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Effects of nano oxide particles on the growth and photosynthetic characteristics of okra plant under water deficiency

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ABSTRACT

Drought, as abiotic stress, has significant detrimental effects on the growth, physiology, yield and nutritional quality of plants. The distinctive characteristics of nanoparticles (NPs) significantly contribute to essential physiological processes, indicating their considerable potential in promoting plant growth. This study investigated the effects of different NPs, including aluminium oxide nanoparticles (ANPs), silica nanoparticles (SNPs) and titanium dioxide nanoparticles (TNPs), on the growth and photosynthesis of okra (*Abelmoschus esculentus* L.) seedlings under drought stress conditions. The growth characteristics of okra plants were assessed after 48 days of watering. Photosynthetic parameters like photosynthetic rate, transpiration rate, intercellular CO_2 concentration (Ci), stomatal conductance and water use efficiency (WUE) were measured with a portable photosynthesis system. The results demonstrated that both ANPs and SNPs can promote the growth and photosynthesis activity of okra plants, with SNPs exhibiting a stronger effect compared to ANPs. The administration of 50 mg · kg^{-1} SNPs for a defined period demonstrated the most pronounced enhancement in growth and photosynthetic properties. In contrast, TNPs were found to have a significantly harmful influence on the growth and photosynthetic properties of the okra plant. These findings lay an important foundation for assessing the effects of nano oxide particles on okra plants.

Keywords: growth, nano oxide particles, okra (*Abelmoschus esculentus* L.), phenotypic traits, photosynthetic characteristics, seedlings, water deficit stress

INTRODUCTION

Nanotechnology has the potential to revolutionise the agriculture industry, offering a range of applications that can improve crop productivity, reduce waste and increase sustainability, including crop protection, nano-fertilisers, water management, soil quality, livestock production and so on (Wang et al., 2022; Gangwar et al., 2023; Wang et al., 2023). Nevertheless, a lot of research is needed to fully understand the impact of nanotechnology on crops, the environment and human health due to its complexity and diversity.

Nanoparticles (NPs) are particles with dimensions ranging from 1 nm to 100 nm, possessing unique physicochemical properties (Nel et al., 2006). NPs can enter plants through various pathways, including

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foliar uptake, root uptake, and through the stomatal openings. Once inside the plant, NPs can translocate to different organs, such as leaves, stems and roots, where they can directly or indirectly affect plant growth and development (Tumburu et al., 2017). The augmented crop growth was demonstrated through the utilisation of silver (Khan et al., 2021), copper (Hoang et al., 2019), silicon (Ahmad et al., 2020) and iron (Hoang et al., 2022) NPs. The utilisation of nano-iron by Dola et al. (2022) has revealed significant improvements in drought tolerance, yield and seed-quality of soybean. The exogenous foliar sprays containing 200 ppm can be effectively employed in soybean-growing regions to mitigate the losses caused by drought stress. Similar results also were observed in foliar application of nano zinc oxide (Faizan et al., 2020). The study of Shehzad et al. (2021) found that using zinc oxide (ZnO) NPs at a concentration of 0.15 mg · L^{-1} have increased secondary metabolite accumulation and silymarin content in milk thistle callus. The study elucidated that the combined application of 100 g · kg^{-1} sewage sludge and titanium dioxide NPs significantly improved the yield and biochemical properties of okra while concurrently reducing heavy metal accumulation (Kumar et al., 2022). The study of Zafar et al. (2021) demonstrated that the green synthesis of zinc NPs from *Sorghum bicolor* L. leaf extract effectively enhances okra plant growth and antioxidant activity under saline conditions, outperforming chemically synthesised counterparts, thereby presenting Zn-GNPs as a viable eco-friendly solution for mitigating salinity stress. And the application of green synthesised zinc oxide NPs significantly improved the growth parameters of okra under salt stress (Alabdallah and Alzahrani, 2020).

Okra, also known as lady's finger, is a green vegetable widely consumed in tropical and subtropical regions. It is a warm-season crop cultivated for its edible seed pods, harvested young and tender for culinary use. Okra is a rich source of vitamins A and C, dietary fibre and antioxidants (Gemede et al., 2015). However, drought significantly impacts okra growth, particularly during early development, leading to stunted plants, reduced stem length and leaf area and fewer, smaller pods with fewer seeds (Razi and Muneer, 2023). Water deficit also affects okra quality, diminishing nutritional and market value by reducing antioxidants, vitamin C and other essential nutrients (Wang et al., 2018). Furthermore, drought-stressed okra plants are more susceptible to diseases and pests, further compromising yield and quality. Therefore, managing water availability and employing irrigation methods are crucial to minimise the detrimental effects of water stress on okra production.

The current landscape of scientific research on abiotic stressors, particularly drought stress and the role of NPs, has gained considerable traction in light of mounting challenges associated with climate change and environmental degradation. Abiotic stressors refer to various environmental conditions that adversely impact plant growth and development, with drought stress emerging as a significant concern in many regions globally. Drought not only reduces water availability but also instigates intricate physiological and biochemical responses within plants, resulting in diminished photosynthetic efficiency, stunted growth and reduced crop yields (González, 2023). In parallel, the emergence of nanotechnology has positioned NPs as potential solutions to alleviate these adverse effects. Recent investigations have demonstrated that NPs, such as metal oxides and carbon-based materials, can enhance plant drought resilience through improved nutrient absorption, increased antioxidant activity and modulation of stress-related gene expression (Parsamian et al., 2023). The intersection of drought stress and NP application presents a significant opportunity in agricultural research, as scientists aim to create innovative strategies to improve plant health and productivity in an increasingly unpredictable climate. A comprehensive review of the existing literature reveals a growing consensus on the positive impact of NPs in mitigating drought stress (El-Saadony et al., 2022), yet further exploration is essential to clarify the underlying mechanisms and address potential environmental and health concerns surrounding their use. Therefore, understanding the synergistic effects of abiotic stressors and nanotechnology is crucial for advancing agricultural sustainability and resilience in the face of ongoing environmental challenges. While the influences of NPs on drought resistance in various crops are well documented, their application in okra plants has been insufficiently explored. Consequently, our research aims to evaluate the effects of nanooxide particles (AlO_2, TiO_2, SiO_2) on the growth and photosynthetic characteristics of okra under water deficit stress.

MATERIALS AND METHODS

In this study, three distinct types of NPs were utilised: aluminium oxide (Al_2O_3, aluminium oxide nanoparticles [ANPs]), silicon dioxide (SiO_2, silica nanoparticles [SNPs]) and titanium dioxide (TiO_2, titanium dioxide nanoparticles [TNPs]). These NPs, purchased from Beijing Dk Nano S&T Ltd. in China, exhibited nearly spherical morphology, with an average particle size of 40 nm.

The pot-experiment with five independent replicates was conducted in a greenhouse with a constant temperature (25 ± 2°C) and humidity (70 ± 5%) at Guiyang University. Okra seeds were cultivated into plastic buckets with a size of 28.0 cm (depth) × 26.0 cm (inner diameter), each pot contained 2 kg of nutrient-enriched soil. NPs (Al_2O_3, SiO_2 and TiO_2) were supplemented in soil with different dosages 0 mg · kg^{-1}, 10 mg · kg^{-1}, 20 mg · kg^{-1}, 30 mg · kg^{-1}, 50 mg · kg^{-1} and 70 mg · kg^{-1} before sowing. This experiment was carried out in a randomised block design. Ten seeds were grown in each pot, the seedlings were watered every 2 days after sprouting, then 10 days after acclimation, the plants

with NPs were watered every 6 days as water deficit condition, while the plants without NPs were watered every 3 days (not subjected to drought stress) as control. Over 48 days, with a total of eight drought treatments administered. Growth characteristics of okra plant were detected after watering 48 days, including height of plant (HP), moisture content (MC), root total length (RTL), number of green leaf (NGL), stem diameter (SD), length of main root (LMR), fresh weight of each plant (FW) and dry weight of each plant (DW). RTL, root projected area (RPA), root surface area (RSA) and leaf projected area (LPA) were measured by using WinRHIZO™ (pro LA2400, Canada). Photosynthetic parameters, including photosynthetic rate (A), transpiration rate (E), intercellular CO_2 concentration (Ci), stomatal conductance to water vapour (gsw), total conductivity to CO_2 (gtc), total conductivity to water vapour (gtw) and water use efficiency (WUE) were determined through portable photosynthesis measurement system (Li-COR LI-6800, USA) (Garen et al., 2022).

All data were presented as mean ± standard deviation of triplicate samples and analysed using one-way analysis of variance (ANOVA) followed by Duncan's test in SPSS 16.0 (IBM Corporation). The significance of treatment effects was considered at a p value <0.05. The subordinate function value method (Chen and Song, 2005) was employed to evaluate the drought resistance of okra plants comprehensively. The calculation of the membership function value was done using SPSS 16.0, with all parameters configured to their default settings. Membership functions can be constructed to represent the degree of tolerance, wherein different ranges of physiological indicators, like leaf water potential or stomatal conductance, are assigned values between 0 and 1. This allows for clear visualisation of tolerance levels, as plants exhibiting higher membership values display greater resilience to drought conditions. By integrating these fuzzy logic models, it becomes feasible to assess and compare the drought resistance of plants under different treatments.

RESULTS

The influence of NPs on growth of okra plant under water stress

The phenotypic traits of okra plants exposed to ANPs in water deficit stress conditions are shown in Table 1. HP, MC, RTL and NGL of plants showed a trend of initially increasing and then decreasing with the increase in ANPs concentration, the maximum value of that were all observed at 30 mg · kg^{-1} concentration under drought stress. The highest SD and LMR of plants were found at 70 mg · kg^{-1} concentration under water stress, which increased by 13.79% and 49.71%, respectively, compared to non-ANPs. Nevertheless, LPA of plants decreased with the increase in ANPs concentration. The remaining characteristics of plants exposed to ANPs subjected to water stress showed no significant differences.

As reported in Table 1, except for MC and NGL, all characteristics of plant exhibited a trend of initially increasing and then decreasing with the increase in SNPs concentration, the highest value of that were identified at 50 mg · kg^{-1} concentration under drought stress. Even, HP, SD and LMR of plants exposed to 50 mg · kg^{-1} SNPs under water deficit significantly increased by 12.28%, 13.36%, and 31.51%, respectively, compared to the control.

In TNPs (Table 1), HP, RTL, RPA and RSA of plants decreased compared non-TNPs under drought stress, except at 50 mg · kg^{-1} concentration. SD and LMR of plants exposed to 50 mg · kg^{-1} TNPs under water stress dramatically increased by 18.66% and 80.56%, respectively, when compared with TNPs-free treatment. No significant influence of TNPs was found in FW, dry DW and MC of okra plant.

The influence of NPs on photosynthesis of okra plant under water stress

From Table 2, ANPs application have no remarkable impact on the photosynthetic parameters of okra plant except gtw and gtc. The gtw of seedling exposed to 50 mg · kg^{-1} ANPs notably increased by 16.67% compared to that without ANPs under water deficit stress. The gtc of okra plants subjected to water stress augmented with the increase of ANPs concentration, the highest of that was investigated at 70 mg · kg^{-1} concentration, which increased by 40.00% compared with that non-ANPs treatment.

For SNPs (Table 2), most photosynthetic performances of okra plant subjected to drought stress showed an increasing trend followed by a decrease with the increase in concentration. All photosynthetic parameters of plants detected were the highest at 50 mg · kg^{-1} SNPs except WUE. In particular, WUE of the plant exposed to SNPs under water stress increased compared to the control except at 50 mg · kg^{-1} concentration. And WUE of plant was markedly improved by using SNPs at 10 mg · kg^{-1}, 20 mg · kg^{-1}, and 30 mg · kg^{-1} compared to that without SNPs under water deficit stress.

The data of photosynthetic physiological indexes in plants exposed to TNPs were recorded in Table 2. It was found that E, A, and Ci of plant were significantly reduced by additive TNPs under drought stress. And the application of TNPs also decreased the gsw, gtw, and gtc of plant compared to TNPs-free treatment under water deficit stress, except TNPs at a concentration of 50 mg · kg^{-1}. WUE of plants under water stress were dramatically decreased by 24.06% and 32.09%, respectively, by application of TNPs with a concentration of 30 mg · kg^{-1} and 70 mg · kg^{-1}, as compared to that without TNPs.

Correlation analysis

Based on the analysis of the correlation between various traits in okra plant exposed to ANPs (Figure 1), WUE

Table 1. Growth parameters of okra plant treated with NPs under water stress.

NPs	Concentration	Irrigation	HP (mm)	SD (mm)	LMR (mm)	FW (g)	DW (g)	MC	RTL (cm)	RPA (cm^2)	RSA (cm^2)	LPA (cm^2)	NGL
ANPs	0	Control	176.88 ± 5.64 a	3.21 ± 0.10 a	64.31 ± 3.52 a	5.02 ± 1.88 a	0.48 ± 0.13 a	0.90 ± 0.02 a	129.61 ± 1.08 a	3.98 ± 0.51 a	12.51 ± 1.6 a	63.91 ± 7.29 a	5.09 ± 0.36 a
	0	Water stress	110.65 ± 3.12 d	2.03 ± 0.07 d	41.56 ± 1.51 b	1.32 ± 0.30 b	0.16 ± 0.05 b	0.88 ± 0.01 c	36.90 ± 2.75 c	0.91 ± 0.13 b	2.86 ± 0.39 b	23.32 ± 1.69 b	2.80 ± 0.31 bc
	10		134.84 ± 4.63 c	2.05 ± 0.04 d	42.22 ± 5.19 b	1.25 ± 0.08 b	0.15 ± 0.01 b	0.88 ± 0.00 c	42.23 ± 2.84 bc	1.04 ± 0.04 b	3.26 ± 0.13 b	18.64 ± 1.20 bc	2.49 ± 0.16 c
	20		139.09 ± 3.90 bc	1.97 ± 0.04 d	46.84 ± 2.8 b	1.32 ± 0.08 b	0.15 ± 0.01 b	0.88 ± 0.00 c	43.18 ± 4.44 bc	0.94 ± 0.11 b	2.97 ± 0.36 b	18.89 ± 0.44 bc	2.54 ± 0.26 bc
	30		143.04 ± 3.17 b	2.18 ± 0.05 c	47.23 ± 2.38 b	1.59 ± 0.18 b	0.16 ± 0.03 b	0.90 ± 0.01 ab	49.57 ± 7.20 b	1.20 ± 0.16 b	3.77 ± 0.49 b	15.17 ± 0.29 c	3.13 ± 0.64 b
	50		114.90 ± 2.02 d	2.07 ± 0.04 d	44.29 ± 4.14 b	1.10 ± 0.09 b	0.12 ± 0.02 b	0.89 ± 0.01 bc	47.74 ± 12.53 b	1.00 ± 0.20 b	3.15 ± 0.62 b	16.16 ± 0.69 c	2.67 ± 0.21 bc
	70		115.14 ± 2.69 d	2.31 ± 0.11 b	62.22 ± 1.55 a	1.28 ± 0.08 b	0.14 ± 0.01 b	0.89 ± 0.00 bc	33.96 ± 2.94 c	0.95 ± 0.10 b	2.98 ± 0.32 b	14.24 ± 0.65 c	2.83 ± 0.16 bc
SNPs	0	Control	180.6 ± 6.87 b	3.07 ± 0.03 b	65.48 ± 3.58 c	4.09 ± 0.37 a	0.52 ± 0.04 a	0.87 ± 0.01 a	128.90 ± 2.38 a	3.78 ± 0.20 a	12.35 ± 2.11 a	50.22 ± 6.00 b	4.02 ± 0.38 a
	0	Water stress	109.72 ± 1.04 e	2.18 ± 0.09 d	41.71 ± 1.50 d	0.99 ± 0.10 c	0.12 ± 0.01 c	0.88 ± 0.00 a	31.72 ± 5.43 f	1.14 ± 0.34 b	3.59 ± 1.06 b	13.25 ± 0.55 e	3.01 ± 0.48 b
	10		120.79 ± 3.36 cd	2.58 ± 0.09 c	65.11 ± 3.65 c	1.68 ± 0.23 bc	0.19 ± 0.05 bc	0.89 ± 0.01 a	45.89 ± 1.85 e	1.74 ± 0.34 b	5.46 ± 1.07 b	19.97 ± 2.41 d	3.19 ± 0.49 ab
	20		125.63 ± 3.26 c	2.43 ± 0.03 c	65.31 ± 3.72 c	1.51 ± 0.82 bc	0.13 ± 0.04 c	0.88 ± 0.09 a	57.08 ± 4.18 d	1.94 ± 0.32 b	6.09 ± 1.01 b	19.04 ± 1.19 d	3.39 ± 0.79 ab
	30		123.34 ± 9.99 c	2.55 ± 0.05 c	76.07 ± 1.91 b	2.00 ± 0.13 bc	0.23 ± 0.01 bc	0.89 ± 0.01 a	78.51 ± 0.84 d	1.84 ± 0.46 b	5.77 ± 1.43 b	27.93 ± 3.15 c	3.57 ± 0.40 ab
	50		202.77 ± 5.61 a	3.48 ± 0.17 a	86.11 ± 3.13 a	4.62 ± 1.72 a	0.51 ± 0.19 a	0.88 ± 0.04 a	116.92 ± 11.79 b	4.02 ± 1.52 a	12.61 ± 4.78 a	60.31 ± 1.53 a	3.67 ± 0.58 ab
	70		113.11 ± 4.19 de	2.60 ± 0.16 bc	61.06 ± 0.75 c	2.33 ± 0.20 b	0.28 ± 0.06 b	0.88 ± 0.02 a	78.24 ± 2.68 c	3.21 ± 0.87 a	9.01 ± 0.90 b	22.24 ± 0.71 d	3.75 ± 0.66 ab
TNPs	0	Control	171.22 ± 4.60 a	3.28 ± 0.21 a	70.02 ± 2.06 b	5.50 ± 2.24 a	0.50 ± 0.12 a	0.90 ± 0.02 a	121.58 ± 8.92 a	3.48 ± 0.34 a	11.27 ± 0.52 a	65.47 ± 2.77 a	5.49 ± 1.22 a
	0	Water stress	111.58 ± 1.66 b	2.09 ± 0.03 c	43.31 ± 1.08 e	2.28 ± 1.30 b	0.21 ± 0.12 b	0.91 ± 0.01 a	34.59 ± 1.00 b	0.92 ± 0.10 b	2.89 ± 0.33 b	28.74 ± 0.64 b	3.67 ± 0.76 b
	10		69.35 ± 6.50 d	2.20 ± 0.04 c	25.70 ± 1.85 g	0.73 ± 0.06 b	0.07 ± 0.01 b	0.90 ± 0.01 a	23.42 ± 3.21 c	0.49 ± 0.10 c	1.54 ± 0.35 c	6.48 ± 0.53 de	3.83 ± 0.29 ab
	20		47.90 ± 2.19 f	2.23 ± 0.07 c	55.09 ± 2.39 d	0.83 ± 0.36 b	0.13 ± 0.12 b	0.86 ± 0.07 a	17.73 ± 0.54 cd	0.36 ± 0.01 c	1.11 ± 0.04 c	7.73 ± 1.58 d	4.56 ± 0.51 ab
	30		61.60 ± 3.86 e	2.23 ± 0.05 c	61.03 ± 0.72 c	0.85 ± 0.14 b	0.10 ± 0.03 b	0.89 ± 0.01 a	15.87 ± 0.59 d	0.38 ± 0.05 c	1.19 ± 0.16 c	8.60 ± 1.26 d	4.44 ± 0.51 ab
	50		96.20 ± 4.31 c	2.48 ± 0.11 b	78.20 ± 2.45 a	1.58 ± 0.22 b	0.14 ± 0.07 b	0.91 ± 0.04 a	28.53 ± 2.35 bc	0.77 ± 0.19 b	2.40 ± 0.60 b	13.46 ± 1.46 c	3.50 ± 1.80 b
	70		66.31 ± 5.38 de	2.11 ± 0.11 c	33.88 ± 3.70 f	0.81 ± 0.09 b	0.08 ± 0.02 b	0.90 ± 0.01 a	11.63 ± 0.45 d	0.33 ± 0.04 c	1.04 ± 0.11 c	4.70 ± 0.40 e	4.08 ± 0.14 ab

ANPs, aluminium oxide nanoparticles; DW, dry weight of each plant; FW, fresh weight of each plant; HP, height of plant; LPA, leaf projected area; MC, moisture content; NGL, number of green leaf; NPs, nanoparticles; RPA, root projected area; RSA, root surface area; RTL, root total length; SD, stem diameter; SNPs, silica nanoparticles; TNPs, titanium dioxide nanoparticles.
Different lowercase letters showed significant differences among treatments at $p \leq 0.05$.

Table 2. Photosynthesis characteristics of seedlings in okra treated with NPs under water stress.

NPs	Concentration	Irrigation	Photosynthesis parameters						
			E ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	A ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Ci ($\mu mol \cdot mol^{-1}$)	gsw ($mol \cdot m^{-2} \cdot s^{-1}$)	gtw ($mol \cdot m^{-2} \cdot s^{-1}$)	gtc ($mol \cdot m^{-2} \cdot s^{-1}$)	WUE ($\mu mol \cdot m^{-2} \cdot s^{-1}$)
ANPs	0	Control	7.52 ± 0.39 a	14.28 ± 0.38 a	321.43 ± 9.25 a	0.35 ± 0.02 a	0.31 ± 0.00 a	0.20 ± 0.01 a	1.90 ± 0.14 c
	0	Water stress	2.10 ± 0.06 b	7.99 ± 0.12 b	206.61 ± 13.62 b	0.09 ± 0.01 bc	0.10 ± 0.00 c	0.06 ± 0.00 e	3.81 ± 0.17 ab
	10		2.56 ± 0.40 b	7.95 ± 0.42 b	207.07 ± 12.81 b	0.09 ± 0.01 bc	0.10 ± 0.01 c	0.06 ± 0.00 e	3.15 ± 0.53 ab
	20		2.60 ± 0.34 b	7.82 ± 0.25 b	215.40 ± 8.05 b	0.08 ± 0.00 c	0.10 ± 0.00 c	0.07 ± 0.00 d	3.05 ± 0.49 b
	30		2.55 ± 0.35 b	7.63 ± 0.40 b	219.72 ± 14.28 b	0.09 ± 0.01 bc	0.11 ± 0.00 bc	0.07 ± 0.00 d	3.02 ± 0.35 b
	50		2.12 ± 0.08 b	8.06 ± 0.62 b	222.33 ± 4.49 b	0.10 ± 0.02 b	0.12 ± 0.01 b	0.08 ± 0.00 c	3.82 ± 0.43 a
	70		2.44 ± 0.41 b	7.81 ± 0.37 b	217.09 ± 11.86 b	0.09 ± 0.01 bc	0.10 ± 0.01 c	0.10 ± 0.00 b	3.24 ± 0.39 ab
SNPs	0	Control	7.14 ± 0.56 b	13.87 ± 0.63 ab	317.39 ± 8.41 b	0.34 ± 0.03 b	0.31 ± 0.01 b	0.20 ± 0.01 b	1.95 ± 0.07 e
	0	Water stress	2.00 ± 0.07 d	7.89 ± 0.51 e	204.87 ± 12.62 e	0.10 ± 0.01 f	0.10 ± 0.00 g	0.06 ± 0.00 f	3.95 ± 0.18 d
	10		2.19 ± 0.02 d	10.09 ± 0.30 d	263.00 ± 3.46 d	0.16 ± 0.01 e	0.14 ± 0.00 f	0.09 ± 0.00 e	4.61 ± 0.10 b
	20		2.53 ± 0.06 d	10.98 ± 0.69 d	274.91 ± 4.08 c	0.21 ± 0.00 d	0.16 ± 0.01 e	0.10 ± 0.00 d	4.33 ± 0.20 c
	30		2.72 ± 0.05 cd	13.21 ± 0.46 bc	314.89 ± 6.55 b	0.29 ± 0.01 c	0.25 ± 0.00 d	0.15 ± 0.00 c	4.86 ± 0.08 a
	50		7.73 ± 0.57 a	14.67 ± 0.83 a	346.95 ± 1.54 a	0.41 ± 0.04 a	0.36 ± 0.01 a	0.23 ± 0.00 a	1.9 ± 0.04 e
	70		3.17 ± 0.10 c	12.35 ± 0.10 c	319.89 ± 2.76 b	0.27 ± 0.01 c	0.26 ± 0.01 c	0.16 ± 0.00 c	3.9 ± 0.14 d
TNPs	0	Control	7.62 ± 0.63 a	13.43 ± 1.09 a	322.16 ± 2.87 a	0.35 ± 0.03 a	0.31 ± 0.00 a	0.20 ± 0.02 a	1.77 ± 0.19 c
	0	Water stress	2.16 ± 0.10 b	8.07 ± 0.49 b	216.04 ± 1.38 b	0.10 ± 0.01 b	0.10 ± 0.00 b	0.06 ± 0.00 b	3.74 ± 0.36 a
	10		1.65 ± 0.09 c	6.61 ± 0.86 c	190.11 ± 2.74 d	0.06 ± 0.00 c	0.06 ± 0.00 c	0.04 ± 0.00 c	4.01 ± 0.31 a
	20		1.37 ± 0.05 c	5.46 ± 0.14 d	148.45 ± 5.27 f	0.04 ± 0.00 c	0.04 ± 0.00 e	0.03 ± 0.00 c	4.00 ± 0.24 a
	30		1.22 ± 0.07 c	3.45 ± 0.31 e	162.88 ± 6.54 e	0.05 ± 0.00 c	0.05 ± 0.00 d	0.03 ± 0.00 c	2.84 ± 0.39 b
	50		1.91 ± 0.05 bc	7.51 ± 0.3 bc	204.84 ± 1.11 c	0.09 ± 0.00 b	0.09 ± 0.00 b	0.06 ± 0.00 b	3.93 ± 0.25 a
	70		1.30 ± 0.05 c	3.29 ± 0.08 e	152.70 ± 2.34 f	0.04 ± 0.00 c	0.04 ± 0.00 e	0.03 ± 0.00 c	2.54 ± 0.09 b

A, photosynthetic rate; ANPs, aluminium oxide nanoparticles; Ci, intercellular CO_2 concentration; E, transpiration rate; gsw, stomatal conductance to water vapour; gtc, total conductivity to CO_2; gtw, total conductivity to water vapour; NPs, nanoparticles; SNPs, silica nanoparticles; TNPs, titanium dioxide nanoparticles; WUE, water use efficiency.

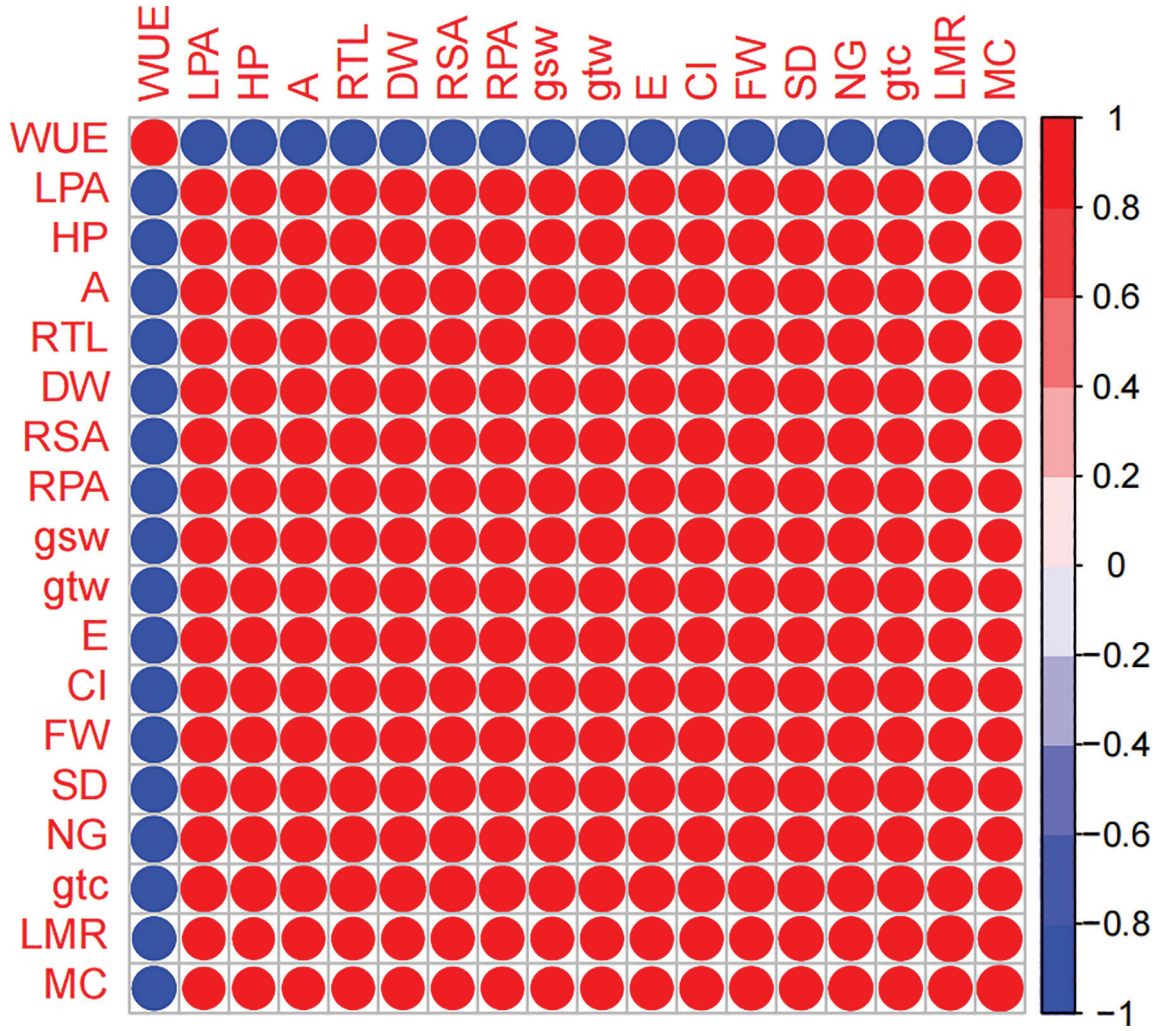

Figure 1. The correlation coefficient of okra plant treated with ANPs under water stress. A, photosynthetic rate; ANPs, aluminium oxide nanoparticles; Ci, intercellular CO_2 concentration; DW, dry weight of each plant; E, transpiration rate; FW, fresh weight of each plant; gsw, stomatal conductance to water vapour; gtc, total conductivity to CO_2; gtw, total conductivity to water vapour; HP, height of plant; LPA, leaf projected area; MC, moisture content; NPs, nanoparticles; RPA, root projected area; RSA, root surface area; RTL, root total length; SD, stem diameter; WUE, water use efficiency.

exhibited a significant negative correlation with other measured parameters, whereas there was a significant positive correlation among the remaining indicators. A similar correlation coefficient was determined in the plant treated by SNPs (Figure 2), WUE also showed a significant negative correlation with all indicators except for LMR and MC. NGL has a significant positive correlation with FW, DW, RTL, RPA, RSA, E, A, Ci, gsw, gtw, and gtc. However, no correlation was found between MC and other measured indicators. Significant correlations were observed between the remaining indicators. The analysis of okra plant with TNPs (Figure 3) revealed a significant negative correlation between WUE and all measured indicators, except length of main root (LMR), MC, and area (A). Similarly, HP has a significant positive correlation with all indicators except for LMR, MC and NGL. NGL exhibited a significant positive correlation with SD, FW, DW, RPA, RSA, E, gsw, gtw, and gtc. Significant correlations were observed between LMR and RPA, RSA, gsw, gtw and gtc. Also, there were notable correlations identified among the remaining indicators.

Drought resistance evaluation of okra plants

Regarding the function values of phenotypic characteristics, okra plant exposed to 50 mg · kg^{-1} SNPs exhibited the highest drought tolerance, followed by the application of 30 mg · kg^{-1} ANPs (Table 3). Moreover, all SNPs treatment, and ANPs addition except for at 50 mg · kg^{-1} concentration have higher drought tolerance compared to the control. Nonetheless, the function values of okra plants treated with TNPs were significantly lower compared to the control, suggesting that the addition of TNPs may have an inhibitory effect on the growth of okra plants under water stress.

Considering the function values of photosynthetic parameters (Table 4), SNPs application can significantly

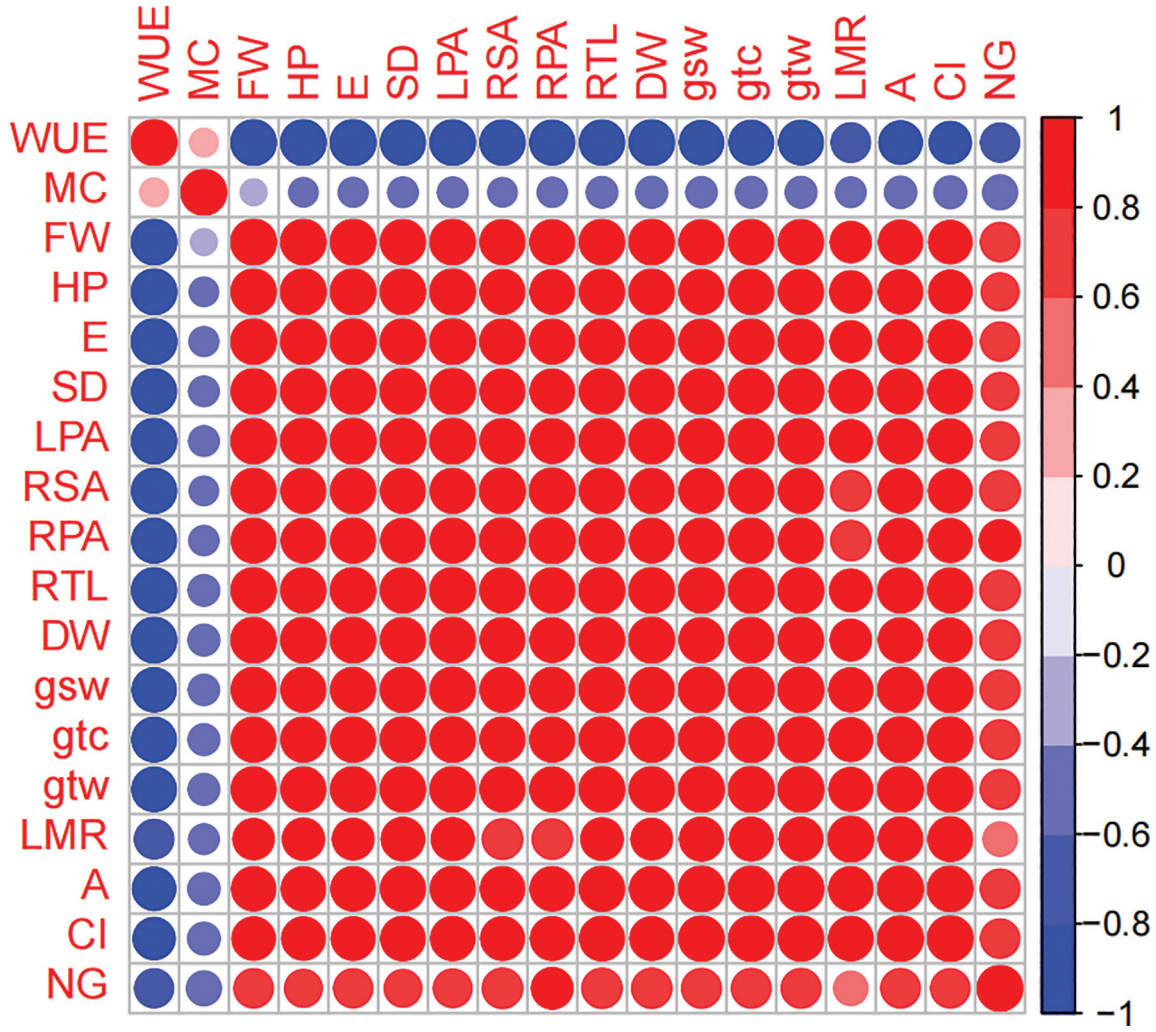

Figure 2. The correlation coefficient of okra plant treated with SNPs under water stress. A, photosynthetic rate; Ci, intercellular CO_2 concentration; DW, dry weight of each plant; E, transpiration rate; FW, fresh weight of each plant; gsw, stomatal conductance to water vapour; gtc, total conductivity to CO_2; gtw, total conductivity to water vapour; HP, height of plant; LPA, leaf projected area; MC, moisture content; NPs, nanoparticles; RPA, root projected area; RSA, root surface area; RTL, root total length; SD, stem diameter; SNPs, silica nanoparticles; WUE, water use efficiency.

improve the drought tolerance of okra plant under water deficit stress compared to the control, while drought resistance of plant has been significantly reduced by using TNPs. It also found that okra plant exposed to 50 mg · kg^{-1} and 70 mg · kg^{-1} ANPs have higher drought tolerance compared to the control.

DISCUSSION

Our study focused on the effects of nano oxide particles, ANPs, SNPs and TNPs, on the growth of okra plants. It was observed that both ANPs and SNPs had a positive effect on the growth of okra, with SNPs exhibiting a stronger effect compared to ANPs. Specifically, the treatment with 50 mg · kg^{-1} of SNPs showed the most significant improvement in okra growth. Conversely, the treatment with TNPs resulted in a clear inhibition of okra growth. These findings highlight the potential of NPs in promoting or inhibiting plant growth under drought conditions. Similar results have also been reported in other plants, SNPs can improve the water absorption capacity of root systems by promoting the growth of root in hawthorn, thereby, making it more resistant to drought stress (Ashkavand et al., 2015). The study by Khan et al. (2020) have also found that SNPs treatments improved plant growth indicators and photosynthesis, and reduced cadmium concentrations in wheat tissues, particularly in grains, both with and without drought stress. The differential effects of ANPs, SNPs and TNPs on okra growth can be attributed to their unique physicochemical properties. SNPs have been shown to enhance potato plant growth by improving Si concentration in shoot, photosynthetic efficiency and antioxidant activity (Saadatian et al., 2022). The smaller size and higher surface area of SNPs compared to ANPs may facilitate better nutrient absorption, water retention and root development, thereby enhancing plant growth under water deficit stress. The findings of Yue et al. (2017) imply that exuded biomolecules or associated microbial activity display a key role in altering NPs

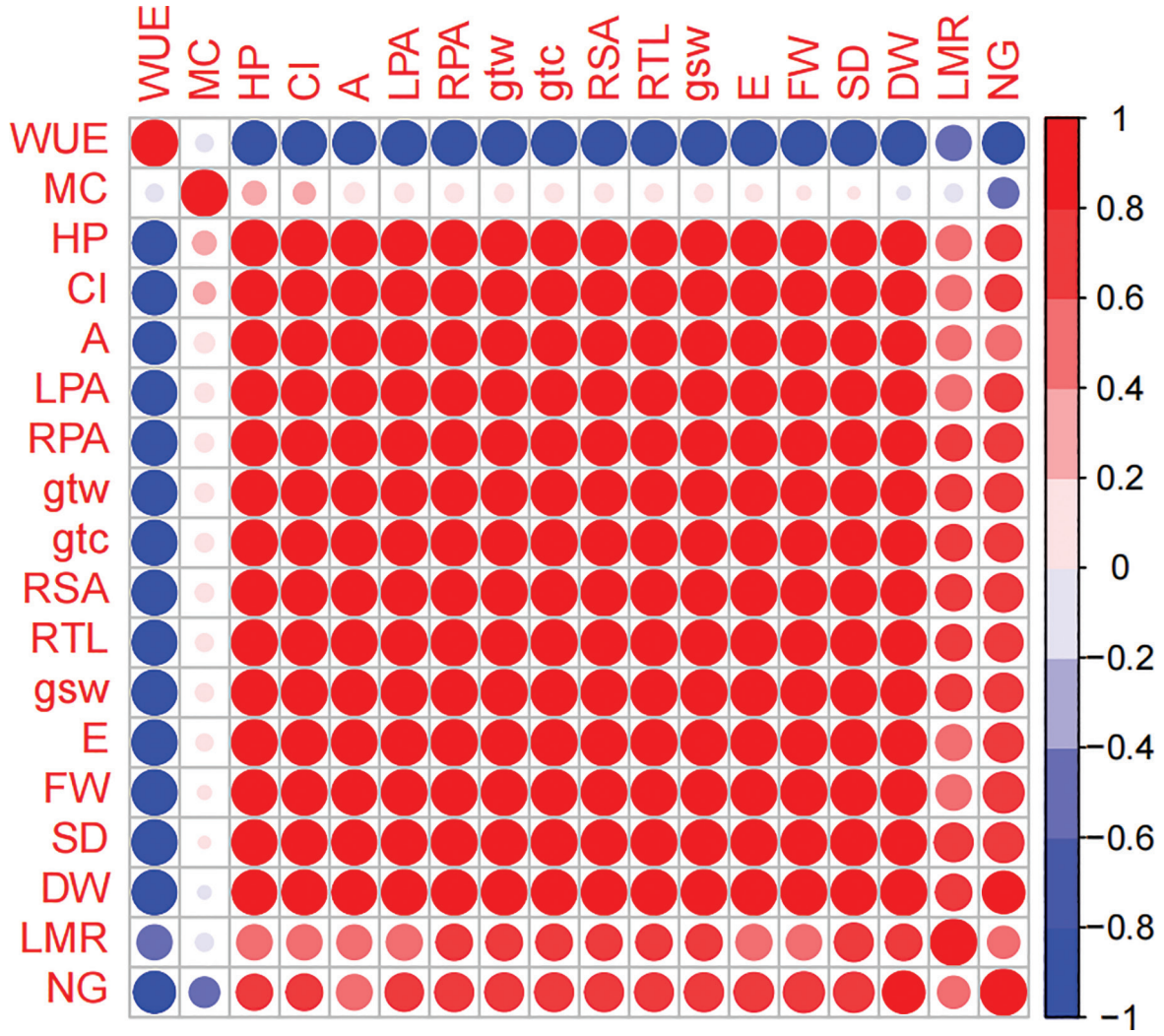

Figure 3. The correlation coefficient of okra plant treated with TNPs under water stress. A, photosynthetic rate; Ci, intercellular CO_2 concentration; DW, dry weight of each plant; E, transpiration rate; FW, fresh weight of each plant; gsw, stomatal conductance to water vapour; gtc, total conductivity to CO_2; gtw, total conductivity to water vapour; HP, height of plant; LPA, leaf projected area; MC, moisture content; NPs, nanoparticles; RPA, root projected area; RSA, root surface area; RTL, root total length; SD, stem diameter; TNPs, titanium dioxide nanoparticles; WUE, water use efficiency.

dissolution and dramatically altering NPs uptake by plants. Hence, the more significant promoting effect of SNPs on the growth of okra may be associated with improvement in rhizospheric microbiome, which has been confirmed by the study of Rajput et al. (2021). On the other hand, TNPs may inhibit okra growth due to their potential toxicity at certain concentrations or their interference with physiological processes such as stomatal conductance and water uptake, which is in agreement with the findings in lettuce (Zahra et al., 2015). However, the increase of SD and LMR of okra plant exposed to TNPs at the concentration of 50 mg · kg^{-1} suggested that the potential influence of varying concentrations on different growth indicators may not be consistent. As per the report from Chavan et al. (2020), TNPs or non-toxic TNPs can serve as valuable fertiliser, effectively enhancing agricultural productivity and soil health, ultimately contributing to increased food production. The study of Yang et al. (2007) also has demonstrated that the improvement of spinach growth can be attributed to the nitrogen fixation process facilitated by nano-anatase TiO_2. Therefore, further research is needed to investigate the mechanisms by which NPs promote or inhibit the growth of okra plant under drought stress.

In addition, the impact of NPs on the photosynthetic activity of okra plant under drought conditions has also been investigated in this present study. It has been observed that ANPs can enhance the gtc and gtw of okra plant under drought stress. On the other hand, SNPs have shown a significant promotion of the photosynthetic parameters of okra plant under water deficit stress, except for the WUE at a concentration of 50 mg · kg^{-1}. Similar to the effects on the growth of okra plant, the promotion of photosynthesis is most pronounced when okra is treated with 50 mg · kg^{-1} of

Table 3. The function values of phenotypic characteristics in okra plant with NPs under water stress.

NPs	Concentration ($mg \cdot kg^{-1}$)	Phenotypic characteristics											Sum	Order
		HP	SD	LMR	FW	DW	MC	RTL	RPA	RSA	LPA	NGL		
ANPs	0	0.00	0.18	0.00	0.46	0.95	0.00	0.19	0.00	0.00	1.00	0.49	3.27	12
	10	0.75	0.26	0.03	0.31	0.64	0.10	0.53	0.44	0.44	0.48	0.00	3.98	8
	20	0.88	0.00	0.26	0.45	0.80	0.18	0.59	0.11	0.11	0.51	0.08	3.97	9
	30	1.00	0.63	0.27	1.00	1.00	1.00	1.00	1.00	1.00	0.10	1.00	9.00	2
	50	0.13	0.29	0.13	0.00	0.00	0.50	0.88	0.31	0.31	0.21	0.28	3.04	13
	70	0.14	1.00	1.00	0.38	0.41	0.66	0.00	0.13	0.13	0.00	0.53	4.38	7
SNPs	0	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.10	18
	10	0.12	0.31	0.53	0.19	0.18	1.00	0.17	0.21	0.21	0.14	0.24	3.30	11
	20	0.17	0.19	0.53	0.15	0.04	0.00	0.30	0.28	0.28	0.12	0.51	2.57	16
	30	0.15	0.29	0.77	0.28	0.28	0.64	0.55	0.24	0.24	0.31	0.75	4.50	6
	50	1.00	1.00	1.00	1.00	1.00	0.47	1.00	1.00	1.00	1.00	0.89	10.36	1
	70	0.04	0.33	0.44	0.37	0.42	0.03	0.55	0.72	0.60	0.19	1.00	4.69	5
TNPs	0	1.00	0.00	0.34	1.00	1.00	0.91	1.00	1.00	1.00	1.00	0.16	8.41	3
	10	0.34	0.28	0.00	0.00	0.00	0.79	0.51	0.27	0.27	0.07	0.32	2.85	15
	20	0.00	0.37	0.56	0.06	0.43	0.00	0.27	0.04	0.04	0.13	1.00	2.90	14
	30	0.22	0.37	0.67	0.08	0.18	0.52	0.18	0.08	0.08	0.16	0.89	3.43	10
	50	0.76	1.00	1.00	0.55	0.49	1.00	0.74	0.74	0.74	0.36	0.00	7.38	4
	70	0.29	0.05	0.16	0.05	0.03	0.86	0.00	0.00	0.00	0.00	0.55	1.99	17

ANPs, aluminium oxide nanoparticles; DW, dry weight of each plant; FW, fresh weight of each plant; HP, height of plant; LMR, length of main root; LPA, leaf projected area; MC, moisture content; NGL, number of green leaves; NPs, nanoparticles; RPA, root projected area; RSA, root surface area; RTL, root total length; SD, stem diameter; SNPs, silica nanoparticles; TNPs, titanium dioxide nanoparticles.

Table 4. The function values of photosynthetic parameters in okra plant with NPs under water stress.

NPs	Concentration ($mg \cdot kg^{-1}$)	Photosynthetic parameters							Sum	Order
		E	A	Ci	gsw	gtw	gtc	WUE		
ANPs	0	1.00	0.83	0.00	0.58	0.00	0.00	0.99	3.40	9
	10	0.71	0.75	0.03	0.56	0.35	0.05	0.16	2.61	13
	20	0.77	0.45	0.56	0.80	0.39	0.11	0.03	3.11	10
	30	0.69	0.00	0.83	0.60	0.46	0.21	0.00	2.79	11
	50	0.00	1.00	1.00	0.00	1.00	0.36	1.00	4.36	4
	70	0.51	0.41	0.67	1.00	0.38	1.00	0.28	4.25	6
SNPs	0	0.00	0.00	0.00	0.00	0.00	0.00	0.69	0.69	17
	10	0.03	0.32	0.41	0.21	0.14	0.16	0.92	2.19	14
	20	0.09	0.46	0.49	0.36	0.20	0.22	0.82	2.64	12
	30	0.13	0.78	0.77	0.62	0.48	0.56	1.00	4.34	5
	50	1.00	1.00	1.00	1.00	0.85	1.00	0.00	5.85	3
	70	0.20	0.66	0.81	0.57	0.52	0.61	0.68	4.05	7
TNPs	0	1.00	1.00	0.85	0.54	1.00	1.00	0.82	6.21	1
	10	0.45	0.70	0.52	0.16	0.40	0.23	1.00	3.46	8
	20	0.16	0.45	0.00	0.01	0.07	0.00	0.99	1.68	15
	30	0.00	0.03	0.18	0.09	0.20	0.05	0.21	0.76	16
	50	0.74	0.46	1.00	1.00	0.95	0.93	0.95	6.03	2
	70	0.08	0.00	0.05	0.00	0.00	0.03	0.00	0.16	18

A, photosynthetic rate; ANPs, aluminium oxide nanoparticles; Ci, intercellular CO_2 concentration; E, transpiration rate; gsw, stomatal conductance to water vapour; gtc, total conductivity to CO_2; gtw, total conductivity to water vapour; NPs, nanoparticles; SNPs, silica nanoparticles; TNPs, titanium dioxide nanoparticles; WUE, water use efficiency.

SNPs. Conversely, TNPs have been found to inhibit the activity of the photosynthetic apparatus in okra plant. The effects of NPs on the photosynthetic activity of okra are consistent with results reported in potato by using foliar spraying SNPs (Saadatian et al., 2022). The promotion of photosynthesis by SNPs could be their ability to enhance the efficiency of light absorption and utilisation in okra leaves. Additionally, SNPs may contribute to the regulation of stomatal conductance, allowing for improved gas exchange and WUE. SNPs addition can enhance Si uptake, which can regulate the activities of the main photosynthetic enzymes of Calvin cycle, especially for RubisCO, thereby, boosting the photosynthetic responses (Mateos-Naranjo et al., 2015). ANPs have been shown to increase gtw and gtc of okra plant under water stress probably by altering photosynthetic pigments and photosystem components. Conversely, the harmful impact of ANPs on wheat was reported by Yanık and Vardar (2018), which resulted in the induction of oxidative stress within plants, and led to damage of the photosynthetic pigment systems. The possible disparity may be related to the concentration, method and duration of ANPs application. On the other hand, the inhibitory effect of TNPs on photosynthesis could be attributed to their interference with chloroplast structure and function, leading to reduced efficiency in light capture and utilisation. As reported by Dias et al. (2019), TNPs can decrease chlorophyll content and inhibit the efficiency of photosystem II in wheat by interfering with the electron transport chain, which can lead to a decreased photosynthetic rate and biomass production. TNPs also was found to adversely affect the antioxidant defence system in plants, leading to the production of reactive oxygen species (ROS) and damage to cell membranes, ultimately causing a reduction in photosynthetic capacity (Gangwar et al., 2023). Certain types of nanomaterials can be taken up by plants and translocated to various parts of the plant, including the leaves. This can have direct or indirect effects on the photosynthetic process of plants. Due to their small size, NPs can penetrate plant tissues and interact with cellular components, potentially altering the photosynthetic machinery (Verma et al., 2022).

NPs can have complex and varied effects on the photosynthetic characteristics of plants, and the actual

effects may depend on the type of nanomaterial, concentration, exposure duration and plant species (Ma et al., 2018). The physiological responses of plants upon exposure to NPs are involved in NPs accumulation in plant, which can directly or indirectly trigger *in vitro* or *in vivo* plant responses; in turn, plant responses can subsequently alleviate the nanotoxicity or decrease the NPs uptake through various pathway (Chahardoli et al., 2020). In the current investigation, it was determined that the optimal drought tolerance in okra plants occurred at a concentration of 50 mg · kg^{-1} of SNPs, as assessed through various morphological indicators. Conversely, the greatest level of drought tolerance was observed in non-TNPs okra plants, primarily due to their photosynthetic characteristics. Regarding the comprehensive assessment of drought resistance based on subordinative function value, it is reasonable to expect diverse outcomes from utilising different tolerance indicators for the selection process. Similar results were also reported in corn (Sinay and Karuwal, 2014).

CONCLUSIONS

Water stress significantly reduced the morphological and photosynthetic parameters of okra plants compared to those grown under optimal watering conditions. The application of SNPs and ANPs mitigated the adverse effects of water deficiency, with SNPs demonstrating superior promotional effects. However, TNPs have an adverse influence on the growth and photosynthetic activity of okra plants. These findings suggest that applying SNPs at a concentration of 50 mg · kg^{-1} could enhance the resilience of okra plants under drought stress.

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AUTHOR CONTRIBUTIONS

For research articles with seven authors, J.W., J.X. and D.S.—methodology; N.C., R.X. and X.T.—validation, formal analysis; D.S., R.X., J.W. and M.Y.—investigation; M.Y. R.X. and J.X.—data curation; J.W. and J.X.— writing-original draft preparation; J.W. and D.S.—project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest.

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