Zinc Oxide Nanoparticles and Seaweed Extracts: A Dual Strategy to Improve Quinoa Growth and Grain Yield

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ABSTRACT

A field experiment was carried out in North Sinai, Egypt during two successive growing seasons 2023/24 and 2024/25 to investigate the effect of the individual and combined foliar applications of seaweed extract (SWE; 3000 mg/L) and zinc oxide nanoparticles (ZnO-NPs; 0, 25, 50, 75 ppm) on the vegetative growth and yield of quinoa (cv. Masr3). A randomized complete block design with a split-plot arrangement was used. Results showed that both SWE and ZnO-NPs significantly improved all measured vegetative parameters (e.g., plant height, number of leaves, leaf area, number of shoots, root length, root number, leaves weight, shoot weight, root weight, inflorescences number, and inflorescences weight) and yield components (e.g., seed cluster number, seed cluster weight, seed weight per plant, 1000-seed weight, and seed yield). The optimal response was observed with the combination of SWE and 50 ppm ZnO-NPs, indicating a strong synergistic effect. This combination enhanced nutrient uptake, boosted antioxidant activity, and sustained photosynthetic efficiency, leading to improved productivity. However, the combined application of SWE and the highest ZnO-NPs dose (75 ppm) resulted in significant declines in growth and yield due to phytotoxic effects, suggesting that excessive ZnO-NPs may cause physiological imbalance when combined with bioactive compounds. The findings highlight that integrating SWE 3000 mg/L with moderate ZnO-NPs doses of 50 ppm offers a sustainable and climate-smart agronomic strategy to enhance quinoa resilience and yield performance in marginal environments.

Keywords: Quinoa, zinc oxide nanoparticles, seaweed extract, foliar spray, climate stress.

INTRODUCTION

Global population growth, projected to reach 9.1 billion by 2050 (Kakani *et al.,* 2020), intensifies pressure on agricultural systems to overcome diminishing arable land and climate-driven abiotic stresses—notably drought, salinity, and temperature extremes—which collectively account for approximately 70% of worldwide yield reductions (Kah *et al.,* 2018). Conventional breeding methods face inherent limitations in developing stress-resilient crops due to insufficient genetic variability under adverse conditions (Zafar *et al.,* 2021), necessitating innovative technological interventions to sustainably enhance productivity. Within this context, quinoa (*Chenopodium quinoa* Willd.) has emerged as a strategic crop for global food security, designated by the FAO (Jacobsen *et al.,* 2003) for its exceptional nutritional profile, which features complete essential amino acids (Ruales and Nair, 1992) and gluten-free seeds, coupled with remarkable environmental resilience (Razzaghi *et al.,* 2012 and Hinojosa *et al.,* 2018). As a facultative halophyte, quinoa tolerates combined salinity stress exceeding 40 dS/m and high-temperature extremes (Adolf *et al.,* 2013 and Rezzouk *et al.,* 2020), enabling its rapid expansion beyond Andean regions into Mediterranean agroecosystems (Präger *et al.,* 2018 and Ahmadi *et al.,* 2019). Despite these advantages, yield instability under escalating climate pressures and the underutilization of byproducts, such as straw (Asher *et al.,* 2020 and Filik, 2020), constrain its full agricultural potential.

Zinc, an essential micronutrient pivotal for enzymatic catalysis, metabolic regulation, protein synthesis, gene expression, and membrane stability in plants and animals (Broadley *et al.,* 2007), directly influences yield outcomes. Nanotechnology, particularly utilizing zinc oxide nanoparticles (ZnO-NPs), offers a transformative solution for enhancing zinc delivery in agriculture (Cakmak, 2008a,b and Sabir *et al.,* 2014). Notably, ZnO-NPs exhibit markedly enhanced efficacy at substantially reduced concentrations (e.g., 20 ppm vs. 150–250 ppm for conventional fertilizers), enabling significant biomass improvements. This performance significantly outperforms conventional zinc fertilizers (Bandyopadhyay *et al.,* 2015 and Milani *et al.,* 2015).

Concurrently, ZnO-NPs optimize zinc metabolism and ameliorate the adverse effects of chemical overfertilization. Their application enhances antioxidant enzyme activity, providing critical protection against reactive oxygen species (ROS)-induced cellular damage by effectively diminishing ROS accumulation (Wan *et al.,* 2019). Furthermore, ZnO-NPs contribute to photosynthetic stability by precisely regulating inter-photosystem electron transport (Landa *et al.,* 2015). Studies consistently correlate elevated zinc levels resulting from nanoparticle applications with accelerated plant growth rates, increased biomass accumulation, and enhanced elongation (Singh *et al.,* 2018). These multifaceted efficiency gains firmly

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establish ZnO nanotechnology as a cornerstone for sustainable biofortification strategies.

Seaweed extracts (SWE) have become an essential component of integrated crop management systems due to their multifaceted biostimulant properties (Elansary *et al.,* 2017 and Goni *et al.,* 2018). These extracts contain a diverse spectrum of bioactive compounds, including vitamins, minerals, proteins, carbohydrates, phytohormones (auxins, gibberellins, cytokinins), polyphenols, alginates, and essential trace elements (Cu, Zn, Mo, B, Co), that collectively enhance plant physiological processes (Battacharyya *et al.,* 2015 and Agregán *et al.,* 2017). Their balanced carbon-to-nitrogen ratio further promotes plant vitality and growth, while commercial formulations include chips, flakes, powders, organic fertilizers, and soil conditioners (Carillo *et al.,* 2020 and Laribi *et al.,* 2023).

Empirical studies demonstrate that foliar application of aqueous SWE (10%) significantly enhances key morphometric parameters, including shoot elongation, root development, leaf count, branch proliferation, dry biomass accumulation, and canopy spread. These morphological improvements translate to consistent yield and quality enhancements across a wide range of horticultural crops. Specific trials have revealed increased fruit production, quality indices, and root mass in strawberries, radishes, cabbage, and tomatoes (Raja and Vidya, 2023), with tomatoes exhibiting notable improvements in vegetative growth and yield attributes. Enhanced bulb depth in onions further corroborates SWE's efficacy (Kakabra, 2024). Complementarily, SWE functions as a multi-mechanism biostimulant by improving rhizosphere health, elevating nutrient assimilation efficiency, and enhancing osmotic regulation. Field validations confirm a 35% increase in soil water retention, stimulated microbial diversity, and upregulated antioxidant enzyme activity (CAT, APX) under abiotic stresses, such as salinity (Aboualhamed and Loutfy, 2020).

As plants mature under SWE supplementation, accelerated nutrient assimilation elevates tissue concentrations of beneficial compounds (Ghanaym *et al.,* 2022 and Sulieman *et al.,* 2023). The extract concurrently confers photoprotective benefits by stimulating ascorbic acid synthesis, mitigating photooxidative damage to the photosynthetic apparatus, suppressing chlorophyll degradation, and elevating chlorophyll content. This functional versatility drives and strengthens physiological resilience, evidenced by significant yield enhancements: quinoa exhibits a 22% grain yield increase at 1 kg/ha SWE, soybeans achieve 31% higher nutrient uptake under rainfed conditions with 15% foliar application, and common beans maintain fatty acid profiles while improving drought tolerance at 4 L/ha.

Although zinc oxide nanoparticles (ZnO-NPs) and seaweed extract (SWE) enhance quinoa plants production individually, we don't yet understand how they work together. Current research doesn't show what happens when both are applied during combined stresses like drought, salt, and heat. It also doesn't measure how we could reuse crop byproducts from stressed plants. This study fills these gaps by spraying quinoa leaves with both ZnO-NPs and SWE together. We carefully measure how the plants adapt and how much they produce, creating a practical dual-technology approach for growing climate-resistant quinoa in poor soils

MATERIAL AND METHODS

1. Experimental Location

The field experiment was conducted at the Experimental Farm of the Faculty of Environmental Agricultural Sciences, Arish University, North Sinai, Egypt (31°08'04.3"N, 33°49'37.2"E). The study spanned two consecutive growing seasons: 2023/2024 and 2024/2025. The site exhibits a semi-arid climate. Meteorological data for both seasons are presented in Table (1).

Soil Mechanical and Chemical Analyses

Mechanical and chemical soil analyses (0–30 cm depth) were performed by the Soil and Water Department (SWD). The soil was classified as sandy loam with the following particle size distribution: 67.1% coarse sand, 19% fine sand, 11.2% clay, and 2.7% silt. Chemical properties indicated alkalinity (pH 8.5), electrical conductivity (1.7 dS m^{-1}), and calcium carbonate content (3.95%). Organic constituents included low organic carbon (1.09 g kg^{-1}) and organic matter (1.88 g kg^{-1}). Soluble cations (meq L^{-1}) were Ca^{2+} (2.9), Na^{+} (2.7), Mg^{2+} (2.18), and K^{+} (0.47); anions comprised HCO_3^- (2.41) and Cl^- (1.29).

Table 1. Meteorological data of El-Arish, North Sinai, region during quinoa growing seasons of 2023/2024 and 2024/2025

Months	Average temperature (°C)	Minimum Air Temperature [°C]	Maximum Air Temperature [°C]	Average Relative Humidity (%)	Total precipitation (mm)	Solar Radiation (MJ/m^2/day)
First season 2023-2024						
October-2023	24.91	21.99	28.95	68.43	6.05	15.72
November-2023	21.88	18.84	26.15	69.31	5.45	12.49
December-2023	17.19	13.54	21.92	69.69	6.55	9.68
January-2024	14.89	11.23	19.36	67.18	22.25	11.36
February-2024	13.42	10.09	17.50	75.76	19.65	14.32
March-2024	16.13	11.96	21.43	68.82	5.95	19.78
April-2024	20.36	15.90	26.30	68.78	2.30	23.33
May-2024	22.56	18.13	28.29	61.92	1.05	25.33
Average and Sum	18.92	15.21	23.74	68.74	138.5	16.50
Second Season 2024-2025						
October-2024	19.46	16.14	23.75	67.68	5.70	13.01
November-2024	15.62	12.04	20.22	62.57	9.70	11.27
December-2024	14.57	10.89	19.55	70.60	6.50	11.93
January-2025	12.94	9.66	17.09	67.48	19.80	12.60
February-2025	17.49	13.03	23.31	64.22	11.20	19.24
March-2025	19.49	14.96	25.58	61.63	6.10	21.61
April-2025	22.96	17.93	29.22	57.66	8.70	26.82
May-2025	17.50	13.52	22.67	64.55	67.70	16.64
Average and Sum	19.46	16.14	23.75	67.68	5.70	13.01

Source: Central Laboratory for Agricultural Climate **(CLAC, Egypt).**

2. Plant Material

The quinoa (*Chenopodium quinoa*) cultivar 'Masr3' was used in this study. Certified seeds were procured from the Agricultural Research Center (ARC), Ismailia, Egypt.

3. Foliar Spray Materials

3.1. Nanoparticles

3.1.1. Preparation Method

Zinc oxide nanoparticles (ZnO-NPs) were synthesized following the method described by Pacholski *et al.* (2002) and Beek *et al.* (2005), which involves the hydrolysis and condensation of zinc acetate dihydrate using potassium hydroxide in an alcoholic medium under low-temperature conditions. The formed nanoparticles settled at the bottom of the solution; the supernatant was discarded, and the resulting precipitate was washed thoroughly with methanol. Finally, the purified ZnO-NPs were redispersed in a solvent mixture consisting of methanol and chloroform (Seow *et al.*, 2009 and Nageh *et al.*, 2022). Commercial Nano-zinc oxide (Nano-ZnO) foliar spray was obtained from Nano Gate Company, Egypt, for application purposes.

3.1.2. Characterization Techniques

Size and Morphology: Transmission electron microscopy (TEM) analysis was conducted using a Talos F200i (Thermo-Scientific) high-resolution instrument operating at an accelerating voltage of 200 kV. Samples were prepared by placing a droplet of the colloidal suspension onto a Formvar carbon-coated 300-mesh copper grid (Ted Pella) and allowing it to dry under ambient air conditions. The TEM image of zinc oxide revealed that the synthesized ZnO particles were in the nanoscale range, with an average size of 20 ± 3 nm and a nearly spherical shape, as shown in Figure (1)

Crystallinity: The crystalline structure of the ZnO-NPs was examined using an XPERT-PRO Powder Diffractometer system, with a 2θ range of 20°–80°, minimum step size of 0.001°, and Cu Kα radiation (λ = 1.54614 Å) as illustrated in Figure (2).

Functional Groups: Attenuated total reflectance Fourier-transform infrared (ATR/FTIR) spectra were obtained using a Vertex 70-RAM II spectrometer (Bruker Analytical, Germany) at room temperature across the spectral range of 400–4000 cm^{-1} as shown in Figure (3).

Optical Properties: Ultraviolet-visible (UV–Vis) absorption spectra were measured using a Cary series UV–Vis–NIR spectrophotometer (Australia) to evaluate the optical properties of the prepared ZnO nanoparticles as presented in Figure (4).

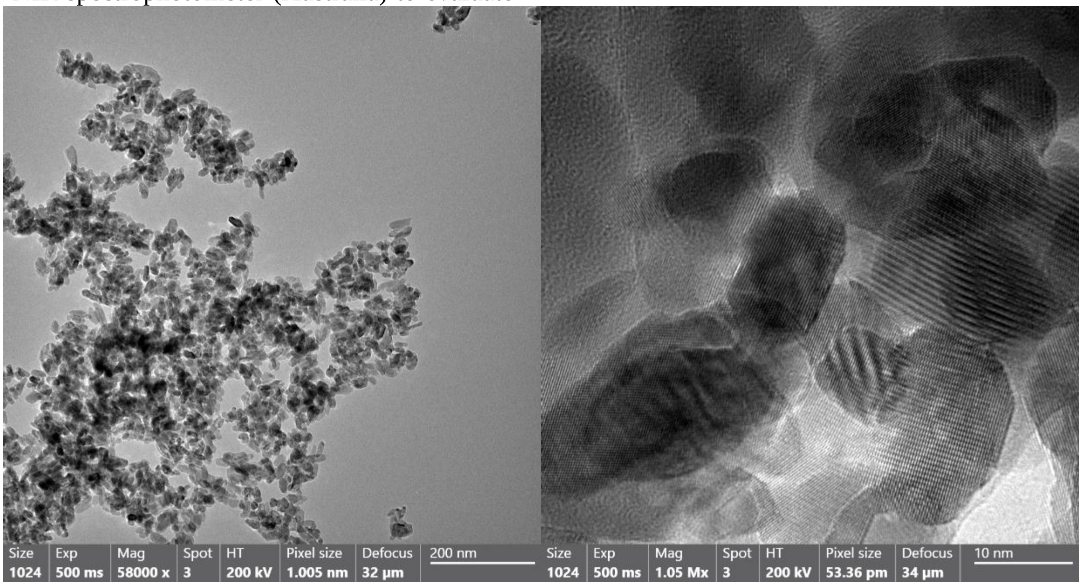

Figure 1. presents the TEM image of ZnO nanoparticles along with the corresponding SAED pattern

Source: *Nano Gate Company, Egypt, provided the data.*

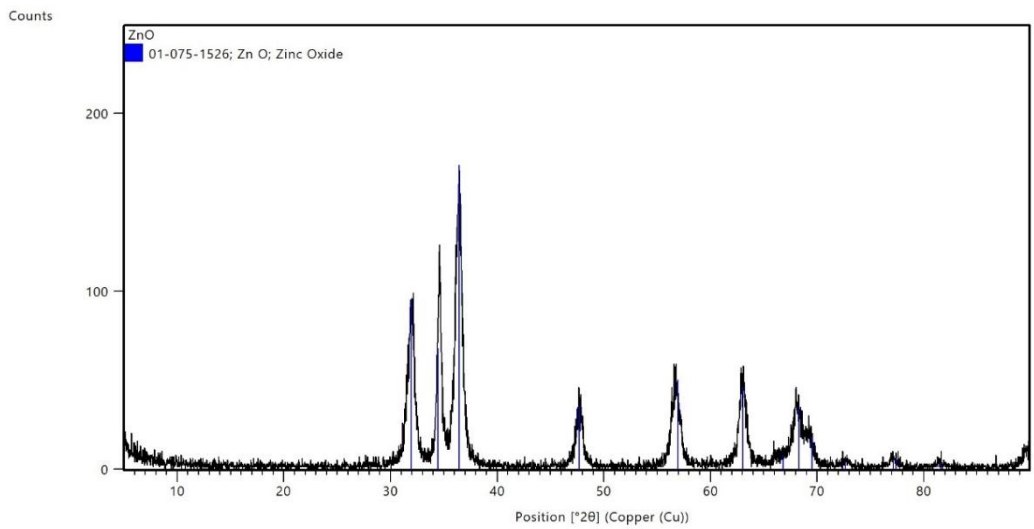

Figure 2:XRD pattern of the synthesized ZnO nanoparticles

Source: Nano *Gate Company, Egypt, provided the data.*

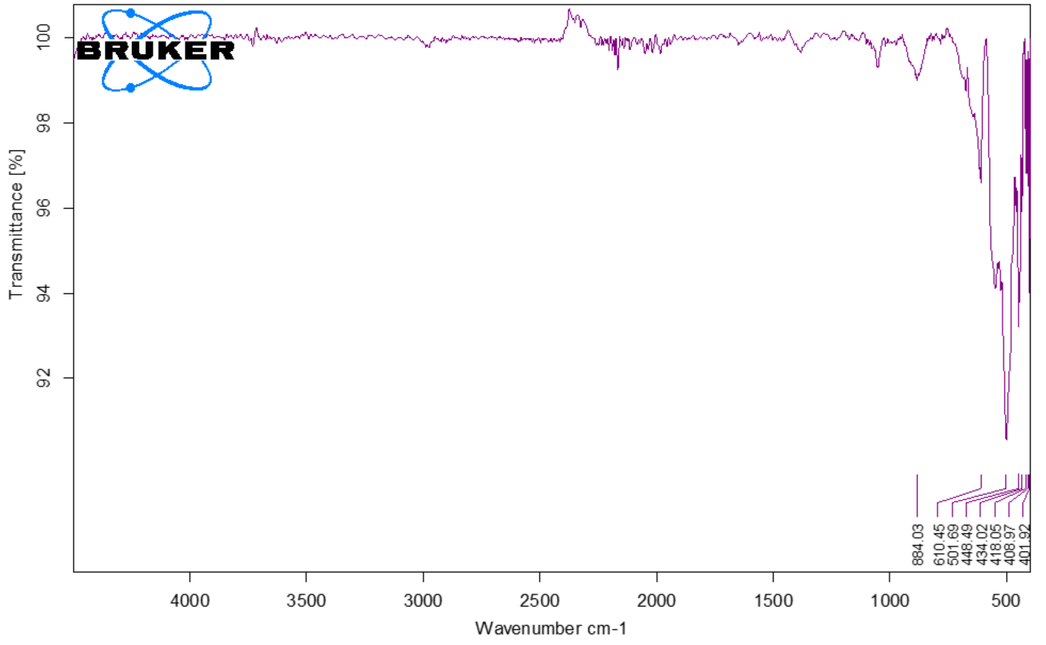

Figure 3 .*FTIR spectrum of as-prepared ZnO-NPs*

Source: Nano *Gate Company, Egypt, provided the data.*

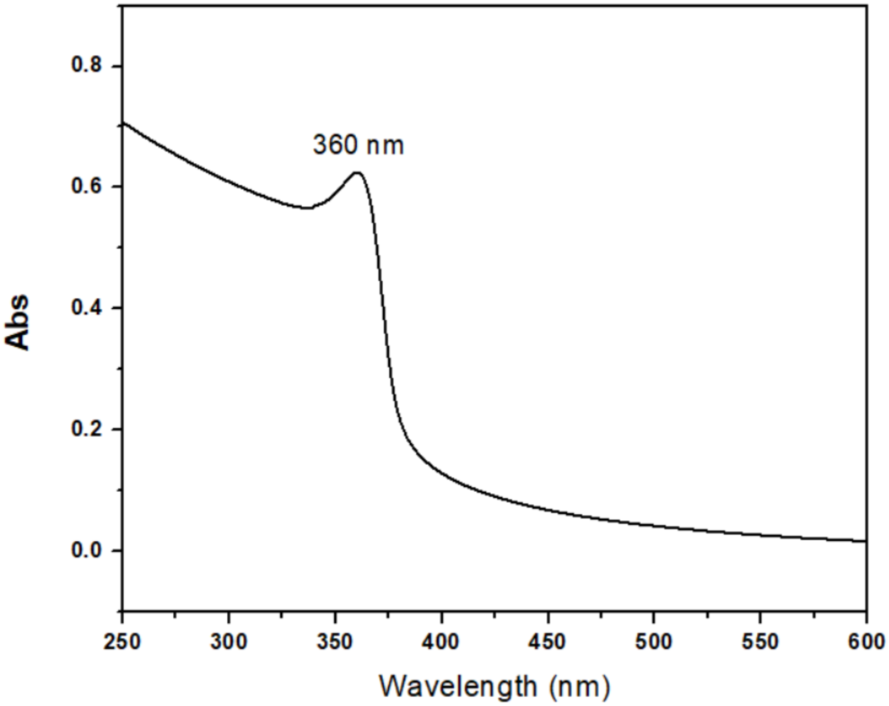

Figure 4. Optical absorption spectrum of the synthesized ZnO nanoparticles

Source: Nano *Gate Company, Egypt, provided the data.*

3.2. Seaweed Extract

A marine-derived seaweed extract (SWE) (Evergreen Agricultural Development Company) was used, with the following composition: 0.9% N, 4% P_2O_5, 10% K_2O, 0.5% S, 16% alginate, and 50% organic matter. The product exhibited a pH of 8–10 and 100% water solubility.

4. Experimental Design and Field Layout

The experiment occupied a total area of 180 m^2. Seeds were manually drilled on 3 December with 50 cm inter-row spacing and 30 cm between hills (planting stations). All recommended agronomic practices for quinoa were rigorously implemented. Farmyard manure was incorporated during land preparation at 20 m^3 $feddan^{-1}$ (~42 m^3 ha^{-1}). Plots received uniform NPK (19:19:19) fertilization at 50 kg $feddan^{-1}$ (~105 kg ha^{-1}), split into two applications: at sowing and 40 days after sowing (DAS). Seedlings were thinned to 5 plants per hill at 30 DAS and one plant per hill at 45 DAS.

A Randomized Complete Block Design (RCBD) with three replications was employed using a split-plot arrangement:

- **Main plots:** SWE concentrations [0 mg L^{-1} (control), 3000 mg L^{-1}] applied at 45 DAS.
- **Sub-plots:** Nano-zinc oxide (Nano-ZnO) concentrations (0, 25, 50, 75 ppm) applied at 30 DAS.

The 2 × 4 factorial designs generated eight treatments encompassing all factor interactions. Treatments were systematically randomized within blocks.

5. Recorded Data

5.1 Vegetative Traits (90 DAS):

Plant height (cm), leaf number, leaf area (cm^2), shoot number, root length (cm), root number, leaf weight (g), shoot weight (g), root weight (g), inflorescence number, and inflorescence weight (g).

5.2 Yield Components (120 DAS):

Seed cluster number, seed cluster weight (g), seed weight per plant (g), 1000-seed weight (g), and seed yield (kg $feddan^{-1}$).

6. Statistical Analysis

Data from both seasons were analyzed using MSTAT-C. A one-way analysis of variance (ANOVA) was used to assess treatment significance (Snedecor and Cochran, 1990). Mean separation utilized Duncan's Multiple Range Test ($P \leq 0.05$) (Duncan, 1955).

RESULTS AND DISCUSSION

1. Effect of seaweed extracts and Nano-zinc oxide as foliar spray on quinoa vegetative traits and their interaction:

As presented in Tables (2 and 3), the application of seaweed extract (SWE) at 3000 mg/L significantly enhanced most measured vegetative traits during the first growing season. Specifically, significant increases were observed in number of leaves, leaves weight, shoot weight, root weight, and number of inflorescences. In contrast, during the second season, the same SWE concentration (3000 mg/L) resulted in a significant increase across ***all*** measured vegetative traits:" plant height, number of leaves, leaf area, number of shoots, root length, root number, leaves weight, shoot weight, root weight, inflorescences number, and inflorescences weight."

The significant enhancement in vegetative growth parameters observed in Tables (2 and 3)

following foliar application of seaweed extract (3000 mg/L) is mechanistically linked to its rich profile of bioactive compounds. **Phytohormones (e.g., auxins, cytokinins)** directly stimulate cell division and elongation (Stirk *et al.*, 2014), driving increases in plant height and leaf expansion. Concurrently, **cytokinins delay senescence** (Battacharyya *et al.*, 2015 and Kulkarni *et al.*, 2019), preserving chlorophyll integrity and extending photosynthetic activity. This is evidenced by the significant increase in leaf photosynthetic pigments and reduction in chlorophyll degradation rates, which collectively sustain carbon assimilation and biomass accumulation (leaves weight, shoot weight).

Critically, SWE components potentiate root system development by inducing lateral and fibrous root formation (Rathore *et al.*, 2009 and Stirk *et al.*, 2014). This architectural expansion enhances the efficiency of nutrient and water acquisition, as reflected in elevated mineral uptake (K, Ca, etc.) in vegetative tissues (Mahmoud *et al.*, 2019 and Petropoulos *et al.*, 2022). The resultant improvement in resource assimilation supports holistic vegetative vigor, explaining increases in leaf number, shoot number, and root biomass. These processes operate synergistically without phytotoxic effects, confirming SWE's role as a biostimulant that optimizes intrinsic physiological processes rather than inducing stress (Mukherjee and Patel, 2020).

Table 2. Effect of seaweed extracts and nano zinc-oxide as foliar spray on (plant height -number of leaves- leaf area - number of shoots- root length - root number) of quinoa vegetative growth after 90 days from sowing during two successive growing seasons 2023/24-2024/25

Characters / Factors	Plant height (cm)	Leaves number	Leaves area (cm^2)	Shoot number	Root length (cm)	Root number
First season 2023/24						
Seaweed						
Without	98.917a	327.08b	90.445a	26.667a	23.250a	16.625a
With	96.083a	340.21a	89.428a	26.500a	25.167a	19.250a
Nano zinc-oxide ppm						
0	76.83c	246.33c	71.52c	23.50b	20.00b	12.17c
25	96.00b	288.33b	85.28b	26.83ab	21.67b	17.08b
50	110.83a	409.67a	103.49a	29.33a	28.83a	22.67a
75	106.33a	390.25a	99.45a	26.67ab	26.33a	19.83ab
Second season 2024/25						
Seaweed						
Without	82.00b	285.50b	80.89b	20.67b	19.58b	16.75b
With	90.00a	334.67a	91.24a	22.83a	22.92a	20.00a
Nano zinc-oxide ppm						
0	69.50c	220.67c	73.03c	15.000c	17.17b	12.500d
25	79.50b	262.00b	82.57bc	19.333b	19.33b	17.333c
50	96.67a	379.00a	95.58a	26.500a	24.83a	22.833a
75	98.33a	378.67a	93.08ab	26.167a	23.67a	20.833b

Table 3. Effect of seaweed extracts and nano zinc-oxide as foliar spray on (Leaves weight-Shoot weight - Root weight -Inflorescences number - Inflorescences weight) of quinoa vegetative growth after 90 days from sowing growth during two successive growing seasons 2023/24-2024/25

Characters / Factors	Leaves weight (g)	Shoot weight (g)	Root weight (g)	Inflorescences number	Inflorescences weight (g)
First season 2023/24					
Seaweed					
Without	96.61b	79.92b	16.92b	28.25b	15.75b
With	105.48a	87.38a	20.33a	33.88a	22.71a
Nano zinc-oxide ppm					
0	69.08d	56.25d	12.83c	23.83c	14.00c
25	84.08c	67.67c	17.00b	30.33b	18.67b
50	131.28a	109.00a	22.50a	34.67ab	22.17a
75	119.72b	101.67b	22.17a	35.47a	22.08a
Second season 2024/25					
Seaweed					
Without	92.17b	81.50b	14.50b	24.42b	15.92b
With	101.33a	85.33a	18.42a	28.92a	20.25a
Nano zinc-oxide ppm					
0	64.67d	54.17d	11.33c	18.83c	12.17c
25	80.00c	65.67c	15.17b	25.33b	17.50b
50	127.50a	111.00a	20.17a	30.67a	22.17a
75	114.83b	102.83b	19.17a	31.83a	20.50a

Regarding nano zinc oxide effect, Tables (2 and 3) indicate that concentrations up to 50 ppm significantly enhanced all measured vegetative traits—plant height, leaf number, leaf area, shoot number, root length, root number, leaves weight, shoot weight, root weight, inflorescences number, and inflorescences weight — during both seasons ($p<0.05$). However, increasing the concentration to 75 ppm showed no statistically significant improvement in any trait compared to the 50-ppm treatment. Foliar application of zinc oxide nanoparticles (ZnO-NPs) significantly enhances vegetative growth through optimized nutrient efficiency, with their Nano-scale dimensions facilitating superior foliar uptake and bioavailability compared to conventional zinc sources *(Prasad et al., 2012).* This enhancement stems from their characteristically small particle size (Figure 1), which promotes efficient foliar absorption and nutrient utilization. Zinc acts as an essential cofactor for enzymes governing carbohydrate metabolism and protein synthesis *(Basavarajeswari et al., 2008)*, while stimulating auxin biosynthesis *(Harris and Mathuma, 2015).* These mechanisms collectively drive cell division and elongation, manifesting as increased plant height *(Khanm et al., 2018),* branching proliferation *(Wang et al., 2018),* and leaf area expansion *(Faizan and Hayat, 2019).* Concurrently, ZnO-NPs enhance photosynthetic efficiency by upregulating chlorophyll synthesis and electron transport *(Islam et al., 2018),* thereby increasing photoassimilate production. Critically, at optimal concentrations (≤50 ppm), ZnO-NPs avoid phytotoxicity and bolster antioxidant capacity *(Wang et al., 2018),* sustaining unimpeded vegetative development.

Table 4. Interaction of seaweed extracts and nano zinc-oxide effects as foliar spray on (plant height -number of leaves- leaf area - number of shoots- root length - root number) of quinoa vegetative growth after 90 days from sowing during two successive growing seasons 2023/24-2024/25

Zinc-oxide concentration ppm / seaweed		Plant height (cm)	Leaves number	Leaves area (cm²)	Shoot number	Root length (cm)	Root number
		First season 2023/24					
Without Seaweed	0	76.7e	221.67d	68.06e	23.67b	18.67e	11.33d
	25	103.3c	295.00c	89.89bc	29.00ab	20.67de	16.17c
	50	105.3bc	364.67b	97.49ab	25.67b	24.00c	18.67bc
	75	110.3b	427.00a	106.37a	28.33ab	29.67b	20.33b
With Seaweed	0	77.00e	271.00c	74.97de	23.33b	21.3cde	13.00d
	25	88.67d	281.67c	80.67cd	24.67b	22.67cd	18.00bc
	50	116.33a	454.67a	109.51a	33.00a	33.67a	26.67a
	75	102.33c	353.50b	92.57bc	25.00b	23.00cd	19.33bc
		Second season 2024/25					
Without Seaweed	0	64.33e	174.33g	69.073d	14.00d	15.67f	11.33e
	25	76.00d	246.33f	77.71cd	17.33cd	17.67ef	15.33d
	50	89.33bc	313.33d	84.69bc	23.00b	19.0cde	19.00c
	75	98.33ab	408.00b	92.09b	28.33a	26.00b	21.33b
With Seaweed	0	74.67d	267.0ef	76.98cd	16.00d	18.67de	13.67d
	25	83.00cd	277.67e	87.43bc	21.33bc	21.00cd	19.33c
	50	104.00a	444.67a	106.45a	30.00a	30.67a	26.67a
	75	98.33ab	349.33c	94.07b	24.00b	21.33c	20.33bc

Table 5. Interaction of seaweed extracts and nano zinc-oxide effects as foliar spray on (Leaves weight-Shoot weight - Root weight -Inflorescences number - Inflorescences weight) of quinoa vegetative growth after 90 days from sowing during two successive growing seasons 2023/24-2024/25

Zinc-oxide concentration ppm seaweed		Leaves weight (g)	Shoot weight (g)	Root weight (g)	Inflorescences number	Inflorescences weight (g)
First season 2023/24						
Without Seaweed	0	51.67f	49.00e	11.00d	23.00d	12.67e
	25	76.67e	68.67d	13.33cd	26.33cd	15.33d
	50	117.00b	95.67c	19.00b	29.33c	16.67cd
	75	141.11a	106.33b	24.33a	34.33b	18.33c
With Seaweed	0	86.50d	63.50d	14.67c	24.67d	15.33d
	25	91.50d	66.67d	20.67b	34.33b	22.00b
	50	145.57a	122.33a	26.00a	40.00a	27.67a
	75	98.33c	97.00c	20.00b	36.50ab	25.83a
Second season 2024/25						
Without Seaweed	0	47.67g	47.00f	10.00e	17.67e	11.33f
	25	72.67f	66.67e	12.00de	22.33d	15.33de
	50	113.00c	101.67c	16.00c	26.33c	17.67cd
	75	135.33b	110.67b	20.00b	31.33ab	19.33bc
With Seaweed	0	81.67e	61.33e	12.67d	20.00de	13.00ef
	25	87.33e	64.67e	18.33bc	28.33bc	19.67bc
	50	142.00a	120.33a	24.33a	35.00a	26.67a
	75	94.33d	95.00d	18.33bc	32.33a	21.67b

2. Effect of seaweed extracts and Nano-zinc oxide as foliar spray on quinoa yield component and their interaction

The application of 3000 mg/L seaweed extract significantly enhanced ($p < 0.05$) all evaluated yield parameters—seed cluster number, seed cluster weight, seed weight per plant, 1000-seed weight, and seed yield—as quantitatively documented in Table (6) in both seasons. The transition from enhanced vegetative growth to superior yield components—grain yield per plant, 1000-grain weight, and Class A grain proportion (Table 6)—is mediated by SWE's multi-targeted bioactivity. Sustained photosynthetic capacity, due to delayed senescence and preserved chlorophyll (Battacharyya *et al.,* 2015), extends photoassimilate production during reproductive stages. This is compounded by efficient nutrient translocation facilitated by SWE-induced root development (Rathore *et al.*, 2009 and Stirk *et al.*, 2014), ensuring optimal mineral supply (K, Ca, etc.) to developing grains (Mahmoud *et al.,* 2019 and Petropoulos *et al.*, 2022).

Crucially, SWE modulates sink strength and assimilate partitioning (Kocira *et al.*, 2018 and Hasan *et al.,* 2021), redirecting carbohydrates toward inflorescences and grains. This elevates grain number, weight, and quality while reducing Class B grains, aligning with reports in quinoa (Hasan *et al.*, 2021), beans (Kocira *et al.*, 2018), and soybeans (Rathore *et al.*, 2009).

As presented in Table (6), foliar application of Nano-zinc oxide at 50 ppm elicited statistically significant increases ($p<0.05$) in all measured yield components—seed cluster number, seed cluster weight, seed weight per plant, 1000-seed weight, and seed yield relative to control treatments during both growing seasons. Conversely, increasing the concentration to 75 ppm resulted in no significant improvement in any yield parameter compared to the 50-ppm application.

The vegetative vigor induced by ZnO-NPs directly translates to improved yield outcomes via source-sink modulation, where enhanced photoassimilates are preferentially allocated to reproductive sinks (Prasad *et al.*, 2012). This promotes fruit set and development through zinc-mediated auxin activity (Harris and Mathuma, 2015), improves yield uniformity via balanced nutrient partitioning, and elevates grain/fruit biomass accumulation by activating starch synthase enzymes (Basavarajeswari *et al.*, 2008). Zinc's role in protein synthesis further enhances the nutritional quality of harvested organs (Harris and Mathuma, 2015). The absence of oxidative stress at optimal doses (Wang *et al.*, 2018) ensures sustained metabolic activity during reproductive stages, maximizing yield quantity and quality."

Table 6. Effect of seaweed extracts and nano zinc-oxide as foliar spray on (Seed cluster number - Seed cluster weight- Seed weight/ plant- 1000 seed weight- Seed yield) of quinoa yield components after 120 days from sowing growth during two successive growing seasons 2023/24-2024/25

Characters Factors	Seed cluster number	Seed cluster weight (g)	Seed weight/ plant (g)	1000 seed weight (g)	Seed yield (kg/ feddan)
First season 2023/24					
Seaweed					
Without	35.92b	74.00b	51.67b	4.23b	**2173.5b**
With	38.42a	81.92a	55.42a	4.44a	**2327.5a**
Nano zinc-oxide ppm					
0	32.50c	60.50c	42.67c	4.03b	1792b
25	35.83b	75.67b	46.33c	4.20b	1967b
50	40.33a	90.50a	66.33a	4.55a	2772a
75	40.00a	85.17a	58.83b	4.57a	2471a
Second season 2024/25					
Seaweed					
Without	33.08b	70.17b	45.75b	4.058b	**1921.5b**
With	34.42a	78.17a	51.33a	4.358a	**2156.0a**
Nano zinc-oxide ppm					
0	29.33d	57.00c	34.67c	3.93b	1456c
25	31.67c	71.83b	41.33b	4.08b	1736b
50	38.33a	86.67a	61.17a	4.40a	2569a
75	35.67b	81.17a	57.00a	4.42a	2394a

Table 7. Interaction of seaweed extracts and nano zinc-oxide effects as foliar spray on (Seed cluster number - Seed cluster weight- Seed weight/ plant- 1000 seed weight- Seed yield) of quinoa yield components after 120 days from sowing growth during two successive growing seasons 2023/24-2024/25

Zinc-oxide concentration ppm Seaweed		Seed cluster number	Seed cluster weight (g)	Seed weight/ plant (g)	1000 seed weight (g)	Seed yield (kg/ feddan)
First season 2023/24						
Without Seaweed	0	30.67e	57.33e	43.00d	3.80e	1806d
	25	35.00cd	74.67d	48.33cd	4.10d	2072cd
	50	37.67bc	77.67cd	55.33bc	4.40bc	2296bc
	75	40.33ab	86.33b	60.00b	4.63ab	2520b
With Seaweed	0	34.33d	63.67e	42.33d	4.27cd	1778d
	25	36.67cd	76.67d	44.33d	4.30cd	1862d
	50	43.00a	103.33a	77.33a	4.70a	3248a
	75	39.67b	84.00bc	57.67b	4.50abc	2422b
2024/25 Second season						
Without Seaweed	0	29.00f	53.33f	32.33e	3.70e	1358e
	25	31.67e	71.00d	39.33d	3.97d	1652d
	50	34.00c	74.00cd	50.00c	4.13cd	2100c
	75	37.67b	82.33b	61.33b	4.43b	2576b
With Seaweed	0	29.67ef	60.67e	37.00de	4.17c	1554de
	25	31.67de	72.67d	43.33d	4.20c	1820d
	50	42.67a	99.33a	72.33a	4.67a	3038a
	75	33.67cd	80.00bc	52.67c	4.40b	2212c

As quantitatively demonstrated in Tables (4 and 5) (vegetative parameters) and Table (7) (yield components), the treatment combining 50 ppm Nano-ZnO with 3000 mg/L seaweed extract (SWE) demonstrated optimal enhancement across all measured growth and productivity metrics. Paradoxically, while Nano-ZnO at 75 ppm alone showed no significant phytotoxicity (maintaining baseline performance, as documented in Tables (4, 5, and 7), its combination with SWE induced substantial reductions in all traits reported in these tables. This antagonism stems from SWE's bioactive compounds potentiating Nano-ZnO's inherent concentration-dependent toxicity, effectively lowering its damage threshold (Nekoukhou *et al.*, 2022 and Zhang *et al.*, 2023). Seaweed biomolecules further amplified oxidative stress, elevating reactive oxygen species (H_2O_2), proline accumulation, and electrolyte leakage (Zoufan *et al.*, 2020), there by overwhelming antioxidant defenses (CAT, SOD, GPX) and causing cellular damage (Guo *et al.*, 2023). Concurrently, adsorption of Nano-ZnO onto SWE's organic matrix disrupted nutrient homeostasis (Yin *et al.*, 2022 and Liu *et al.*, 2023), impairing photosynthesis and protein synthesis. Collectively, these mechanisms explain the physiological dysregulation (Rico *et al.*, 2011) uniquely observed under 75 ppm Nano-ZnO + SWE in Tables (4, 5, and 7)."

CONCLUSION

The findings of this study demonstrate that the foliar application of seaweed extract (SWE, 3000 mg/L) in combination with zinc oxide nanoparticles (ZnO-NPs, 50 ppm) produced a strong synergistic effect, resulting in significant improvements in all measured vegetative growth traits and yield components of quinoa. This optimized treatment enhanced physiological performance, nutrient uptake efficiency, and overall productivity, highlighting its potential as a sustainable agronomic practice under conditions of climate stress. In contrast, although the application of ZnO-NPs at 75 ppm alone did not adversely affect growth, its combination with SWE led to marked phytotoxicity, significantly reducing all growth and yield metrics. These results underscore the importance of optimizing nanoparticle concentrations when used in combination with biostimulants to avoid antagonistic interactions. Overall, the study provides a promising framework for integrating natural biostimulants with Nano-based foliar fertilizers as part of climate-smart strategies to improve crop resilience and productivity in marginal environments.

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الملخص العربي

جسيمات أكسيد الزنك النانوية ومستخلصات الطحالب: استراتيجية مزدوجة لتعزيز نمو ومحصول حبوب الكينوا

داليا عبد العاطى سليمان

نفذت تجربة حقلية في شمال سيناء، مصر، خلال موسمي النمو المتتاليين ٢٠٢٣/٢٠٢٤ و ٢٠٢٤/٢٠٢٥ بهدف دراسة تأثير الرش الورقي بشكل منفرد وعند الجمع بين كلا منالمستخلص الطحلبي (SWE) ؛(٣٠٠٠ ملجم/لتر) وجسيمات أكسيد الزنك النانوية (ZnO-NPs؛ ٠، ٢٥، ٥٠، ٧٥ جزء في المليون) على النمو الخضري ومحصول الكينوا (صنف مصر ٣). واستُخدم تصميم القطاعات العشوائية الكاملة بترتيب القطاعات المنشقة (Split-plot). وأظهرت النتائج أن كلاً من المستخلص الطحلبي وجسيمات أكسيد الزنك النانوية أديا إلى تحسن معنوي في جميع معايير النمو الخضري المقاسة (مثل: ارتفاع النبات، عدد الأوراق، مساحة الورقة، عدد الفروع، طول الجذور، عدد الجذور، وزن الأوراق، وزن المجموع الخضري، وزن الجذور، عدد النورات، وزن النورات) ومكونات المحصول (مثل: عدد العناقيد البذررية، وزن العناقيد البذرية، وزن البذور/نبات، وزن الألف بذرة، ومحصول البذور). وسُجلت أفضل استجابة معنوية عند الجمع بين المستخلص الطحلبي وتركيز ٥٠ جزء في المليون من جسيمات أكسيد الزنك النانوية، مما يشير إلى وجود تأثير تآزري قوي. وقد عزز هذا التوليف امتصاص العناصر الغذائية، ورفع النشاط المضاد للأكسدة، وحافظ على كفاءة عملية التمثيل الضوئي، مما أدى إلى تحسين الإنتاجية. ومع ذلك، أدى التطبيق المشترك للمستخلص الطحلبي وأعلى جرعة من جسيمات أكسيد الزنك النانوية (٧٥ جزء في المليون) إلى انخفاضات معنوية في النمو والمحصول نتيجة تأثيرات سامة نباتية (Phytotoxic)، مما يوحي بأن الجرعات المفرطة من جسيمات أكسيد الزنك النانوية قد تسبب اختلالاً فسيولوجياً عند دمجها مع المركبات الحيوية النشطة. وتسلط النتائج الضوء على أن دمج المستخلص الطحلبي بتركيز ٣٠٠٠ ملجم/لتر مع جرعات معتدلة من جسيمات أكسيد الزنك النانوية (٥٠ جزء في المليون) يُعد إستراتيجية زراعية مستدامة وذكية مناخياً لتعزيز مرونة نبات الكينوا وأدائه الإنتاجي في البيئات الهامشية.

الكلمات المفتاحية :الكينوا، جزيئات أكسيد الزنك النانوية، مستخلص الطحالب البحرية، الرش الورقي، الإجهاد المناخي.