Journal of Innovative Agriculture
Research Article

Zinc oxide nanoparticles as a foliar spray for alleviating drought-induced oxidative stress in Strawberry

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Volume: 13, Issue: 4, Pages: 11-23
DOI: https://doi.org/10.37446/jinagri/rsa/13.4.2026.11-23
Received: 12 August 2026 / Revised: 1 October 2026 /Accepted: 11 October 2026 / Published: 25 November 2026

Background: Drought stress is a major constraint to strawberry production, causing reductions in plant growth, chlorophyll content, and overall productivity through oxidative damage. The present study investigated the effectiveness of foliar-applied green synthesized zinc oxide nanoparticles (ZnO-NPs), prepared using *Calotropis gigantea* leaf extract, in alleviating drought-induced oxidative stress in strawberry plants.

Methods: A completely randomized factorial pot experiment was conducted under well-watered and drought conditions using different ZnO-NP concentrations (0, 50, 100, and 200 ppm). Growth attributes, including plant height, leaf width, shoot length, root length, root fresh and dry weights, chlorophyll content (SPAD), and antioxidant enzyme activities (superoxide dismutase, SOD, and catalase, CAT), were evaluated.

Results: The results demonstrated that drought stress adversely affected plant growth and physiological performance; however, foliar application of ZnO-NPs significantly improved several morphological and biochemical traits. Plants treated with ZnO-NPs exhibited greater chlorophyll content, enhanced root development, and increased activities of antioxidant enzymes, indicating improved protection against oxidative damage. Higher nanoparticle concentrations generally produced better responses, particularly under drought conditions, by strengthening the antioxidant defense system and improving plant tolerance to water deficit.

Conclusion: The findings suggest that green synthesized ZnO-NPs represent an environmentally friendly and sustainable nanofertilizer capable of enhancing drought resilience and maintaining strawberry growth under limited water availability. This study highlights the potential application of nanotechnology as an innovative strategy for improving crop productivity and water stress tolerance, contributing to sustainable agricultural production under changing climatic conditions.

Keywords: *Zinc oxide, nanoparticles, foliar spray, drought stress, strawberry crop*

Introduction

Water and food production are correlated globally, with irrigated farmland accounting for almost 40% of global agricultural output. Water is in short supply in the Mediterranean area, necessitating an evaluation of present water consumption practices (Winter et al., 2017; Borgo, 2026). The growing population raises the need for food, which increases the irrigated area, which has grown eight times over the previous century (Angelakis et al., 2020). Water is in short supply in the Mediterranean area, necessitating an evaluation of present water consumption practices. The growing population raises the need for food, which increases the irrigated area, which has grown eight times over the previous century (Abdelkhalik et al., 2019; Sharafi et al., 2024). Global warming and droughts are currently the most common links between climate change and anomalies. According to current projections, over 1.8 billion people will experience a complete water deficit in the first quarter of the twenty-first century, and 65% of people will experience a partial water shortage. Numerous efforts are being undertaken to increase water productivity (WP) through research in order to mitigate future global changes and guarantee food security. Consequently, efficient advancements in irrigation and management practices are required to increase the rational and efficient usage of water (Sabir and Sari, 2019; Cafaro et al., 2026). Worldwide, grain cereals accounted for over 50% of the total crop, and the utilization of their seeds is crucial for the manufacturing of both food and industrial raw materials. Simultaneously, grain crops experience severe water scarcity, exhibiting diverse physiological, morphological, biochemical, and molecular reactions to the dry spell. During the vegetative and reproductive stages of plant growth, a water deficiency can result in detrimental, reversible, and permanent physiological changes in the plant. Food security is threatened since the cost of fertilizers and irrigation rises annually in tandem with the cost of raw resources, which are required to apply them in agricultural output (Elam et al., 2021). Nanotechnology has a wide range of applications, from medicine delivery to soil remediation, wastewater cleanup, and controlled fertilizers. Numerous NPs are being used more often every day in several industries, including agriculture where they are used as fertilizers and stress-relieving agents. A nanoparticle that has been designed is one that is smaller than 100 nm in size and has at least one dimension, such as zinc oxide (ZnO), titanium dioxide (TiO2), etc. However, as the usage of NPs grows, so do the risks of their unintentional leakage into undesirable areas, including ponds or groundwater (Marcon et al., 2021). In consequence of its participation in several enzyme activities and metabolic processes, zinc (Zn) is a micronutrient that is crucial for both plants and animals. Zinc deficiency in people causes malnutrition and a number of illnesses, while it causes poor yield levels in plants (Praharaj et al., 2021). However, if present in greater amounts than allowed limits, it also poses major dangers to the ecosystems of the soil and water. Zn has a critical soil value between 70 and 400 mg/kg (Santos et al., 2023). One of the most pervasive public health issues is zinc deficiency, which affects around 50% of the world's significant agricultural soils. Zn insufficiency is the fifth most significant cause causing sickness and disease globally and the eighth most significant factor in emerging nations. Around one-third of the world's population consumes insufficient amounts of zinc, which results in a loss of 28 million life years every year (El-Aziz, 2022). These nanoparticles, when applied as a foliar spray, have been found to enhance the antioxidant defense system of strawberry plants, thereby reducing oxidative damage caused by drought stress. The use of zinc oxide nanoparticles as a foliar spray has been shown to enhance the antioxidant defense system in strawberry plants, thereby mitigating drought-induced oxidation stress (Jiang et al., 2023). The application of zinc oxide nanoparticles as a foliar spray has shown promising results in mitigating drought-induced oxidative stress in strawberry plants. Zinc oxide nanoparticles have gained attention for their potential as a remedial Nano fertilizer in mitigating drought-induced oxidation stress in strawberry plants (Latha et al., 2022). The preparation of Nano fertilizers is one key area in which nanotechnology has benefited agriculture. Unlike conventional fertilizers, which are made of natural materials, Nano fertilizers are made of manufactured components that give nutrients to plants more effectively and precisely. These Nano fertilizers make use of tiny particles, including zinc oxide nanoparticles, which may enter the plant's tissues and release nutrients right at the cellular level (Thounaojam et al., 2021). Strawberry's growth and yield have been demonstrated to be improved by Nano fertilizers, such as zinc oxide nanoparticles. For instance, studies have shown that applying zinc oxide nanoparticles to the leaves of strawberry plants may greatly improve their agro-morphological characteristics, photosynthesis, biomass production, and yield (Javed et al., 2022). Strawberry plant germination and growth have been discovered to be favorably impacted by zinc oxide nanoparticles. For instance, research on strawberry plants revealed that adding ZnO nanoparticles significantly improved germination and growth. In addition, it has been shown that zinc oxide nanoparticles are essential for plant metabolism (Sun et al., 2020). Therefore, the objectives of the present study were to investigate the potential effects of foliar application of green ZnO-NPs, biosynthesized using *Calotropis gigantea* leaf extract, on physiological and biochemical attributes including growth, oxidative damage, and antioxidant system of strawberry under various water levels (Ahmed et al., 2023). This study specifically explores the possibility of using various doses of ZnO-NPs to reduce the oxidative stress caused by drought. By triggering the antioxidant system in strawberry plants in water-strapped settings, it was hypothesized that foliar spraying ZnO-NPs may enhance strawberry development. To the best of our knowledge, this experiment is the first to show the protective role of ZnO-NPs in the presence or absence of drought stress in strawberry.

Materials and Methods

Study site

The research was conducted in The University of Sargodha, Punjab, Pakistan. Stain-free steel shovel was used to collected soil from 1 to 15cm depth for soil testing including pH, salt adsorption ratios, and electrical conductivity (EC). The study's source of NPs was Alfa Aesar's Zinc nanoparticles. The ZnO-NPs have a purity of 97%, a particle size range of 50 to 100 nm, a surface area per gram of 20e50 m2, and a density of 5.2 g/m3. Weighing the necessary quantity of ZnO-NPs for each treatment, a solution was made with deionized water. Each solution underwent a half-hour of ultra-sonication to ensure appropriate Fe-NP diffusion. The necessary quantity was then made with deionized water and put to the pots a week before the seeding.

Pot experiment

For the investigation, the local variety of strawberry variety was chosen. Five kilograms of sieved soil were put to the pots during the Rabi season. The rate of the amendment that was chosen was based on earlier outcomes. The samples were thoroughly wetted to remove the dust, and any leftover moisture was then dried by the sun. At the time of sowing, the experiment was done in ambient conditions with a 64±7% relative humidity and a 33/22°C Day/night temperature. Strawberry seeds were washed for 2 minutes using a 2.6% chloride and sodium hypochlorite solution. For the purpose of removing extra chloride content from the seeds' surface, the seeds were washed with distilled water. A four-replicate per treatment totally randomized design was used to sow the 8 seeds in each container. Four healthy plants were still present in each container after two weeks (figure. 1) (Periasamy and Baskar, 2018).

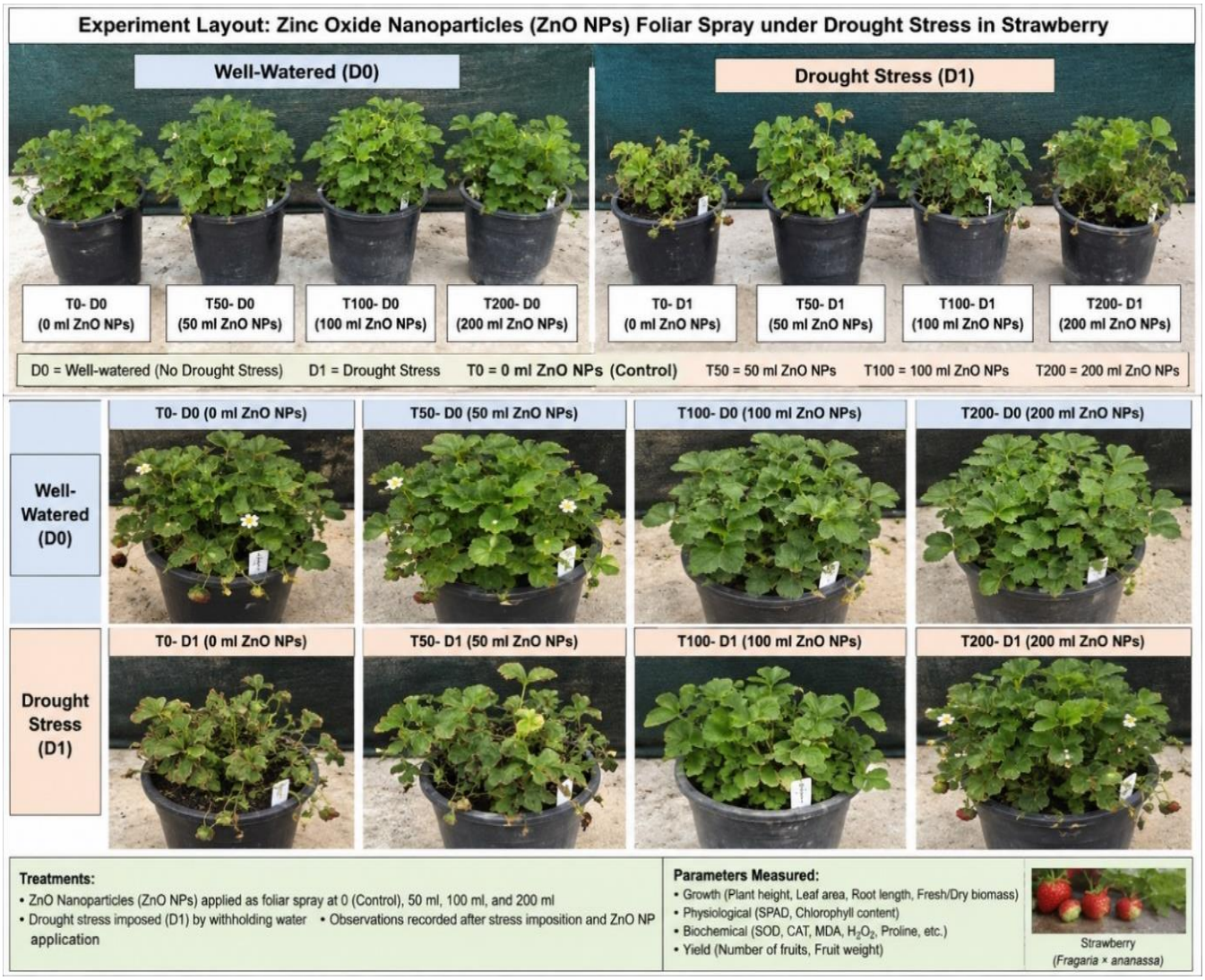

Figure. 1 Layout of Experiment.

Preparation and extraction of nanoparticles

In order to prepare the extract that converted zinc ions into zinc nanoparticles (ZnO), 50g of finely chopped, dried, and cleaned leaves were combined with 100 mL of distilled water that had been sterilized. The mixture was then brought to a boil for 60 minutes, or until the aqueous solution's color lightened to pale yellow. Filter paper was used to filter the extract once it had cooled to room temperature. In order to be used in further research, the extract was refrigerated (Onitsuka et al., 2019).

ZnO nanoparticle preparation

The nanoparticles were produced by heating 50 ml of Calotropis gigantea leaf extract to a temperature between 60 and 80 degrees Celsius using a stirrer-heater. 5 grammes of zinc nitrate were added to the solution as soon as it reached 60 degrees Celsius. This mixture is then cooked until a thick, deep yellow paste forms. The paste was then placed in a ceramic crucible and heated for two hours in an air-fired furnace to 400 degrees Celsius. Once a light-yellow powder was obtained, it was appropriately collected and packed for characterization reasons. Crushing the stuff in a mortar and pestle allowed us to characterize it (Velgosova et al., 2024).

Preparation of nanomaterials sprays

Table 1 Preparation of working solution from stock.

Stock solution(ml)	Distilled water(ml)	Clay soil solution	Treatment (PPM)
0 ml	100 ml	0 ml	T0(only distilled water)
5 ml	92.5ml	2.5 ml	T1(50ppm)
10 ml	85 ml	5 ml	T2(100ppm)
20 ml	70 ml	10 ml	T3(200ppm)

The effects of drought stress on strawberry seedlings, and strawberry root stock were examined in this study, as well as the topical use of ZnO nanoparticles to mitigate the effects of drought (Alamdari et al., 2020).

Conditions for experimentation

Plants were put in the nursery area where they were exposed to sunlight. With an average relative humidity of about 26%, the daily mean temperature was roughly 34 °C during the day and 23 °C at night. Thirty identical-sized plants were transplanted into clay pots and kept at the maximum capacity of the field in order to give the plants the proper amount of water prior to the experiment. Every day, every plant's field capacity was maintained (Kumari, 2018).

Testing configuration

A factorial experiment was conducted using a completely randomized design (CRD) under glasshouse conditions to investigate the effects of foliar-applied zinc oxide (ZnO) nanoparticles on drought tolerance in strawberry plants. Uniform strawberry seedlings of the selected variety were transplanted into pots containing clay soil and maintained under uniform growing conditions, including soil moisture and field capacity, until the establishment of the plants. The experiment consisted of different ZnO nanoparticle concentrations (50, 100 and 200 ppm), applied as foliar sprays to the leaves, along with a control treatment without ZnO nanoparticles. The treatments were evaluated under both well-watered and drought-stress conditions. Distilled water was used as a foliar spray in the control treatment to maintain consistency in application procedures. Drought stress was imposed by regulating irrigation, whereas well-watered plants were maintained at the required soil moisture level. Each treatment was replicated four times, and the experimental units were arranged randomly within the glasshouse. Foliar applications were performed using a hand sprayer to ensure uniform coverage of the leaf surfaces while avoiding excessive runoff. Plant growth, physiological, and biochemical parameters were assessed 15 days after the initiation of drought stress to determine the effectiveness of ZnO nanoparticles in improving drought tolerance in strawberry plants (Zhang et al., 2010).

Chlorophyll content (SPAD)

The chlorophyll meter (SPAD 502, Minolta, Japan) was used to measure the relative leaf chlorophyll concentration of five leaves from each experimental unit in a nondestructive manner. For every treatment, the average quantity of chlorophyll in the leaves was determined (Iravani et al., 2018).

SOD and CAT

Nitrobluetetrazolium (NBT) photochemical reduction was used to measure SOD activity. The reaction mixture including phosphate buffer (25 mM, pH 7.0), EDTA (0.1 mM), APX (0.25 mM), H2O2 (1.0 mM), and enzyme extract was used to test the APX activity. At 290 nm, absorbance reduction was recorded for 60 s. The oxidation of guaiacol to tetraguaiacol was used to measure GPX activity, and the change in absorbance was observed at 470 nm. With regard to H2O2 dissociation, CAT activity was evaluated, and the decline in absorbance at 240 nm was observed. All enzyme activity is reported as U g 1 FW. (Singh et al., 2020).

Statistical analysis

The data obtained from the factorial experiment were subjected to a two-way analysis of variance (ANOVA) to evaluate the effects of ZnO nanoparticle concentrations and water regimes (well-watered and drought-stress conditions) on the growth, physiological, and biochemical attributes of strawberry plants. The analysis was used to determine the main effects of ZnO nanoparticle concentrations and water regimes, as well as their interaction effects. Treatment means were compared using the least significant difference (LSD) test at a 5% probability level to identify significant differences among treatments. All statistical analyses were performed using an appropriate statistical software package.

Results and Discussion

The initial physical and chemical analysis of the experimental soil indicated favorable conditions for strawberry cultivation. The soil exhibited a low electrical conductivity (EC) of 0.812 dS m^{-1}, measured by the conduction method, indicating non-saline soil conditions suitable for normal plant growth. The soil pH was 6.55, determined using a glass electrode pH meter, reflecting a slightly acidic to near-neutral reaction that is conducive to optimum nutrient availability. The organic carbon content was 1.6%, estimated by the Walkley–Black rapid titration method, suggesting moderate organic matter status. The soil was well supplied with available nitrogen (365.7 kg ha^{-1}), phosphorus (104.4 kg ha^{-1}), and potassium (23.8 kg ha^{-1}), determined using the alkaline permanganate, $NaHCO_3$ extractable Olsen, and 1N neutral ammonium acetate methods, respectively. Overall, the soil possessed suitable physicochemical properties and adequate fertility to support the evaluation of zinc oxide nanoparticle treatments under normal and drought stress conditions (table 2).

Table 2. Basic physical and chemical properties of soil from field site.

Particulars	Values	Method used
Electrical conductivity(dsm-1)	0.812	Conduction method
Soil Ph	6.55	Glass electrode pH meter
Organic carbon	1.6	Walkley black and rapid titration method
Available nitrogen(kgha-1)	365.7	Alkaline permagnate method
Available Phosphorus(kgha-1)	104.4	NaHCo3 extractable Olsen method
Available Potassium (kgha-1)	23.8	1N Neutral ammonia acetate

Effect of drought stress and foliar application of ZnO nanoparticles on plant growth attributes

Plant height

The treatment of D0T4 (Zno concentration 200 ml) was anticipated to have the most influence on the plant's height (28cm) when considering the individual effects of applied Zno NPs concentrations on rough strawberry plant, D1T4 (22cm) had the lowest estimated height for rough strawberry plant. Data analysis using variance (ANOVA) revealed that neither drought stress nor Zno NPs foliar sprays could substantially alter plant height. Furthermore, it was shown that there was a statistically significant combined effect of drought stress and foliar ZnO treatments on the parameter.

Leaf width

The foliar application of zinc oxide nanoparticles (ZnO-NPs) influenced leaf width under both well-watered (D0) and drought stress (D1) conditions. Under normal irrigation (D0), leaf width increased progressively from 1.24 cm in the untreated control (T0) to 1.30 cm, 1.37 cm, and 1.38 cm with the application of 50, 100, and 200 ppm ZnO-NPs, respectively, indicating a positive effect of nanoparticle supplementation on leaf expansion. Under drought stress (D1), leaf width was comparatively higher than the control across most treatments, with the maximum value (1.48 cm) recorded at 50 ppm (T50), followed by 1.46 cm at 100 ppm (T100) and 1.43 cm at 200 ppm (T200), compared with 1.40 cm in the

untreated control. These findings suggest that foliar application of ZnO-NPs helped maintain leaf growth under water-deficit conditions, although the response varied with nanoparticle concentration, with 50 ppm producing the greatest improvement in leaf width under drought stress (table 3).

Table 3. The effects of foliar application of ZnO NPs on plant leaf width.

No. of Treatment	D0	D1
T0ml	1.24	1.4
T50ml	1.3	1.48
T100ml	1.37	1.46
T200ml	1.38	1.43

Shoot length

The foliar application of zinc oxide nanoparticles (ZnO-NPs) produced variable effects on shoot length under both normal (D0) and drought stress (D1) conditions. Under well-watered conditions (D0), the untreated control (T0) recorded the highest shoot length (45.00 cm), while plants treated with 50 ppm, 100 ppm, and 200 ppm ZnO-NPs showed shoot lengths of 42.33 cm, 43.22 cm, and 44.22 cm, respectively, indicating only slight differences among treatments. In contrast, under drought stress (D1), foliar application of ZnO-NPs significantly improved shoot growth compared with the untreated control. The maximum shoot length (57.33 cm) was observed in plants treated with 100 ppm (T100), followed by 55.22 cm at 50 ppm (T50), whereas the control (T0) and 200 ppm (T200) treatments recorded 50.11 cm and 45.33 cm, respectively. These results indicate that moderate concentrations of ZnO-NPs, particularly 100 ppm, were more effective in enhancing shoot growth under drought stress, suggesting their potential role in improving plant vigor and tolerance to water deficit (table 4).

4. Effect of ZnO NPs treatment shoot length.

No. of Treatment	D0	D1
T0ml	45	50.11
T50ml	42.33	55.22
T100ml	43.22	57.33
T200ml	44.22	45.33

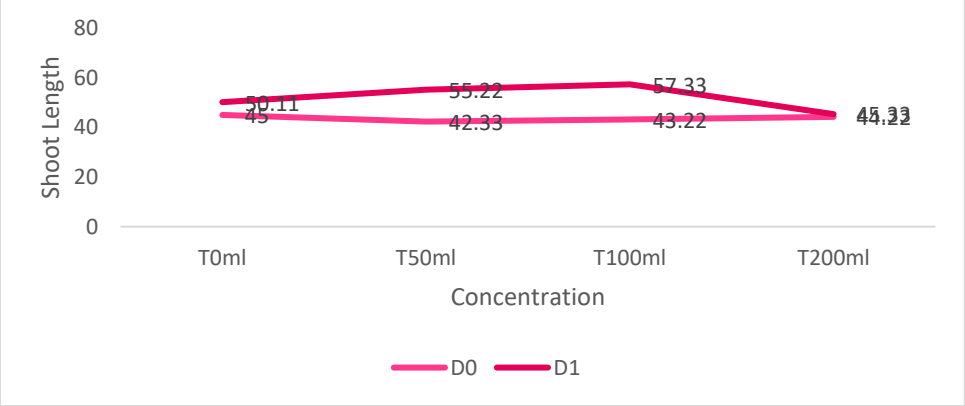

Figure. 2 Effect of ZnO NPs treatment shoot length.

Root length

The foliar application of zinc oxide nanoparticles (ZnO-NPs) had a positive influence on root length under both well-watered (D0) and drought stress (D1) conditions. Under normal irrigation (D0), root length increased progressively from 23.00 cm in the untreated control (T0) to 25.00 cm, 28.00 cm, and 29.33 cm with the application of 50, 100, and 200 ppm ZnO-NPs, respectively, indicating a concentration-dependent improvement in root growth. Under drought stress (D1), ZnO-NP application markedly enhanced root development at moderate concentrations, with the maximum root length (33.76 cm) recorded at 100 ppm (T100), followed by 32.66 cm at 50 ppm (T50), compared with 25.00 cm in the untreated control. However, root length declined to 23.00 cm at the highest concentration (200 ppm), suggesting that excessive ZnO-NP application may reduce its beneficial effects under water-deficit conditions. These results indicate that moderate concentrations of ZnO-NPs, particularly 100 ppm, were most effective in promoting root growth and improving the adaptive response of strawberry plants to drought stress (table 5).

Table 5. Effect of ZnO NPs treatment on root of strawberry.

No. of Treatment	D0	D1
T0ml	23	25
T50ml	25	32.66
T100ml	28	33.76
T200ml	29.33	23

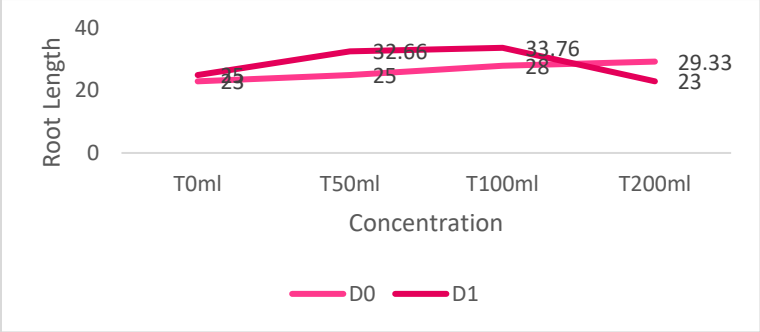

Figure. 3 Effect of ZnO NPs treatment on root of strawberry.

Root fresh weight

The foliar application of zinc oxide nanoparticles (ZnO-NPs) positively influenced root fresh weight under both well-watered (D0) and drought stress (D1) conditions. Under normal irrigation (D0), the untreated control (T0) recorded the lowest root fresh weight (1890 mg), whereas plants treated with 50 ppm (T50) exhibited the highest value (2564.23 mg), followed by 100 ppm (2447.50 mg) and 200 ppm (2365.23 mg). Under drought stress (D1), root fresh weight was markedly reduced in all treatments; however, foliar application of ZnO-NPs improved root biomass compared with the untreated control (987.23 mg). The highest root fresh weight under drought was observed at 200 ppm (1154.56 mg), closely followed by 100 ppm (1150.65 mg), while 50 ppm produced a value of 1021.54 mg. These findings indicate that ZnO-NP application alleviated the adverse effects of drought on root biomass, with moderate to higher concentrations (100–200 ppm) being more effective in maintaining root fresh weight under water-deficit conditions (table 6).

Table 6. Effect of ZnO NPs treatment on root fresh weight.

No. of treatment	**D0(conc)**	**D1(dro)**
T0ml	1890	987.23
T50ml	2564.23	1021.54
T100ml	2447.5	1150.65
T200ml	2365.23	1154.56

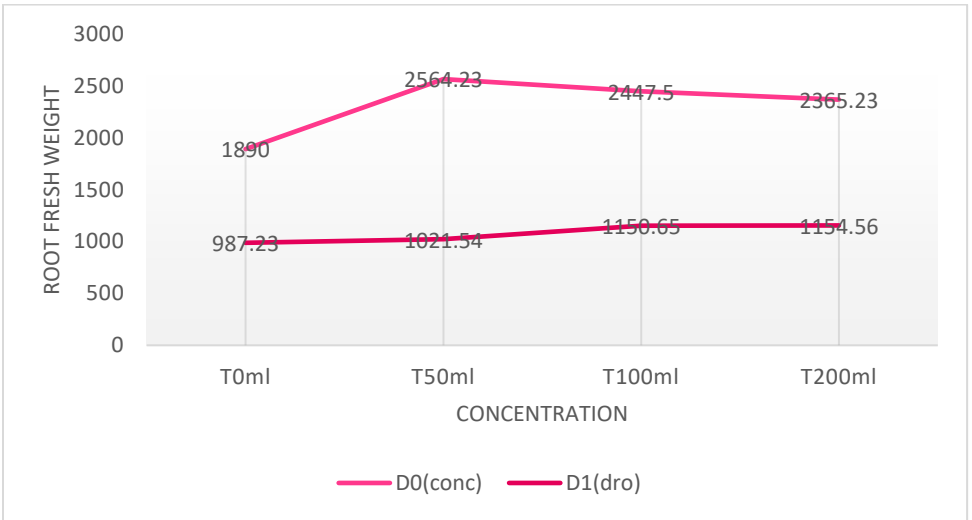

Figure. 4 Effect of ZnO NPs treatment on root fresh weight.

Root dry weight

The foliar application of zinc oxide nanoparticles (ZnO-NPs) significantly improved root dry weight under both well-watered (D0) and drought stress (D1) conditions. Under normal irrigation (D0), the untreated control (T0) recorded the lowest root dry weight (313.25 mg), while ZnO-NP-treated plants exhibited progressively higher values of 453.21 mg, 503.56 mg, and 506.44 mg at 50, 100, and 200 ppm, respectively. Under drought stress (D1), root dry weight declined across all treatments; however, ZnO-NP application alleviated the adverse effects of water deficit. The highest root dry weight (192.32 mg) was observed in plants treated with 100 ppm (T100), followed closely by 200 ppm (190.23 mg) and 50 ppm (182.50 mg), whereas the untreated control recorded the lowest value (152.75 mg). These results indicate that foliar application of ZnO-NPs enhanced root biomass accumulation and improved drought tolerance in strawberry plants, with 100 ppm proving to be the most effective concentration for maintaining root dry matter under water-stress conditions (table 7).

Table 7. Effect of ZnO NPs treatment on root dry weight

No. of Treatment	D0(conc)	D1(dro)
T0ml	313.25	152.75
T50ml	453.21	182.5
T100ml	503.56	192.32
T200ml	506.44	190.23

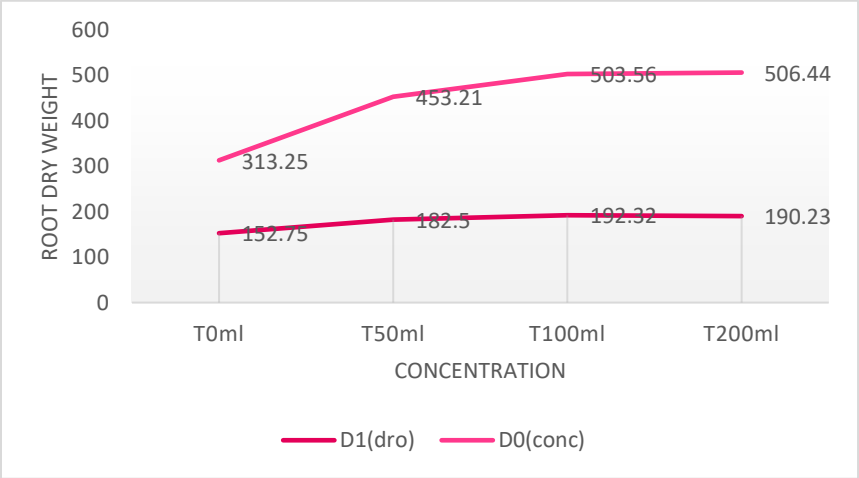

Figure. 5 Effect of ZnO NPs treatment on root dry weight

SPAD

The foliar application of zinc oxide nanoparticles (ZnO-NPs) enhanced chlorophyll content (SPAD values) in strawberry plants under both well-watered (D0) and drought stress (D1) conditions. Under normal irrigation (D0), SPAD values increased from 45.23 in the untreated control (T0) to 47.50, 49.35, and 49.65 following the application of 50, 100, and 200 ppm ZnO-NPs, respectively, indicating improved chlorophyll accumulation with increasing nanoparticle concentration. Under drought stress (D1), chlorophyll content declined in all treatments due to water limitation; however, ZnO-NP application partially alleviated this reduction. The highest SPAD value (35.96) was recorded in plants treated with 50 ppm (T50), followed by 33.76 at 100 ppm (T100), while both the untreated control (T0) and 200 ppm (T200) recorded 33.25. These findings suggest that foliar application of ZnO-NPs improved chlorophyll retention under drought conditions, with 50 ppm being the most effective concentration for maintaining photosynthetic pigments and reducing the detrimental effects of water stress on strawberry plants (table 8).

Table 8. Effect of ZnO NPs treatment on leaf chlorophyll content of strawberry.

No. of Treatment	D0	D1
T0ml	45.23	33.25
T50ml	47.5	35.96
T100ml	49.35	33.76
T200ml	49.65	33.25

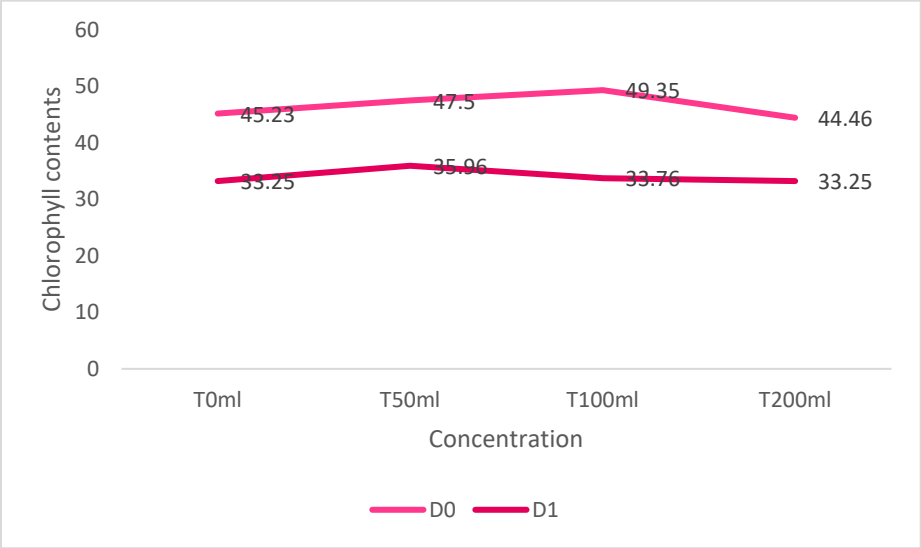

Figure. 6 Effect of ZnO NPs treatment on leaf chlorophyll content of strawberry.

Data analysis by variance (ANOVA) revealed that the Zno-Nps foliar treatment under drought stress was significant, and the individual effect of normal conditions was shown to be very significant for the chlorophyll content of the strawberry plant's leaves. Additionally, the combined effect of drought stress and ZnO NPs concentrations on the parameter was not statistically significant. Given this, statistical analysis revealed that the amount of chlorophyll in the leaves of strawberry plants may have been impacted by applied ZnO concentrations and drought stress. Furthermore, the parameter under study is impacted by the combined effects of drought stress and ZnO concentrations. As we can see from the comparison of the data, the concentration of ZnO nanoparticles in D1T4 (49.65) has the maximum effect on the SPAD level of the strawberry leaves.

Antioxidant enzymes

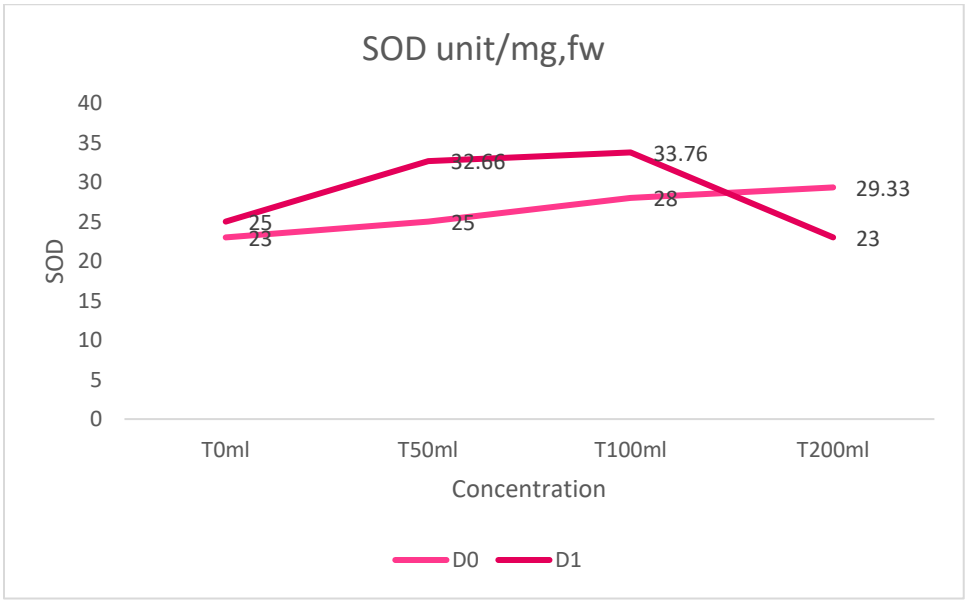

Figure. 7 Effect of ZnO NPs treatment on SOD of strawberry.

Water stress induction significantly raised the activity of the antioxidant enzymes like SOD (Fig. 7). In comparison to control plants, during drought stress, SOD activities were increased. ZnO-treated plants demonstrated an extra increase in SOD activities under both stress (drought) and non-stress (well-watered) conditions. However, SOD enzyme activity was calculated maximum in strawberry leaves under the treatment D1T3.

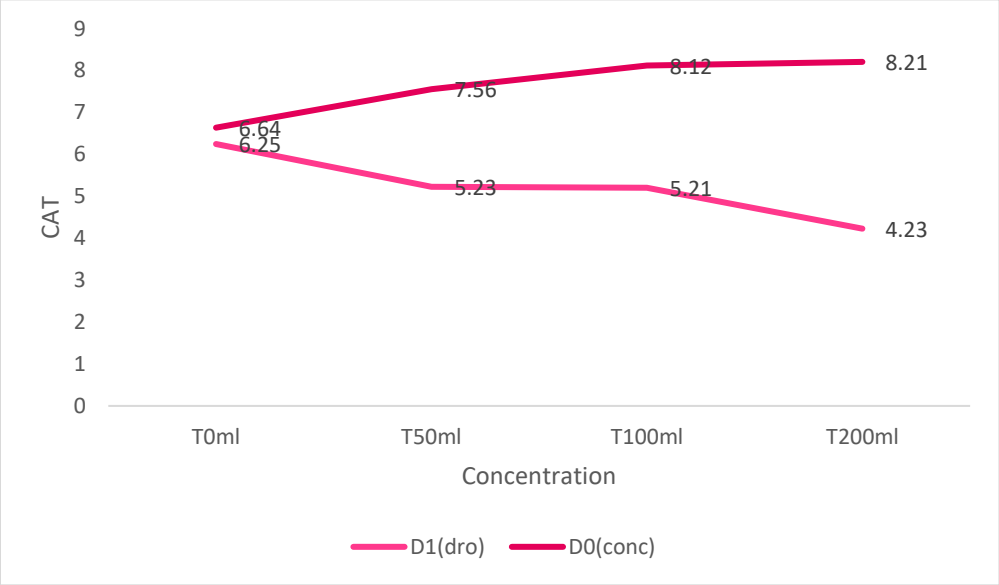

Figure. 8 Effect of ZnO NPs treatment on oxidation enzyme on CAT enzyme strawberry.

Water stress induction significantly raised the activity of the antioxidant enzymes SOD and CAT (Fig. 7&8). In comparison to control plants, during drought stress, SOD and CAT activities were increased. ZnO-treated plants demonstrated an extra increase in SOD and CAT activities under both stress (drought) and non-stress (well-watered) conditions. However, CAT enzyme activity was calculated maximum in strawberry leaves under the treatment D0T4.

DISCUSSION

It's a young and growing field of research, and it's clear that more progress will be made in the future so that this work may be applied to minimize the negative effects of abiotic stresses on plants. Zinc is a very important and scarce nutrient for plants. Interest in nanotechnology has been rapidly increasing in recent years due to its many potential uses in a variety of industries, including agriculture. Green synthetic zinc oxide nanoparticles (ZnO-NPs) have many advantages over ZnO-NPs made by traditional chemical processes. Due to their morphology, size, and shape, the biogenic zinc oxide nanoparticles that are produced may improve plant growth and production. As a matter of fact, the green synthesis approach leaves the environment mostly intact (Del Buono et al., 2021). Zinc (Zn) interacts with phospholipids and sulfhydryl groups to assist regulate and stabilize cell membranes, particularly in stressed plants. Recent investigation showed that ZnO-NPs enhanced physiological and biological activity under abiotic stress, including heavy metal, salt, cold, and drought (Kabir et al., 2021). The current study showed that treating ZnO-Nps enhanced the number of leaves. Our findings strongly support the ZnO regulates root development to withstand drought stress. In another study, researchers examined how ZnO Nps decreased shoot biomass and enhanced root development (Luca et al., 2022). The results showed that exogenous ZnO.NP increased SPAD value in tandem with the development of the chlorophyll fluorescence apparatus, hence improving aborigine resistance to drought stress. It's possible to attribute these positive outcomes of foliar ZnO NP administration to increased RWC and stabilized membrane integrity (Ghani et al., 2022). As ZnO concentrations increased in strawberry, greater activities of SOD and CAT were seen, demonstrating the significance of the coupled activity of these enzymes in guaranteeing the homeostasis redox. SOD is the first enzyme that protects against oxidative stress by converting O_2 - into H_2O_2, whereas CAT detoxifies H_2O_2. It's probable that the increase in SOD activity in both species results from the generation of H_2O_2, which activates the H_2O_2 signaling path. It has been shown that zinc is crucial for shielding plant cells from oxidative stress. The typical zinc content of whole strawberry grains is between 20 and 35 g kg-1 dry matter. Applying zinc topically to the strawberry roots greatly enhanced their development, which in turn increased their absorption of micronutrients (Ghani et al., 2022).

Conclusion

The findings of this study suggest that foliar application of green-synthesized zinc oxide nanoparticles (ZnO-NPs), prepared using *Calotropis gigantea* leaf extract, may improve the drought tolerance of strawberry plants. Different concentrations of ZnO-NPs influenced plant growth, chlorophyll content, and antioxidant enzyme activity under well-watered and drought-stress conditions, indicating their potential role in maintaining physiological functions and strengthening antioxidant defense mechanisms under water deficit. Moreover, the green synthesis of ZnO-NPs represents a promising approach for exploring environmentally conscious nanotechnology applications in agriculture. However, the

effectiveness of these nanoparticles depends on their concentration, application conditions, and drought severity. As yield and productivity were not directly measured, no conclusions can be drawn regarding their effects on strawberry fruit production. Further field validation is needed to establish appropriate application rates and assess nanoparticle accumulation and potential effects on soil and plant health. Overall, this study highlights the potential of green-synthesized ZnO-NPs as a foliar treatment for supporting the physiological performance of strawberry plants under drought stress.

Acknowledgement

The authors sincerely acknowledge the support and cooperation of their respective institutions and research facilities. Special thanks are extended to all individuals who contributed to the successful completion of this research.

Author contributions

All authors contributed to the conceptualization, methodology, data collection, and interpretation of the research findings. The manuscript was prepared, reviewed, and approved by all authors.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this research. No personal, financial, or institutional relationships influenced the study.

Ethics approval

All research activities were conducted in accordance with relevant ethical guidelines and research standards. No ethical concerns arose during the study, and necessary permissions were obtained where applicable.

Funding

We declare that there is no external funding for this work.

AI tool usage declaration

AI-assisted tools were used exclusively for language refinement, grammar correction, and improving manuscript readability. The authors reviewed, edited, and verified all content and take full responsibility for the accuracy and originality of the manuscript.

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