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IMPACT OF CHITOSAN ZINC OXIDE NANOPARTICLES ON PEA PLANT (*PISUM SATIVUM* L.) GROWTH AND YIELD UNDER DROUGHT STRESS: A COMPARISON OF APPLICATION MODES

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Abstract

Food security is threatened by drought stress globally, which significantly impacts crop growth and yield, including pea (*Pisum sativum* L.) plants. This study investigates the effects of variously applied Chitosan Zinc Oxide Nanoparticles (CHT-ZnO NPs) on pea plants grown in pots under drought stress. The present study evaluated the impact of chitosan-zinc oxide nanoparticles (CHT-ZnO NPs; 6.5, 12.5, 25, 50, 100, 200 and 400 ppm) applied via three different modes like foliar (leaf spray), soil, and combined foliar + soil, under three irrigation regimes (80%, 60%, and 40% field capacity (FC) on growth attributes and yield of *Pisum sativum* L. cv. Meteor. Growth and yield parameters were measured, which included length, fresh weight, dry weight of both shoot and root leaf number/plant, total number of seeds/pod, and weight of seeds/plant to evaluate the mode-dependent effectiveness of treatments. Results of the study indicated a significant decrease in mentioned parameters under drought conditions. However, the foliar application of treatments significantly improved the growth and yield of pea in comparison with combined (foliar + soil) and soil-applied treatments. Foliar application of 200 and 400 ppm of chitosan zinc oxide nanoparticles significantly increased growth and yield under both levels of water stress (60% FC and 40% FC). This study highlights the potential of 200 and 400 ppm of CHT-ZnO NPs as an effective treatment to enhance drought tolerance in pea plants, with foliar application emerging as the most effective mode for improving growth and yield under drought.

Key words: Chitosan zinc oxide nanoparticles; Drought stress; Foliar application; Growth; *Pisum sativum*; Yield

Introduction

Climate change worldwide has impacted agricultural productivity by significantly reducing the yield and quality of vegetable crops, due to drought stress being one of the environmental factors (Park *et al.*, 2025) by altering plant metabolism, which results in morphological, physiochemical, and genetic variations (Haghpanah *et al.*, 2024). 50% of the world's arid and semi-arid areas are affected by drought (Wahab *et al.*, 2022). In semi-arid regions, due to the frequent droughts and scarcity of water, the agricultural systems face significant limitations (Bhrijavasi *et al.*, 2024). Pea (*Pisum sativum* L.), a cool-season leguminous crop, plays a vital role in human nutrition due to its high protein content, carbohydrates, sugars, vitamin A and C, phosphorus, calcium, and amino acids (Naz *et al.*, 2022). As a legume crop, pea has the capacity to fix 200 kg ha^{-1} nitrogen from the air (Gungaabayar *et al.*, 2023) thus improving soil fertility. Rather than the vegetative stage, the reproductive phase of the pea is more sensitive to water stress (Osman, 2015) which has threatened the pea production worldwide (Bagheri *et al.*, 2023) due to strenuous pollination, seed formation, flowers, and pods abortion, and shortened reproductive phase, need to increase pea yield (Kausar *et al.*, 2023). Under such environmental challenges, to ensure the sustainability of agricultural practices for enhanced crop resilience, it is essential to adopt innovative strategies (Nadeem *et al.*, 2025).

In modern ages, incorporating agriculture and nanotechnology has untied new boundaries, proposing its capability to improve plant growth and to ensure sustainable agricultural practices by promoting crop resilience to environmental stresses (Zaman *et al.*, 2025). Zinc (Zn), being an essential micronutrient, maintains the integrity of bio-membranes and has a prime role in protein synthesis, the production of reproductive organs, and seeds in plants (Tanwar, 2021). ZnO nanoparticles (ZnO NPs), in comparison to conventional ionic formulas, possess a more diverse size, shape, dissolution rate, and surface properties, which facilitate plant Zn supplementation (Šebesta *et al.*, 2022). To enhance the stability and bioavailability of ZnO, the inclusion of chitosan (a biodegradable, non-toxic, and biocompatible biopolymer) to encapsulate or stabilize ZnO NPs is very important (Qu *et al.*, 2025). Chitosan (CHT), a natural polymer, is non-toxic, biodegradable, biocompatible, and affordable, promotes plant growth and increases yield by combating the harmful effects of abiotic stress (Abobatta, 2023). Its nanomaterials have emerged as highly promising biomolecules (Shinde *et al.*, 2024) which plays an important role in plant growth and development (Methela *et al.*, 2023) by acting controlled release carrier and intake of fertilizers, biocides, and plant hormones, capable of protecting the biological system from adverse effects caused by different environmental factors such as temperature, light, and pH (Giglou *et al.*, 2022). The composite formed by the combination of chitosan and zinc oxide nanoparticles is with improved biological activity and material stability, where chitosan can complement the properties of zinc oxide nanoparticles (Dejene & Abtew, 2025).

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The efficiency of these nanocomposites is influenced not only by their physicochemical characteristics but also by the mode of application. Research focusing particularly on chitosan ZnO nanoparticles, with its mode of application particularly in the context of varying drought severities, is still in its nascent stages, whereas several studies have been done to explore the individual effects of ZnO NPs and chitosan on plant performance under stress. To maximize the benefits and optimize treatment strategies, it is important to understand the interactive relationship between drought regimes, nanoparticle concentration, and mode of application on plants. This study hypothesized that the integration of chitosan and zinc oxide nanoparticles would provide a synergistic effect that might enhance drought tolerance and increases yield potential in *Pisum sativum* under water-limited conditions. The basic aim of this research was to evaluate effect of chitosan-coated zinc oxide nanoparticles on the growth and seed yield of pea growing under different drought regimes and to identify the best mode of application with suitable concentration of treatments.

Materials and Methods

During the growing season of 2022-2023, from October to January pot study was done in a completely randomized design (with factorial sets) containing three replicates at Shakargarh district, Narowal, Pakistan, and it took 90 days from seed sowing to harvest. This experiment was conducted for the screening of the most effective treatment of chitosan zinc oxide nanoparticles and the mode of application. Geographically, the area is located at 32°15′38.3″ N and 75°10′37.4″ E and categorized as a semiarid region. Topsoil with a soil depth of 0–20 cm was used as a planting medium and was taken from the Shakargarh, district Narowal, Pakistan. Pots (each with height of 30cm and 25cm diameter). were filled with 14 kg of soil. Certified pea seeds, Meteor variety, were sourced from Talib Fertilizers and co. Shakargarh district, Narowal, Pakistan. Each pot filled with 14 kg of sandy loam dry soil was planted on October 24, 2023, with 10 seeds under wire house conditions. After germination, the standard agronomic practices (weed, pest, and disease management) were done as per requirement. On a regular basis, pot rotation was done randomly, and weeds were removed manually from pots. Before the rain wire house was covered carefully with a transparent polythene sheet completely. Two weeks after germination, 5 plants per pot were left after thinning. Until the pre-flowering stage (BBCH-40), all pots were watered at the same field capacity before drought induction. When the pea plants reached the 40 BBCH growth stage, the various drought regimes, i.e., control (80% FC), moderate water stress/drought (60% FC), and severe water stress (40% FC), were imposed, maintained, and monitored daily with the help of a soil moisture meter (Lutron PMS-714). During the whole time of the experiment, to keep the soil moisture content at the required FC, water was added as required. After 10 days of maintaining the drought, CHT-ZnO NPs suspensions were applied via three different modes: foliar, soil, and combined foliar + soil. For foliar application, plants were sprayed to full wetness using approximately 14 ± 0.5 mL of suspension per plant. For soil application, 100 ± 1 mL of the suspension was applied directly to the soil of each pot. In the combined foliar + soil treatment, the total suspension volume was equally divided using the two methods: 7 ± 0.25 mL per plant was applied as a foliar spray, and 50 ± 0.5 mL per pot was applied to the soil. All applications used the same nanoparticle concentrations and were administered simultaneously at the designated growth stage, i.e., BBCH 40. Within each replication, the treatments were applied randomly to experimental units.

The following treatments were applied with three modes of application (Table 1).

Sampling: Three representative plants from each pot were randomly selected at the time of harvest to study the growth and yield attributes of pea plants. The selected plants were gently uprooted and cleaned properly with tap water to remove adhesive soil from the root surface, and then paper towel was used to remove excess water.

Shoot and root length; With the help of measuring tape shoot length was estimated by measuring length of main stem from the base (at the soil level) to the apex. Similarly, the root length was measured carefully from the base of the stem to the tip of the primary root using the measuring tape.

Shoot and root fresh weight; After measuring length, the shoot and root parts were separated using a pair of scissors. The fresh weight roots and shoots were measured immediately after harvesting using a portable digital balance.

Shoot and root dry weight: The shoot and root samples were placed in labelled paper envelopes for measuring the dry weight. The samples were then dried in the shade for 96 hours and then dried (70 ± 2°C) for 48 hours in an oven.

Number of leaves per plant: The total number of fully expanded, green leaves on each selected plant was counted and recorded. Senesced or severely damaged leaves were excluded from the count.

Yield attributes: After harvesting, at the maturity stage, yield-related parameters were noted for three plants per pot (selected randomly). All measurements were taken under uniform conditions across all treatments to minimize bias.

Number of pods per plant: The number of pods/ plant was estimated by manually counting all the developed pods.

Number of seeds per pod: The number of viable seeds in each pod was counted manually.

Seed weight/ plant: Seeds from each pod of plant were weighed with a digital balance, and the weight was recorded in grams.

Statistical analysis

Three-way ANOVA was done to analyse data after which Tukey's HSD post-hoc test was done Software used was Statistix 8. These analyses were performed in 3 replications for the all studied attribute at the probability level of $p \leq 0.05$.

Table 1. List of Treatments.

Sr. No.	Treatments	Mode of application
1.	DI @ 80% moisture of FC (Control)	Foliar
2.	DI @ 80% moisture of FC (Control)	Soil
3.	DI @ 80% moisture of FC (Control)	Foliar + Soil
4.	DI @ 60% moisture of FC	Foliar
5.	DI @ 60% moisture of FC	Soil
6.	DI @ 60% moisture of FC	Foliar + Soil
7.	DI @ 40% moisture of FC	Foliar
8.	DI @ 40% moisture of FC	Soil
9.	DI @ 40% moisture of FC	Foliar + Soil
10.	12.5 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar
11.	12.5 ppm CHT-ZnO NPs @ 80% moisture of FC	Soil
12.	6.5 + 6.5 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar + Soil
13.	12.5 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar
14.	12.5 ppm CHT-ZnO NPs @ 60% moisture of FC	Soil
15.	6.5 + 6.5 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar + Soil
16.	12.5 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar
17.	12.5 ppm CHT-ZnO NPs @ 40% moisture of FC	Soil
18.	6.5 + 6.5 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar + Soil
19.	25 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar
20.	25 ppm CHT-ZnO NPs @ 80% moisture of FC	Soil
21.	12.5 + 12.5 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar + Soil
22.	25 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar
23.	25 ppm CHT-ZnO NPs @ 60% moisture of FC	Soil
24.	12.5 + 12.5 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar + Soil
25.	25 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar
26.	25 ppm CHT-ZnO NPs @ 40% moisture of FC	Soil
27.	12.5 + 12.5 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar + Soil
28.	50 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar
29.	50 ppm CHT-ZnO NPs @ 80% moisture of FC	Soil
30.	25 + 25 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar + Soil
31.	50 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar
32.	50 ppm CHT-ZnO NPs @ 60% moisture of FC	Soil
33.	25 + 25 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar + Soil
34.	50 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar
35.	50 ppm CHT-ZnO NPs @ 40% moisture of FC	Soil
36.	25 + 25 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar + Soil
37.	100 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar
38.	100 ppm CHT-ZnO NPs @ 80% moisture of FC	Soil
39.	50 + 50 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar + Soil
40.	100 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar
41.	100 ppm CHT-ZnO NPs @ 60% moisture of FC	Soil
42.	50 + 50 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar + Soil
43.	100 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar
44.	100 ppm CHT-ZnO NPs @ 40% moisture of FC	Soil
45.	50 + 50 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar + Soil
46.	200 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar
47.	200 ppm CHT-ZnO NPs @ 80% moisture of FC	Soil
48.	100 + 100 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar + Soil
49.	200 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar
50.	200 ppm CHT-ZnO NPs @ 60% moisture of FC	Soil
51.	100 + 100 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar + Soil
52.	200 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar
53.	200 ppm CHT-ZnO NPs @ 40% moisture of FC	Soil
54.	100 + 100 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar + Soil
55.	400 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar
56.	400 ppm CHT-ZnO NPs @ 80% moisture of FC	Soil
57.	200 + 200 ppm CHT-ZnO NPs @ 80% moisture of FC	Foliar + Soil
58.	400 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar
59.	400 ppm CHT-ZnO NPs @ 60% moisture of FC	Soil
60.	200 + 200 ppm CHT-ZnO NPs @ 60% moisture of FC	Foliar + Soil
61.	400 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar
62.	400 ppm CHT-ZnO NPs @ 40% moisture of FC	Soil
63.	200 + 200 ppm CHT-ZnO NPs @ 40% moisture of FC	Foliar + Soil

Table 2. Impact of various modes of application of chitosan zinc oxide nanoparticles on the shoot length, root length, shoot fresh weight, shoot dry weight, root fresh weight, and root dry weight under different drought levels.

	Treatments	Shoot length (cm)	Root length (cm)	Shoot fresh weight (g)	Shoot dry weight (g)	Root fresh weight (g)	Root dry weight (g)
		Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
80% FC	Foliar DI	57.3 ± 1.45 A-E	14.7 ± 0.88 C-H	23.3 ± 0.94 D-J	5.6 ± 0.33 F-M	1.5 ± 0.20 A-J	0.8 ± 0.08 C-N
	Foliar 12.5 ppm	54.7 ± 0.88 B-G	15.3 ± 0.88 B-G	22.6 ± 1.53 E-K	5.7 ± 0.53 F-M	1.7 ± 0.24 A-J	0.8 ± 0.06 C-K
	Foliar 25 ppm	56.3 ± 1.45 B-F	15.7 ± 0.67 B-G	23.5 ± 0.92 D-J	6.1 ± 0.74 E-L	2.0 ± 0.33 A-G	0.8 ± 0.09 C-L
	Foliar 50 ppm	59.7 ± 0.88 A-D	17.7 ± 1.20 A-E	27.1 ± 0.71 B-F	6.7 ± 0.27 C-J	1.9 ± 0.11 A-H	0.9 ± 0.07 B-J
	Foliar 100 ppm*	60.7 ± 1.20 A-C	18.3 ± 0.33 A-D	29.1 ± 0.86 B-C	8.2 ± 0.39 B-E	2.0 ± 0.14 A-G	1.0 ± 0.06 A-E
	Foliar 200 ppm***	66.3 ± 1.45 A	22.3 ± 1.20 A	35.6 ± 1.20 A	12.0 ± 0.76 A	2.6 ± 0.09 A	1.2 ± 0.06 A
	Foliar 400 ppm8**	63.3 ± 1.20 A-B	20.3 ± 0.33 A-B	32.4 ± 1.40 A-B	9.8 ± 0.47 A-B	2.6 ± 0.25 A	1.2 ± 0.05 A-B
	Soil DI	37.3 ± 1.45 M-U	13.3 ± 0.88 D-I	16.7 ± 1.19 K-T	5.3 ± 0.15 H-N	1.6 ± 0.17 A-J	0.8 ± 0.05 C-O
	Soil 12.5 ppm	37.7 ± 1.20 L-U	13.7 ± 0.33 D-I	17.6 ± 0.52 J-R	5.0 ± 0.45 H-O	1.6 ± 0.18 A-J	0.8 ± 0.04 C-M
	Soil 25 ppm	39.7 ± 1.33 K-S	13.3 ± 0.88 D-I	18.1 ± 0.53 J-Q	6.0 ± 0.48 E-L	1.6 ± 0.18 A-J	0.8 ± 0.02 C-N
	Soil 50 ppm	39.7 ± 0.88 K-S	14.7 ± 0.33 C-H	19.8 ± 0.98 I-P	6.3 ± 0.31 D-L	1.6 ± 0.16 A-J	0.9 ± 0.07 B-J
	Soil 100 ppm	38.3 ± 1.20 L-T	15.3 ± 1.20 B-G	23.0 ± 0.78 D-J	6.5 ± 0.24 C-J	2.1 ± 0.13 A-F	1.0 ± 0.04 A-F
	Soil 200 ppm	41.7 ± 1.45 I-Q	18.3 ± 0.88 A-D	26.4 ± 1.04 B-H	8.6 ± 0.44 B-D	2.4 ± 0.22 A-B	1.1 ± 0.04 A
	Soil 400 ppm	40.0 ± 1.15 K-R	17.7 ± 1.20 A-E	24.8 ± 0.55 C-I	7.7 ± 0.55 B-G	2.4 ± 0.32 A	1.0 ± 0.13 A-E
	Foliar + Soil DI	41.0 ± 2.08 J-Q	15.7 ± 0.33 B-G	20.6 ± 0.64 G-M	5.3 ± 0.15 H-N	1.5 ± 0.09 A-J	0.7 ± 0.04 C-P
	Foliar + Soil 6.25 + 6.25 ppm	42.0 ± 1.15 I-Q	16.3 ± 0.88 B-F	20.2 ± 1.13 H-N	5.7 ± 0.12 F-M	1.7 ± 0.24 A-J	0.8 ± 0.05 C-L
	Foliar + Soil 12.5 + 12.5	41.7 ± 1.20 I-Q	17.3 ± 0.88 A-E	22.9 ± 1.05 E-J	6.3 ± 0.42 C-K	1.7 ± 0.21 A-J	0.7 ± 0.06 C-P
	Foliar + Soil 25 + 25 ppm	46.3 ± 0.88 G-M	17.3 ± 0.88 A-E	23.5 ± 0.69 D-J	6.8 ± 0.26 C-I	1.8 ± 0.13 A-J	0.8 ± 0.04 C-L
	Foliar + Soil 50 + 50 ppm	50.7 ± 1.45 D-I	17.7 ± 0.33 A-E	25.1 ± 0.81 C-I	6.5 ± 0.24 C-J	1.8 ± 0.10 A-J	0.9 ± 0.03 A-I
	Foliar + Soil 100 + 100 ppm	49.7 ± 2.40 E-J	20.3 ± 0.88 A-B	30.7 ± 1.44 A-C	9.7 ± 0.57 A-B	2.4 ± 0.08 A-D	1.1 ± 0.05 A-D
	Foliar + Soil 200 + 200 ppm	46.7 ± 1.20 G-L	18.3 ± 0.33 A-D	28.6 ± 1.12 B-E	8.7 ± 0.48 B-C	2.4 ± 0.16 A-B	1.0 ± 0.05 A-G
60% FC	Foliar DI	50.7 ± 2.03 D-I	11.3 ± 1.20 F-K	14.3 ± 1.58 N-X	4.0 ± 0.37 L-R	1.1 ± 0.17 E-J	0.5 ± 0.06 J-R
	Foliar 12.5 ppm	48.0 ± 1.00 F-K	12.3 ± 1.20 E-J	13.6 ± 0.52 P-Z	4.1 ± 0.55 K-R	1.2 ± 0.26 E-J	0.6 ± 0.05 I-Q
	Foliar 25 ppm	49.7 ± 1.67 E-J	12.7 ± 0.88 E-J	14.5 ± 0.76 M-W	4.5 ± 0.65 J-P	1.5 ± 0.34 A-J	0.6 ± 0.09 I-Q
	Foliar 50 ppm	53.0 ± 1.00 C-H	14.7 ± 1.76 C-H	18.1 ± 0.76 J-Q	5.1 ± 0.26 H-O	1.5 ± 0.16 A-J	0.6 ± 0.10 G-Q
	Foliar 100 ppm*	54.0 ± 1.73 C-G	15.3 ± 0.33 B-G	20.1 ± 0.74 I-O	6.6 ± 0.29 C-J	1.5 ± 0.17 A-J	0.8 ± 0.09 C-N
	Foliar 200 ppm***	59.7 ± 2.03 A-D	19.3 ± 1.20 A-C	26.6 ± 0.19 B-G	9.4 ± 0.67 B	2.1 ± 0.11 A-F	1.0 ± 0.08 A-F
	Foliar 400 ppm**	56.7 ± 1.86 B-F	17.3 ± 0.33 A-E	23.4 ± 0.40 D-J	8.2 ± 0.53 B-E	2.1 ± 0.20 A-E	1.0 ± 0.04 A-G
	Soil DI	30.7 ± 2.03 S-W	10.3 ± 1.45 G-K	7.7 ± 1.88 Z-b	3.6 ± 0.15 N-R	1.1 ± 0.20 E-J	0.5 ± 0.01 J-R
	Soil 12.5 ppm	31.0 ± 1.73 R-W	10.7 ± 0.67 G-K	8.6 ± 1.53 W-b	3.4 ± 0.37 N-R	1.1 ± 0.20 E-J	0.5 ± 0.01 J-R
	Soil 25 ppm	33.0 ± 2.00 Q-W	10.3 ± 1.45 G-K	9.1 ± 0.64 V-b	4.4 ± 0.45 J-Q	1.1 ± 0.19 E-J	0.5 ± 0.06 J-R
	Soil 50 ppm	33.0 ± 1.53 Q-W	11.7 ± 0.67 F-K	10.8 ± 0.41 T-b	4.7 ± 0.25 I-P	1.2 ± 0.13 E-J	0.6 ± 0.10 H-Q
	Soil 100 ppm	31.7 ± 1.86 R-W	12.3 ± 0.67 E-J	14.0 ± 0.38 O-X	4.9 ± 0.34 H-O	1.6 ± 0.12 A-J	0.7 ± 0.04 D-P
	Soil 200 ppm	35.0 ± 1.00 O-V	15.3 ± 1.33 B-G	17.4 ± 0.87 J-S	7.0 ± 0.42 C-I	1.9 ± 0.21 A-H	0.8 ± 0.08 C-K
	Soil 400 ppm	33.3 ± 0.67 Q-W	14.7 ± 1.76 C-H	15.8 ± 0.66 L-U	6.1 ± 0.45 E-L	1.9 ± 0.27 A-H	0.8 ± 0.12 C-N
	Foliar + Soil DI	34.3 ± 2.60 P-W	12.7 ± 0.67 E-J	11.6 ± 0.52 R-b	3.6 ± 0.15 N-R	1.0 ± 0.08 E-J	0.5 ± 0.05 J-R
	Foliar + Soil 6.25 + 6.25 ppm	35.3 ± 1.76 O-U	13.3 ± 1.33 D-I	11.2 ± 1.37 S-b	4.1 ± 0.07 K-R	1.2 ± 0.26 E-J	0.6 ± 0.05 I-Q
	Foliar + Soil 12.5 + 12.5	35.0 ± 1.53 O-V	14.3 ± 1.33 C-H	13.9 ± 1.82 P-Y	4.7 ± 0.32 H-P	1.3 ± 0.23 D-J	0.6 ± 0.04 I-Q
	Foliar + Soil 25 + 25 ppm	39.7 ± 0.33 K-S	14.3 ± 0.67 C-H	14.5 ± 0.52 M-X	5.2 ± 0.20 H-N	1.3 ± 0.18 C-J	0.5 ± 0.09 J-R
	Foliar + Soil 50 + 50 ppm	44.0 ± 1.53 H-O	14.7 ± 0.88 C-H	16.1 ± 1.67 L-U	4.9 ± 0.34 H-O	1.3 ± 0.15 B-J	0.6 ± 0.06 I-Q
	Foliar + Soil 100 + 100 ppm	43.0 ± 2.00 I-P	17.3 ± 1.45 A-E	21.7 ± 1.10 F-L	7.9 ± 0.34 B-F	1.9 ± 0.10 A-I	0.7 ± 0.06 D-P
	Foliar + Soil 200 + 200 ppm	40.0 ± 1.53 K-R	15.3 ± 0.67 B-G	19.6 ± 2.06 I-P	7.1 ± 0.55 C-H	1.9 ± 0.11 A-H	0.8 ± 0.01 C-L
40% FC	Foliar DI	36.7 ± 0.33 N-U	7.7 ± 0.67 J-K	9.0 ± 1.40 V-b	2.1 ± 0.31 Q-R	0.8 ± 0.17 J	0.4 ± 0.08 Q-R
	Foliar 12.5 ppm	34.0 ± 1.53 P-W	8.3 ± 0.88 I-K	8.3 ± 0.81 X-b	2.5 ± 0.59 P-R	0.9 ± 0.23 G-J	0.4 ± 0.04 N-R
	Foliar 25 ppm	35.7 ± 1.45 O-U	8.7 ± 0.88 I-K	9.2 ± 0.53 V-b	2.8 ± 0.56 O-R	1.2 ± 0.32 E-J	0.4 ± 0.11 N-R
	Foliar 50 ppm	39.0 ± 1.53 K-T	10.7 ± 0.67 G-K	12.8 ± 0.99 Q-Za	3.4 ± 0.28 N-R	1.2 ± 0.13 E-J	0.5 ± 0.07 L-R
	Foliar 100 ppm*	40.0 ± 0.58 K-R	11.3 ± 0.88 F-K	14.8 ± 1.01 M-V	5.0 ± 0.19 H-O	1.2 ± 0.16 E-J	0.6 ± 0.06 H-Q
	Foliar 200 ppm***	45.7 ± 0.33 G-N	15.3 ± 1.45 B-G	21.2 ± 0.52 F-L	7.8 ± 0.71 B-F	1.8 ± 0.09 A-J	0.8 ± 0.05 C-K
	Foliar 400 ppm**	42.7 ± 0.33 I-P	13.3 ± 0.88 D-I	18.1 ± 0.71 J-Q	6.6 ± 0.61 C-J	1.8 ± 0.23 A-J	0.8 ± 0.03 C-L
	Soil DI	16.7 ± 0.33 a	6.3 ± 0.33 K	7.7 ± 0.73 Y-b	2.0 ± 0.20 R	0.8 ± 0.17 I-J	0.4 ± 0.05 R
	Soil 12.5 ppm	17.0 ± 0.58 Z-a	6.7 ± 0.67 K	6.8 ± 0.49 a-b	1.8 ± 0.30 R	0.8 ± 0.18 J	0.4 ± 0.04 Q-R
	Soil 25 ppm	19.0 ± 0.58 Z-a	6.3 ± 0.33 K	6.9 ± 0.28 a-b	2.8 ± 0.44 O-R	0.8 ± 0.19 J	0.4 ± 0.04 Q-R
	Soil 50 ppm	19.0 ± 0.58 Z-a	7.7 ± 0.67 J-K	7.4 ± 0.66 a-b	3.1 ± 0.21 N-R	0.9 ± 0.15 H-J	0.5 ± 0.09 L-R
	Soil 100 ppm	17.7 ± 0.88 Z-a	8.3 ± 1.76 I-K	8.7 ± 0.54 V-b	3.3 ± 0.44 N-R	1.3 ± 0.13 D-J	0.6 ± 0.01 J-R
	Soil 200 ppm	21.0 ± 2.89 X-a	11.3 ± 0.67 F-K	12.1 ± 1.17 Q-b	5.4 ± 0.42 G-N	1.6 ± 0.22 A-J	0.7 ± 0.05 E-P
	Soil 400 ppm	19.3 ± 2.60 Z-a	10.7 ± 0.67 G-K	10.4 ± 0.66 U-b	4.4 ± 0.36 J-Q	1.6 ± 0.30 A-J	0.6 ± 0.05 F-Q
	Foliar + Soil DI	20.3 ± 0.88 Y-a	8.7 ± 0.67 I-K	6.2 ± 0.58 b	2.0 ± 0.20 R	0.7 ± 0.07 J	0.3 ± 0.06 R
	Foliar + Soil 6.25 + 6.25 ppm	21.3 ± 0.33 X-a	9.3 ± 0.67 H-K	7.6 ± 0.61 Z-b	2.5 ± 0.12 P-R	0.9 ± 0.23 G-J	0.4 ± 0.03 P-R
	Foliar+Soil 12.5 + 12.5	21.0 ± 1.15 X-a	10.3 ± 0.67 G-K	8.5 ± 2.02 W-b	3.1 ± 0.23 N-R	0.9 ± 0.23 G-J	0.4 ± 0.03 R
	Foliar+Soil 25 + 25 ppm	25.7 ± 2.19 W-a	10.3 ± 1.33 G-K	9.1 ± 0.71 V-b	3.6 ± 0.33 N-R	1.0 ± 0.15 F-J	0.4 ± 0.04 O-R
	Foliar + Soil 50 + 50 ppm	30.0 ± 2.52 T-X	10.7 ± 0.33 G-K	10.7 ± 1.84 T-b	3.5 ± 0.31 H-O	1.0 ± 0.12 F-J	0.5 ± 0.02 K-R
	Foliar + Soil 100 + 100 ppm	29.0 ± 3.79 U-Y	13.3 ± 0.33 D-I	16.3 ± 1.43 L-U	5.7 ± 0.24 F-M	1.6 ± 0.14 A-J	0.7 ± 0.04 D-P
	Foliar + Soil 200 + 200 ppm	26.0 ± 2.00 V-Z	11.3 ± 0.67 F-K	14.3 ± 2.22 N-X	5.1 ± 0.21 F-M	1.6 ± 0.14 A-J	0.6 ± 0.05 J-Q

Means followed by different letters in the same column are significantly different at $p \leq 0.05$ according to the LSD test. No. of * on treatment indicates the effectiveness of treatment (within each irrigation regime) ***significantly outperforming treatment** Second Best treatment * Third best

Table 3. Impact of various modes of application of chitosan zinc oxide nanoparticles on number of leaves per plant, number of pods per plant, number of seeds per pod and weight of seeds per plant under different drought levels.

Treatments		Number of leaves	Number of pods	Number of seeds per pod	Weight of seeds per plant
		Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
80% FC	Foliar DI	83.3 ± 1.45 E-M	8.66 ± 0.67 F-P	5.33 ± 0.44 A-I	20.22 ± 1.52 B-F
	Foliar 12.5 ppm	85.7 ± 2.73 D-K	8.33 ± 0.33 G-P	5.50 ± 0.29 A-H	20.88 ± 1.08 B-E
	Foliar 25 ppm	88.3 ± 2.03 C-J	9.33 ± 1.20 E-O	5.67 ± 0.17 A-G	21.56 ± 1.16 A-C
	Foliar 50 ppm	92.3 ± 3.48 B-I	11.66 ± 0.67 B-I	6.00 ± 0.29 A-E	22.86 ± 1.72 A-B
	Foliar 100 ppm***	106.7 ± 3.71 A-C	13.33 ± 0.33 A-E	6.33 ± 0.17 A-C	24.04 ± 0.47 A-B
	Foliar 200 ppm*	113.7 ± 3.18 A	17.66 ± 0.67 A	7.33 ± 0.33 A	27.92 ± 1.94 A
	Foliar 400 ppm**	100.3 ± 3.53 A-F	15.66 ± 0.33 A-B	7.33 ± 0.33 A	27.92 ± 1.94 A
	Soil DI	86.0 ± 3.61 D-K	8.66 ± 0.67 F-P	5.17 ± 0.17 A-I	19.60 ± 0.20 B-G
	Soil 12.5 ppm	85.0 ± 2.08 D-L	9.66 ± 0.67 D-N	5.50 ± 0.50 A-H	20.98 ± 2.41 B-D
	Soil 25 ppm	87.0 ± 4.16 D-K	10.33 ± 0.67 D-L	5.67 ± 0.44 A-G	21.44 ± 1.05 A-C
	Soil 50 ppm	86.3 ± 6.94 D-K	10.66 ± 0.88 D-K	5.83 ± 0.33 A-F	22.10 ± 0.68 A-B
	Soil 100 ppm	93.0 ± 2.08 B-H	10.66 ± 0.88 D-K	6.33 ± 0.44 A-C	24.02 ± 1.50 A-B
	Soil 200 ppm	104.0 ± 4.04 A-D	14 ± 1.00 A-D	6.83 ± 0.44 A-B	25.92 ± 1.45 A-B
	Soil 400 ppm	99.7 ± 6.33 A-F	13 ± 0.58 B-F	6.00 ± 0.58 A-E	22.76 ± 2.12 A-B
	Foliar + Soil DI	83.0 ± 2.65 F-M	9.66± 1.20 D-N	5.83 ± 0.17 A-F	22.16 ± 0.81 A-B
	Foliar + Soil 6.25 + 6.25 ppm	87.3 ± 2.91 D-K	8.66 ± 1.20 F-P	5.83 ± 0.33 A-F	22.10 ± 0.68 A-B
	Foliar + Soil 12.5 + 12.5	85.3 ± 3.76 D-L	9± 0.58 E-P	6.83 ± 0.17 A-B	26.00 ± 1.32 A-B
	Foliar + Soil 25 + 25 ppm	86.3 ± 2.03 D-K	10.33 ± 0.33 D-L	5.83 ± 0.17 A-F	22.20 ± 1.22 A-B
	Foliar +Soil 50 + 50 ppm	95.7 ± 3.28 A-G	12.33 ± 0.33 B-G	6.17 ± 0.17 A-D	23.40 ± 0.21 A-B
	Foliar + Soil 100 + 100 ppm	108.3 ± 2.60 A-B	15.33 ± 0.67 A-C	6.67 ± 0.17 A-B	25.34 ± 1.02 A-B
	Foliar + Soil 200 + 200 ppm	102.3 ± 2.60 A-E	12.66 ± 0.88 B-G	7.33 ± 0.33 A	27.92 ± 1.94 A
60% FC	Foliar DI	50.0 ± 1.53 S-b	5.33 ± 0.33 N-R	3.42 ± 0.65 H-O	10.21 ± 2.13 H-N
	Foliar 12.5 ppm	52.3 ± 2.33 S-b	5.33 ± 0.67 N-R	3.58 ± 0.46 G-O	10.61 ± 1.45 H-N
	Foliar 25 ppm	55.0 ± 1.53 R-a	6.33 ± 0.67 K-R	3.67 ± 0.22 F-O	10.83 ± 0.59 H-N
	Foliar 50 ppm	59.0 ± 2.00 O-Y	6.66 ± 0.88 J-R	4.00 ± 0.14 D-N	11.81 ± 0.10 H-L
	Foliar 100 ppm*	73.3 ± 3.28 I-Q	9.33 ± 0.67 E-O	4.08 ± 0.46 D-N	12.09 ± 1.46 H-J
	Foliar 200 ppm***	80.3 ± 3.71 G-N	12 ± 1.00 B-H	4.92 ± 0.51 B-K	14.45 ± 1.02 D-H
	Foliar 400 ppm**	77.7 ± 3.18 H-O	12.66 ± 0.33 B-G	4.75 ± 0.38 B-L	13.99 ± 0.77 F-H
	Soil DI	52.7 ± 1.76 S-b	4.66 ± 0.88 P-R	2.92 ± 0.30 J-O	8.63 ± 0.94 H-N
	Soil 12.5 ppm	51.7 ± 2.85 S-b	5.66 ± 0.88 M-R	3.25 ± 0.66 I-O	9.49 ± 1.66 H-N
	Soil 25 ppm	53.7 ± 6.33 R-b	6.33 ± 0.33 K-R	3.42 ± 0.36 H-O	10.17 ± 1.33 H-N
	Soil 50 ppm	53.0 ± 4.93 S-b	6.66 ± 0.88 J-R	3.25 ± 0.14 I-O	9.63 ± 0.65 H-N
	Soil 100 ppm	59.7 ± 3.53 O-X	7.33 ± 0.88 I-Q	3.92 ± 0.30 E-O	11.59 ± 0.97 H-M
	Soil 200 ppm	72.3 ± 2.03 J-Q	10 ± 0.58 D-M	4.42 ± 0.22 C-M	13.05 ± 0.59 G-I
	Soil 400 ppm	66.3 ± 3.53 L-U	9 ± 0.58 E-P	3.75 ± 0.88 F-O	11.15 ± 2.72 H-N
	Foliar + Soil DI	49.7 ± 3.93 T-b	5.33 ± 0.88 N-R	3.58 ± 0.30 G-O	10.57 ± 0.77 H-N
	Foliar + Soil 6.25 + 6.25 ppm	54.0 ± 1.00 R-b	5.66 ± 0.88 M-R	3.75 ± 0.25 F-O	11.15 ± 1.10 H-N
	Foliar + Soil 12.5 + 12.5	52.0 ± 4.51 S-b	5.66 ± 0.88 M-R	4.08 ± 0.36 D-N	12.01 ± 0.63 H-K
	Foliar + Soil 25 + 25 ppm	53.0 ± 3.06 S-b	7.66 ± 0.88 H-Q	4.08 ± 0.22 D-N	12.13 ± 1.07 H-J
	Foliar + Soil 50 + 50 ppm	62.3 ± 2.60 N-W	8.33 ± 0.67 G-P	3.92 ± 0.30 E-O	11.59 ± 0.97 H-M
	Foliar + Soil 100 + 100 ppm	75.0 ± 1.15 H-P	10.66 ± 0.88 D-K	4.75 ± 0.38 B-L	14.09 ± 1.38 E-H
	Foliar + Soil 200 + 200 ppm	69.0 ± 3.06 K-S	11.66 ± 1.20 B-I	5.08 ± 0.55 B-J	14.95 ± 1.25 C-H
40% FC	Foliar DI	36.0 ± 1.15 a-b	3.33 ± 0.33 Q-R	1.93 ± 0.71 N-O	4.63 ± 1.40 N
	Foliar 12.5 ppm	38.3 ± 1.76 Z-b	5 ± 0.58 O-R	2.10 ± 0.60 N-O	5.11 ± 1.09 L-N
	Foliar 25 ppm	41.0 ± 1.00 X-b	4.66 ± 0.88 P-R	2.18 ± 0.37 N-O	5.43 ± 0.74 J-N
	Foliar 50 ppm	45.0 ± 1.53 W-b	7 ± 0.58 J-Q	2.52 ± 0.26 M-O	6.33 ± 0.73 I-N
	Foliar 100 ppm *	55.7 ± 1.86 Q-Z	7.33 ± 0.67 I-Q	2.60 ± 0.60 L-O	6.37 ± 1.02 I-N
	Foliar 200 ppm***	68.3 ± 2.19 K-T	11.66 ± 0.88 B-I	3.40 ± 0.24 H-O	8.53 ± 0.57 H-N
	Foliar 400 ppm **	66.0 ± 4.16 M-V	11 ± 1.00 C-J	3.52 ± 0.26 G-O	8.85 ± 0.82 H-N
	Soil DI	38.7 ± 1.45 Z-b	2.33 ± 0.33 R	1.77 ± 0.27 O	4.37 ± 0.40 N
	Soil 12.5 ppm	37.7 ± 2.40 Z-b	3.33 ± 0.33 Q-R	2.18 ± 0.38 N-O	5.52 ± 1.13 J-N
	Soil 25 ppm	39.7 ± 6.23 Z-b	5.66 ± 0.88 M-R	1.98 ± 0.15 N-O	4.96 ± 0.22 M-N
	Soil 50 ppm	39.0 ± 5.29 Z-b	6 ± 1.00 L-R	1.93 ± 0.16 N-O	4.90 ± 0.62 M-N
	Soil 100 ppm	45.7 ± 3.18 W-b	5.66 ± 0.67 M-R	2.30 ± 0.32 M-O	5.72 ± 0.55 J-N
	Soil 200 ppm	56.7 ± 4.10 P-Z	8.33 ± 0.67 G-P	2.58 ± 0.17 L-O	6.48 ± 0.40 I-N
	Soil 400 ppm	47.0 ± 3.21 V-b	8.33 ± 0.88 G-P	2.48 ± 0.39 M-O	5.95 ± 0.83 J-N
	Foliar + Soil DI	35.7 ± 3.53 b	3.33 ± 0.67 Q-R	2.10 ± 0.44 N-O	5.21 ± 0.96 K-N
	Foliar + Soil 6.25 + 6.25 ppm	40.0 ± 1.53 X-b	3.66 ± 0.33 Q-R	2.27 ± 0.27 M-O	5.63 ± 0.33 J-N
	Foliar + Soil 12.5 + 12.5	38.0 ± 4.00 Z-b	3.33 ± 0.67 Q-R	2.60 ± 0.45 L-O	6.57 ± 1.33 I-N
	Foliar + Soil 25 + 25 ppm	39.0 ± 2.65 Z-b	5.33 ± 0.33 N-R	2.60 ± 0.15 L-O	6.53 ± 0.38 I-N
	Foliar + Soil 50 + 50 ppm	48.3 ± 2.03 U-b	7.33 ± 0.88 I-Q	2.80 ± 0.29 K-O	7.00 ± 0.60 I-N
	Foliar + Soil 100 + 100 ppm	61.0 ± 1.73 O-W	7.33 ± 0.67 I-Q	3.50 ± 0.42 G-O	8.69 ± 0.48 H-N
	Foliar + Soil 200 + 200 ppm	53.7 ± 2.96 R-b	8.33 ± 0.88 G-P	3.28 ± 0.58 H-O	8.47 ± 0.77 H-N

Means followed by different letters in the same column are significantly different at $p \leq 0.05$ according to the LSD test. No. of * on treatment indicates the effectiveness of treatment (within each irrigation regime) ***significantly outperforming treatment** Second Best treatment * Third best

Results

Growth attributes: In the current work, it was observed that drought levels (i.e., 60% and 40% of field capacity) cause significant ($p \leq 0.05$) impact on growth attributes of the pea plant, and three-way ANOVA interactions (NP concentration × drought × mode) were also found to be significant at $p \leq 0.05$. This significant interaction indicates that the response of pea growth attributes to different NP concentrations depended jointly on the drought level and the mode of NP application. The application of chitosan zinc oxide nanoparticles resulted in significant increase in growth parameters, as presented in the Table. 2. At 80% of field capacity, foliar application of 200 ppm chitosan zinc oxide nanoparticles resulted in the significant increase in shoot length (15%), root length (33%), shoot fresh wt. (52%), shoot dry wt. (6%), root fresh wt. (13%), root dry wt. (25%). Under the same conditions, 400 ppm resulted in similar results for root fresh and dry weight. In case of other parameters, 400 ppm showed better growth pattern compared to control and all other treatments, but it was less effective than 200 ppm. While the other two modes of application didn't perform well in comparison with the foliar mode of application, where soil DI (control) exhibited the least growth. A significant decline in the growth attributes of pea plants growing under drought stress (60% and 40% of FC) in comparison with the control (80% of FC), but foliar application of 200 ppm CHT ZnO NPs resulted in significant increase in length of shoot length (17%) and root (42%). Fresh (46%), and dry weight (49%) of shoot root fresh weight (50%), and root dry weight (1.0 g) under 60% of FC where in plants growing under 40% of FC shoot length (45.7 cm), root length (15.3 cm), shoot fresh weight (21.2 g), shoot dry weight (7.8 g), root fresh weight (1.8 g), and root dry weight (0.8 g) was recorded followed by 400 ppm. Other modes of application, i.e., soil and combined (foliar + soil), did not perform well as foliar mode of application, while the lowest growth attributes were recorded in soil treated plants under both drought levels, i.e., 60% and 40% of FC. Moderate drought (60% of FC) and severe drought (40% of FC) significantly influence the number of leaves per plant in comparison with the control (80% of FC), as presented in Table 3, and the application of chitosan zinc oxide nanoparticles under all modes of application. A significant improvement in the number of leaves (36%) growing under 80% of FC (control) by the application of 200 ppm CHT ZnO NPs followed by the combined mode (foliar + soil) 100 + 100 ppm (30) and 27% by foliar application of 100 ppm. Other well-performed treatments, were foliar 400 ppm and soil 200 ppm. Under moderate drought stress, there was a significant (40-50%) increase in the number of leaves, per plant by foliar application of 200 ppm followed by 400 ppm, respectively, compared with their respective control. Combined (foliar + soil) application of 100+100 ppm of CHT ZnO NPs produced 75.0 leaves per plant, while 200 ppm and 100 ppm applied in the soil, producing 72.3 and 59.7 leaves per plant, respectively. Under severe drought (40% of FC), in comparison to all modes of applications and treatments with foliar mode of application resulted in significant increase (30-55%) by producing 68.3 and 66.0 leaves per plant when 200 and 400 ppm were applied respectively. Whereas 200 ppm of soil and 100+100 ppm of combined mode of application produced 56.7 and 61.0 leaves per plant.

Yield attributes: In the present study, it was observed that both drought levels (i.e., 60% and 40% of FC) caused significant impact ($p \leq 0.05$) on the yield attributes of pea plants (Table 3). Whereas variously applied CHT ZnO NPs significantly increased the reproductive performance of pea plants under all water regimes. At 80% of FC, foliar 200 and 400 ppm showed a significant increase in the number of pods per plant, the number of seeds per pod, and the weight of seeds per plant compared to their respective control. Application of foliar 100, 200, and 400 ppm resulted in 13.33, 17.66, 15.66 number (No.) of pods/ plant, 6.33, 7.33, 7.33 Seed No./ pod, and 24.04, 27.92, 27.92 seed weight/ plant, respectively. The efficiency of both treatments, 200 and 400 ppm, remained the same for the number of seeds per pod and the weight of seeds per plant under normal moisture level, while their trends changed under drought conditions, where 200 ppm performed well under 60% of FC and 400 ppm resulted slight improvement under 40% of FC. 200+200ppn of foliar+soil and foliar 200 ppm showed the same (27.92g) results for the weight of seed per plant. 200 and 400 ppm soil applied treatments showed a pronounced increase by producing 6.83 and 6.00 seeds per pod, respectively. Foliar DI (control) resulted in a significant decrease in yield by producing 8.66 pods and 20.22 g seed weight per plant. A significant increase in the yield of plants growing under moderate drought (60% of FC) by the foliar application of 200 ppm, which produced 12 number of pods per plant, 4.92 number of seeds per pod, and 14.45 weight of seeds per plant whereas 14.95g seed weight/ plant was recorded by the combined application of 200+200 ppm CHT ZnO NPs. An increase in yield attributes was also recorded by foliar application of 400 ppm, which resulted in 12.66 No. pods/ plant, 4.75 No. of seeds/ pod, and 13.99 seed weight/ plant. Among soil treatments, 200 ppm produced 13.05g weight of seeds per plant, while other treatments did not show any pronounced results. At severe drought (40% of FC), 400 ppm remained the most effective treatment with the foliar mode of application, with a pronounced increase in yield by producing 11 No. of pods/ plant, 3.52 No. of seeds/ pod, and 8.85 seed weight/ plant. Moderate yield was recorded by 200 ppm of soil-applied treatment, 6.48 g weight of seeds per plant.

Discussion

The present study expressed that drought stress altered the growth performance of pea plants by reducing their shoot length, root length, shoot fresh weight, shoot dry weight, root fresh weight, and root dry weight. These results were consistent with that reported earlier (Arafa *et al.*, 2021) and (Sutulienė *et al.*, 2023) who also found similar inhibitory effects of moisture stress on morphological/growth characters of pea plants. Reduced length of both shoot and root under 60% and 40% field capacity, highlight the suppression of cell elongation and meristematic activity due to water deficit conditions (Bhattacharya, 2021). Drought-related reduction in cell turgor pressure and disruption of signaling hormones such as auxin and gibberellin might be the reason for reduced cell elongation and growth (Wahab *et al.*, 2022). Similar to other growth attributes, the decline in shoot and root fresh and dry biomasses under drought conditions was in line with reports of other researchers (Lahuta *et al.*, 2022; Pandey *et al.*, 2023) who also observed that water shortage reduced carbon assimilation, impaired cell division and elongation and limited translocation of photoassimilates. Under drought stress, the reduced photosynthetic activity and nutrient uptake further restrict biomass allocation and tissues elongating (Bagheri *et al.*, 2023). However, application of CHT-ZnO NP improved both shoot and root elongation and enhanced leaf formation, leaf expansion, shoot and root biomass under drought stress and these results supported the similar findings (Abdeen *et al.*, 2023). Zinc is crucially important in activating enzymes like carbonic anhydrase and RNA polymerase for protein synthesis, cell division (to promote meristem activities), chlorophyll biosynthesis, leaf morphogenesis and stomatal development (Umair Hassan *et al.*, 2020). Moreover, Zn is also involved in tryptophan metabolism, which is the main metabolite from which auxin (IAA) is produced which is essential for root and shoot elongation (Sourati *et al.*, 2022). Furthermore, ZnO NPs have ability to maintain cell turgidity and structural integrity by improving RWC, nutrient and water uptake in plants which facilitate leaf development and enhanced root growth to promote biomass production even under stress condition (Raza *et al.*, 2025). This enhancement in plant biomass could be attributed to improved photosynthetic activity as ZnO NPs enhance chlorophyll contents, carotenoids and growth hormones such as auxin and cytokinin to improve dry matter of plant (Liu *et al.*, 2022; Seleiman *et al.*, 2023). Moreover, the ZnO NPs helps to maintain turgor pressure which enable sustained cell expansion by increasing sugar accumulation and modulating proline levels (El-Saadony *et al.*, 2022).

Being a major abiotic factor, drought stress disrupts reproductive development and reduces yield potential of leguminous crops such as pea (Nadeem *et al.*, 2019). The current study demonstrated that drought at both 60% and 40% field capacity adversely affected yield such as pod No./ plant, seed No./ pod and seed weight/ plant. A reduction in seed set of pea plants under drought conditions was observed in this study, and the findings were in line with the results of Farooq *et al*., (2017) who also observed reduced seed set. Seed set is highly sensitive to drought stress and the reduction in this parameter is often linked to poor pollen viability, ovule fertilization failure, and early embryo abortion (Jiang *et al.*, 2019). The decrease is primarily attributed water deficiency and limited nutrient intake disrupts hormonal homeostasis particularly reducing auxin and cytokinin levels while increasing abscisic acid (ABA) which is a major cause of decline in floral organs (Wahab *et al.*, 2022). These processes are highly energy-dependent and are susceptible to oxidative stress. However, the application of ZnO NPs, especially foliar applied 200 and 400 ppm, significantly mitigated these effects and reflected the multifaceted role of zinc in promoting reproductive success under stress. The CHT-ZnO NPs application improved the number of seeds per pod across all drought levels and the results were in agreement with the findings of (Ghiyasi *et al.*, 2023) who also showed improved seed number and size per plant under the application of ZnO NPs. In the current study, it was also observed that CHT-ZnO NPs improved all studied yield related parameters under all drought levels. This improvement could be attributed to Zn-induced osmotic adjustment, RWC improvement (to sustain turgor pressure of the cells), and photosynthate supply during seed filling (Chattha *et al.*, 2022). Moreover, Zn is known to synthesize structural proteins and enzymes (e.g., cellulose synthase, amylases and proteases), to support pod elongation and to enhance starch in seeds (Singh *et al.*, 2024). Zinc is also reported to enhanced nitrogen metabolism and supports pod tissue growth and delayed senescence (Gao *et al.*, 2022). Improved the number of pods per plant, the number of seeds per pod, and the weight of seeds per plant was also correlated with better assimilation of nutrients to enhance yield potential. Moreover, yield improvement under 200 and 400 ppm CHT-ZnO NPs confirms the superior functionality of nano-Zn in maintaining seed-filling duration and efficiency. The improvement in yield attributes not only confirms Zn's role in improving reproductive attributes of pea plants but also highlights the importance of CHT-ZnO NPs as a potent nano-enabled strategy for boosting crop productivity under water-limited environments. Foliar mode of application was the best among all nanoparticles because it might get easier access to above ground plant parts, like leaf stomata and cuticle compared to roots (for soil application), which might affect the behavior of nanoparticles (Wu & Li, 2022). In present study, higher CHT-ZnO NPs dose (400 ppm) showed less benefits compared to the 200 ppm treatment. The reasons for their limited role in plant growth might be due to nanoparticle aggregation, potential phytotoxicity, or interference with nutrient uptake (Sheteiwy *et al.*, 2021). Hence, careful optimization of nanoparticle concentration is suggested to avoid antagonistic effects and to improve crop yield in a sustainable way. The consistent superiority of 200 ppm CHT-ZnO NPs over 400 ppm CHT-ZnO NPs indicates an optimal threshold for NPs based nutrient delivery, beyond which phytotoxicity or nutrient imbalance may occur due to particle aggregation or oxidative stress. (El-Saadony *et al.*, 2022). Nodulation, grain yield and N2 -fixation ability in legumes are often limited by Zn deficiency so by applying Zn through foliar mode might have overcome the zinc deficiency which is caused by nutrient imbalance during drought stress. Zinc is essential for auxin production and this phytohormone is reported to improve nodule number and weight (Sharifi, 2016) thus nitrogen fixing ability might also have improved resulting in higher growth and yield attributes of pea.

Conclusion

This study explored the role of soil, foliar, and combined (foliar + soil) applied chitosan-zinc oxide nanoparticles (CHT-ZnO NPs) in the range of 6.5-400 ppm to improve drought tolerance in pea plants grown in pots and subjected to various irrigation regimes such as 80%, 60%, and 40% field capacity. Drought stress significantly declined the growth and yield of pea plants. However, the foliar application of 200 and 400 ppm CHT-ZnO NPs effectively mitigated these adverse impacts by improving length fresh and dry weights of both shoot and root, leaf No./ plant, No. of seeds/ pod, and seed weight/ plant and ultimately improving the growth and yield traits even under severe drought stress. Compared to the control, the nano-enabled formulation provided better results under moderate drought. The findings suggest that foliar application of 200 and 400 ppm of CHT ZnO NPs have more potential to mitigate drought stress in pea compared to soil application method. Future studies should focus on the molecular mechanisms underlying the enhanced stress tolerance conferred by CHT–ZnO NPs, particularly the regulation of stress-related gene expression. Moreover long-term field trials across diverse agro-ecological zones are recommended to validate the consistency and scalability of these findings under variable environmental conditions.

References

Abdeen, S.A., H.H. Hefni and A.H. Mady. 2023. Foliar application of chitosan zinc oxide nanoparticles on wheat productivity and water use efficiency under deficit irrigation water. *J. Cent. Eur. Agric.*, 24: 476-490.

Abobatta, W. 2023. Chitosan: A promising plant stimulant. *Int. J. Agric. Sci. Food Technol.*, 9(4): 98-103.

Arafa, S.A., K.A. Attia, G. Niedbała, M. Piekutowska, S. Alamery, K. Abdelaal, T.K. Alateeq, M.A. Ali, A. Elkelish and S.Y. Attallah. 2021. Seed priming boost adaptation in pea plants under drought stress. *Plants*, 10(11): 2201.

Bagheri, M., C.S. Santos, D. Rubiales and M.W. Vasconcelos. 2023. Challenges in pea breeding for tolerance to drought: Status and prospects. *Ann. Appl. Biol.*, 183(2): 108-120.

Bhattacharya, A. 2021. Effect of soil water deficit on growth and development of plants: A review. In: *Soil Water Deficit and Physiological Issues in Plants*. Springer, Singapore, pp. 393-488.

Bhrijavasi, G., D. Anusha, K. Mishra and R. Chawla. 2024. Underutilized fruit crops in semi-arid climates: Challenges, innovations, and future prospects. *Int. J. Adv. Biochem. Res.*, 8: 488-496.

Chattha, M.U., T. Amjad, I. Khan, M. Nawaz, M. Ali, M.B. Chattha, H.M. Ali, R.Y. Ghareeb, N.R. Abdelsalam and S. Azmat. 2022. Mulberry-based zinc nanoparticles mitigate salinity-induced toxic effects and improve the seed yield and zinc bio-fortification of wheat by improving antioxidant activities, photosynthetic performance, and accumulation of osmolytes and hormones. *Front. Plant Sci.*, 13: 920570.

Dejene, B.K. and M.A. Abtew. 2025. Chitosan/zinc oxide (ZnO) nanocomposites: A critical review of emerging multifunctional applications in food preservation and biomedical systems. *Int. J. Biol. Macromol.*, 316: 144773.

El-Beltagi, H.S., K.A. El-Naqma, M.I. Al-Daej, M.M. El-Afry, W.F. Shehata, M.F. El-Nady, A.M. Ismail, W.F. Eltonoby, A.A. Rezk and M.M.S. Metwaly. 2024. Effects of zinc nanoparticles and proline on growth, physiological and yield characteristics of pea (*Pisum sativum* L.) irrigated with diluted seawater. *Cogent Food Agric.*, 10(1): 2348695.

El-Saadony, M.T., A.M. Saad, S.M. Soliman, H.M. Salem, E.-S.M. Desoky, A.O. Babalghith, A.M. El-Tahan, O.M. Ibrahim, A.A. Ebrahim and T.A. Abd El-Mageed. 2022. Role of nanoparticles in enhancing crop tolerance to abiotic stress: A comprehensive review. *Front. Plant Sci.*, 13: 946717.

Farooq, M., N. Gogoi, S. Barthakur, B. Baroowa, N. Bharadwaj, S.S. Alghamdi and K.H. Siddique. 2017. Drought stress in seed legumes during reproduction and seed filling. *J. Agron. Crop Sci.*, 203(2): 81-102.

Gao, F., X. Zhang, J. Zhang, J. Li, T. Niu, C. Tang, C. Wang and J. Xie. 2022. Zinc oxide nanoparticles improve lettuce (*Lactuca sativa* L.) plant tolerance to cadmium by stimulating antioxidant defense, enhancing lignin content and reducing the metal accumulation and translocation. *Front. Plant Sci.*, 13: 1015745.

Ghiyasi, M., Y. Rezaee Danesh, R. Amirnia, S. Najafi, J.M. Mulet and R. Porcel. 2023. Foliar applications of ZnO and its nanoparticles increase safflower (*Carthamus tinctorius* L.) growth and yield under water stress. *Agronomy*, 13(1): 192.

Giglou, M.T., R.H. Giglou, B. Esmaeilpour, R. Azarmi, A. Padash, M. Falakian, J. Śliwka, G. Gohari and H.M. Lajayer. 2022. A new method in mitigation of drought stress by chitosan-coated iron oxide nanoparticles and growth stimulant in peppermint. *Ind. Crops Prod.*, 187: 115286.

Gungaabayar, A., A. Jha, T. Warkentin, D. Knight, G. Penner and B. Biligetu. 2023. Forage yield and biological nitrogen fixation of pea–cereal intercrops for hay production. *Agron. J.*, 115(2): 607-619.

Haghpanah, M., S. Hashemipetroudi, A. Arzani and F. Araniti. 2024. Drought tolerance in plants: Physiological and molecular responses. *Plants*, 13(21): 2962.

Jiang, Y., R. Lahlali, C. Karunakaran, T.D. Warkentin, A.R. Davis and R.A. Bueckert. 2019. Pollen, ovules, and pollination in pea: Success, failure, and resilience in heat. *Plant Cell Environ.*, 42(1): 354-372.

Kausar, A., N. Zahra, H. Zahra, M.B. Hafeez, S. Zafer, A. Shahzadi, A. Raza, I. Djalovic and P.V. Prasad. 2023. Alleviation of drought stress through foliar application of thiamine in two varieties of pea (*Pisum sativum* L.). *Plant Signal. Behav.*, 18(1): 2186045.

Lahuta, L.B., J. Szablińska-Piernik and M. Horbowicz. 2022. Changes in metabolic profiles of pea (*Pisum sativum* L.) as a result of repeated short-term soil drought and subsequent re-watering. *Int. J. Mol. Sci.*, 23(3): 1704.

Liu, Z., J. Meng, Z. Sun, J. Su, X. Luo, J. Song, P. Li, Y. Sun, C. Yu and X. Peng. 2022. Zinc application after low temperature stress promoted rice tillers recovery: Aspects of nutrient absorption and plant hormone regulation. *Plant Sci.*, 314: 111104.

Methela, N., A. Pande, M.S. Islam, W. Rahim, A. Hussain, D.-S. Lee, B.-G. Mun, N.M.J. Raj, S.-J. Kim, Y. Kim and B.-W. Yun. 2023. Chitosan-GSNO nanoparticles: A positive modulator of drought stress tolerance in soybean. *BMC Plant Biol.*, 23: 639.

Nadeem, M., J. Li, M. Yahya, A. Sher, C. Ma, X. Wang and L. Qiu. 2019. Research progress and perspective on drought stress in legumes: A review. *Int. J. Mol. Sci.*, 20(10): 2541.

Nadeem, M., N. Shakoor, M. Adeel, I. Azeem, M. Zain, Y. Li, U. Zaheer, J. Javed, R. Khalid and P. Zhang. 2025. Environmental and safety aspects of nanotechnology in genetically modified crops for sustainable agriculture. *Physiol. Plant.*, 177(3): e70239.

Naz, S., M.U. Latif, S.T.A. Haider, S. Ali, H. Sardar, R. Ahmad and M.A. Anjum. 2022. Potential of foliar application of micronutrients on growth, yield, quality and nutraceutical properties of pea (*Pisum sativum* L.). *Pak. J. Bot.*, 54(3): 931-942.

Osman, H.S. 2015. Enhancing antioxidant–yield relationship of pea plant under drought at different growth stages by exogenously applied glycine betaine and proline. *Ann. Agric. Sci.*, 60(2): 389-402.

Pandey, J., E. Devadasu, D. Saini, K. Dhokne, S. Marriboina, A.S. Raghavendra and R. Subramanyam. 2023. Reversible changes in structure and function of photosynthetic apparatus of pea (*Pisum sativum*) leaves under drought stress. *Plant J.*, 113(1): 60-74.

Park, J., S.H. Lee, J. Lee, S.H. Wi, T.C. Seo, J.H. Moon and S. Jang. 2025. Growing vegetables in a warming world: A review of crop response to drought stress, and strategies to mitigate adverse effects in vegetable production. *Front. Plant Sci.*, 16: 1561100.

Qu, B., Z. Xiao and Y. Luo. 2025. ZnO-nanoparticles and stage-based drought tolerance in wheat (*Triticum aestivum* L.): effect on morpho-physiology, nutrients uptake, grain yield and quality. *Sci. Rep.*,15:5309

Raza, M.A.S., F. Muhammad, M. Farooq, M.U. Aslam, N. Akhter, M. Toleikienė, M.A. Binobead, M.A. Ali, M. Rizwan and R. Iqbal. 2025. ZnO nanoparticles and stage-based drought tolerance in wheat (*Triticum aestivum* L.): Effect on morpho-physiology, nutrients uptake, seed yield and quality. *Sci. Rep.*, 15: 5309.

Seleiman, M.F., A. Ahmad, B.A. Alhammad and E. Tola. 2023. Exogenous application of zinc oxide nanoparticles improved antioxidants, photosynthetic, and yield traits in salt-stressed maize. *Agronomy*, 13(10): 2645.

Šebesta, M., S. Kurtinová, M. Kolenčík and R. Illa. 2022. Enhancement of stress tolerance of crop plants by ZnO nanoparticles. In: *Sustainable Agriculture Reviews 53: Nanoparticles: A New Tool to Enhance Stress Tolerance*. pp. 287-325. Springer.

Sharifi, R. S. 2016. Application of biofertilizers and zinc increases yield, nodulation and unsaturated fatty acids of soybean *Zemdirbyste-Agriculture* 103(3): 251-258.

Sheteiwy, M.S., H. Shaghaleh, Y.A. Hamoud, P. Holford, H. Shao, W. Qi, M.Z. Hashmi and T. Wu. 2021. Zinc oxide nanoparticles: potential effects on soil properties, crop production, food processing, and food quality. *Environ. Sci. Pollut. Res. Int.* 28:36942-36966.

Shinde, N.A., P.G. Kawar and S.G. Dalvi. 2024. Chitosan-based nanoconjugates: A promising solution for enhancing crops drought-stress resilience and sustainable yield in the face of climate change. *Plant Nano Biol.*, 7: 100059.

Singh, A., V.D. Rajput, S. Lalotra, S. Agrawal, K. Ghazaryan, J. Singh, T. Minkina, P. Rajput, S. Mandzhieva and A. Alexiou. 2024. Zinc oxide nanoparticles influence on plant tolerance to salinity stress: Insights into physiological, biochemical, and molecular responses. *Environ. Geochem. Health*, 46: 148.

Sourati, R., P. Sharifi, M. Poorghasemi, E. Alves Vieira, A. Seidavi, N.A. Anjum, Z. Sehar and A. Sofo. 2022. Effects of naphthaleneacetic acid, indole-3-butyric acid and zinc sulfate on the rooting and growth of mulberry cuttings. *Int. J. Plant Biol.*, 13(3): 245-256.

Sutulienė, R., A. Brazaitytė, S. Małek, M. Jasik and G. Samuolienė. 2023. Biochemical responses of pea plants to drought stress and in the presence of molybdenum trioxide nanoparticles. *Plant Soil*, 492: 381-397.

Tanwar, A. 2021. Role of zinc-based nanoparticles in the management of plant diseases. In: *Nanotechnology in Plant Growth Promotion and Protection*. A.P. Ingle (ed.). Wiley, Hoboken, NJ, pp. 239-258.

Umair Hassan, M., M. Aamer, M.U. Chattha, T. Haiying, B. Shahzad, L. Barbanti, M. Nawaz, A. Rasheed, A. Afzal and Y. Liu. 2020. The critical role of zinc in plants facing the drought stress. *Agriculture*, 10(9): 396.

Wahab, A., G. Abdi, M.H. Saleem, B. Ali, S. Ullah, W. Shah, S. Mumtaz, G. Yasin, C.C. Muresan and R.A. Marc. 2022. Plants' physio-biochemical and phyto-hormonal responses to alleviate the adverse effects of drought stress: A comprehensive review. *Plants*, 11(13): 1620.

Wu, H. and Z. Li. 2022. Nano-enabled agriculture: How do nanoparticles cross barriers in plants? *Plant Comm.*, 3(6): 100346.

Zaman, W., A. Ayaz and S. Park. 2025. Nanomaterials in agriculture: A pathway to enhanced plant growth and abiotic stress resistance. *Plants*, 14(5): 716.