NARDI FUNDULEA, ROMANIA
ROMANIAN AGRICULTURAL RESEARCH, NO. 42, 2025
www.incda-fundulea.ro; doi.org/10.59665/rar4265
First Online: June, 2025. DII 2067-5720 RAR 2025-181

Mitigating of Water Stress on Potato Physiological-Agronomic Traits by the Foliar Application of Seaweed Extract and Zinc Oxide Nanoparticles

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ABSTRACT

Severe drought conditions adversely affect potato physiology, leading to reduced gas exchange, altered photosynthetic pigments, and diminished growth, ultimately impacting tuber yield. Seaweed extract and ZnO-NPs offer a sustainable solution to mitigate the harmful effects of drought on physiological and agronomic traits of potato, ensuring environmental safety and sustainability. To mitigate this adversely effects, two experiments were conducted in the winter seasons of 2021/2022 and 2022/2023 at the experimental farm of the College of Sciences and Humanities of the University of Shaqra (Al-Quwayiyah Governorate). Three adjacent field experiments were performed under three water regimes using a randomized complete block design with a split plot arrangement with three replications. In each one of these, three rates of seaweed extract were distributed in the main plots, whereas three rates of ZnO-NPs were applied in the sub-plots. Moderate and severe water stress negatively influenced physiological and agronomic traits of potato. Nonetheless, applying 1000, and 2000 mg L^{-1} of seaweed extract and 50 and 100 mg L^{-1} of ZnO-NPs, respectively, alone or in combination mitigated these adverse effects of both water stress at 50 and 75% of the available soil moisture depletion on various physiological and yield traits in potato plants, including net photosynthesis up to 17.52%, transpiration rate up to 17.18%, stomatal conductance up to 10.19%, and intercellular CO_2 levels up to 8.31%. These treatments also improved water use efficiency up to 2.94%, relative water content up to 11.16%, and chlorophyll content up to 13.50%, alongside increasing the number of tubers per plant up to 11.43% and total yield per hectare up to 9.38%. Our results indicated that application of seaweed extract and ZnO-NPs alone or in combination, effective strategy in mitigating the harmful effects on drought stress on potato physio-agronomic traits.

Keywords: drought stress, potato, seaweed extract, tuber yield, ZnO-NPs.

INTRODUCTION

Drought significantly impacts potato cultivation, leading to reduced growth, yield, and physiological responses due to the crop's shallow root system and high water requirements (Nasir and Tóth, 2022; Al-Taey and Hussain, 2023). As climate change exacerbates drought conditions, the vulnerability of potatoes to water stress increases, with studies indicating that drought can reduce tuber yield by varying degrees across different genotypes (Gervais et al., 2021; Nasir and Tóth, 2022). For instance, drought-tolerant cultivars like Bannock Russet and Nipigon exhibit only a 15-20% yield reduction compared to more sensitive varieties, which can experience losses up to 91% (Gervais et al., 2021). Effective management strategies, including the use of drought-resistant cultivars, improved irrigation techniques, and agronomic practices such as nutrient management and mulching, are essential to mitigate these adverse effects and sustain potato production under water-limited conditions (Al-Taey and Hussain, 2023; Abdel-Azeem et al., 2024).

The application of seaweed extracts as foliar treatments significantly enhances various physiological and agronomic parameters in potato cultivation. Specifically, a 10% concentration of Kappaphycus sap has been shown to improve chlorophyll content and SPAD readings, thereby boosting photosynthetic efficiency, as noted by Garai et al. (2021) and Saleh et al. (2024). Enhanced leaf gas exchange rates facilitate better carbon absorption, crucial for plant health and productivity (Mbuyisa et al., 2023). Additionally, seaweed extracts contribute to increased plant height, leaf area, and biomass accumulation, with treatments like 2% seaweed extract notably enhancing

Received 15 May 2025; accepted 19 June 2025.

vegetative growth characteristics (Saleh et al., 2024). Furthermore, optimal application can lead to tuber yield increases of up to 32% compared to control treatments, while also improving nutritional qualities such as ascorbic acid levels and tuber hardness (Garai et al., 2021). Overall, these findings underscore the potential of seaweed extracts in sustainable potato production practices (Garai et al., 2021; Mbuyisa et al., 2023; Saleh et al., 2024).

Foliar application of zinc oxide nanoparticles (ZnO-NPs) significantly enhances physiological and biochemical parameters in potato plants, particularly under stress conditions. Previous studies indicated that ZnO-NPs improve chlorophyll content, leading to enhanced light energy absorption and electron transport rates, which boosts photosynthetic efficiency and reduces oxidative stress (Chanu and Upadhyaya, 2019; Al-Selwey et al., 2023). Optimal doses of ZnO-NPs (50-100 mg L^{-1}) have been shown to increase plant height, biomass, and leaf area, resulting in improved tuber yield, including greater average tuber weight and quantity, especially during water stress (Faizan et al., 2021; Al-Selwey et al., 2023). Additionally, ZnO-NPs enhance the nutritional quality of tubers by increasing levels of ascorbic acid, crude protein, and essential minerals (Faizan et al., 2021; Al-Selwey et al., 2023). However, it is crucial to monitor concentrations, as excessive application may lead to phytotoxic effects, causing oxidative stress and reduced plant performance (Chanu and Upadhyaya, 2019; Al-Selwey et al., 2023). Thus, careful regulation of ZnO-NP concentrations is essential for optimizing their benefits in potato production.

Therefore, it was profitable to investigate the potential of foliar nutrients such as seaweed extract and ZnO nanoparticles (ZnO-NPs) in mitigating drought stress impacts on gas exchange attributes, plant water potential traits, photosynthetic pigments, tuber yield, and associated attributes of potato plants.

MATERIAL AND METHODS

Site description

Two field trials conducted on the 'Cara' potato cultivar at the Experimental Farm of the College of Science and Humanities, Shaqra University, Al-Quwayiyah Governorate, in the winter seasons of 2021/2022 and 2022/2023. The experimental farm was located at 819 m above sea level, 24º22' E longitude and 44º46' N latitude in the center of Saudi Arabia's kingdom. This site received an average relative humidity of 46.60-47.50%, and an average temperature of 21.1°C during the day and 10.30°C at night. To identify soil properties, soil samples were collected prior to sowing and then air-dried, ground, sieved, and stored for further analysis. The soil experiment included a comprehensive analysis of physical and chemical parameters using Jackson's (1973) methods, which were detailed in Table 1. Maize was the previous crop planted during both seasons.

Table 1. Physicals and chemicals analyses of experimental sites at 30 cm depth of soil

Seasons	Available			pH	EC mmh/v	Clay %	Silt %	Fine sand %	Texture
	N	P	K						
2021/2022	7.12	2.58	37	7.09	1.26	23.25	29.65	47.10	Loam
2022/2023	7.12	2.66	55	7.15	1.22	25.34	32.35	42.31	Loam

Field Experimental Design

Three adjacent trials representing three different irrigation regimes were conducted in a randomized complete block design using a split-plot scheme with three replications: well-watered (irrigation when 25% of available soil moisture was depleted (ASMD), moderately (irrigation when 50% of ASMD), and severe (irrigation when 75% of ASMD). The main plot received three levels of foliar application of seaweed extract: no application, low application (1000 mg L^{-1}), and high application (2000 mg L^{-1}). Foliar application of ZnO-NPs at concentrations of 0, 50, and 100 mg L^{-1} was assigned to sub-plots.

Planting procedure

The experimental field was completely ploughed. On December 1st in both seasons, cut seedy explants weighing approximately 40 g were planted in dry soil and irrigated. They were planted 0.80 meters wide and 0.20 meters apart between hills on one side of a ridge. The experimental plot was made up of five ridges that measured 5.00 m long and 0.80 m wide, covering a total area of 20 m^2. The drip irrigation system used 0.8 m drip laterals and 0.2 m emitters along polyethylene pipelines. Potato plants were sprayed twice during the growing season, once at 60 days post-planting (approximately 12-15 leaves) and again 15 days later (approximately 25-30 leaves), with the assigned treatments. In both years, harvesting took place 120 days after planting. Other recommended agricultural practices for commercial potato production, from planting to harvesting, were carried out in accordance with the guidelines established by Saudi Arabia's Ministry of Environment, Water, and Agriculture.

Recorded data

Leaf gas exchange traits

On the 85th day after sowing, five plants were randomly selected to measure the gas exchange characteristics of the leaves, such as photosynthetic rate (µmol $CO_2/m^2/s$), stomatal conductance ($mol/m^2/s$), intracellular CO_2 concentration (µmol/mol), and transpiration rate (mmol $H_2O/m^2/s$). These measurements provided valuable insights into potato plants' physiological functions.

Between 9 and 11 a.m. on sunny days, the gas exchange characteristics of the third leaf on the upper part of each plant were measured using a portable LI-6400XT photosynthesis system (LI-COR, 1998). To maintain optimal environmental conditions in the leaf chambers, the best management was achieved by using a battery.

Plant water potential

The water use efficiency (WUE) was measured by dividing the rate of photosynthetic (Pn) by the rate of transpiration (TR). Leaf relative water content (RWC) was calculated using the formula (fresh mass - dry mass) / (turgid mass - dry mass) × 100, as per Farouk et al. (2020). Whereas, proline (µmol g^{-1} 'FW') was measured spectrophotometrically at 520 nm using Magne and Larher's (1992) modified ninhydrin procedure.

Photosynthetic pigments

Photosynthetic pigment concentrations (as mg/g fresh weight) of carotenoids, chlorophyll a (Chl a), and chlorophyll b (Chl b) were determined in fresh potato leaves at 85 days after sowing using spectrophotometric analysis, as recommended by Moran (1982).

Yield measurement

At harvest time, select 10 plants at random from each experimental plot and measured various variables such as tuber number per plant, total yield per plant (g), and total yield per hectare (ton). The total tuber yield per plot, measured in kilograms, was calculated by converting the yield obtained from the central area of 8 square meters of the experimental units into tons per hectare for both seasons.

Statistical analysis

Each sub-plot in a randomized complete block design with split-plot arrangement with three replications was analyzed for leaf gas exchange traits, photosynthetic pigments, and tuber yield traits in accordance with Gomez and Gomez (1984). Gomez and Gomez (1984) demonstrated the use of the least significant difference test to compare mean differences between treatments.

RESULTS

Gas exchange traits

The interactive effects of water stress, seaweed extract, and ZnO-NPs foliar application significantly influenced leaf gas exchange traits in potato plants (Figure 1), with statistical significance ($p \leq 0.05$). Increased water stress negatively impacted these traits, leading to reduced growth and physiological performance. However, the application of 1000, and 2000 mg L^{-1} of seaweed extract and 50 and 100 mg L^{-1} of ZnO-NPs mitigated these adverse effects, enhancing plant resilience under both mild and severe water stress conditions. Specifically, ZnO-NPs improved growth attributes, nutrient uptake, and antioxidant enzyme activity, thereby promoting better gas exchange and overall plant health. Similarly, seaweed extracts were shown to enhance physiological traits and yield, particularly when combined with optimal irrigation practices. Thus, integrating these treatments can effectively support potato cultivation in water-limited environments.

The mitigating effects of seaweed extract, and ZnO-NPs foliar application were found at increasing water stress regimes. Under a moderate water stress condition of 50% of ASMD, the application of 50 mg L^{-1} and 100 mg L^{-1} of ZnO-NPs resulted in enhancements in net photosynthesis by 9.1-17.52 and 9.98-15.7%; transpiration rate by 9.86-17.18 and 12.81-15.32%; stomatal conductance by 6.97-10.19 and 8.45-9.4%; and intercellular CO_2 by 6.37-8.3 and 7.7-8.31%, respectively, under the application of 1000 and 2000 mg L^{-1} of seaweed extract, in contrast to the severe water stress condition of 75% of ASMD.

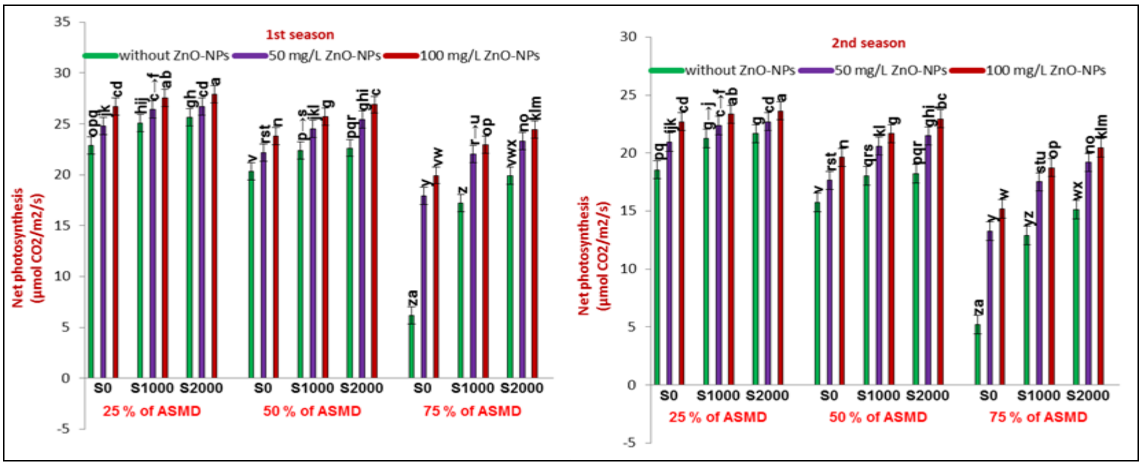

Figure 1a. Net photosynthesis (µmol $CO_2/m^2/s$) of potato as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

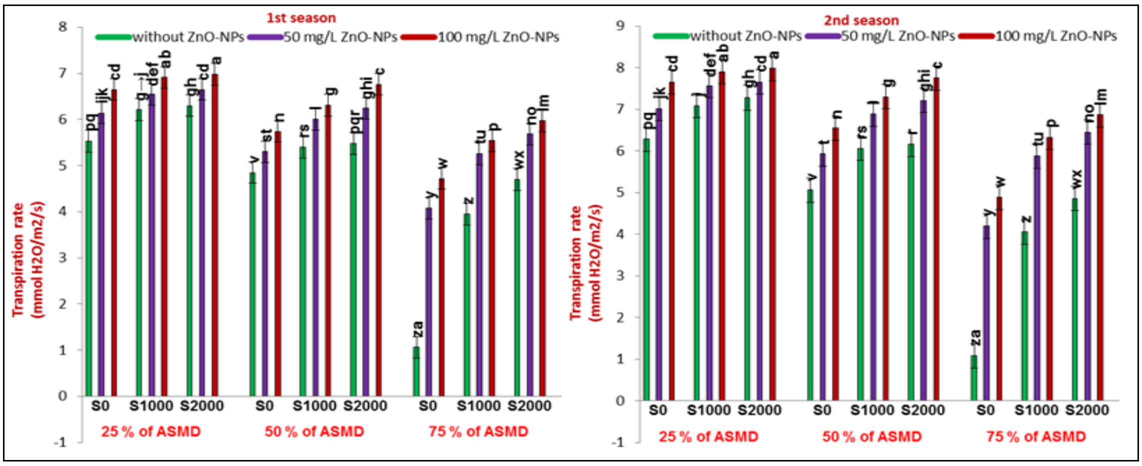

Figure 1b. Transpiration rate (mmol $H_2O/m^2/s$) of potato as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

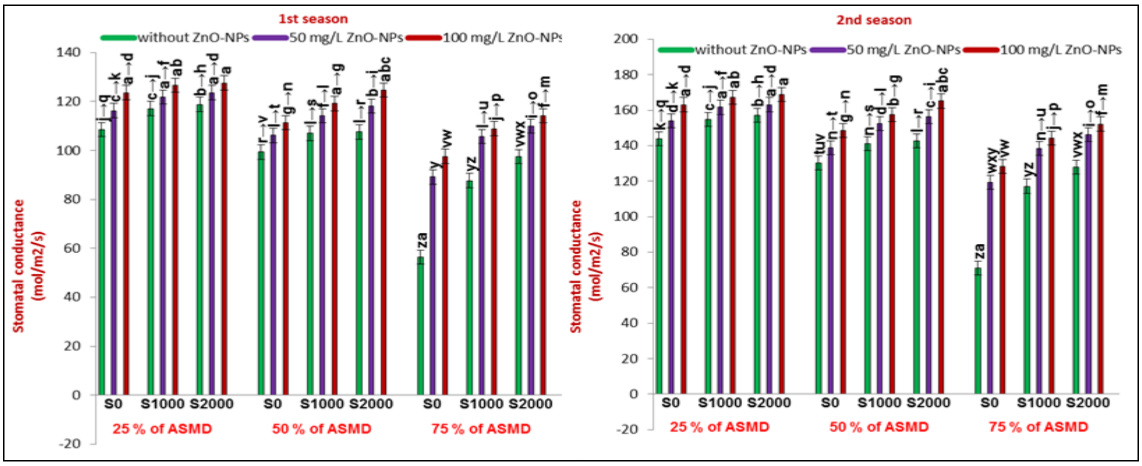

Figure 1c. Stomatal conductance (mol/m^2/s) of potato as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

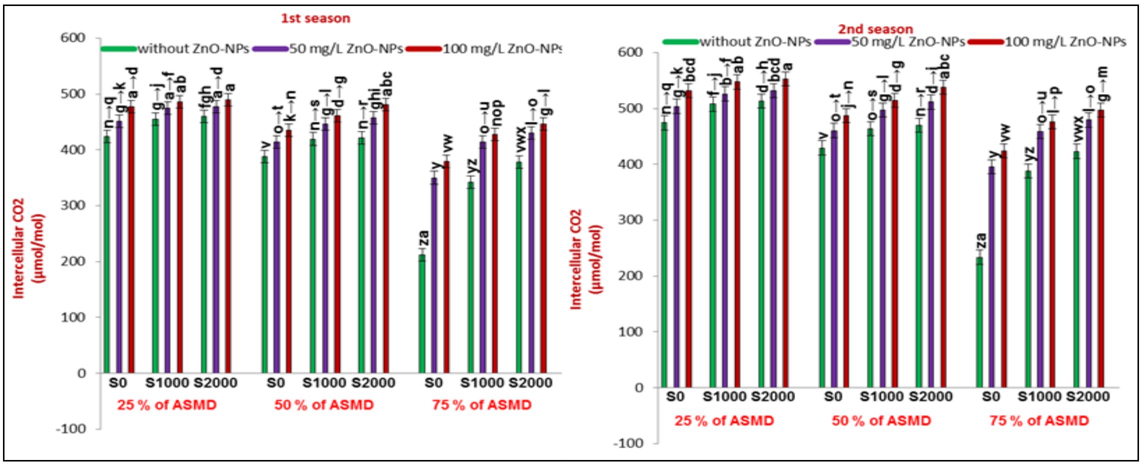

Figure 1d. Intercellular CO_2 (μmol/mol) of potato as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

Water potential traits

The interactive effect of water stress, seaweed extract, and ZnO-NPs foliar application significantly influences water potential traits (Figure 2), as evidenced by water use efficiency (WUE), relative water content (RWC), and proline content ($p \leq 0.05$) in potato plants. Water stress adversely affects physiological traits, including relative water content (RWC) and water use efficiency (WUE), in contrast this in proline content, leading to reduced yields and impaired growth. However, the application of 1000, and 2000 mg L^{-1} of seaweed extracts and 50 and 100 mg L^{-1} of ZnO-NPs and have been shown to enhance physiological responses, improving water use efficiency (WUE), relative water content (RWC), and proline content, thereby mitigating the negative impacts of drought stress.

The mitigating effects of seaweed extract, and ZnO-NPs foliar application were recorded at increasing water stress regimes. Under the extreme water stress condition of 75% of ASMD, the application of 50 mg L^{-1} and 100 mg L^{-1} of ZnO-NPs enhanced water use efficiency by 0.74-2.94 and 0.68-2.76%, respectively; proline concentration was elevated by 23.41-34.45 and 33.06-58.35%, correspondingly, under the application of 1000 and 2000 mg L^{-1} seaweed extract, in comparison to the moderate water stress condition of 50% of ASMD. Conversely, under the moderate water stress condition of 50% of ASMD, the application of 50 mg L^{-1} and 100 mg L^{-1} of ZnO-NPs augmented relative water content percentage by 7.41-11 and 8.88-11.16%, respectively, when applying 1000 and 2000 mg L^{-1} seaweed extract, in contrast to the severe water stress condition of 75% of ASMD.

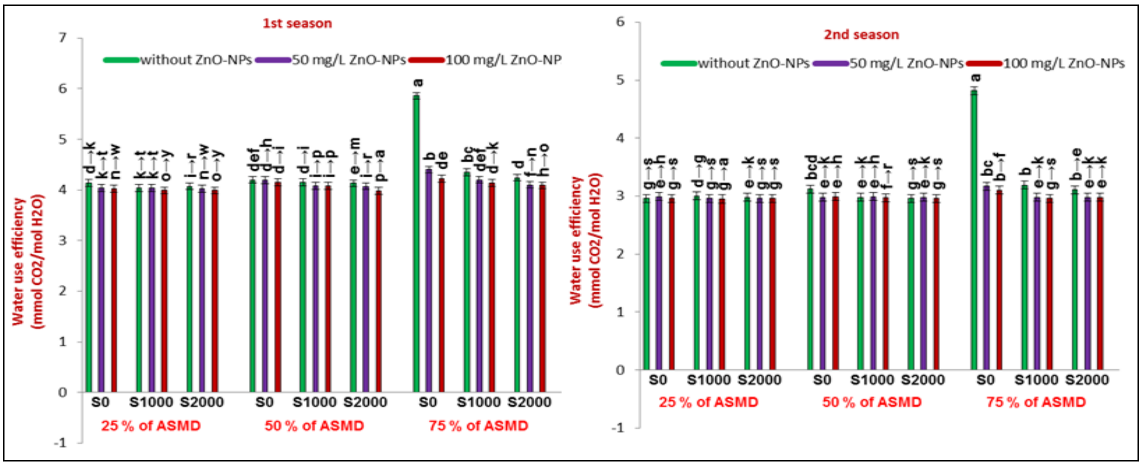

Figure 2a. Water use efficiency of potato as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

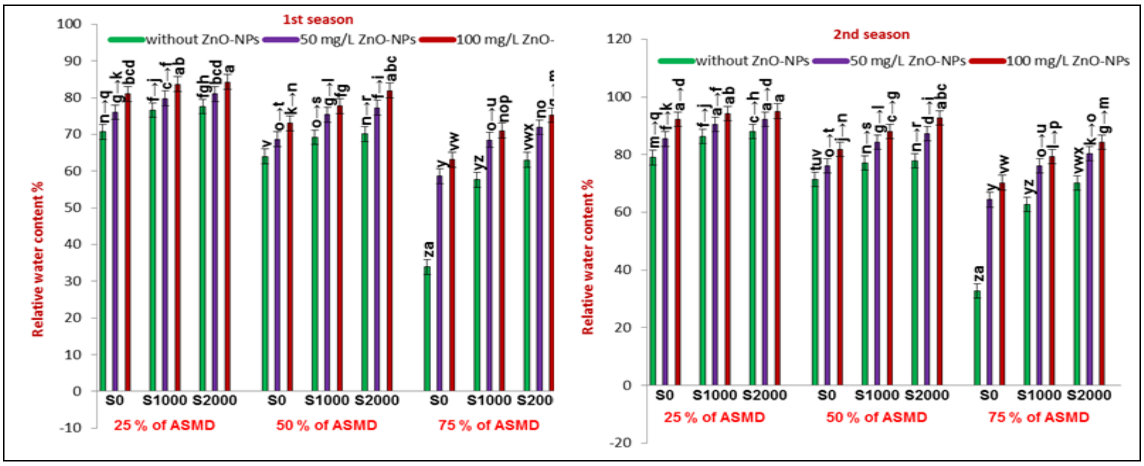

Figure 2b. Relative water content % of potato as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

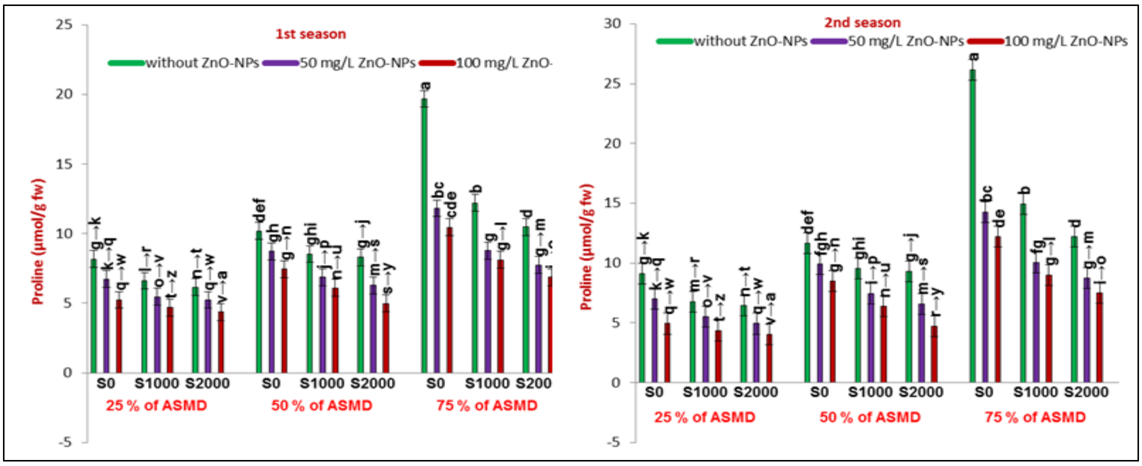

Figure 2c. Proline (µmol g^{-1} fw) of potato as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

Photosynthetic pigments traits

The interactive effects of water stress, seaweed extract, and ZnO-NPs foliar application significantly influence photosynthetic pigment traits in potatoes (Figure 3), particularly chlorophyll a, chlorophyll b, and carotenoids. Water stress negatively impacts these pigments, leading to reduced photosynthetic efficiency and productivity, as evidenced by decreased net photosynthetic rates and chlorophyll fluorescence under drought conditions. However, the application of ZnO-NPs and seaweed extracts has been shown to mitigate these adverse effects, enhancing pigment concentrations and overall plant health. Specifically, ZnO-NPs at concentrations of 50 and 100 mg L^{-1} improved leaf gas exchange and pigment content, while seaweed extracts at concentrations of 1000, and 2000 mg L^{-1} also contributed to nutrient uptake and stress alleviation. Thus, integrating these treatments can effectively enhance the resilience of potato crops under water-limited conditions.

The mitigating effects of seaweed extract, and ZnO-NPs foliar application were detected at increasing water stress regimes. In a moderate water stress condition of 50% of ASMD, the administration of 50 mg L^{-1} and 100 mg L^{-1} of ZnO-NPs resulted in enhancements of Chlorophyll a by 4.76-7.17 and 5.44-7.02%, chlorophyll b by 4.72-5.98 and 5-6.45%, and Carotenoid by 4.2-13.5 and 5.58-6.81%, respectively, following the application of 1000 and 2000 mg L^{-1} of seaweed extract, in contrast to the severe water stress condition of 75% of ASMD.

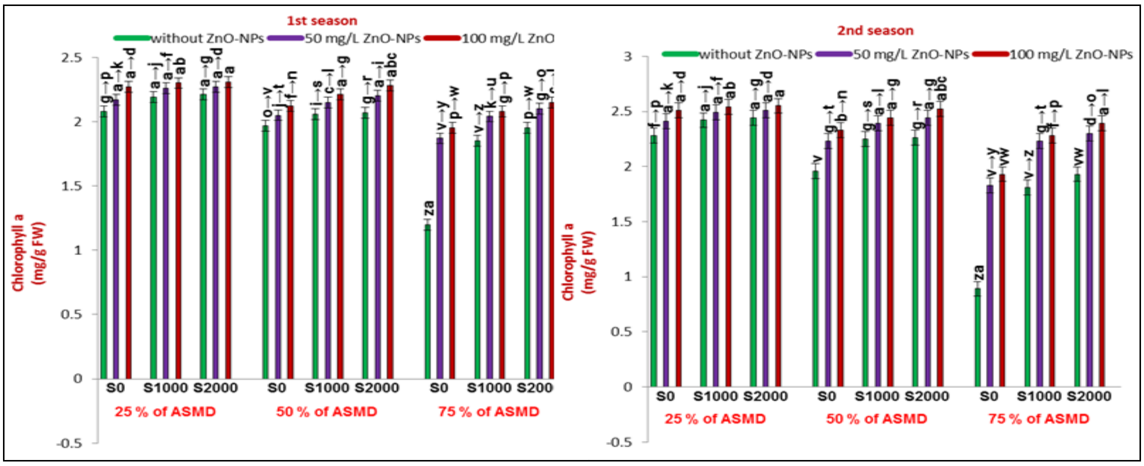

Figure 3a. Chlorophyll a (μmol g^{-1} fw) of potato as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

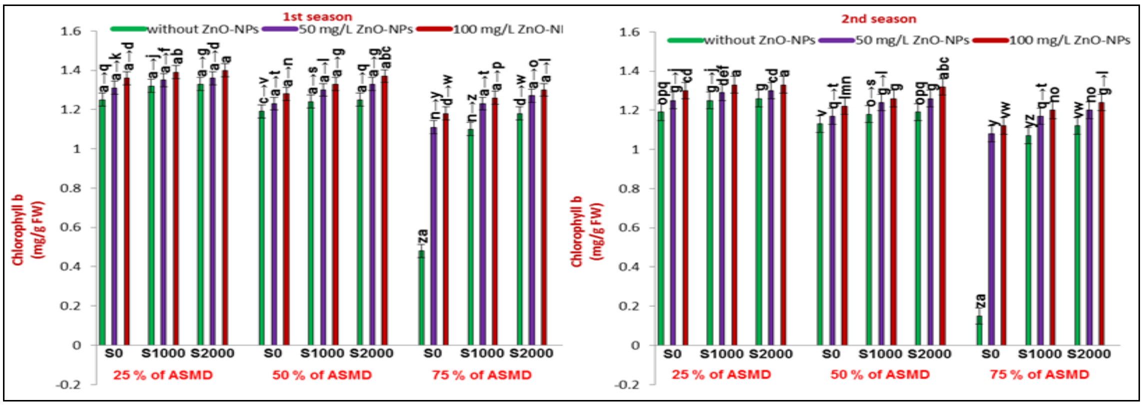

Figure 3b. Chlorophyll b (μmol g^{-1} fw) of potato as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

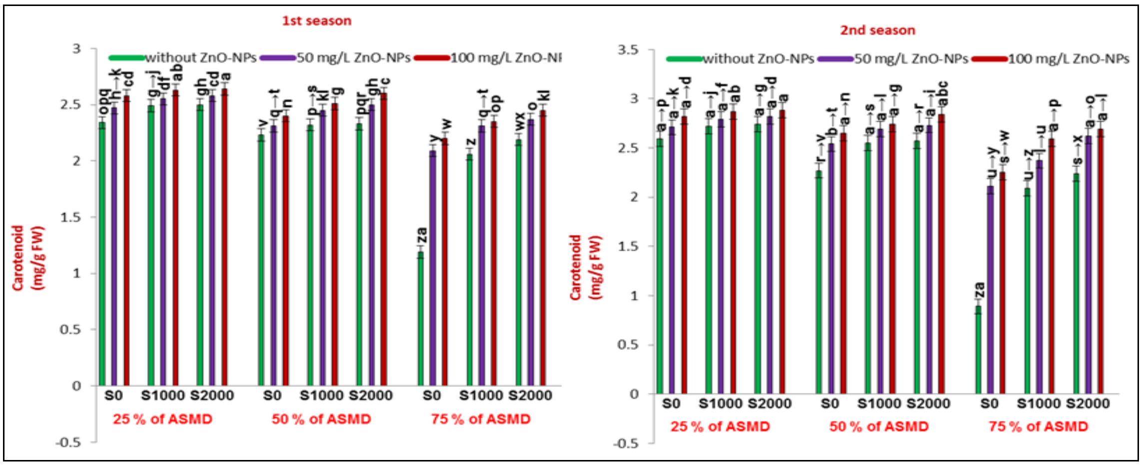

Figure 3c. Carotenoid (μmol g^{-1} fw) of potato as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

Tuber yield and its related traits

The interactive effects of water stress, seaweed extract, and ZnO-NPs foliar application on potato yield are significant (Figure 4), particularly in terms of the number of tubers per plant and overall yield per hectare. Increased water stress negatively impacts these yield parameters. The application of seaweed extracts, particularly at concentrations of 1000 and 2000 mg L^{-1}, alongside ZnO-NPs at 50 and 100 mg L^{-1}, has been shown to enhance tuber yield and related traits even under severe water stress conditions. Furthermore, the use of these foliar applications not only mitigates the adverse effects of drought but also promotes nutrient uptake and antioxidant activity, thereby improving plant resilience and productivity. Overall, integrating these treatments can lead to sustainable potato production practices that optimize yield while minimizing environmental impacts.

The mitigating effects of seaweed extract, and ZnO-NPs foliar application were observed at increasing water stress regimes. In a moderate water stress conditions of 50% of ASMD, the administration of 50 mg L^{-1} and 100 mg L^{-1} of ZnO-NPs resulted in enhancements in the number of tubers per plant by 5.03-9.54% and 5.97-11.43%; total yield per plant by 6.64-10.29% and 7.29-9.61%; and total yield per hectare by 4.77-9.38% and 5.23-8.7% respectively, following the application of 1000 mg L^{-1} and 2000 mg L^{-1} of seaweed extract, in contrast to a severe water stress condition of 75% of ASMD.

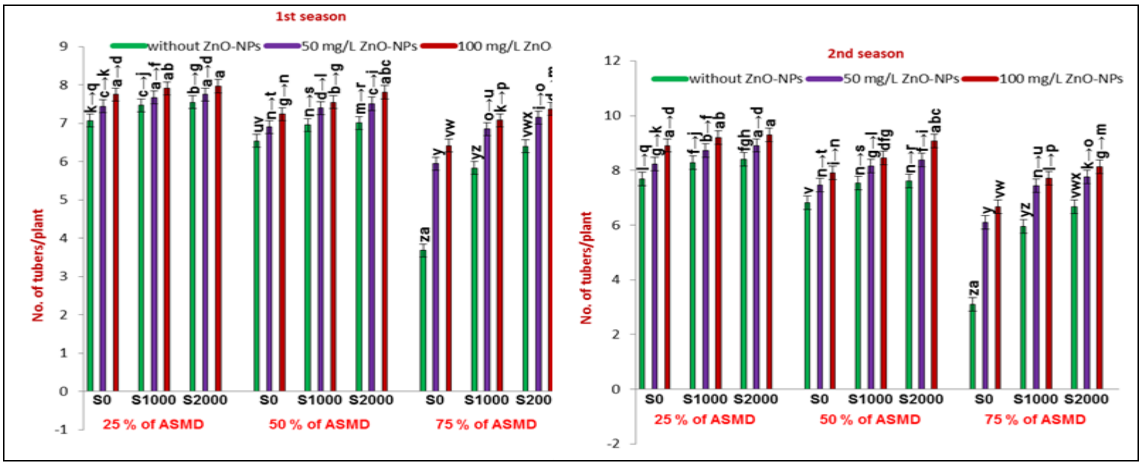

Figure 4a. No. of tubers/plant as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

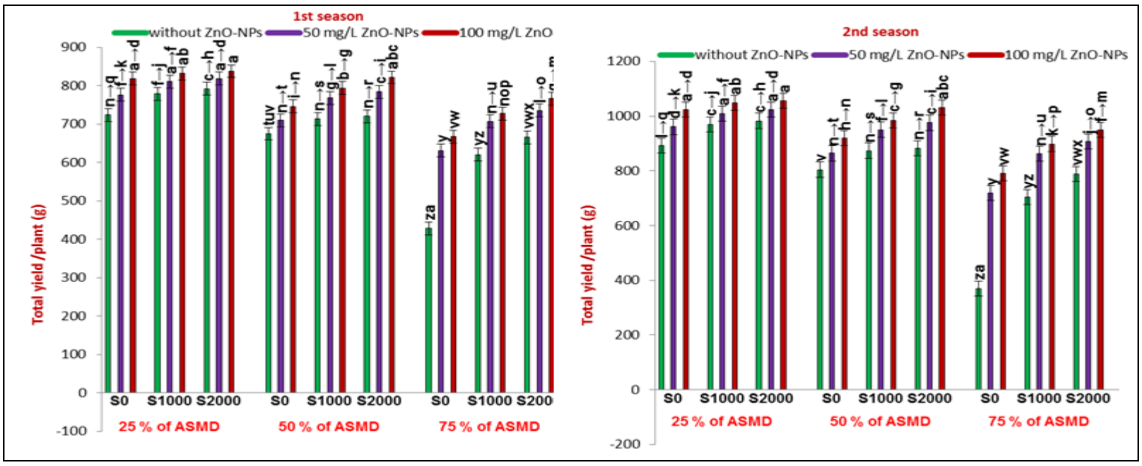

Figure 4b. Total yield /plant (g) as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

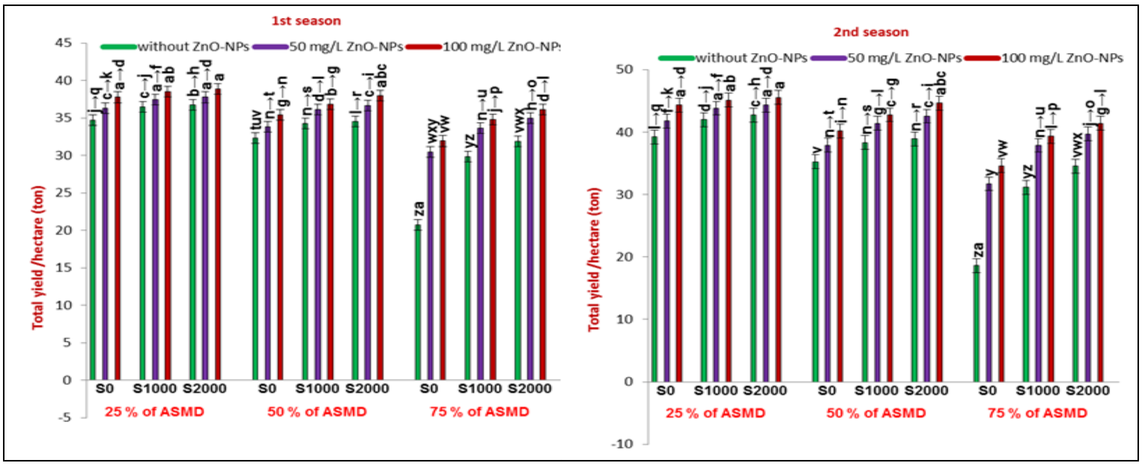

Figure 4c. Total yield /hectare (ton) as affected by Seaweed extract (S), ZnO-NPs foliar application (Z) under well-watered [25% of available soil moisture depletion (ASMD)], moderately (50% of ASMD), and severe (75% of ASMD) in both seasons. Bars with the same letters do not differ significantly ($p \leq 0.05$).

DISCUSSION

The application of seaweed extract in potato plants demonstrates significant potential in mitigating the adverse effects of water stress, particularly under moderate conditions (50% of ASMD). Specifically, the use of 1000 and 2000 mg L^{-1} seaweed extract, combined with 50 mg L^{-1} and 100 mg L^{-1} of ZnO nanoparticles, resulted in notable improvements in physiological parameters such as net photosynthesis (up to 17.52%), transpiration rate (up to 17.18%), stomatal conductance (up to 10.19%), and intercellular CO_2 concentration (up to 8.3%) compared to severe water stress (75% of ASMD) (Al-Selwey et al., 2023; Seleiman et al., 2023). These enhancements are attributed to the bioactive compounds in seaweed extracts that promote plant resilience against abiotic stresses, thereby improving growth and yield traits under water deficit conditions (Mbuyisa et al., 2023; Kumar et al., 2024). Furthermore, the synergistic effects of ZnO nanoparticles further bolster these physiological responses, highlighting the efficacy of combining bio stimulants and nanotechnology in agricultural practices (Al-Selwey et al., 2023).

The application of seaweed extract and zinc oxide nanoparticles (ZnO-NPs) significantly influences the physiological responses of potato plants under varying water stress conditions. At severe water stress

(75% of ASMD), the application of ZnO-NPs at concentrations of 50 mg L^{-1} and 100 mg L^{-1}, combined with seaweed extract (1000 and 2000 mg L^{-1}), enhanced water use efficiency by 0.74-2.94% and proline content by 23.41-58.35% compared to moderate stress (50% of ASMD) (Al-Selwey et al., 2023; Nunes et al., 2024). Conversely, under moderate stress, these ZnO-NPs increased relative water content by 7.41-11.16% when paired with seaweed extract (Al-Selwey et al., 2023; Seleiman et al., 2023). The findings suggest that while ZnO-NPs improve stress tolerance and physiological traits, their effectiveness is modulated by the severity of water stress, highlighting the potential for integrated nutrient management strategies in potato cultivation under drought conditions (Al-Selwey et al., 2023; Seleiman et al., 2023).

The application of zinc oxide nanoparticles (ZnO-NPs) in conjunction with seaweed extract has been shown to significantly enhance the chlorophyll content and carotenoid levels in potato plants under moderate water stress conditions. Specifically, at a moderate water stress regime of 50% of the available soil moisture deficit (ASMD), the application of ZnO-NPs at concentrations of 50 mg L^{-1} and 100 mg L^{-1} resulted in increases in chlorophyll a (4.76-7.17% and 5.44-7.02%), chlorophyll b (4.72-5.98% and 5-6.45%), and carotenoids (4.2-13.5% and 5.58-6.81%) when combined with 1000 and 2000 mg L^{-1} of seaweed extract, respectively. This synergistic effect is attributed to the ability of ZnO-NPs to enhance plant metabolism and mitigate oxidative stress, thereby improving physiological traits under drought conditions (Thounaojam et al., 2021; Sallam et al., 2022; Seleiman et al., 2023). Furthermore, the use of seaweed extract alone has been recognized for its beneficial effects on plant growth and stress tolerance, indicating its potential as a complementary treatment in agricultural practices (Backes et al., 2017).

The application of seaweed extract, particularly in conjunction with zinc oxide nanoparticles (ZnO-NPs), has been shown to significantly enhance potato yield under varying water stress conditions. In moderate water stress (50% of ASMD), the application of ZnO-NPs at concentrations of 50 mg L^{-1} and 100 mg L^{-1}, alongside seaweed extract at 1000 and 2000 mg L^{-1}, resulted in notable increases in the number of tubers per plant (5.03-11.43%), total yield per plant (6.64-10.29%), and total yield per hectare (4.77-9.38%) compared to severe water stress (75% of ASMD) (Al-Selwey et al., 2023; Seleiman et al., 2023; Nunes et al., 2024). Seaweed extracts are rich in bioactive compounds that promote plant resilience against abiotic stresses, enhancing nutrient uptake and antioxidant activity, which collectively contribute to improved growth and yield under drought conditions (Binnoubah et al., 2022; Kumar et al., 2024). Thus, integrating seaweed extracts with ZnO-NPs presents a promising strategy for mitigating the adverse effects of water stress on potato crops.

CONCLUSIONS

At a moderate water stress regime of 50% of the available soil moisture deficit (ASMD), the application of 50 mg L^{-1} and 100 mg L^{-1} of zinc oxide nanoparticles (ZnO-NPs), which, when combined with seaweed extract at 1000 and 2000 mg L^{-1} significantly enhanced various physiological and yield traits in potato plants compared to severe water stress at 75% ASMD. Specifically, 50 mg L^{-1} and 100 mg L^{-1} of ZnO-NPs which, when combined with seaweed extract at 1000 and 2000 mg L^{-1} improved, net photosynthesis, transpiration rates, stomatal conductance, and intercellular CO_2 levels, leading to increased water use efficiency (WUE) and relative water content. Additionally, chlorophyll a, b, and carotenoid levels were elevated, contributing to better overall plant health and productivity. The number of tubers per plant and total yield per hectare were also positively affected, particularly with the 100 mg L^{-1} ZnO-NPs treatment, which, when combined with seaweed extract at 1000 and 2000 mg L^{-1}, further mitigated the adverse effects of water stress, and enhancing tuber yield traits of the potatoes.

ACKNOWLEDGEMENTS

The author would like to thank the Deanship of Scientific Research at Shaqra University for supporting the work.

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