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Improving Cassava Crop Under Saline Stress As Auxiliary Source for Wheat Flour Using Zinc Sulfate Nanoparticles (Znso$_4$ Nps)

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CASSAVA (*Manihot esculenta*) is a salt-sensitive crop, making its production in new lands difficult. This study aimed to improve cassava growth and production in a salt-stressed environment using zinc nanoparticles. The experiments were conducted under fully controlled conditions. Besides a control, cassava plants were irrigated with three different salinity levels. As the cause of the water salinity, irrigation was carried out using 3,000, 3,500, and 4,000 parts per million sodium chloride. Zinc sulfate nanoparticles ($ZnSO_4$ NPs) at 50, 100, and 150 parts per million was also sprayed on the plants. After recording the fresh weight of the tubers and the number of tubers per plant, the root/shoot ratio was computed (After recording the fresh weight of the tubers and the number of tubers per plant, the root/shoot ratio was computed). However, depending on the salt chloride, cassava development was considerably hindered, beginning at 3,500 ppm of salt chloride. The treatment of 3000 ppm Na+ Cl - 100 ppm $ZnSO_4$ NPs did not significantly slow down Cassava growth by increasing plant height, leaf area, number of leaves per plant, number of main stems and lateral branches, and total chlorophyll content. Moreover, the treatment of 3000 ppm Na+ Cl-100 ppm ZnSO4 NPs promoted the accumulation of total starch in fibrous roots and enhanced crop characteristics of Cassava plants. In conclusion, treated cassava plants with nano-zinc helped them grow in new lands using irrigation water under high-salinity conditions as high as 3,000 parts per million. Moreover, the antioxidant content of the plant increases with increased exposure to salt stress.

Keywords: Cassava (*Manihot esculenta*), Water salinity, Nano Zinc Sulfate, Salt chloride, Drought.

1. Introduction

Food crop production is severely hampered by the salinity of irrigation water, which is usually dominated by salt chloride. There aren't many salt-tolerant genotypes available despite a lot of work Hussein, M. and Camila El-Dedin. (2025). The effects of salinity and drought on plants range from morphological alterations to molecular reactions Nahar et al., 2016; Sourour et al. (2017). Although the initial effects of salt stress and drought on plants are similar, prolonged exposure to salt stress can result in harmful ion effects and nutritional imbalances in plants. Drought and salt stress affect different morphological and molecular levels of plants Kaur & Asthir, (2017), Cao et al. (2023). Osmotic stress, ion toxicity, and nutritional imbalances are typically caused by salinity stress in plants, which can impair growth and lower yield Aslam et al. (2017), Zörb et al. (2019). Test plants become considerably more toxic when the sodium chloride concentration rises (Abdelkader et al. (2024). Due to the reduced water potential of the soil solution, plants exposed to high salt levels have trouble absorbing water and nutrients, which causes dehydration and stunted growth. Furthermore, the buildup of harmful ions like sodium (Na+) and chloride (Cl−) can interfere with vital metabolic functions like protein synthesis and photosynthesis and upset cellular homeostasis (Geilfus et al. (2018), Abdelkader et al. (2024). Reduced chlorophyll content, lower photosynthetic efficiency, and altered nutrient uptake are all ways that salt commonly affects plant physiology, which

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results in decreased plant vigor and productivity Ashraf et al. (2015), Iqbal et al. (2020), El-Beltagi et al. (2023).

Soil salinity, which NaCl frequently dominates, is one of the primary stressors limiting food crop development, according to Gupta & Huang (2014) and Cheng et al. (2018). Salt tolerance has been extensively studied in many other plants Gupta & Huang. (2014), Flowers et al. (2015), Ibrahim, 2016, Cheng et al. (2018), Emad M.M. Salem and Hosam El-Din A. Shoman. (2021), Abdelwanis et al. (2022). In addition to endogenous phytohormone modulators like gibberellin (GA), abscisic acid (ABA), and indole-3-acetic acid (IAA), it is partially associated with osmoprotectants like proline and sugars and elevated activity of antioxidant enzymes like catalase (CAT), peroxidase (POD), and superoxide dismutase (SOD). The high starch content of cassava (Manihot esculenta Crantz) makes it one of the most significant tropical food crops. Its ability to thrive in marginal regions where other crops fail, infertile soil, and harsh, low-rainfall climates Bull et al. (2011), Cheng et al. (2018), Suliman et al. (2024) as well as its innate ability to withstand stressful situations Ibrahim et al. (2024) make it abiotic stress-tolerant Suliman et al. (2024). The drought tolerance traits of this crop have been emphasized in most pertinent studies and reviews Cheng et al. (2018), El-Saadony et al. (2024).

Moreover, The FAO has classified this crop as "moderately sensitive to salt stress." Its cultivation will probably be extended to soil zones affected by salinization Cheng et al. (2018) as part of an increasing effort to promote agricultural production in marginal (currently unproductive) lands Shabala et al. (2015) and because of the growing demand for cassava production. However, this crop's salt tolerance mechanisms have not yet been studied.

According to reports, not all plants are negatively impacted by high salt levels because some blue-green algae and C4 plant species in particular families also require the Na ion Cabot et al. (2014). The same Na ion effects are also seen in cassava.

For example, Cheng et al. (2018) and EL-Bauome et al. (2024) found that low concentrations of NaCl (8.5 and 17 mM) increased the biomass output of cassava in vitro and indicated a connection between the plants' ex vitro and in vitro salt tolerance traits.

The root: shoot ratio of cassava increased with rising NaCl at four tested values of 0, 50, 100, and 150 mM, according to Abdelkader et al. (2019), who also found that salt stress at 40 and 80 mM NaCl improved the nutritional levels in cassava plant leaves.

The possibility of growing cassava in new lands has been repeatedly studied, but only to study the effect of soil salinity. However, the new study investigated the effect of irrigation water salinity on the growth and production of cassava plants. One of the reasons for this study is that the main problem in the new lands now, and in some areas of the Delta, is the salinity of irrigation water. The main objective of using nano fertilizers was to provide rapid absorption and impact on plant growth. It also helps plants withstand such environmental conditions. Ahmed M.S. et al. (2025).

2. Materials and Methods

2.1. Materials

The experiment used analytical-quality chemicals and reagents from several suppliers. Zinc sulfate ($ZnSO_4$) and EBT (Eriochrome Black T) were purchased from Sigma-Aldrich Chemical Company, St. Louis, MO 68178, USA. Spectrophotometer kits for quantitative measurements were obtained from the Egyptian Biotechnology Company (Biodiagnostics), Giza, Egypt.

2.2. Methods

2.2.1. Plant identification

Cassava (*Manihot esculenta*) cuttings were provided by the Vegetative Propagation Department, located at the Agricultural Research Center of the Ministry of Agriculture in Giza, Egypt. The plant was obtained from the department's farm at the Agricultural Research Center. Plant registration was conducted at National Research Centre. A voucher specimen bearing the plant number (M264) was stored in a suitable location in the herbarium of National Research Centre, Egypt, for documentation purposes.

2.2.2. Plant preparation:

The experiment was carried out over two consecutive seasons, from March to July (2022–2023) and (2023–2024), at the experimental research station in the Nubaria area in Beheira. Cassava cuttings were obtained from the experimental farm of the Agricultural Research Center in Giza. 25 cm long cuttings were taken and stored immediately in a wet cloth to maintain viability. In order to experiment, plants were treated. Simultaneously, the freshwater was salinized with Na+Cl- (coarse salt from Rashid marshes) to compensate for the three saline brackish water concentrations (3000, 3500, and 4000 ppm) in comparison to the non-saline treatment (control).

2.2.3. Plant Treatments

Four saline treatments (0, 3000, 3500, and 4000 ppm) were used to irrigate ten-month-old cassava cuttings from plants grown at the Agricultural Research Center's Experimental Station in twelve mixtures. At three-day intervals, irrigation water treatments will be delivered twice a week. On November 3, cassava plants were planted 100 cm apart on the side of the drip lines in the permanent field. Cassava plants were harvested 120 days after planting, and three plants were chosen as typical samples to assess the plants' quality and productivity throughout the two growing seasons.

As advised, the fertilizers will be applied to each pot at the appropriate time. Some fertilizers were used as a base fertilizer during soil preparation, consisting of 1.5 kilograms of superphosphate calcium (15.5% P2O5) and sulfur (5 kg of potassium sulfate) (48% K2O) per 150 m2 of soil. A dose of organic fertilizer was applied before planting for all treatments involving the application of organic matter. Table (1) shows the analysis of a soil sample taken directly from the agricultural soil.

Table 1. Mechanical and chemical properties of the experimental soil.

Physical analysis		**Chemical analysis**			
		Cations (mEq/L-1)		**Anions (mEq/L-1)**	
		Ca++	8.7	CO3-	Zero
Sand	84.2%	Mg++	4.0	HCO3-	0.52
Silt	11.8%	Na+	2.3	Cl-	11.48
Clay	4.1 %	K+	1.0	SO4--	4.0
Texture class: Loamy sand					
Soil pH	7.7	Available N 0.78%		Soil pH	
E.C (dS/m)	1.6	Available P 0.32%		E.C (dS/m)	
Organic matter	3.54 %	Available K 0.46%			

As advised, the fertilizers will be applied to each pot at the appropriate time. Some fertilizers were used as a base fertilizer during soil preparation, consisting of 1.5 kilograms of superphosphate calcium (15.5% P_2O_5) and sulfur (5 kg of potassium sulfate) (48% K_2O) per 150 m2 of soil. A dose of organic fertilizer was applied before planting for all treatments involving the application of organic matter. Table (1) shows the analysis of a soil sample taken directly from the agricultural soil.

2.2.4. Nanoparticles preparation

The solvent emulsification-diffusion method created the zinc sulfate nanoparticles as a nano-formulation Ezzat et al. (2017), El-Saadony et al. (2024). The Egyptian Patent Office, Academy of Scientific Research & Technology, has granted this study an under-reviewed patent that covers the pertinent measurement data and the nano-preparation procedure with number 56/2020.

For quicker absorption, we changed the zinc sulfate from its natural state to that of nanoparticles. Next, we sprayed three distinct concentrations on the plants: 50, 100, and 150 parts per million. Spraying began at 60 days of age and was repeated three times during the growing season, every 15 days.

2.2.5. Parameters of vegetative growth

For each treatment, three plants were chosen randomly and labeled in each replicate 120 days after planting. The following characteristics were noted: Total chlorophyll content, plant height, number of main stems and lateral branches, leaf area, and number of leaves per plant.

2.2.6. Tuber yield and its constituent parts

Once the fresh weight of the tubers and the quantity of tubers per plant were noted, the root/shoot ratio was computed using the following formula: The ratio of tuber weight (g/plant) to shoot weight (g/plant). In addition, measurements were made of the tuber's length, diameter, and dry matter percentage.

2.2.7. Determination of chemical composition of tubers

Nelson (1974), Aboueldis et al. (2025) described the method to determine the proportion of starch. Colorimetrically, the percentage of total carbohydrates was determined as grams of glucose per 100 grams of dry tuber weight using the James et al. (1995) method. The A.O.A.C. (1990) Mohamed et al. (2022) approach was used to determine the total fiber content of root tubers. Cassava tubers' nitrogen content was determined using the methods outlined in Abdelwanis et al. (2023). Phosphorus concentration was estimated spectrophotometrically at 650 nm, according to El-Mehy et al. (2023). The method outlined by Brown & Lilleland (1946) and a flame photometer were used to test potassium.

2.2.8. Antioxidant determination

2.2.8.1. DPPH assessment

Stable DPPH was employed to measure and evaluate the extracts' ability to scavenge free radicals. 50 µl of extracts and 2.95 ml of 200 µmol DPPH were mixed. At a wavelength of 517 nm, the absorbance against pure methanol was measured following an hour of dark incubation. Trolox was utilized to create the standard curve. For every gram of Cassava sample, the Trolox equivalent (mg TE) was utilized to express the results Abdelkader et al. (2024), Abdelazeez et al. (2025).

2.2.8.2. ABTS assessment

Following the methods recommended by El-Beltagi et al. (2023), the ABTS+ free radical scavenging test was carried out to assess the antioxidant activity using the ABTS+ method. Using a spectrophotometer, Nouman et al. (2014) and Mohammed et al. (2024) determined the dry matter's total phenolic content.

2.2.9. The total phenolics content determination

A spectrophotometer was used to measure the total phenolic contents in the dry matter. The absorbance was measured at 765 nm. Gallic acid was used to produce the calibration curve Nouman et al. (2014), Mohammed et al. (2024).

2.2.10. The total flavonoid content determination

Distilled water (4.3 ml), aqueous ethanol extracts (0.5 ml), 10% aluminum chloride (0.1 ml), and 1 M potassium acetate (0.1 ml) were mixed. The absorbance at 415 nm was measured using a spectrophotometer after a 30-minute room temperature incubation period. Using quercetin, the calibration curve was produced. Three different computations were performed to find the extracts' total flavonoid content, and the results were averaged. Shah & Hossain, (2014) Moghazee et al. (2025).

2.2.11. Statistical Analysis

The obtained data was statistically processed using the analysis of variance (two-way ANOVA). The means were compared using Duncan's multiple range tests and the least significant difference (LSD) at the $p \leq 0.05\%$ probability level.

3. Results and Discussion

3.1. Effect of Salinity Levels on Cassava Vegetative Growth:

Cassava's capacity to tolerate salinity stress and react to nano zinc sulfate supplementation is demonstrated by vegetative growth parameters, which include plant height, number of leaves, leaf area, fresh weight, dry weight, and chlorophyll content (Table 2). Plant height, number of leaves per plant, leaf area, fresh weight, and dry weight all decreased due to salinity's substantial effect on cassava vegetative growth. Osmotic stress, decreased water uptake, and ion toxicity contributed to the cassava's growth inhibition as salinity levels rose. Compared to the control, plant height dropped by 1.8% in the first season and 2.3% in the second season at 3,000 ppm NaCl. Compared to the control, plant height dropped by 1.8% in the first season and 2.3% in the second season at 3,000 ppm NaCl. With plant height dropping by 15.5% in the first season and 23.9% in the second, the decrease became more noticeable at 3,500 ppm. High salinity significantly inhibits cassava growth, as evidenced by the most severe effect at 4,000 ppm, where plant height dropped by 42.9% in the first season and 38.8% in the second. Cruz et al. (2018).

Similar trends were observed in the number of leaves per plant. At 3,000 ppm, leaf number declined by 6.2% in the first and 10.6% in the second seasons. At 3,500 ppm, the reduction increased to 27.6% and 29.6%, while at 4,000 ppm, the number of leaves decreased drastically by 39.5% in the first season and 46.9% in the second season. Leaf area was also severely affected, decreasing by 4.9% at 3,000 ppm in the first and 13.7% in the second seasons. At 3,500 ppm, leaf area was reduced by 34.7% in the first and 40.6% in the second seasons. The most significant reduction occurred at 4,000 ppm, with leaf area declining by 46.1% and 44.5% in the first and second seasons, respectively. These findings suggest that increased salinity has a detrimental effect on cassava's capacity to increase the surface area of its leaves, which in turn impacts photosynthesis and the general growth of the plant. As salinity increased, both leaf fresh weight and dry weight decreased similarly. At 3,000 ppm, dry weight dropped by 11.4% and 8.4%, respectively, while fresh weight dropped by 10.2% in the first season and 20.5% in the second. Dry weight decreased by 22.7% and 13.8% at 3,500 ppm, while fresh weight decreased by 32.5% in the first season and 25.8% in the second. The most drastic decreases were seen at 4,000 ppm, where dry weight dropped by 48.4% and 54.4%, and fresh weight dropped by 44.1% in the first season and 39.2% in the second. These findings indicate that salt stress significantly inhibits biomass accumulation, likely due to impaired nutrient uptake and physiological stress Sanghamithre & Menon, 2014; Aboyeji et al. (2019), Rehman et al. (2023), Glala et al. (2025).

We found that salinity hurt the vegetative characteristics of the plant. Ionic and osmotic stress are the two ways plants respond to salt stress. The accumulation and increased soluble salt concentration in the root zone causes osmotic stress. As a result, plants struggle to supply water to the soil (physiological drought). It is challenging to extract water and vital minerals from the soil because the salt ion causes osmosis to increase. Carillo et al. (2020), Glala et al. (2025).

3.2. Effect of Zinc Spray Treatments on Cassava Vegetative Growth

By improving plant growth parameters, zinc supplementation was essential in reducing the adverse effects of salinity stress; in comparison to 50 ppm Zn, plant height increased by 1.2% in the first season and 2.9% in the second season when cassava plants treated with 100 ppm Zn at 3,000 ppm salinity (Table 2). Likewise, 100 ppm Zn increased plant height by 4.2% and 7.1% at 3,500 ppm compared to 50 ppm Zn. Compared to 50 ppm Zn, zinc application at 100 ppm increased plant height by 6.3% in the first season and 16.3% in the second, even at the highest salinity level of 4,000 ppm. Supplementing with zinc also increased the number of leaves. Compared to 50 ppm Zn at 3,000 ppm, 100 ppm Zn increased leaf number by 4.6% in the first season and 9.7% in the second. The increase was 12.1% in the second season and 16.0% in the first season at 3,500 ppm. Zinc supplementation at 100 parts per million (ppm) increased leaf number by 6.1% in the first and 20.8% in the second seasons, even at 4,000 parts per million. Zinc application also significantly impacted leaf area; compared to 50 ppm Zn in the first season, 100 ppm Zn increased leaf area by 5.6% at 3,000 ppm, 9.9% at 3,500 ppm, and 8.4% at 4,000 ppm. Zinc supplementation supports biomass production by improving nutrient absorption and stress tolerance Suliman & Saleh, (2022), El-Naggar et al. (2024).

Table 2. Effect of irrigation with salinity levels and spraying of nano zinc sulfate compounds on vegetative characters of cassava plants.

First season							
Treatments		**Plant height (cm)**	**No. of leaves/ plant**	**Leaves area (cm²/plant)**	**Leaves fresh weight (g/ plant)**	**Leaves Dry weight (g/ plant)**	**Chlorophyll content**
Salinity	**$ZnSO_4$**						
Control 0.0 ppm		168**	153.3**	281.3*	1870.2*	146.2*	41.7*
3000 ppm	50 ppm	165*	144.5	267.5	1680.4	129.5	39.5
	100 ppm	167**	151.2	278.3*	1820.4*	149.2**	39.4
	150 ppm	166*	148.7*	272.8	1793.6	147.8*	39.1
3500 ppm	50 ppm	142	111.1	183.6	1261.9	112.9	41.3*
	100 ppm	148	128.9	201.8	1499.3	131.6	38.1
	150 ppm	148	131.1	118.2	1498.8	131.3	35.2
4000 ppm	50 ppm	96	92.7	151.6	1046.4	75.4	45.8*
	100 ppm	102	98.4	164.3	1121.6	97.5	46.4**
	150 ppm	103	96.2	162.1	1094.1	92.1	42.8
Second season							
Treatments		Plant height (cm)	No. of leaves/ plant	Leaves area (cm²/ plant)	Leaves fresh weight (g/ plant)	Leaves Dry weight (g/ plant)	Chlorophyll content
Salinity	$ZnSO_4$						
Control 0.0 ppm		175**	161.3**	293.4*	1780.3*	133.9*	39.4
3000 ppm	50 ppm	171*	144.1	253.2	1414.5	122.7	41.1
	100 ppm	176**	158.1*	281.4*	1694.3*	142.8**	42.1*
	150 ppm	176**	151.9	283.2*	1601.3	138.4**	39.9
3500 ppm	50 ppm	133	113.6	174.4	1320.4	116.1	44.9**
	100 ppm	138	127.4	197.4	1427.4	121.3	42.1
	150 ppm	139	129.1	195.2	1428.1	119.5	44.1**
4000 ppm	50 ppm	107	85.6	162.7	1082.2	61.1	41.8
	100 ppm	121	103.4	174	1193.1	85.9	42.6*
	150 ppm	120	99.7	171.3	1182.7	81.3	41.1

The values in the column having the same letter are not significantly different at P= 0.05. * Indicates that it is the highest value and the best value recorded.

3.3. Effect of Salinity and Zinc Treatments on Cassava Yield

3.3.1. Effect of salinity on Cassava yield: The number, weight, size, and dry matter content of cassava tubers were all significantly impacted by salinity. Because of osmotic stress and nutritional imbalances, tuber growth and productivity dramatically decreased as salinity rose. Compared to the control, tuber numbers decreased by 17.4% in the first season and 25.2% in the second season at 3,000 ppm (Table 3). With tuber numbers falling by 40.3% and 38.5% in the first and second seasons, this decline grew to 3,500 ppm. The most significant decrease in tuber number occurred at the

highest salinity level of 4,000 ppm, which reached 48.4% in the first season and 62.2% in the second.
In a similar vein, as salinity rose, tuber weight decreased. With a 0.08% decrease in the first season and a 6.0% decrease in the second, the tuber weight decreased very little at 3,000 ppm. Tuber weight was significantly impacted at 3,500 ppm, declining by 26.8% in the first season and 23.2% in the second. The decrease was even more pronounced at 4,000 ppm, as tuber weight decreased by 41.8% in the second season and 48.1% in the first season compared to the control.
The decrease in tuber length was notable, which decreased by 14.0% and 18.9% in the first and second seasons at 3,000 ppm, respectively. Tuber length decreased by 26.9% and 30.1% at 3,500 ppm, whereas at 4,000 ppm, the reductions reached 38.4% and 51.7% in the first and second seasons, respectively.
Salinity also hurt tuber diameter, which decreased by 8.6% in the first season and 10.8% in the second at 3,000 ppm. High salinity levels significantly affect tuber development, as evidenced by the reductions of 28.9% and 24.5% at 3,500 ppm and 37.6% and 53.8% at 4,000 ppm. It is interesting to note that under moderate salinity, the dry matter content slightly increased. This is probably because the tuber tissues had more solids as water uptake became more challenging. Dry matter rose 6.7% in the first season and 9.8% in the second season at 3,000 ppm. Dry matter rose by 10.7% and 6.4%, respectively. These results are consistent with earlier studies showing that salinity stress inhibits nutrient absorption and utilization efficiency, thereby reducing cassava growth and yield. In particular, it has been demonstrated that salinity reduces the absorption of vital nutrients like potassium, which inhibits the growth of tubers and biomass.

3.3.2. Effect of sulfate nanoparticles Spray Treatments;

Zinc supplementation enhanced nutrient uptake, enzyme activity, and carbohydrate transport, thereby reducing the adverse effects of salinity. Comparing 100 ppm Zn to 50 ppm Zn at 3,000 ppm salinity, the former increased the tuber number by 17.5% in the first season and 25.7% in the second.
In the first and second seasons, tuber numbers increased by 27.4% and 24.1%, respectively, at 3,500 ppm and 100 ppm Zn. Compared to 50 ppm Zn, 100 ppm Zn increased tuber number by 6.2% in the first season and 21.6% in the second, showing some benefit even at the highest salinity level of 4,000 ppm (Table 3). Zinc supplements also improved tuber weight. Tuber weight increased by 3.6% in the first and 9.3% in the second seasons at 3,000 ppm Zn, compared to 50 ppm Zn. Compared to 50 ppm Zn in the first and second seasons, 100 ppm Zn increased tuber weight by 17.2% and 7.9% at 3,500 ppm, respectively. Comparing 100 ppm Zn to 50 ppm Zn at 4,000 ppm, the tuber weight increased by 7.6% in the first season and 4.7% in the second. Comparable patterns were noted for tuber length, with increases of 13.2% and 19.1%, respectively, at 3,000 ppm and 100 ppm Zn in the first and second seasons. At 3,500 ppm, tuber length improved by 1.4% in the first and 21.9% in the second seasons. At 4,000 ppm, 100 ppm Zn increased tuber length by 1.0% in the first season and 17.6% in the second season compared to 50 ppm Zn.
Zinc application also had a positive effect on dry matter content. Comparing 100 ppm Zn to 50 ppm Zn at 3,000 ppm, the dry matter content rose 5.2% in the first season and 7.8% in the second. At 4,000 ppm, 100 ppm Zn increased dry matter by 12.0% in the first season and 13.5% in the second, while the improvement was 5.2% and 10.1% at 3,500 ppm.
Zinc supplementation promotes biomass production by enhancing nutrient absorption and stress tolerance Abdelwanis et al. (2022), Suliman et al. (2024).

3.3.3. Interaction between Salinity and Zinc Treatments

The best results were obtained when moderate salinity and zinc supplementation were combined to lessen the effects of salinity stress. With only a 2.2% decrease in tuber weight and a 3.7% reduction in tuber length at 3,000 ppm NaCl, 100 ppm Zn helped keep yield parameters near control levels.
Tuber weight was 17.3% higher at 100 ppm Zn than 50 ppm Zn, minimizing the yield decline at 3,500 ppm NaCl. Even though tuber weight and size were still lower than the control at the highest salinity level of 4,000 ppm, 100 ppm Zn still lessened some of the adverse effects, as evidenced by a 17.6% increase in tuber length and a 7.6% increase in weight when compared to 50 ppm Zn. Overall, salinity dramatically decreased the growth and yield of cassava tubers, with the most significant effect seen at 3,500–4,000 ppm NaCl. At moderate levels, zinc supplementation at 100 ppm reversed the effects of salinity and improved tuber quality and yield. Zinc still had advantages at extremely high salinity (4,000 ppm) but could not completely stop yield losses. According to the relationship between zinc and salinity, zinc improves nutrient uptake and metabolic activity, which in turn helps cassava withstand salt stress.
These findings align with research showing that applying zinc improves nutrient uptake, water relations, and antioxidant defense mechanisms, thereby increasing plant tolerance to salinity stress. For instance, zinc has been shown to alleviate the adverse effects of salinity in various crops by stimulating proline metabolism and enhancing antioxidant enzyme activities.

Table 3. Effect of irrigation with salinity levels and spraying of nano zinc sulfate compounds on cassava tubers.

Salinity	$ZnSO_4$	Tubers number/plant	Tuber weight (g)	Tuber/ shoot ratio	Tuber length (cm)	Tuber diameter (cm)	Dry matter (%)
First season							
Control 0.0 ppm		12.4*	364.4*	1.68	48.4*	4.42	34.52
3000 ppm	50 ppm	10.3	364.1*	1.55	41.6	4.04	36.83
	100 ppm	12.1*	362.3*	1.82*	47.1	4.53*	41.55*
	150 ppm	11.9	359.3	1.73*	48.6*	4.58*	42.63*
3500 ppm	50 ppm	7.3	266.8	1.46	35.4	3.14	36.63
	100 ppm	9.3	312.8	1.43	35.9	3.61	38.53
	150 ppm	9.2	326.4	1.32	35.2	3.64	41.18*
4000 ppm	50 ppm	6.4	189.2	1.31	29.8	2.76	36.73
	100 ppm	6.8	203.6	1.25	30.1	2.78	41.32*
	150 ppm	6.3	198.7	1.31	29.9	2.85	41.91*
Second season							
Control 0.0 ppm		13.5**	341.7*	1.78*	48.3*	4.61	32.11
3000 ppm	50 ppm	10.1	321.4	1.64	39.2	4.11	35.26
	100 ppm	12.7**	351.4**	1.71*	46.7*	4.51*	43.13*
	150 ppm	12.9	355.9**	1.73*	48.3*	4.57*	43.11*
3500 ppm	50 ppm	8.3	262.3	1.51	33.8	3.48	34.84
	100 ppm	10.3	283.1	1.62	41.2	3.82	39.33
	150 ppm	10.7*	288.5	1.61	41.4	3.82	41.04
4000 ppm	50 ppm	5.1	198.8	1.35	23.3	2.13	35.53
	100 ppm	6.2	193.4	1.41	27.4	2.74	40.31
	150 ppm	6.7	206.1	1.37	27.6	2.79	41.14

The values in the column having the same letter are not significantly different at P= 0.05. * Indicates that it is the highest value and the best value recorded.

3.4. Chemical composition

The data related to water salinity's effect on cassava plants' chemical composition are shown in Table (4) and Figure (1). The resulting data makes it abundantly evident that high salinity levels in irrigation water significantly harm the elements and chemicals in tubers under study. In comparison to the untreated control treatment, the irrigation treatment with the lowest concentration of irrigation water salinity produced the highest values of total nitrogen (%), phosphorus (%), potassium (K%), starch (%), total carbohydrates (%), and total fiber (%) throughout the study's two seasons.

The findings in Table (4) demonstrated that the combined effects of salinity significantly impacted the amount of nitrogen (N). Nitrogen levels peaked at 0.93 and 88% under ideal circumstances (control), demonstrating robust nutrient uptake and plant health. Nitrogen content sharply declined as stress levels rose. Under salinity stress, zinc supplementation assisted in preserving the chemical makeup of cassava tubers. Compared to 50 ppm Zn, 100 ppm Zn at 3,000 ppm increased the starch content by 5.1% in the first season and 7.9% in the second. The increase was 9.7% in the second season and 13.6% in the first season at 3,500 ppm. Zinc supplementation increased starch content by 12.1% in the first season and 14.1% in the second, even at 4,000 ppm. Nutrient content and total carbohydrates showed comparable gains El-Naggar et al. (2024), Abdelazeez, et al. (2025).

Zinc is essential for reducing the adverse effects of salinity on cassava growth and chemical composition, as shown by the interaction between zinc treatments and salinity. With only slight decreases in plant height, leaf area, and biomass accumulation, 100 ppm Zn helped keep growth parameters near control levels at moderate salinity (3,000 ppm). The decrease in chemical composition was lessened by zinc at 3,500 ppm; the starch content was 13.6% higher at 100 ppm Zn than at 50 ppm Zn. Even though growth and yield were still below the control at the highest salinity level (4,000 ppm), zinc application significantly reduced losses by enhancing tuber weight, starch accumulation, and nutrient uptake Neama et al. (2016) and El-Naggar et al. (2024).

3.5. Antioxidant capacity

Table (5) shows how applied salinity treatments affected cassava tubers' antioxidant activity and total phenolic content (mg g-1 D.wt.) grown under salinity levels. The results clearly show that the antioxidant activity and total phenolic content were at their highest levels compared to the control. Additionally, compared to the control, the salinity level raised cassava leaves' antioxidant activity and total phenolic content. The production of reactive oxygen species (ROS), including singlet oxygen, superoxide, hydrogen peroxide, and hydroxyl radicals, is typically caused by the highest salt concentration, which also hinders the movement of electrons within the various subcellular compartments. ROS increased the accumulation of non-enzymatic antioxidants like tocopherol and phenolic compounds, which improved the antioxidant system's defense Mohammed et al. (2025).

On the other hand, plants exposed to highly salinized water generated more antioxidant molecules Wahab et al. (2022). These chemicals are produced by physiological processes activated when a plant experiences environmental stress Hasanuzzaman et al. (2020), Suliman et al. (2025).

Table 4. Effect of irrigation with salinity levels and spraying of nano zinc sulfate compounds on cassava tubers.

First season							
Treatments		Starch (%)	Total carbohydrates (%)	Total fibers (%)	N (%)	P (%)	K (%)
Salinity	$ZnSO_4$						
Control 0.0 ppm		52.32	69.56**	2.92*	0.93**	0.34*	1.06*
3000 ppm	50 ppm	46.57	57.47	2.63	0.81	0.28	0.98*
	100 ppm	48.91*	65.21*	2.83*	0.86	0.29	0.74
	150 ppm	51.34*	66.29*	2.86*	0.88*	0.31*	0.63
3500 ppm	50 ppm	42.72	55.12	2.61	0.74	0.24	0.85
	100 ppm	48.55*	59.22	2.78	0.81	0.27	0.78
	150 ppm	48.61*	59.08	2.79	0.83*	0.28	0.73
4000 ppm	50 ppm	41.19	51.93	2.43	0.62	0.24	0.82
	100 ppm	46.37	59.43	2.61	0.71	0.28	0.76
	150 ppm	48.13*	61.04	2.63	0.76	0.28	0.72
Second season							
Treatments		Starch (%)	Total carbohydrates (%)	Total fibers (%)	N (%)	P (%)	K (%)
Salinity	$ZnSO_4$						
Control 0.0 ppm		51.11*	66.84*	2.83*	0.88*	0.31*	1.07*
3000 ppm	50 ppm	51.83*	57.94	2.81*	0.76	0.27	0.85*
	100 ppm	52.41*	65.29*	2.91**	0.84*	0.27	0.73
	150 ppm	52.94*	66.31*	2.93**	0.85*	0.29*	0.81
3500 ppm	50 ppm	42.93	54.73	2.42	0.73	0.24	0.74
	100 ppm	48.39	59.41	2.74	0.81	0.25	0.71
	150 ppm	49.11*	60.37	2.77	0.82*	0.28*	0.75
4000 ppm	50 ppm	42.62	53.12	2.22	0.71	0.26	0.72
	100 ppm	49.23*	55.38	2.51	0.78	0.27	0.68
	150 ppm	49.71*	57.21	2.58	0.79	0.27	0.68

* Indicates that it is the highest value and the best value recorded.

Table 5. Total phenolic content, flavonoids contents and antioxidant capacity of Cassava extract.

Sample	Total phenols (mg GAE/ml)	Total flavonoids (mg CE/ml)	DPPH (mg TE/ml)	ABTS (mg TE/ml)
4000 ppm	0.85	0.64	0.82	0.64
Control	0.81	0.59	0.77	0.62

GAE= gallic acid equiv. CE = catechin equiv. TE = Trolox equiv.

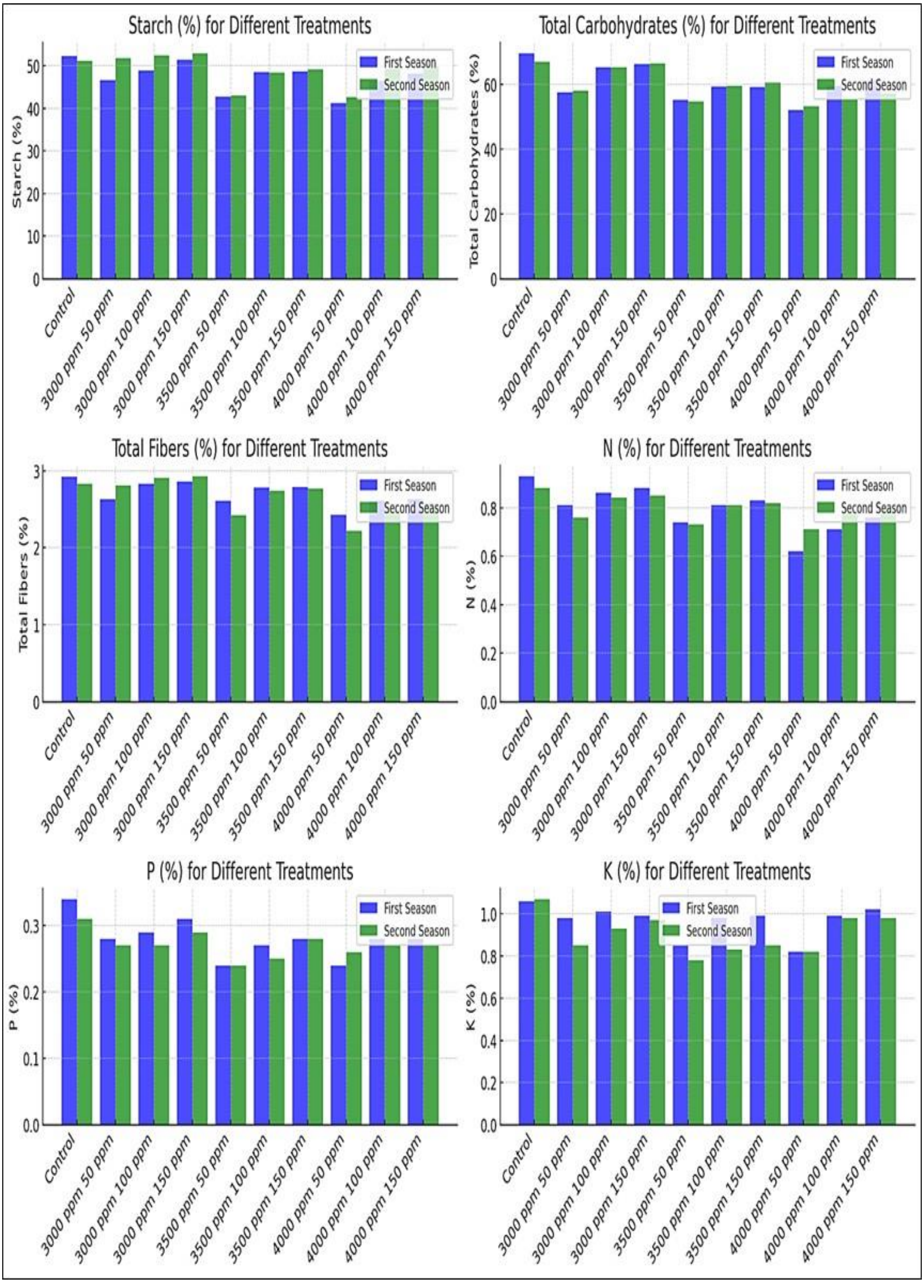

Fig. 1. Effect of irrigation with salinity levels and spraying of nano zinc sulfate compounds on the chemical and quality characteristics of cassava tubers.

4. Conclusion

This study highlighted the feasibility of growing cassava in new lands containing saline irrigation water. The study also examined salinity levels and their impact on cassava growth and production. The experiments revealed the feasibility of growing cassava in new lands using saline irrigation water at a concentration of less than 3,000 parts per million (ppm). The experiment also studied the effect of fertilization with nano-compounds, such as zinc sulfate, which was prepared in the laboratory. The study demonstrated that using zinc sulfate nano-fertilization is one of the methods that helps plants grow and adapt to saline conditions. The optimum concentration of zinc sulfate was 100 ppm, which contributed to improving the chemical properties of the crop and increasing its ability to tolerate salinity. There was no significant difference between it and 150 ppm. The results also indicated that plants grown and irrigated at saline levels contained higher levels of antioxidants, which contribute to treating many diseases and increasing the value of the cassava crop. This method of fertilization has been used at the experimental level and has not been used at the practical level yet.

Authors' statement

AAS: Methodology, Formal analysis, Writing – review & editing, Writing – original draft. **SAS**: Visualization, Writing – review & editing, Writing – original draft. **ASM**: Methodology, Writing – review & editing, Writing – original draft. **GSK**: Methodology, Formal analysis, Writing – review & editing, Writing – original draft. **DMM**: Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Writing – review & editing, Writing – original draft.

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Declaration of competing interest

The authors confirm that they have no conflicts of interest with respect to the study described in this manuscript.

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