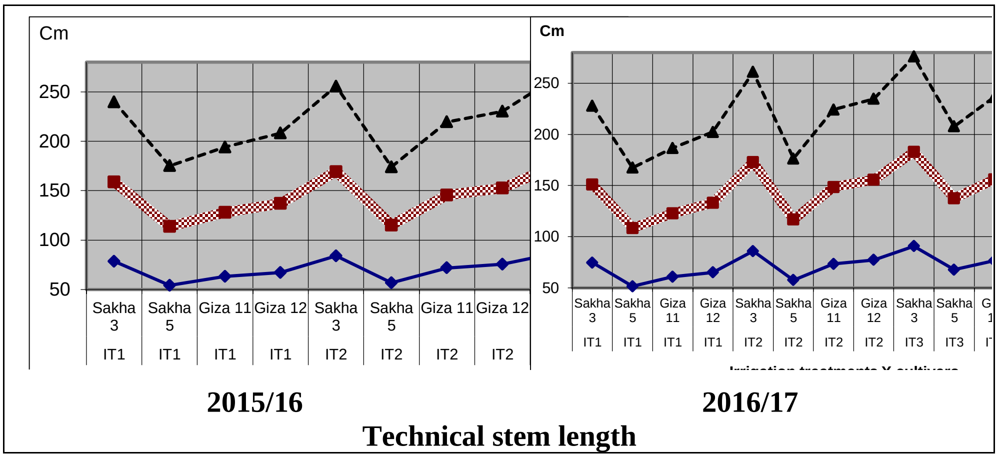


Fig. 4. Interaction among irrigation treatments, flax cultivars and nano-zno treatments on technical stem length.

Seed yield and its related characters

With reference to oil percentage trait, there was a noticeable changeThis significant reduction with decreasing irrigations might be due to abortion of some flowers and reduction in the probability of developing flower to capsule as a result of the relationship between water stress and different physiological processes occurring in plant (Leilah *et al* 2010). On the other hand, irrigate two irrigations after life irrigation provided adequate moisture during critical physiological stages (initiation of flowering and seed filling) which increases photosynthesis responsible for carbohydrate formation, seed filling and final seed yield (Rashwan *et al* 2016).

Where there was no significant difference among the three tested irrigation treatments, which may be due to the genetic factors that have the main effect on this trait. These results are in agreement with those obtained by Baud and Lepiniec (2010). They reported that oil content is mainly controlled by genotype and genotype × environment interactions.

Mean values for number of capsules per plant, seed yield per hectare, oil percentage and oil yield per hectare with respect to the studied flax cultivars during 2015/16 and 2016/17 seasons are listed in Table (5). In both seasons, the analysis of variance for seed yield and its related characters showed highly significant differences among flax cultivars. In that respect, Sakha 5 recorded the highest values for all previous mentioned traits, followed by Giza 11 cv., then Giza 12 cv. which ranked the third without a significant difference with Sakha 3 for only seed yield per hectare. However, the lowest values were noticed by Sakha 3 cultivar in both seasons.

The trend of data was so clear and similar to expectations as it is known that, the oil types are superior in seed yield and its related characters compared with fiber types, while dual purpose types came in the intermediate.

The highest means of seed yield and its related characters for Sakha 5 as an oil type are attributed to the genetic constitution of this cultivar. Similar findings were reported by Rashwan (2013), who noted that, Line 22 (Sakha 5 cultivar before certifying) recorded the highest values of number of fruiting branches per plant, number of capsules per plant, number of seeds per capsule, fertility percentage, seed yield per hectare, oil percentage and oil yield per hectare. On the other hand, Sakha 3 recorded the lowest values of these traits. Moreover, El-Seidy *et al* (2010 and 2015), Rashwan *et al* (2016) and El-Refaey *et al* (2017) pointed out that, oil types produced the maximum values of seed yield and its related characters, followed by dual purpose types, while the lowest values were recorded by fiber types.

The foliar application of zinc- oxide NPs positively affected seed yield characters (Table 5), application of the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the highest values of seed characters with highly significant variations under the lowest concentration (50 mg/ Litre) which ranked the second, whereas the control treatment recorded the lowest seed characters values. These results are in harmony with those obtained by (Bakry *et al* 2012, Omidian *et al* 2012 and Tahir *et al* 2014) where they found that Zinc foliar application increased number of capsules per plant, seed yield per faddan, protein and oil biosynthesis in seeds, oil percentage and oil yield per faddan. Also, (Raliya *et al* 2015) reported that zinc-oxide NPs increased number of flowers and fruits yield in tomato, and the fruits were also relatively bigger and heavier.

The interaction between irrigation treatments and flax cultivars had highly significant effect on number of capsules per plant in both seasons, seed yield per hectare and oil yield per hectare in the second season only, while it was only significant in the first one for oil percentage and oil yield per hectare (Fig. 5). However, Sakha 5 under two irrigations after life irrigation treatment recorded the highest values for these traits.

The interaction between irrigation treatments and nano-zno treatments had highly significant effect on seed yield per hectare (Fig. 6). However, application of the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the highest values of these traits under two irrigations after life irrigation treatment in both seasons.

The interaction between flax cultivars and nano-zno treatments had highly significant effect on number of capsules per plant in the second season and oil yield per hectare in the first one. On the other hand, it was only significant for these traits in the other season (Fig. 7). Application of the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the highest values under Sakha 5 cultivar.

Table 5. Means of seed yield and its related characters as affected by irrigation treatments, flax cultivars and nano-ZnO treatments in the two seasons:

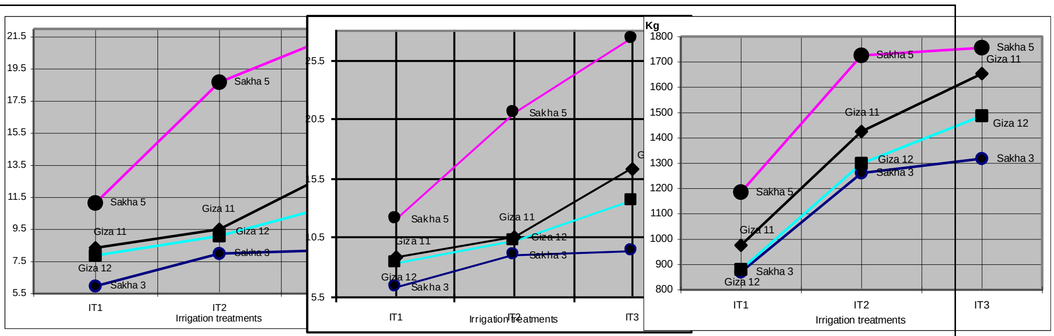
Factors	No. of capsules per plant		Seed yield perhectare(Ton)		Oil percentage (%)		Oil yield per hectare (Kg)	
	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17
Irrigation treatments (I)								
IT1	8.333 c	8.922 c	1.002 c	0.9773 c	33.27	32.686	334.05 c	326.4 c
IT2	11.32 b	12.69 b	1.353 b	1.435 b	33.49	32.678	453.10 b	477.8 b
IT3	13.65 a	16.70 a	1.514 a	1.554 a	33.05	32.775	500.24 a	517.8 a
Cultivars (C)								
Sakha 3	7.400 d	8.222 d	1.180 c	1.160 d	28.8 d	26.63 d	339.84 d	310.2 d
Sakha 5	17.21 a	20.19 a	1.472 a	1.555 a	38.51 a	40.59 a	566.87 a	631.5 a
Giza 11	10.42 b	11.91 b	1.317 b	1.351 b	33.75 b	34.18 b	444.49 b	461.8 b
Giza 12	9.374 c	10.76 c	1.189 c	1.222 c	31.99 c	29.46 c	380.36 c	359.2 c
Nano-ZnO treatments (N)								
Control	10.07 c	11.49 c	1.258 c	1.284 c	32.25 c	31.66 c	405.8 c	414 c
Nano-ZnO1	11.18 b	12.94 b	1.293 b	1.327 b	33.40 b	32.85 b	431.86 b	444 b
Nano-ZnO2	12.06 a	13.88 a	1.318 a	1.355 a	34.16 a	33.63 a	450.26 a	464.1 a
I	**	**	**	**	N.S.	N.S.	**	**
C	**	**	**	**	**	**	**	**
N	**	**	**	**	**	**	**	**
I x C	**	**	N.S.	**	N.S.	N.S.	*	**
I x N	N.S.	N.S.	**	**	N.S.	N.S.	N.S.	N.S.
C x N	*	**	N.S.	N.S.	N.S.	N.S.	**	*
I x C x N	**	*	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

IT_1= only life irrigation, IT_2= irrigate one irrigation after life irrigation and IT_3= Irrigate two irrigations after life irrigation.

Means designated by the same letter in the same column are not significantly different a according to Duncan's Test.

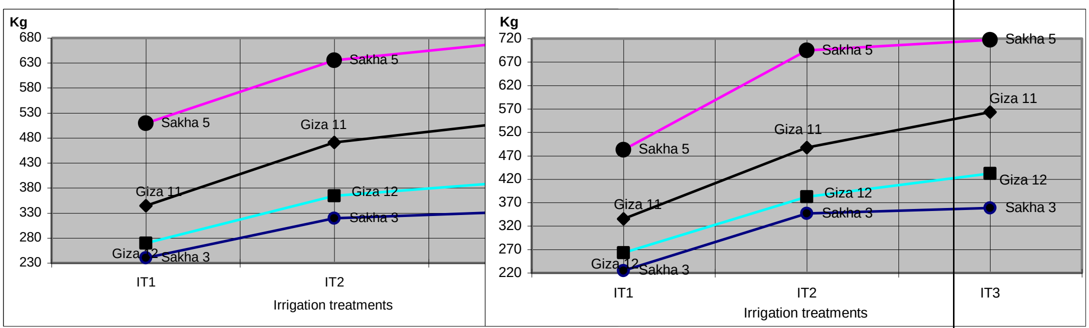
***, ** and N.S.indicate $P < 0.05$, $P < 0.01$ and not significant, respectively.**

The effect of the second order interaction (irrigation treatments x cultivars x nano-zno treatments) was highly significant for number of capsules per plant in the first season and only significant in the second one, (Fig. 8), where the application of the highest concentration of zinc-oxide NPs (100 mg/Litre) on Sakha 5 cultivar under two irrigations after life irrigation treatment recorded the highest number of capsules per plant, in both seasons.



2015/16 2016/17 2016/17

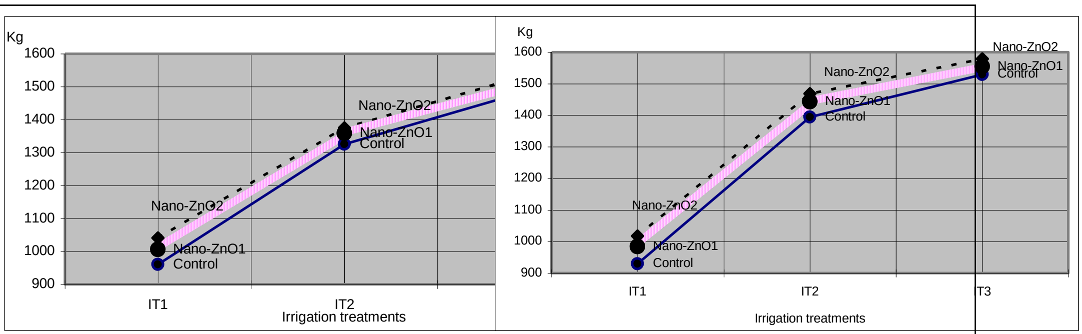
No. of capsules per plant Seed yield per hectare



2015/16 2016/17

Oil yield per hectare

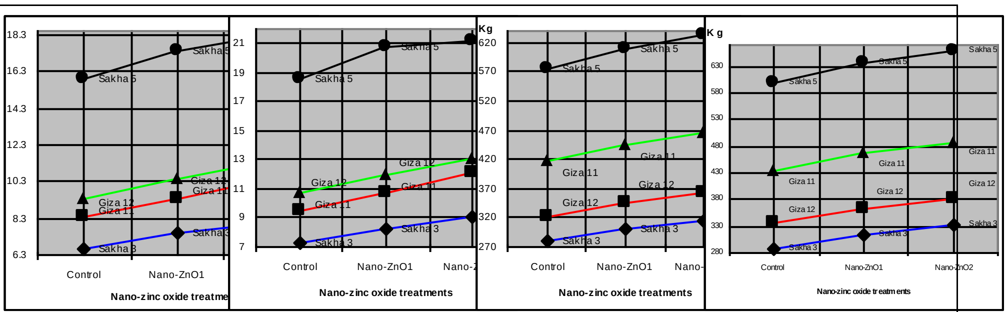
Fig. 5. Interaction between irrigation treatments and flax cultivars on No. of capsules per plant, seed yield per hectare and oil yield per hectare.



2015/16 2016/17

Seed yield per hectare

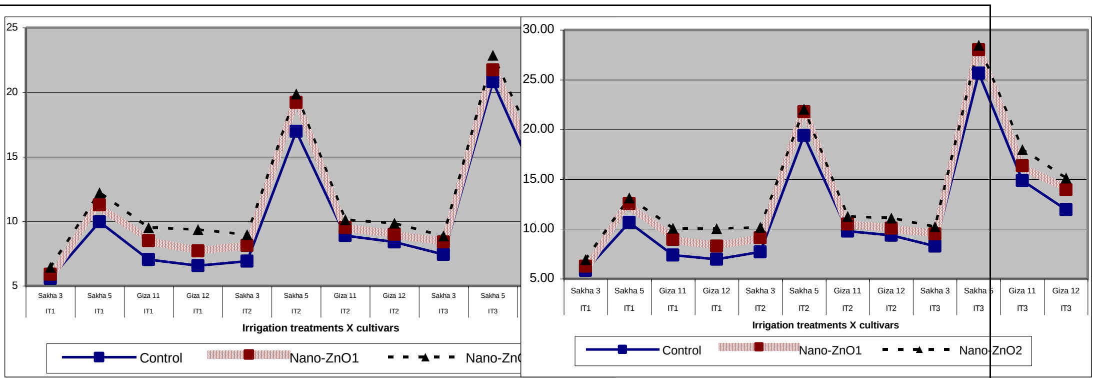
Fig. 6. Interaction between irrigation and nano-zno treatments on seed yield per hectare.



2015/16 2016/17 2015/16 2016/17

No. of capsules per plant Oil yield per hectare

Fig. 7. Interaction between flax cultivars and nano-zno treatments on No. of capsules per plant and oil yield per hectare.



2015/16 2016/17

No. of capsules per plant

Fig. 8. Interaction among irrigation treatments, flax cultivars and nano-zno treatments on No. of capsules per plant.

Fiber yield and its technological characters

The analysis of variance for the combined data (among the three irrigation treatments) with regard to fiber length, fiber fineness, total fiber percentage and fiber yield per hectare showed highly significant differences among the three tested irrigation treatments for all traits. The trend of data for these traits in regard to irrigation treatments was not unified as presented in Table 6. In both seasons, the tallest fiber length, the most coarseness fiber and the highest fiber yield per hectare were observed under irrigation treatment (two irrigations after life irrigation), whereas the highest total fiber percentage was recorded by irrigation treatment (one irrigation after life irrigation). On the other hand, irrigation treatment (only life irrigation) gave the shortest fiber length, the finest fiber and the lowest values of fiber percentage and fiber yield per hectare, in both seasons. It is clear that, flax plants that grew under limited water conditions produced less fiber yield compared to plants under adequate water conditions that may be due to the positive effect of adequate water on increasing plant height, technical stem length and straw yields per plant and per hectare, which define fiber biomass and consequently fiber yield. These findings are in the same line with those found by Gabiana (2005) who obtained only one third of fiber yield per plant under rainfed cultivation compared to irrigated cultivation. Also, Bauer *et al* (2015) found a significant increment in fiber yield in irrigated plants compared to rainfed plants. Moreover, Rashwan *et al* (2016) reported that, four irrigations during flax growing season including sowing and life irrigations recorded the tallest fiber length, the highest total fiber percentage and the highest fiber yield per faddan.

Statistical analysis showed highly significant differences for fiber length, fiber fineness, fiber percentage and fiber yield per hectare among the four flax cultivars. Data presented in Table (6) show the previous mentioned traits values for the tested cultivars during the both seasons. Results indicated that Sakha 3 cv. gave the tallest fiber length, the finest fiber, the highest total fiber percentage and fiber yield per hectare in both seasons, followed by Giza 12 which ranked in the second grade in these traits with insignificant differences with Giza 11 for fiber length and with Sakha 5 for fiber fineness. On the other hand, the shortest fiber length, the lowest total fiber percentage and fiber yield per hectare were obtained by Sakha 5 in both seasons, while the most coarseness fiber was obtained by Giza 11 in both seasons. Worthy to note that, the trend of fiber traits was similar to that of plant height and technical stem length, and although Giza 12 produced the highest straw yield per plant and per hectare, it ranked the second in fiber traits.

Table 6. Means of fiber yield and its technological characters as affected by irrigation treatments, flax cultivars and nano-ZnO treatments in the two seasons

Factors	Fiber length (cm)		Fiber fineness (N.m)		total fiber percentage(%)		Fiber yield per hectare (Kg)	
	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17
Irrigation treatments (I)								
IT1	55.87c	53.93 c	244.1 a	282.1 a	13.84 c	14.45 c	390 c	391.7 c
IT2	62.37 b	66.04 b	236.4 b	269.8 b	15.13 a	15.84 a	782.09 b	796.6 b
IT3	66.84 a	68.64 a	225.6 c	258.2 c	14.35 b	15.17 b	978.98 a	997.2 a
Cultivars (C)								
Sakha 3	75.74 a	76.28 a	256.9 a	295.2 a	17.37 a	18.13 a	899.21 a	880.7 a
Sakha 5	49.58 c	50.32 d	230.1 b	264.4 b	10.71 d	11.40 d	381.61 d	374.0 c
Giza 11	60.71 b	61.66 c	221.7 c	254.0 c	14.31 c	15.01 c	768.26 c	802.4 b
Giza 12	60.74 b	63.22 b	233.0 b	266.5 b	15.37 b	16.08 b	819.02 b	857.1 a
Nano-ZnO treatments (N)								
Control	60.21 c	60.30 c	239.4 a	274.4 a	14.31 c	15.05 b	688.69 c	698.7 c
Nano-ZnO1	62.00 b	62.72 b	235.3 b	270.0 b	14.44 b	15.16 ab	717.40 b	729.3 b
Nano-ZnO2	62.87 a	65.58 a	231.5 c	265.4 c	14.57 a	15.25 a	745.02 a	757.6 a
I	**	**	**	**	**	**	**	**
C	**	**	**	**	**	**	**	**
N	**	**	**	**	**	**	**	**
I x C	**	**	N.S.	N.S.	N.S.	*	**	**
I x N	**	**	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
C x N	*	**	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
I x C x N	**	**	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

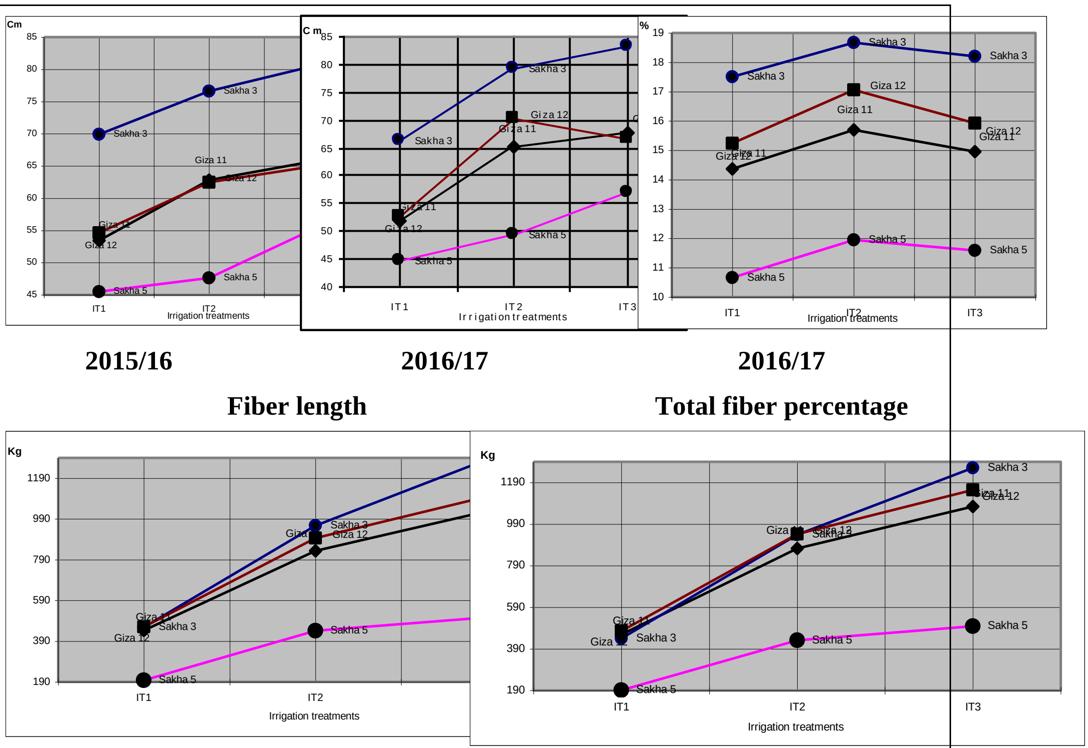
IT_1= only life irrigation, IT_2= irrigate one irrigation after life irrigation and IT_3= Irrigate two irrigations after life irrigation.
Means designated by the same letter in the same column are not significantly different a according to Duncan's Test.
***, ** and N.S.indicate $P < 0.05$, $P < 0.01$ and not significant, respectively.**

These results may be due to the loss variations in straw yield per hectare after retting among the different types of flax, whereas the loss for dual-purpose (Giza 11 and Giza12) was higher than the other fiber type Sakha 3, and consequently fiber percentage was proportionally with the loss in straw yield after retting (Rashwan *et al* 2016). These results are in harmony with those obtained by El-Refaey *et al* (2010 and 2013), who reported that, fiber types-generally- exceeded dual and oil types in fiber length, fiber fineness, fiber percentage and fiber yield per hectare due to genetic potential. Also, Bauer *et al* (2015) mentioned that, the fiber-type cultivars had higher fiber content in later harvests compared with seed type cultivars.

The obtained results in Table (6) cleared that fiber length, fiber fineness, fiber percentage and fiber yield per hectare were highly significantly affected by foliar application of zinc-oxide NPs in both seasons. As expected, a highly significant increment in fiber length, total fiber percentage and fiber yield per hectare was observed as a result for increasing plant height, technical stem length, stem diameter and straw yield per hectare by the foliar application of Zno NPs, the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the highest values of these traits, followed by the lowest concentration (50 mg/Litre), and finally the control treatment recorded the lowest values. This may be due to the role of zinc in promoting the cell division, cell enlargement and fundamental metabolic reaction and acceleration protein synthesis which affects fiber properties. (Abdel Shafy *et al* 2001 and Nofal *et al* 2011).

A contradictory trend was observed concerning to fiber fineness, the foliar application of the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the coarsest fiber, while the control treatment recorded the finest fiber, it supports the fact that there is a negative relationship between the main stem diameter and the fiber fineness (El-Refaey *et al* 2010 and 2013). This may be due to zinc element presence which increases lignin content in some plants because of its effect on activating lignin biosynthesis genes (Liu *et al* 2018). In addition, there is a negative relationship between fiber fineness and lignin content (Meshram and Palit 2012).

Highly significant interactions between irrigation treatments and flax cultivars were observed in (Fig. 9) for fiber length and fiber yield per hectare traits, in both seasons. However, Sakha 3 under two irrigations after life irrigation treatment recorded the tallest fiber and the highest fiber yield per hectare. Also, these interactions were only significant for total fiber percentage in the second season; however, Sakha 3 under one irrigation after life irrigation treatment recorded the highest fiber percentage. Besides, the interaction between irrigation treatments and nano-zno treatments had highly significant effect on fiber length (Fig. 10). However, application of the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the tallest fiber length under two irrigations after life irrigation treatment in the both seasons with insignificant difference with one irrigation after life irrigation treatment in the second season only. The interaction between flax cultivars and nano-zno treatments had only significant effect on fiber length in the first season while it was highly significant in the second one (Fig. 11). Application of the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the tallest fiber under Sakha 3 cultivar, in both seasons.



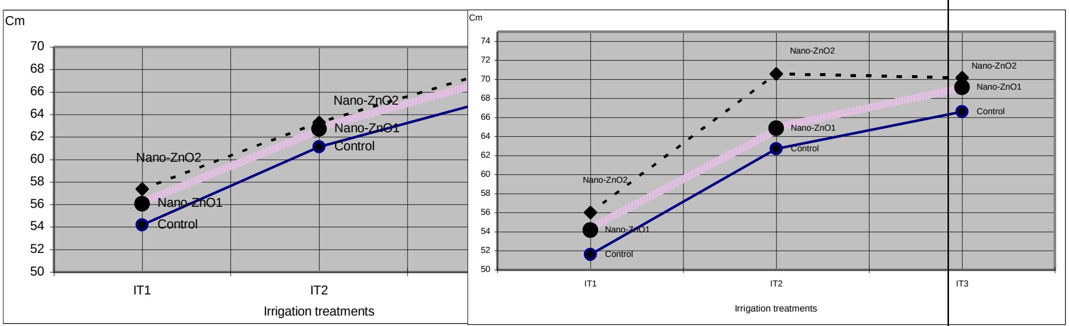
2015/16 2016/17 2016/17

Fiber length Total fiber percentage

2015/16 2016/17

Fiber yield per hectare

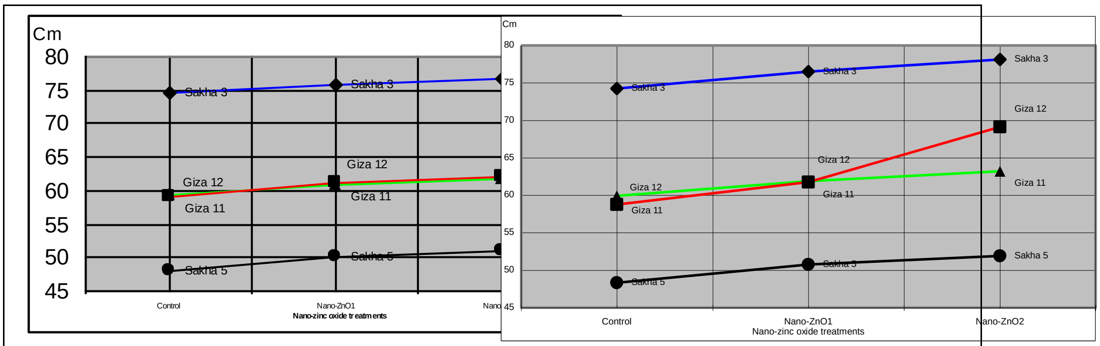
Fig. 9. Interaction between irrigation treatments and flax cultivars on fiber length, total fiber percentage and fiber yield per hectare.



2015/16 2016/17

Fiber length

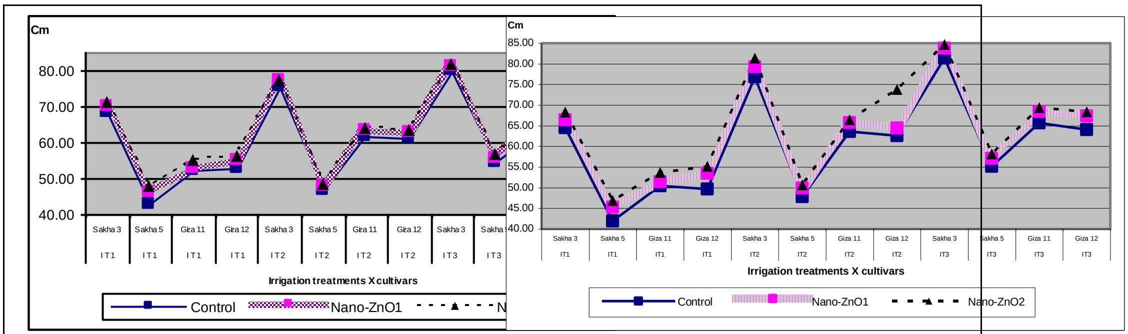
Fig. 10. Interaction between irrigation treatments and nano-zno treatments on fiber length.



2015/16 **2016/17**

Fiber length

Fig. 11. Interaction between flax cultivars and nano-zno treatments on fiber length.



2015/16 **2016/17**

Fiber length

Fig. 12. Interaction among irrigation treatments, flax cultivars and nano-zno treatments on fiber length.

The effect of the second order interaction (irrigation treatments x flax cultivars x nano-zno treatments) was highly significant for fiber length, (Fig. 12), where the application of the highest concentration of zinc-oxide NPs (100 mg/Litre) on Sakha 3 cv. under two irrigations after life irrigation treatment recorded the highest values of fiber length, in both seasons.

CONCLUSION

From this study, it can be concluded that, flax plants exposed to water deficit stress during any of growth stages affect significantly physiological and yield traits. Also, irrigation treatment of two irrigations after life irrigation achieved the best traits under this study. Under one irrigation treatment chlorophyll concentrations were decreased, however, proline and enzymes activity were increased. Among the cultivars, Sakha 3 cultivar was superior in plant height, technical stem length, fiber length, fiber fineness, total fiber percentage and fiber yield per hectare traits. Meanwhile, Giza 11 and Giza 12 cultivars highly significantly surpassed the other cultivars in main stem diameter and straw yield per hectare. On the other hand, Sakha 5 recorded the highest values of number of capsules per plant, seed, oil yields per hectare and oil percentage. Foliar application of Zno-NPs had a high significant effect on all yield traits compared to control treatment; the highest concentration of zinc-oxide NPs (100 mg/Litre) recorded the highest values of all these traits. Although this actual increment due to increase of the applied ZnO-NPs from 50 to 100 ppm, it isn't recommended to apply higher concentrations to avoid negative impact of these nanoparticles. Thus, it is necessary to explore ZnO-NPs toxicity and behavior in water, living organisms (biota) and soil individually, and their toxicity in combination. Also, there is an urgent need to assess the environmental hazard that occurs with the application of ZnO-NPs in the soil to can determine the permitted levels of usage for these nanoparticles accurately.

ACKNOWLEDMENT

The authors would like to thank all members of PPB Lab. and EPCRS Excellence Centre (Accredited according to ISO/17025, 9001, 14001 and OHSAS/18001) Department of Agricultural Botany, Faculty of Agriculture, Kafrelsheikh University, Kafr-Elsheikh, Egypt.

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تأثير الرش الورقي بنانو أكسيد الزنك على بعض أصناف الكتان تحت معاملات ري مختلفة.

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أقيمت تجربتان حقليتان بحقل ارشاد زراعي بمدينة المحلة الكبرى– محافظة الغربية– مصر، وذلك خلال الموسمين الشتويين ٢٠١٥/٢٠١٦ و ٢٠١٦/٢٠١٧ بهدف دراسة تأثير الرش الورقي بتركيزات مختلفة من جزيئات أكسيد الزنك النانوية (معاملة الكونترول وتشمل الرش بماء مقطر فقط ، الرش بتركيز ٥٠ جزء في المليون ، الرش بتركيز ١٠٠ جزء في المليون) على بعض الصفات الفسيولوجية ومكونات المحصول وكذلك صفات الجودة لأربعة أصناف من الكتان (سخا ٣ ، سخا ٥ ، جيزه ١١، جيزة ١٢) وذلك تحت ثلاث معاملات ري مختلفة (رية المحاياه فقط ، ريه واحدة بعد رية المحاياه، ريتين بعد ريه المحاياه). تم تطبيق معاملات الري المختلفة من خلال ثلاث تجارب ري منفصلة كل موسم ، وقد نفذت كل تجربة ري بتصميم القطع المنشقة مرة واحدة في ثلاث مكررات ، حيث وزعت الأصناف عشوائياً في القطع الرئيسية ، بينما وزعت تركيزات الرش الورقي بجزيئات أكسيد الزنك النانوية في القطع الشقية. وتتلخص أهم النتائج المتحصل عليها فيما يلي: تفوقت معاملة الري (ريتين بعد ريه المحاياه) وأعطت اعلى القيم بالنسبة لجميع صفات القش (طول النبات، الطول الفعال، قطر الساق الرئيسي، محصولي القش للنبات وللهكتار) وكذلك صفات عدد الكبسولات للنبات، محصولي البذور و الزيت للهكتار، طول الألياف ومحصول الألياف للهكتار. في حين سجلت معاملة الري (ريه واحدة بعد ريه المحاياه) اعلى نسبة مئوية للألياف الكلية.في المقابل تم الحصول على أعلى نعومة للألياف تحت معاملة الري (رية المحاياه فقط) بينما لم تكن الفروق معنوية بين معاملات الري الثلاثة بالنسبة لصفة النسبة المئوية للزيت بالبذور. سجل الصنف سخا ٣ أعلى القيم لصفات طول النبات الكلي، الطول الفعال، طول الألياف، نعومة الألياف، النسبة المئوية للألياف الكلية ، محصول الألياف للهكتار، بينما سجل الصنفين جيزة ١١ وجيزة ١٢ أعلى القيم لصفات سمك الساق الرئيسي ومحصول القش للهكتار. في المقابل، سجل الصنف سخا ٥ أعلى القيم لصفات عدد الكبسولات للنبات، النسبة المئوية للزيت بالبذور، محصولي البذور والزيت للهكتار. وأدت معاملة الرى لمرة واحدة (رية المحاياه فقط) إلى نقص معنوي في تركيز الكلورفيل بينما زاد تركيز البرولين ونشاط الانزيمات المضادة للأكسدة فى موسمى الدراسة. وقد أدى الرش الورقي بجزيئات أكسيد الزنك النانوية الى زيادة معنوية لجميع صفات القش والبذرة والألياف فيما عدا صفة نعومة الألياف وقد ادي الرش بالتركيز الأعلى (١٠٠ جزء في المليون) الى تسجيل اعلى القيم لتلك الصفات.

المجلة المصرية لتربية النبات ٢٣(١) : ١١٩ - ١٤٥ (٢٠١٩)