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The Role of Nano-Titanium and Nano-Curcumin in the Production of Biofuel from Sunflower Plants (*Helianthus annuus* L.) Exposed to Water Stress

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Abstract

The sunflower (*Helianthus annuus* L.) is one of the economically important crops that can be used for biofuel production, which aids in protecting the environment against the negative effects of fossil fuels. There is an increasing need for employing modern materials and technologies such as nanotechnology as the Iraqi environment is subjected to more heat waves and desertification. One of these modern materials is nano-titanium, which is distinguished by its small particle size and high efficiency for agricultural applications. Natural extracts such as curcumin are used due to their curcumin content, a phenolic compound that allows plants to endure periods of drought and limited water availability. To that end, a field experiment was executed in the Botanical Garden of the Department of Biology, College of Education for Pure Sciences (Ibn Al-Haitham), University of Baghdad, during the growing season of 2024-2025. This research study was aimed at examining the impact of spraying with nano-titanium at concentrations (0, 50, 100 $mg.L^{-1}$) and nano-curcumin at concentrations (0, 25, 75 $mg.L^{-1}$) on sunflower plants that were subjected to water stress by using different irrigation intervals (5, 10, and 15 days), including a control treatment. The findings indicated a significant impact on plant height, number of leaves, the water content, total chlorophyll concentration, vitamin E level, and the percentage of seed oil. Furthermore, the interactions among treatments were significantly effective with respect to most of the studied traits.

Keywords: Titanium, Curcumin, Nanoparticles, Biodiesel, *Helinthus annuns* L., Water stress**.**

1. Introduction

Sunflower (*Helianthus annuus* L.) is one of the most important oilseed crops in the family Asteraceae (Compositae)[1]. There are many cultivars, some of which are grown to provide seeds that are high in antioxidants and nutritional content, such as vitamin E, while others are grown for seeds that supply high oil[2]. Traditionally, the oil from sunflower seeds has been used in the treatment of various diseases and inflammatory processes[3]. Recently, sunflower oil has emerged as an important source for biofuel production[4]. For all the above reasons, sunflower is a common crop grown in Iraq, with a high nutritional and economic importance, second only to soybean in the local and global markets[5]. It is very adaptable and can grow well under a wide range of environmental conditions and be grown in spring and autumn[6]. Water stress or drought stress arises from environmental changes such as reduced water availability and low precipitation and is regarded as one of the main indicators of desertification. It represents both a global and regional challenge and is commonly classified into three levels: mild, moderate, and severe stress[7]. Water stress exerts harmful effects on plants by decreasing their water content, inducing stomatal closure, inhibiting growth, reducing photosynthetic efficiency, and disrupting metabolic balance, which may ultimately lead to plant death[8]. Consequently, plants activate various defense mechanisms to mitigate these adverse effects, including drought-escape strategies through accelerated growth to minimize water loss[9], as well as the activation of enzymatic and non-enzymatic antioxidant systems[10]. These systems counteract the accumulation of reactive oxygen species (ROS), which cause oxidative damage to lipids, nucleic acids, and proteins, leading to complex and potentially lethal cellular alterations[11].

Nanotechnology is an emerging area where the fundamental structural unit a nanometer has a value of one billionth of a meter[12]. Due to certain unique physical and chemical properties, nanoparticles behave very differently than bulk materials; hence, nanoparticles have been used by researchers in many areas including medicine and agriculture. Nanoparticles are used, in part, due to their ability to elicit morphological and physiological changes in plants and because they are so small they have a high surface area allowing for greater plant-tissue interaction[13].

Titanium dioxide (TiO_2) is found in nature in some crystalline forms, while most TiO_2 is found in the mineral ilmenite ($FeTiO_3$) found in igneous and metamorphic rocks[14]. Nano-titanium is known for being lightweight but strong and has been used in a number of industrial and commercial applications, including agriculture. Studies have demonstrated that nano-titanium has positive results on plant growth and productivity and positively affect plant growth through increased photosynthetic efficiency through both chlorophyll and protein synthesis and antioxidant enzymes like catalase (CAT) and peroxidase (POD)[15].

Among the plant-based nano-extracts evaluated in previous studies is nano-curcumin extract, which contains curcumin, a strong antioxidant and anti-inflammatory material that is frequently used in medical and industrial applications for its superb capacity to neutralize free radicals[16]. Curcumin can enhance nutrient-use efficiency in plants due to its phenolic nature, which is super important in reducing drought stress because something like environmentally beneficial aquaporins are membrane proteins that promote and facilitate water movement across cellular membranes[17].

Sunflower seeds are one of the primary sources for the production of biofuel, which is a viable biodegradable, non-toxic, and environmentally friendly substitute for traditional petroleum-derived fuels[18]. Biofuel can be produced from either direct extraction from sunflower seeds or from the residue of processed seeds. However, the biofuel sector is underdeveloped in many parts of the world, including Iraq, largely due to insufficient availability of oilseed resources, in addition to unavoidable environmental factors such as drought, salinity, and high temperatures, which have all reduced productivity of oilseed crops[19].Sunflower-derived biofuel is biodegradable, emits low emissions of harmful gases like CO and SO compounds, has a high combustion efficiency, and is combusted with conventional fuel blends.

Biofuels have the potential to be wholly restorative, renewable fuels. This study aims to produce an environmentally friendly biofuel from sunflower subjected to water stress and to evaluate the efficiency of different concentrations of nano-titanium and nano-curcumin to reduce the negative effects of water stress through foliar application on sunflower leaves.

2. Materials and Methods

A field experiment was performed in the 2024–2025 growing season in the Botanical Garden of the Department of Life Sciences, College of Education for Pure Sciences (Ibn Al-Haitham), University of Baghdad, to evaluate the effect of foliar application of nano-titanium and nano-curcumin on sunflower (Helianthus annuus L.) plants subjected to water stress. The experiment was done following a Randomized Complete Block Design (RCBD) with three replications. Water stress was imposed by watering every 5, 10, and 15 days, which included a control treatment that was watered every 5 days. Also, three nano-titanium concentrations (0, 50, and 100 $mg.L^{-1}$) and three nano-curcumin concentrations (0, 25, and 75 $mg.L^{-1}$) were included in the experiment. Thus, the trial contained a total of 81 experimental units. The field was plowed, leveled, and subdivided into 1×1 m^2 plots containing 4 rows spaced 15 cm apart. Sunflower

seeds were planted on September 16, 2024. All agronomic practices were standard, and water stress was imposed 24 days after planting.
Stock solutions of nano-titanium and nano-curcumin were prepared by dissolving 1 g of each material in distilled water and adjusting the volume to 1000 mL. Working concentrations were then prepared using standard dilution procedures. Nano-titanium treatments were applied as foliar sprays in the early morning at the 4–6 leaf stage, and nano-curcumin treatments were applied 72 hours later under the same spraying conditions.
The following growth and physiological parameters were measured:

- Plant height (cm): measured from the soil surface to the apex of the plant.
- Number of leaves: counted per plant.
- Relative water content (%): determined following the method described in reference[20].
- Total chlorophyll (mg.g-1FW): estimated according to the procedure of[21].
- Vitamin E concentration: quantified using the method of[22].
- Seed oil percentage (%): assessed according to the method of[23].

Data were subjected to analysis of variance (ANOVA) at a significance level of 0.05, and treatment means were compared using the Least Significant Difference (LSD) test as implemented in the GenStat software package[24].

3. Results

The findings in **Table 1** show a significant impact on mean plant height due to increasing irrigation intervals. Irrigation every 15 days produced the greatest mean plant height (88.85 cm), while the lowest mean height (75.81 cm) occurred with irrigation every 5 days. The table also indicates a significant increase in plant height due to increasing concentrations of nano-titanium.

Table 1. Effect of water stress, nano-titanium and nano-curcumin concentrations, and their interactions on plant height (cm).

Drought Stress	Nano-Curcumin (C) mg.L^{-1}	Nano-titanium spray concentrations (T) (mg.L^{-1})			C×D
		0	50	100	
5	0	66.00	70.00	76.33	70.78
	25	72.00	75.33	81.00	76.11
	75	79.00	80.33	82.33	80.56
10	0	54.67	64.67	73.00	80.56
	25	84.00	101.00	117.33	64.11
	75	90.33	91.00	110.33	100.78
15	0	79.33	89.67	88.33	85.78
	25	91.00	91.00	85.67	89.22
	75	82.00	96.67	96.00	91.56
Mean effect of titanium concentrations (T)		77.59	84.41	90.04	1.79
LSD (0.05)	Effect T= 1.03				
	Effect T×C×D= 2.95				
D × T					
Drought Stress		T concentrations (mg.L^{-1})			Mean D
		0	50	100	
5		72.33	75.22	79.88	75.81
10		76.33	85.55	100.22	87.36
15		84.11	92.44	90.00	88.85
LSD (0.05)		17.17			1.78
C × T					
Curcumin (mg.L^{-1})		T concentrations (mg.L^{-1})			Mean C
		0	50	100	
0		66.66	74.78	79.22	73.55
25		82.33	89.11	94.66	88.70
75		83.77	89.33	96.22	89.77
LSD (0.05)		N.S			0.65

Changing the nano-titanium concentration from 0 to 100 mg.L^{-1} resulted in an increase in mean plant height from 77.59 cm to 90.04 cm. Likewise, mean plant height increased significantly with increasing concentrations of nano-curcumin from 0 to 75 mg.L^{-1} with mean plant height increasing from 73.56 cm to 89.77 cm over that range. There was a significant interaction between irrigation intervals and concentrations of nano-titanium. Irrigating every 10 days with nano-titanium at a concentration of 100 mg.L^{-1} produced the highest interaction value (100.22 cm), while the lowest value (72.33 cm) occurred with irrigation every 5 days with 0 mg.L^{-1} nano-titanium. There was no significant interaction between the concentrations of nano-titanium and nano-curcumin; however, a significant interaction was found between irrigation interval and nano-curcumin concentration. The highest value of 100.78 cm was found with irrigation every 10 days and with a nano-curcumin concentration of 75 mg.L $^{-1}$. The lowest value was measured at 64.11 cm, with a concentration of 25 mg.L^{-1} and irrigation every 10 days. A significant three-way interaction of all factors was also observed; the highest value of 117.33 cm was observed when nano-titanium was applied at the concentration of 100 mg.L^{-1} and 25 mg.L^{-1} nano-curcumin, irrigated every 10 days; the lowest, 54.67 cm, with neither nano-titanium or nano-curcumin applied (0 mg.L^{-1}) and irrigated every 10 days.
Results in **Table 2** illustrate a significant effect of mean leaf number based on watering intervals. A significant decrease in leaf number occurred as watering intervals increased. Each 15-day watering interval produced the least mean number of leaves at 18.00 leaves.plant^{-1} while the 5-day watering interval produced the highest mean value of 20.67 leaves.plant^{-1}.

Table 2. Effect of water stress, nano-titanium and nano-curcumin concentrations, and their interactions on the number of leaves (leaves.plant^{-1})

Drought Stress	Nano-Curcumin (C) mg.L^{-1}	Nano-titanium spray concentrations (T) (mg.L^{-1})			C×D
		0	50	100	
5	0	17.67	19.67	21.00	19.44
	25	20.67	21.00	21.33	21.00
	75	21.33	21.67	21.67	21.56
10	0	16.33	15.67	17.33	16.44
	25	18.33	17.33	20.33	18.67
	75	19.00	20.67	20.67	20.11
15	0	11.33	14.00	15.67	13.67
	25	17.33	20.67	23.67	20.56
	75	20.33	19.67	19.33	19.78
Mean effect of titanium concentrations (T)		18.04	18.93	20.11	0.90
LSD (0.05)	Effect T= 0.51				
	Effect T×C×D= 1.50				
D × T					
Drought Stress		T concentrations (mg.L^{-1})			Mean D
		0	50	100	
5		19.89	20.78	21.33	20.67
10		17.89	17.89	19.44	18.41
15		16.33	18.11	19.56	18.00
LSD (0.05)		0.83			0.56
C × T					
Curcumin (mg.L^{-1})		T concentrations (mg.L^{-1})			Mean C
		0	50	100	
0		15.11	16.44	18.00	16.52
25		18.78	19.67	21.78	20.07
75		20.22	20.67	20.56	20.48
LSD (0.05)		0.89			0.58

A significant increase in leaf number was observed when nano-titanium concentration increased from 0 to 100 mg.L^{-1} from an estimated mean of 18.04 to 20.11 leaves.plant^{-1}. Similarly, increasing the nano-curcumin concentration from 0 to 75 mg.L⁻¹, significantly increased leaf number from an estimated mean of 16.52 to 20.48 leaves.plant⁻¹. The irrigation interval in addition to nano-titanium concentration was significant, suggesting that an interaction occurred. Each 5-day watering interval with 100 mg.L⁻¹ of nano-titanium produced the highest interaction value at 21.33 leaves.plant⁻¹ and the lowest interaction value at 16.33 leaves.plant⁻¹ when using a 15-day watering interval and 0 mg.L⁻¹ of nano-titanium. Results indicate a significant interaction between concentrations of nano-titanium and nano-curcumin. The highest value (21.78 leaves.plant⁻¹) was produced with both 100 mg.L⁻¹ of nano-titanium and 25 mg.L⁻¹ of nano-curcumin, while the lowest value (15.11 leaves.plant⁻¹) was observed with 0 mg.L⁻¹ of both materials. There was also a significant interaction between irrigation intervals and nano-curcumin concentration. Irrigating every 5 days at 75 mg.L⁻¹ of nano-curcumin resulted in the highest value (21.56 leaves.plant⁻¹), while the lowest value (13.67 leaves.plant⁻¹) was found when irrigating every 15 days with 0 mg.L⁻¹ of nano-curcumin. A significant three-way interaction was found, with the highest value (23.67 leaves.plant⁻¹) resulting from irrigation every 15 days with 100 mg.L⁻¹ of nano-titanium and 25 mg.L⁻¹ of nano-curcumin. The lowest value (11.33 leaves.plant⁻¹) was observed with 15-day irrigation under both 0 mg.L⁻¹ of nano-titanium and nano-curcumin.

Table 3 indicates a notable effect on the average relative water content (RWC) as irrigation intervals increased. The highest relative water content (RWC) occurred with an irrigation interval of 15 days (78.92%) and the lowest (69.85%) with an interval of 5 days. The increase in the concentration of nano-titanium increased relative water content (RWC) from 71.41% to 76.10%, with increasing doses from 0 to 100 mg.L⁻¹.

Table 3. Effect of water stress, nano-titanium and nano-curcumin concentrations, and their interactions on water content (%).

Drought Stress	Nano-Curcumin (C) mg.L^{-1}	Nano-titanium spray concentrations (T) (mg.L⁻¹)			C×D
		0	50	100	
5	0	62.54	67.46	68.07	66.08
	25	66.39	70.67	70.87	69.31
	75	69.98	74.77	76.81	73.86
10	0	63.99	96.74	70.91	68.22
	25	74.80	77.50	77.87	76.72
	75	76.79	78.15	78.74	77.89
15	0	72.46	75.91	77.39	75.25
	25	73.91	80.66	80.94	78.50
	75	81.77	83.91	73.31	82.99
Mean effect of titanium concentrations (T)		71.41	75.44	76.10	0.21
LSD (0.05)	Effect T= 0.12				
	Effect T×C×D= 0.35				
D × T					
Drought Stress		T concentrations (mg.L^{-1})			Mean D
		0	50	100	
5		66.31	71.03	71.92	69.75
10		71.86	75.13	75.84	74.28
15		76.05	80.76	80.54	78.25
LSD (0.05)		0.19			0.12
C × T					
Curcumin (mg.L⁻¹)		T concentrations (mg.L^{-1})			Mean C
		0	50	100	
0		66.33	71.10	72.12	69.85
25		71.70	76.28	76.56	74.85
75		76.18	78.94	79.62	78.35
LSD (0.05)		0.21			0.14

Also, increasing the concentration of nano-curcumin with increasing doses (0 to 75 $mg.L^{-1}$) increased average relative water content (RWC) from 76.85% to 78.25%. The analysis showed a highly significant interaction of irrigation interval and nano-titanium concentration. The highest interaction value (80.76%) was found with the irrigation interval of 15 days at 50 $mg.L^{-1}$ nano-titanium concentration and the lowest (66.31%) for an irrigation interval of 5 days with 0 $mg.L^{-1}$ concentration of nano-titanium. A highly significant interaction of nano-titanium concentration with nano-curcumin and nano-titanium concentration was also detected. The highest average relative water content (RWC) values of 79.62% were found for the combination of 100 $mg.L^{-1}$ nano-titanium and 75 $mg.L^{-1}$ nano-curcumin concentrate for nano-titanium and the lowest relative water content was observed at 0 $mg.L^{-1}$ nano-titanium and nano-curcumin concentrations for both factors, with values of 66.33%.

There was a significant interaction between nano-curcumin concentrations and irrigation intervals. The highest value (82.99%) was observed when irrigation was every 15 days with 75 $mg.L^{-1}$ of nano-curcumin; the lowest value (66.08%) was associated with 0 $mg.L^{-1}$ of nano-curcumin and 5 days of irrigation. There was also a significant three-way interaction. Highest value (83.91%) occurred when irrigation was every 15 days, with nano-titanium (50 $mg.L^{-1}$) and nano-curcumin (75 $mg.L^{-1}$); the lowest value occurred every 5 days, with both materials at 0 $mg.L^{-1}$.

The findings displayed in **Table 4** indicate a statistically important decrease in mean total chlorophyll content caused by longer irrigation intervals.

Table 4. Effect of water stress, nano-titanium and nano-curcumin concentrations, and their interactions on total chlorophyll content ($mg.g^{-1}$).

Drought Stress	Nano-Curcumin (C) $mg.L^{-1}$	Nano-titanium spray concentrations (T) ($mg.L^{-1}$)			C×D
		0	50	100	
5	0	0.0837	0.0827	0.0820	0.0828
	25	0.0823	0.0817	0.0820	0.0820
	75	0.0800	0.0810	0.0807	0.0805
10	0	0.0773	0.0717	0.0737	0.0742
	25	0.0707	0.0707	0.0713	0.0709
	75	0.0657	0.0693	0.0717	0.0689
15	0	0.0647	0.0627	0.0680	0.0651
	25	0.0613	0.0613	0.0647	0.0624
	75	0.0473	0.0573	0.0583	0.0543
Mean effect of titanium concentrations (T)		0.0703	0.0709	0.0725	0.0013
LSD (0.05)	Effect T= 0.00068				
	Effect T×C×D= 0.0021				

D × T				
Drought Stress	T concentrations ($mg.L^{-1}$)			Mean D
	0	50	100	
5	0.0820	0.0818	0.0815	0.0818
10	0.0712	0.0706	0.0722	0.0713
15	0.0578	0.0604	0.0637	0.0606
LSD (0.05)	0.0011			0.00065

C × T				
Curcumin ($mg.L^{-1}$)	T concentrations ($mg.L^{-1}$)			Mean C
	0	50	100	
0	0.0752	0.0723	0.0746	0.0740
25	0.0714	0.0712	0.0727	0.0718
75	0.0694	0.0692	0.0702	0.0679
LSD (0.05)	0.0013			0.00091

The irrigation of plants every 15 days produced the lowest chlorophyll content (0.0606 $mg.g^{-1}$) with irrigation at 5 days generating the maximum chlorophyll content (0.0818 $mg.g^{-1}$).

Increasing nano-titanium concentration from 0 to 100 $mg.L^{-1}$ caused a significant rise in total chlorophyll content from 0.0703 to 0.0725 $mg.g^{-1}$. However, the increase of nano-curcumin concentration from 0 to 75 $mg.L^{-1}$ caused a significant decline in chlorophyll content from 0.0740 to 0.0674 $mg.g^{-1}$. Meanwhile, the interaction between irrigation interval and nano-titanium concentration was significant, where irrigation every 5 days and 0 $mg.L^{-1}$ gave the highest value (0.0820 $mg.g^{-1}$), and irrigation every 15 days and 0 $mg.L^{-1}$ produced the lowest value (0.0578 $mg.g^{-1}$). Likewise, a significant interaction between nano-titanium and nano-curcumin concentration was observed. The largest value (0.0752 $mg.g^{-1}$) was at 0 $mg.L^{-1}$ for both nano-titanium and nano-curcumin, while the lowest (0.0692 $mg.g^{-1}$) was for 50 $mg.L^{-1}$ nano-titanium with 75 $mg.L^{-1}$ nano-curcumin. There was a significant interaction between the irrigation interval and concentration of nano-curcumin. Irrigation every five days with 0 $mg.L^{-1}$ of nano-curcumin produced the highest chlorophyll value (0.0828 $mg.g^{-1}$). Conversely, the lowest chlorophyll value (0.0543 $mg.g^{-1}$) was produced by irrigating every 15 days with 75 $mg.L^{-1}$ of nano-curcumin. A significant three-way interaction was also detected, where an irrigation interval of every five days with the 0 $mg.L^{-1}$ treatment of both nano-materials produced the highest chlorophyll value (0.0837 $mg.g^{-1}$). The lowest chlorophyll value of 0.0473 $mg.g^{-1}$ resulted from the 15 day irrigation interval with 0 $mg.L^{-1}$ of nano-titanium and 75 $mg.L^{-1}$ of nano-curcumin.

Table 5 shows a significant increase in mean vitamin E content with increasing irrigation intervals. Irrigation every 15 days produced the highest mean value (46.281 $\mu g.g^{-1}$), whereas irrigation every 5 days resulted in the lowest (35.081 $\mu g.g^{-1}$).

Table 5. Effect of water stress, nano-titanium and nano-curcumin concentrations, and their interactions on vitamin E content ($\mu g \cdot g^{-1}$).

Drought Stress	Nano-Curcumin (C) $mg.L^{-1}$	Nano-titanium spray concentrations (T) ($mg.L^{-1}$)			C×D
		0	50	100	
5	0	27.110	29.933	31.763	29.602
	25	33.433	35.257	41.150	36.613
	75	33.527	40.960	42.593	39.027
10	0	23.260	42.477	43.543	36.427
	25	27.613	38.627	44.157	36.466
	75	37.087	43.560	51.620	44.089
15	0	31.677	35.160	38.610	35.149
	25	36.507	41.220	55.983	44.570
	75	36.470	44.187	43.100	41.252
Mean effect of titanium concentrations (T)		31.854	39.042	43.502	0.563
LSD (0.05)	Effect T= 0.422				
	Effect T×C×D= 1.151				
D × T					
Drought Stress		T concentrations ($mg.L^{-1}$)			Mean D
		0	50	100	
5		31.537	35.383	38.502	35.081
10		29.320	41.554	46.107	38.994
15		34.884	40.189	45.898	40.324
LSD (0.05)		0.603			0.127
C × T					
Curcumin ($mg.L^{-1}$)		T concentrations ($mg.L^{-1}$)			Mean C
		0	50	100	
0		27.349	35.857	37.972	33.726
25		32.518	38.368	46.763	39.216
75		35.694	42.902	45.771	41.456
LSD (0.05)		0.695			0.394

Increasing nano-titanium concentration from 0 to 100 mg.L⁻¹ significantly increased vitamin E content from 31.854 to 43.502 µg.g⁻¹. Similarly, increasing nano-curcumin concentration from 0 to 75 mg.L⁻¹ increased vitamin E content from 33.726 to 41.526 µg.g⁻¹. A significant interaction between irrigation interval and nano-titanium concentration was found, with 10-day irrigation and 100 mg.L⁻¹ nano-titanium producing the highest value (46.107 µg.g⁻¹), while the lowest (29.320 µg.g⁻¹) occurred at 10-day irrigation with 0 mg.L⁻¹ nano-titanium. A significant interaction between nano-titanium and nano-curcumin concentrations was also recorded. The maximum value (46.763 µg.g⁻¹) was observed with 100 mg.L⁻¹ nano-titanium and 25 mg.L⁻¹ nano-curcumin, while the minimum value (27.349 µg.g⁻¹) occurred at 0 mg.L⁻¹ nano-titanium and 0 mg.L⁻¹ nano-curcumin. The interaction between irrigation interval and nano-curcumin was significant. Irrigation every 15-day interval with 25 mg.L⁻¹ nano-curcumin produced the greatest value (44.570 µg.g⁻¹), while the minimum value (29.602 µg.g⁻¹) occurred with 5-day irrigation and 0 mg.L⁻¹ nano-curcumin. A significant three-way interaction was also detected. Irrigation every 15-day interval and 100 mg.L⁻¹ nano-titanium and 25 mg.L⁻¹ nano-curcumin produced the largest value (55.983 µg.g⁻¹) while the lowest value (23.260 µg.g⁻¹) occurred on a 10-day irrigation schedule and 0 mg.L⁻¹ nano-titanium and nano-curcumin.

Table 6 shows a significant impact on mean oil content with longer irrigation intervals. The mean percentage of oil content was highest (50.10%) when irrigated every 15 days, while the lowest oil content obtained under 5 days of irrigation was 45.32%. The nano-titanium concentration affected oil content significantly.

Table 6. Effect of water stress, nano-titanium and nano-curcumin concentrations, and their interactions on plant oil percentage (%).

Drought Stress	Nano-Curcumin (C) mg.L⁻¹	Nano-titanium spray concentrations (T) (mg.L⁻¹)			C×D
		0	50	100	
5	0	41.40	44.13	45.40	43.64
	25	42.00	47.07	46.80	45.29
	75	45.73	48.87	46.50	47.03
10	0	40.73	45.77	45.83	44.11
	25	45.70	47.70	46.40	46.60
	75	43.67	45.03	51.53	46.74
15	0	40.87	45.67	46.33	44.29
	25	43.00	52.00	65.80	53.60
	75	51.97	56.30	48.97	52.41
Mean effect of titanium concentrations (T)		43.90	48.06	49.29	1.272
LSD (0.05)	Effect T= 0.622				
	Effect T×C×D= 1.929				
D × T					
Drought Stress		T concentrations (mg.L⁻¹)			Mean D
		0	50	100	
5		43.04	46.69	46.23	45.32
10		43.37	46.17	47.92	45.82
15		45.28	51.32	53.70	50.10
LSD (0.05)		1.156			0.963
C × T					
Curcumin (mg.L⁻¹)		T concentrations (mg.L⁻¹)			Mean C
		0	50	100	
0		41.00	45.19	45.86	44.01
25		43.57	48.92	53.00	48.50
75		47.20	50.07	49.00	48.73
LSD (0.05)		1.116			0.751

As the nano-titanium concentration was increased from 0 to 100 mg.L⁻¹, oil content increased significantly from 43.90% to 49.29%. Oil content was also affected significantly as the nano-curcumin concentration increased from 0 to 75 mg.L⁻¹ while oil content increased significantly from 44.01% to 48.73%. Interactions were also observed between irrigation interval and nano-titanium concentration. The greatest oil concentration (53.70%) was recorded as the irrigation interval was extended to 15 days and 100 mg.L⁻¹ nano-titanium concentrations were utilized. However, the lowest value (43.04%) was found under a 5-day irrigation interval at 0 mg.L⁻¹ nano-titanium concentration. Interactions were also observed between nano-titanium and nano-curcumin concentrations. The highest value (53.00%) was shown at irrigation every 15 days with a nano-titanium concentration of 100 mg.L⁻¹ and a nano-curcumin concentration of 25 mg.L⁻¹, while the lowest value occurred at 0 mg.L⁻¹ for both nano-materials (41.00%). A significant interaction was noted among the irrigation interval and nano-curcumin concentration in this category; irrigation every 15 days at 25 mg.L⁻¹ nano-curcumin had the highest value (53.60%) and the lowest value (43.64%) occurred under an irrigation interval of every 5 days and 0 mg.L⁻¹ nano-curcumin. The three-way interaction for all factors was significant; irrigation every 15 days, and a nano-titanium concentration of 100 mg.L⁻¹, and a nano-curcumin concentration of 25 mg.L⁻¹ produced the highest oil content (65.80%), and the lowest oil content occurred again at the same intervals for both nano-materials, but at a concentration of 0 mg.L⁻¹.

4. Discussion

Drought ultimately causes a decline in the water available to the plant within the soil particles that surround the roots of the plant, affecting plant elongation[8], cell division, and behavior of the apical meristem. It causes the production of reactive oxygen species (ROS), which affects plant hormones, specifically abscisic acid (ABA), leading to senescence and leaf abscission[25] as well as stomatal closure, which limits gas exchange, and increases the enzyme chlorophyllase, which speeds up chlorophyll degradation and is related to leaf drop[26].

The results indicate that increased irrigation intervals led to stomatal closure as a water content conservation behavioral response[27]. Sunflower has a significant ability to withstand drought and limited available water[28] due to natural adaptations in root architecture, stem structure, and leaf shape and structure[29]. Drought inhibits or decreases photosynthesis enzyme systems, which includes decreases in Rubisco activity[21], which reduces ATP synthesis and may increase photorespiration and, ultimately, the processes associated with carbon fixation, carbohydrate development, and dry matter accumulation[22].

As well as noted an increase in vitamin E concentration of sunflower seeds can be observed. Vitamin E, otherwise known as α-tocopherol[23], is a strong antioxidant that protects phospholipids in the cell membrane under water stress[11]. Sunflowers may wash an innate defense mechanism under drought conditions by triggering the antioxidant activity, both enzymatic and non-enzymatic[25], to compensate for deficits of water in cells for vegetative growth and accumulation of biomass and yield components under stress like seed filling and oil formation, which is a critical factor for biofuel production[26]. The increased vitamin E content of the seeds will improve the stability and, subsequently, the quality of oil as a biofuel source.

Nano-titanium has an important role in regulating antioxidant activity but also provids stimulation of water and nutrient uptake, and enhances plant hormone levels, especially auxin for cell elongation, plant height, preventing leaf abscission[27], maintaining cellular water potential and osmotic balance, and improving photosynthetic efficiency[28]. Nano-titanium, due to its nanoscale size and large surface area, can easily penetrate cellular membranes, increase nutrient and water uptake, cover photosynthesis, and protect chloroplasts[29,30]. Vitamin E accumulates in plastid membranes to protect from oxidation and ROS; nano-titanium has been observed to enhance the protective effect, leading to increased vitamin E accumulation in seeds.

Nano-curcumin particles also play a crucial role in the fight against ROS based on phenolic compounds in curcumin, which promote water and nutrient uptake and repair the damage caused by drought stress, as well as enhance enzymatic and non-enzymatic antioxidants. These compounds protect chloroplasts from oxidative damage, maintain photosynthesis, and promote dry matter that is deposited in seeds for the synthesis of carbohydrates, proteins, and fatty acids[17]

5. Conclusion

The results from the current study demonstrate that drought stress, along with the foliar application of nano-titanium and nano-curcumin, increased the productivity of sunflower plants. Increasing irrigation intervals had a positive effect on stimulating vegetative growth, while the foliar application of titanium at 100 $mg.L^{-1}$ reduced the negative impact of drought. Similarly, nano-curcumin at 25 $mg.L^{-1}$ promoted water and nutrient uptake. Foliar application with these nanomaterials also promoted vegetative and reproductive growth in sunflower and enhanced both enzymatic and non-enzymatic antioxidant systems in the plants, ultimately improving seed oil quality for use in biodiesel production.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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