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Effect of Brackish Water Irrigation on Maize Root Growth, Electrical Conductivity and Nutrient Availability in Coastal Saline Soil

Nanda Abhipsa; Barala Jatiprasad*; Patel Sonali; Alomar Rahaf; Dash A.K. & Jena Dinabandhu

Department of Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences (IAS), Siksha 'O' Anusandhan Deemed to be University, Bhubaneswar, Odisha, India-751030

**Corresponding author: jati.barala@gmail.com*

ABSTRACT

Irrigation with brackish water is a common practice in coastal Odisha during winter and summer season because of scarcity of good quality irrigation water. Soil salinity developed with brackish water irrigation affects root growth and nutrient availability due to osmotic stress and ion toxicity. The adverse effect of salinity can be mitigated through application of phosphatic and zinc fertilizer. With this hypothesis we tried to evaluate the effects of phosphorous and zinc on electrical conductivity of saturated paste (ECe), nutrient availability and root growth of maize irrigated with normal water (SW_0- EC 0.6 dS m^{-1}) and brackish water (SW_1- EC 8 dS m^{-1}). The maize received four levels of P fertilizer (P_1 – 15mg P kg^{-1} soil basal; P_2 – 30mg P kg^{-1} soil basal; P_3 – 30 mg P kg^{-1} in two splits and P_4 – 45 mg P kg^{-1} in two splits) and two levels of zinc (Zn_0 – zinc control and Zn_1 – nano zinc 5% @ 1.25 mg kg^{-1} soil). Brackish water irrigation (SW_1) significantly ($p \leq 0.05$) increased the soil ECe (212%), available phosphorus (70%) and sodium (250%) but decreased the organic carbon, available Ca, Mg and DTPA Zn by 18,14, 16 and 3% respectively over SW_0 treatment. The root length, root weight, root volume, root density and CEC of roots in SW_1 treatment were decreased by 36%, 37%, 29%, 12% and 22%, respectively over SW_0. Application of phosphorus and nano zinc fertilizer significantly ($p \leq 0.05$) increased the maize biomass yield, root length and availability of phosphorus, potassium, magnesium and zinc in soil. These findings suggested that brackish water upto EC 8 dS m^{-1} with phosphorus and zinc fertilizer is recommended for winter and summer crops in coastal saline areas.

Key words: Brackish water, phosphorus, zinc, K^+/Na^+ ratio, maize

INTRODUCTION

Soil salinization has become a worldwide resource and environmental problem, which seriously affects the stability of the agricultural ecosystem and the development of agricultural economy (Xie *et al*., 2022). Salinity, due to over-accumulation of NaCl, is usually of great concern and the most injurious factor in arid and semi-arid regions. Saline soils are widespread on Earth, and their genesis may be natural or accelerated by the extension of irrigated agriculture, and human activity (Turan *et al*., 2010).

The coastal belt of Odisha extends over 480 kilometers from mouth of Subarnarekha river in the north to the Chilika lake in the south. Due to the proximity of sea, cyclonic hazard and saltwater ingress through tidal channels have restricted the availability of acceptable quality of water for irrigation (Das *et al*., 2020). Generally, farmers in coastal region use brackish water for irrigation during rabi and summer season. The salinity developed with brackish water irrigation reduces crop yield because of osmotic stress, ion toxicity and nutrient imbalances.

Maize (*Zea mays* L.) is an important cereal crop grown in 165 million hectares of land producing 850 million tons of grain with an average grain yield of 5200 kg ha^{-1}. Under saline stress condition, it shows the sign of wilting although there is adequate soil moisture. Seed germination and early seedling growth stages are more sensitive to salinity than later developmental stages. Hyper-osmotic stress and toxic effects of sodium and chloride ions may delay or inhibit germination, reduces plant growth and leads to severe nutritional imbalances in maize.

Phosphorus is a component of the complex nucleic acid structure of plants, which regulates protein synthesis. It is, therefore, important in cell division and development of new tissue. Phosphorus is also associated with complex energy transformations in the plant. Adding phosphorus to soil low in available phosphorus promotes root growth and winter hardiness, stimulates tillering, and often hastens maturity. Application of sufficient P to saline soil can alleviate the negative effects of salinity on plant growth and development, and improve the salt tolerance of plants (Su *et al*., 2022).

Zinc regulates a variety of plant metabolic activities including glucose metabolism, cell wall formation, gene expression, protein synthesis, and respiration (Broadley *et al*., 2007). Because zinc has a regulated mechanism or a regulatory role in the Na and Cl absorption and translocation rate (Alpaslan *et al*., 1999), they hypothesized that applying zinc to salt-affected soils could reduce potential Na^+ and Cl^- harm in the plant.

Zinc decreases excessive Na uptake in saline soil by influencing the structural integrity and permeability of the stem cell membrane and improves the K^+/Na^+ ratio in plants exposed to salinity. Therefore, cell membranes show high permeability or leakage of some compounds from the roots under Zn deficiency. The metabolic defect in plant cells is linked to zinc and phosphorus imbalance (Mirvat *et al*., 2006). Therefore, in this study we hypothesized that can phosphorus and zinc mitigate the salinity stress condition by increasing the nutrient availability and root growth in saline soil.

The objectives of this study were to evaluate the effect of brackish water irrigation, phosphorus and zinc on (i) soil ECe, nutrient availability and maize yield, (ii) root growth and nutrient content.

MATERIALS AND METHODS

Study site

During august 2023, this pot culture study was undertaken in the greenhouse of Institute of Agriculture Science (IAS), SOA Deemed to be University, Bhubaneswar, Odisha, India, located at latitude 20.2961°N, longitude 85.8245°E and 58 m above mean sea level.

Climate, soil and crop management practices in coastal saline soil

Coastal saline soils in Odisha, covers about 0.40 million hectares with a narrow strip along the Bay of Bengal. The climate of the coastal region is tropical humid with mean annual rainfall of 1497 mm (80% received during the month of June to September) with mean temperature 30.3°C in the summer and 21.3°C in winter. The soils are categorized as Vertic Halaquepts with high clay content, heavy texture, high water holding capacity and poor drainage. The ECe of surface soil during month of may ranges from 6 to 10 dS m^{-1}, and in some locations, it can reach 30 dS m^{-1}. The farmers in this region use brackish water for growing different crops during winter and summer seasons due to lack of good quality irrigation water.

Collection of soil and brackish water sample for pot experiment

The clay loam saline soil used for the pot culture study was collected from village Astaranga in Puri district, Odisha which is situated 1 km away from Bay of Bengal. The field was mono-cropped with rice during kharif season. Farmers grow different crops during winter – summer season with brackish water but, the yield is low. The surface soil (0-15 cm depth) samples in bulk were collected from the field and brought to the laboratory, air dried, processed, and used for pot culture study. The physico-chemical properties of soil are presented in **Table 1**. The brackish water used in the study was brought from the Bay of Bengal at Konark seashore. The EC of seawater was 38 dS m^{-1} which was diluted to 8 dS m^{-1} for use as irrigation water in the study.

Soil properties

The soil was acidic in reaction (pH 4.98) having electrical conductivity of saturated soil paste 2.93 dS m^{-1}. The soil was clay loam in texture with sand 45.55%, silt 22.5% and clay 31.95%. The bulk density, particle density and porosity of the soil was 1.33 g cm^{-3}, 2.11 g cm^{-3} and 37% respectively. The CEC of the soil was 7.5 meq $100g^{-1}$. The soil was high in organic carbon content (1.65%), medium in available N (439.0 kg ha^{-1}) and high in both available P (35 kg ha^{-1}) and K (472.0 kg ha^{-1}). The available Ca and Mg content was 6.5 meq $100g^{-1}$ and 16.4 meq $100g^{-1}$ respectively. The soil was rich in sodium (1449.0 kg ha^{-1}). The DTPA extractable Zn was 0.82 mg kg^{-1} showing high Zn status (**Table 1**).

Table 1. Physico-chemical properties of experimental soil

Parameters	Value
Soil pH	4.98
ECe (dS m^{-1})	2.93
Sand (%)	45.55
Silt (%)	22.50
Clay (%)	31.95
Soil texture	Clay loam
Bulk Density (g cm^{-3})	1.33
Particle Density (g cm^{-3})	2.11
Porosity (%)	37.00
Cation Exchange Capacity (meq $100g^{-1}$)	7.5
Organic carbon (%)	1.65
Available nitrogen (kg ha^{-1})	439.0
Available Phosphorous (kg ha^{-1})	35.0
Available potassium (kg ha^{-1})	472.0
Available calcium (meq $100g^{-1}$)	6.5
Available magnesium (meq $100g^{-1}$)	16.4
Available sodium (kg ha^{-1})	1449.0
DTPA zinc (mg kg^{-1})	0.82

Treatments and experimental design

The study was conducted in a 3-factorial completely randomized design with three replications and 16 treatment combinations consists of two levels of brackish water (SW_0- saline control EC - 0.6 dS m^{-1}; SW_1- brackish water irrigation EC - 8 dS m^{-1}), four doses of phosphorous **(**P_1- 15 mg P kg^{-1} as basal, P_2- 30 mg P kg^{-1} as basal, P_3- 30 mg P kg^{-1} in two splits, and P_4- 45 mg P kg^{-1} in two splits) and two doses of zinc (Zn_0 - zinc control, and Zn_1- nano zinc 1.25 mg kg^{-1}). The recommended dose of fertilizer for maize crop was 120-60- 90 kg N-P_2O_5-K_2O ha^{-1}.

About 2.5 kg of processed soil was taken in polythene lined earthen pots and treated with required amount of N @ 120 kg ha^{-1} (weight basis) in two splits through granular urea. Phosphorous through SSP was applied as per the treatments. A common dose of potassium @ 90 kg ha^{-1} (weight basis) through MOP was applied at sowing time. Nano zinc (5% Zn) @ 1.25 mg kg^{-1} mixed with 100g FYM was applied as per the treatments.

All the pots were irrigated with normal water up to field capacity and 3 number of hybrid maize seeds (variety- NMH-51) of 90-100 days duration were sown on 21st November 2023. The emergence of seedlings was recorded on 26th November 2023. After seedling emergence, 2 seedlings were kept in each pot. The pots were irrigated with normal water up to 19th December 2023. Top dressing with nitrogen and phosphorus was done on 23rd December 2023.

The maize crop in SW_1 treatments were irrigated with brackish water on 20th December 2023 up to field capacity point. Same amount of normal water was given to SW_0 treatments. In total, the crop received 17 numbers of brackish water irrigation during the crop growth period.

The crop was harvested on 29th January 2024 just before the tasseling stage (64th day of germination). The harvested crop was left on the floor for sun drying and biomass yield was recorded. The harvested plants of each pot were put in envelops and kept in hot air oven at 50-60 ^{o}C temperature, ground and kept for analysis. Soil samples were collected at 22, 40, 51 and 64 days of seedling emergence and at harvest.

Root studies

Out of 16 treatments, 8 treatments ($SW_0P_1Zn_0$, $SW_0P_1Zn_1$, $SW_0P_4Zn_0$, $SW_0P_4Zn_1$, $SW_1P_1Zn_0$, $SW_1P_1Zn_1$, $SW_1P_4Zn_0$, and $SW_1P_4Zn_1$) were selected for root studies. Two plants from each treatment were collected and washed under running water for several times until it is free from soil particles. The cleaned roots were kept inside an absorbent paper till free from moisture. The length of the roots was measured by using a scale. The volume of the roots was estimated by putting it inside a measuring cylinder following the displacement method. The roots were kept under shade for drying. After drying, the weight of the roots was recorded. Based on the weight and volume, the density of the roots was calculated.

Soil, plant and root analysis

The sand, silt and clay content of soil were determined by Bouyoucos hydrometer as given by Piper (1950). The Bulk density, particle density and porosity of soil were determined by core method (Black, 1965). Soil pH was determined in 1:2.5 soil water ratio by pH meter (ELICOL1613) as described by Jackson (1973). As suggested by Jackson (1973) the electrical conductivity of saturated soil paste was determined in 1:1 soil-water ratio by conductivity meter (ELICOCM 180 conductivity meter). The organic carbon content of soil was determined by wet digestion procedure of Walkley and Black (1934) as out lined in soil chemical analysis (Page *et al.,* 1982). Available nitrogen content of soil was determined by alkali $KMnO_4$ method (Subbiah and Asija, 1956) using Kelplus Nitrogen auto analyser (Kelplus: Model classic DX). Available P in soil was determined by Bray No 1 method (Bray and Kurtz, 1945). The available K and Na which includes water-soluble and exchangeable K and Na was extracted with neutral normal ammonium acetate and estimated with a flame photometer (Model Systonics, 128) as described by Hanway and Hidel, 1952. The calcium and magnesium were determined using EDTA by Versenate Complexometric titration method as given by Jackson (1973). The DTPA extractant was used for estimation of available Zn by Atomic Absorption Spectrometer (Systronics AAS 263) (Lindsay and Norvell, 1978). Soil CEC was determined by leaching exchangeable cations with neutral normal NH_4OAc followed by removal of excess salt by 60% ethanol. The absorbed NH_4^+ was determined by distillation of the soil with magnesia (MgO) as described by Jackson (1973).

The diacid digested root samples were analysed for P, K, Ca, Mg, Zn and Na as described by Jackson (1973). The cation exchange capacity of root samples was determined by the procedure as described by Helmy and Elgabaly (1958). Air-dried roots were ground in a willey mill and one gram of roots was soaked with few drops of water in a 250 ml beaker. Roots were immersed in 1 N ammonium acetate for 30 minutes followed by subsequent washing with distilled water to free the extra ammonium acetate adsorbed by the roots. At least three washings each with 100 ml water were adequate. Further, these root samples were immersed twice in 25 ml 1 N KCl for 5 minutes each to displace the adsorbed NH_4^+ ions. The volume of KCl was made up to 50 ml. The NH_4^+ thus obtained in the extract was estimated by the standard Kjeldahl method. Root CEC was expressed in milli-equivalent per 100g roots.

Statistical analysis

The biomass yield, nutrient content and nutrient ratio was recorded, complied in appropriate tables and analysed statistically as per the procedure appropriate to the design (Panse and Sukhatme, 1985). Statistical differences between treatments were determined by Duncan Multiple Range Test (DMRT) using MSTATC software. Histograms were drawn through MS Excel. The critical difference (C.D) and statistical error of means (SEM) (SPSS and OPSTAT software) were used to express the analysed data.

RESULTS AND DISCUSSION

Effect of brackish water, phosphorus and zinc on soil properties

The pH of the soil at harvest were higher than the initial value (4.98) which varied between 5.26 to 6.27 in SW_0 treatments and 4.77 to 5.74 in SW_1 treatments (**Figure 1)**. Brackish water @ 8 dS m^{-1} significantly decreased the soil pH by 9% over normal water irrigation. Phosphorus application through P_3 and P_4 treatments significantly ($\leq$ 0.05) decreased the soil pH by 6 and 7.5% respectively over P_1. The mean interaction effects of brackish water and phosphatic fertilizer were significant ($\leq$ 0.05) recording highest pH (6.24) in the SW_0P_2 treatment and lowest in the SW_1P_4 treatment (5.14). Application of nano zinc fertilizer decreased soil pH by 2% over zinc control, although both were statistically at par. In consistence with the present result, Zhang *et al.* (2010) revealed that application of well water had a higher soil pH than application of brackish water in the saline soil of the coastal region may result from the increased concentration of HCO_3^- ions (Wang *et al.* 2011). Similar results were reported by Ding *et al.* (2020).

Electrical conductivity of saturated soil paste (ECe)

Brackish water irrigation influences soil ECe at different stages of growing period. It ranged from 3.40 - 5.85 dS m^{-1} at 22days, 9.10 - 12.35 dS m^{-1} at 40 days and 15.25 - 20.13 dS m^{-1} at 51 days after seedling emergence (**Figure 2**). The ECe values in SW_0 treatments (1.36 - 2.65 dS m^{-1}) after the harvest of maize crop were lower than the initial value (2.93 dS m^{-1}) might be due to the leaching of soluble salts below the root zone. However, with brackish water irrigation, the ECe values significantly ($\leq$ 0.05) increased by 212% over SW_0. These values (ECe 5.59 – 8.54 dS m^{-1}) were above the critical limit of salinity. Similar results were reported by Feng *et al.* (2015), Zhang *et al.* (2020) and Zheng *et al.* (2020). They found that saline water irrigation could bring more salt into soil and long-term use of saline water for irrigation without drainage or soil leaching measures would cause the risk of soil salinization.

Application of phosphatic fertilizer did not have much beneficial effect on soil ECe. Averaged over salinity and zinc, the ECe value in P_1 treatment was 3.78 dS m^{-1} and increased significantly (≤ 0.05) by 34% in P_2, 27% in P_3 and 38% in P_4. Application of nano zinc did not have much impact on the soil ECe. This result is consistent with Bouras *et al.* (2023). They demonstrated that application of saline water irrigation had a significant effect on soil ECe but, P fertilization practices during the two growing seasons did not have any significant effect on soil ECe.

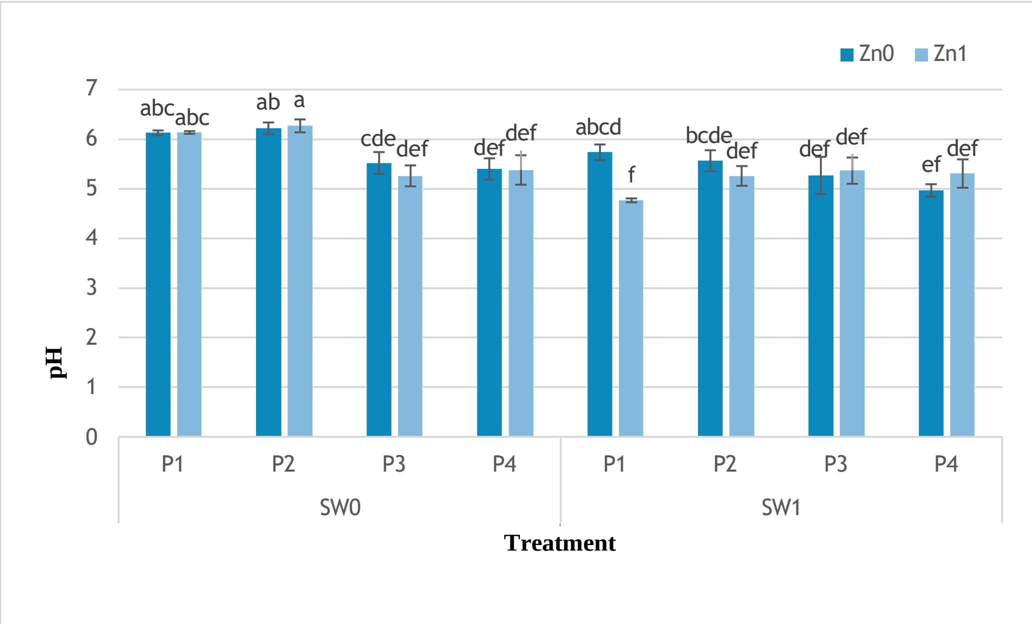

Figure 1. Effect of brackish water irrigation on soil pH during crop growth period. Each value at harvest is mean of three replications ± SE. Means followed by the same letter are not significantly different according to Duncan's multiple range test (p≤0.05).
Note: SW_0 - normal water, SW_1 - brackish water EC 8 dS m^{-1}, P_1-15 mg p kg^{-1} basal, P_2- 30 mg P kg^{-1} basal, P_3- 30 mg P kg^{-1} two splits, P_4- 45 mg P kg^{-1} two splits, Zn_0-zinc control, Zn_1- nano zinc- 1.25 mg kg^{-1} soil

Organic carbon content

The organic carbon content of the soil ranged from 1.69 to 1.96% in SW_0 treatments and 1.12 to 1.75% in SW_1 treatments (**Figure 3**). There was build up of OC in soil treated with SW_0 whereas, application of brackish water (SW_1) significantly (≤ 0.01) reduced the organic carbon content of soil by 18% over SW_0 treatments. Addition of higher dose of phosphate (P_2, P_3 and P_4) decreased the organic carbon content of soil by 2-7% over P_1. Similar observations were also recorded in zinc treatments. The mean organic carbon content of the soil in Zn_0 treatment (averaged over salinity and phosphorus) was 1.78% which was significantly (≤ 0.05) decreased by 12% in Zn_1 treatment. The interaction effects of zinc and salinity were significant at 1% level of significance indicating highest OC content (1.87%) in SW_0Zn_0 treatment and lowest (1.33%) in SW_1Zn_1 treatment. Similar observations were also recorded by Seita *et al.* (2013) and Wang *et al.* (2023). They found that the main reason for the low levels of surface SOC in saline - alkaline paddy soils was associated with the procedure of salt- leaching and drainage, which could result in enhanced desorption and removal of dissolved organic carbon (DOC) and subsequent reduction of SOC in top soil. Wang *et al.* (2023) revealed that the high rates of phosphorus with organic fertilization resulted in a small reduction of SOC in the saline − alkaline paddy subsoil which was probably attributed to improvement of soil physical and chemical conditions and there was evidence that high rate of phosphorus fertilization increased the abundance of the carbon-degrading bacteria, such as *Rhodocyclates* and *Xanthomonadales*.

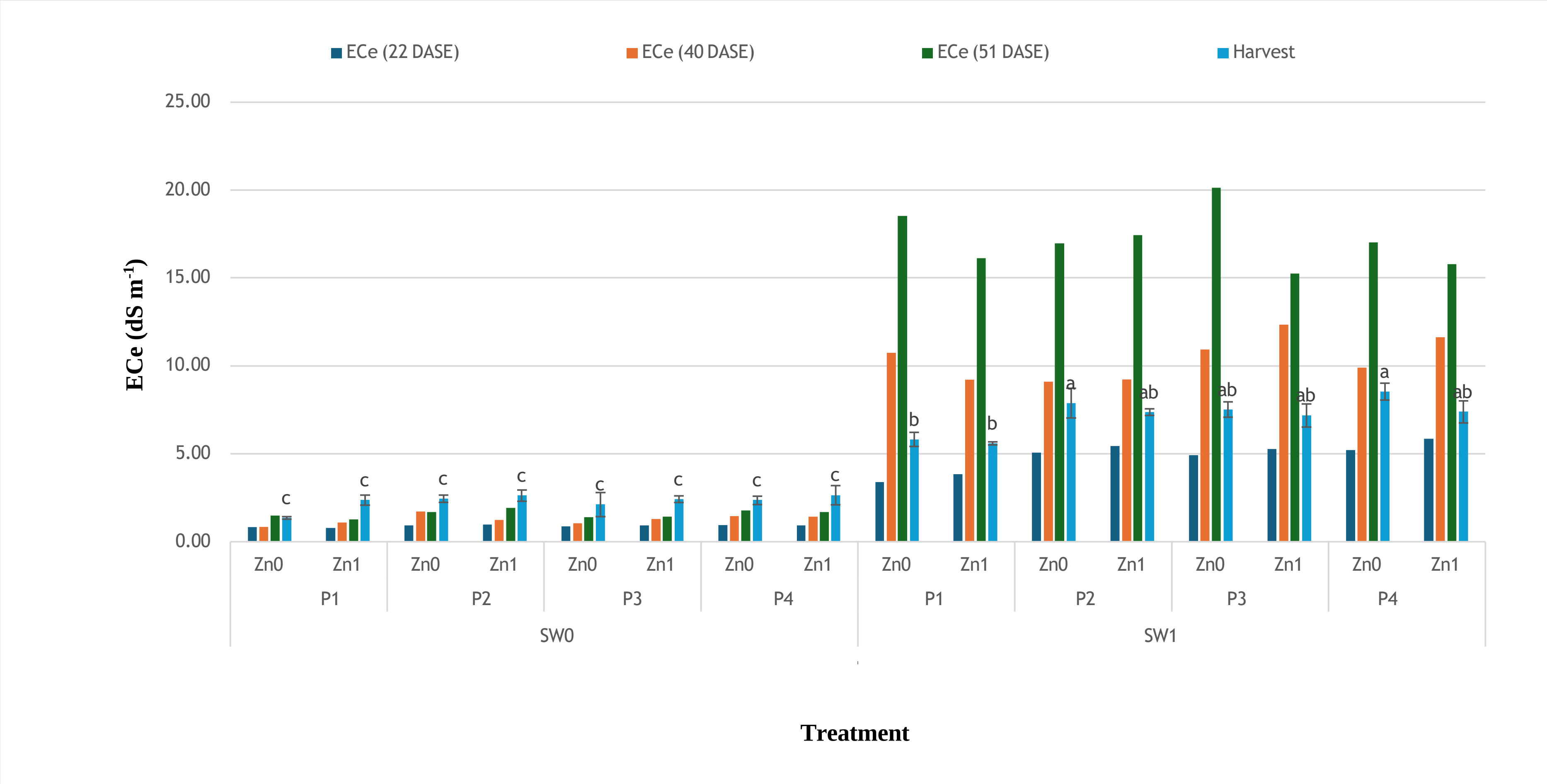

Figure 2. Effect of brackish water irrigation on ECe (dS m^{-1}) during crop growth period. Each value at harvest is mean of three replications ± SE. Means followed by the same letter are not significantly different according to Duncan's multiple range test ($p \leq 0.05$).
Note: SW_0 - normal water, SW_1 - brackish water EC 8 dS m^{-1}, P_1-15 mg P kg^{-1} basal, P_2- 30 mg P kg^{-1} basal, P_3- 30 mg P kg^{-1} two splits, P_4- 45 mg P kg^{-1} two splits, Zn_0-zinc control, Zn_1- nano zinc- 1.25 mg kg^{-1}

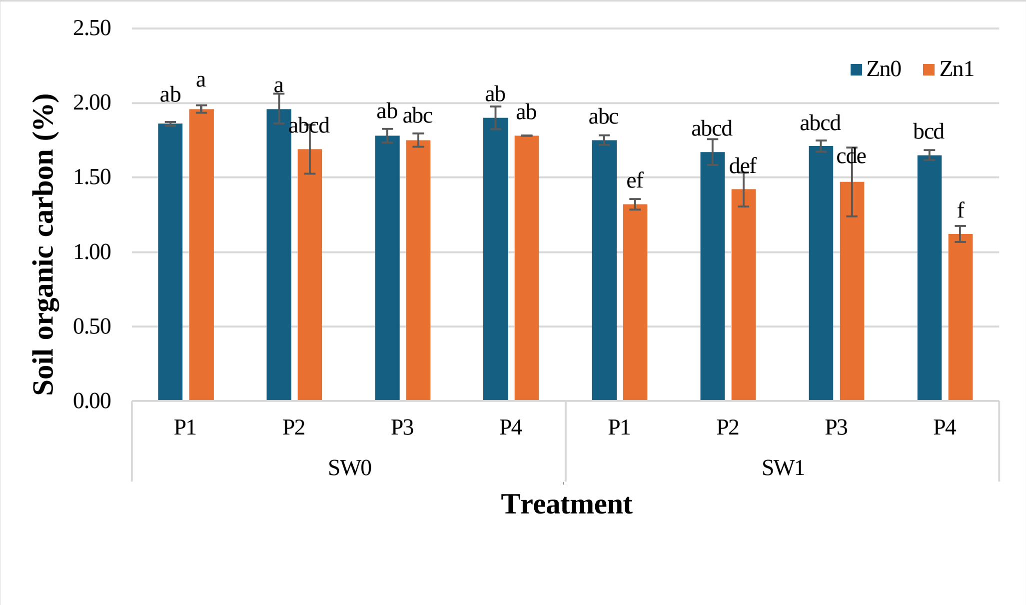

Figure 3. Organic carbon (%) status of soil after crop harvest. Each value is mean of three replications ± SE. Means followed by the same letter are not significantly different according to Duncan's multiple range test ($p \leq 0.05$).

Note: SW_0 - normal water, SW_1 - brackish water EC 8 dS m^{-1}, P_1-15 mg P kg^{-1} basal, P_2- 30 mg P kg^{-1} basal, P_3- 30 mg P kg^{-1} two splits, P_4- 45 mg P kg^{-1} two splits, Zn_0-zinc control, Zn_1- nano zinc- 1.25 mg kg^{-1}

Available phosphorus

In all treatments, the available P in soil was higher than the initial value (35 kg ha^{-1}). It ranged from 46 to 92 kg ha^{-1} in SW_0 treatments and 90 to 140 kg ha^{-1} in SW_1 treatments (**Table 2).** The ANOVA results presented in **Table 2** indicated that there is significant difference in the available phosphorus content of soil in SW_0 and SW_1 treatments at 1% level of significance. The mean available P (averaged over phosphorus and zinc) was 67 kg ha^{-1} in SW_0 treatment and significantly increased by 70% in SW_1 treatment. Similar observation was reported by Li *et al.* (2018). They reported that the low salt content can promote the amount and activity of phosphorus in soil. Compared with the control, the phosphorus content is higher than that of the control at 2 g L^{-1}.

Phosphate fertilization benefits the available P status of soil. It was 71.5 kg ha^{-1} in P_1 treatment and significantly (≤ 0.05) increased by 18% in P_2, 31% in P_3 and 58% in P_4 treatment. Application of nano zinc fertilizer has a positive effect on the available phosphorus status of the soil. The mean available phosphorus in Zn_0 treatment was 87 kg $ha^{-1}$and significantly (≤ 0.05) increased by 8% in Zn_1 treatment. This is possible due to an increase in root activity and the solubilization of insoluble phosphorus to soluble form. As per ANOVA results, the interaction mean of SW x P x Zn is significant at 5% level of significance with highest (140 kg ha^{-1}) available P in $SW_1P_4Zn_1$ treatment.

Available potassium

The available potassium in soil was higher than the initial value (472 kg ha^{-1}) which ranged from 459.2 to 588.8 kg ha^{-1} in SW_0 treatments and from 436.9 to 517.9 kg ha^{-1} in SW_1 treatments. Application of brackish water, phosphatic or zinc fertilizer did not have any significant effect on available potassium. A similar trend was also observed in the case of nano zinc treatment (**Table 2**). In contrast, El-Sharkawy *et al.* (2022) observed that application of Zn fertilizer improved P and K availability, reduced the soil sodium concentration and sodium adsorption ratio and balanced the cationic ratio, which improved the rice yield.

Available calcium

The mean available calcium content in SW_0 treatment was 11.9 meq $100g^{-1}$ and significantly (≤ 0.05) decreased by 14% in SW_1 indicating that brackish water irrigation has an adverse effect on available calcium **(Table 2)**. Further the interaction effect of SW_1P_4 was statistically significant over SW_0P_2, SW_1P_2 and SW_1P_3 at 1% level of significance. Addition of nano zinc fertilizer did not have any significant effect on available calcium. Similar result was reported by Wang *et al.* (2023). They observed that soil ECe and SAR were increased with increasing in EC_{iw} and Na^+ ion in the irrigation water, which could participate in exchange reaction with $Ca^{2+}$and Mg^{2+} in the soil colloid. The exchangeable Ca^{2+} and Mg^{2+} ions were leached into deep soil with rainfall and irrigation.

Available magnesium

The available magnesium content in different treatments after harvest of maize crop varied from 8.30 to 9.83 meq $100g^{-1}$ in SW_0 treatments and 6.80 to 8.50 meq $100g^{-1}$ in SW_1 treatments. All these values were lower than the initial content (16.4 meq $100g^{-1}$) indicating the depletion of available magnesium from soil due to crop removal (**Table 2**).

The ANOVA results presented in **Table 2** indicated that there is significant difference in the available magnesium content of soil in SW_0 and SW_1 treatments at 1% level of significance. The mean available magnesium content (averaged over phosphorus and zinc) in SW_0 treatment was 9.092 meq $100g^{-1}$ and significantly (≤ 0.05) decreased by 16% in SW_1 treatment over SW_0.

However, application of phosphate through P_2, P_3 and P_4 treatments significantly increased the available magnesium by 6%, 16% and 8% respectively over P_1. Application of nano zinc fertilizer did not have much impact on available magnesium. The interaction means of salinity and phosphorus are significant at 1% level of significance and SW_0P_2 treatment recorded the highest available magnesium content among all other treatment combinations.

DTPA Zn

Initial DTPA zinc content of soil was 0.82 mg kg^{-1} and it varied between 0.35 to 1.94 mg kg^{-1} in SW_0 treatment and from 0.34 to 1.97 mg kg^{-1} in SW_1 treatments after the crop harvest (**Table 2**).

Application of brackish water irrigation and phosphorus did not have significant effect on DTPA zinc content in soil. However, the interaction effect of SW x P is significant at 1% level of significance recording the highest DTPA zinc in SW_0P_1 treatment. Further, the data also confirms the antagonistic relationship between phosphorus and zinc. At higher levels of phosphorus, the availability of zinc decreases. A similar trend is observed in the present study. With application of P_3 and P_4 treatment, the DTPA zinc content decreased whereas the maximum available zinc was recorded in P_1 treatment.

The soil was rich in zinc (0.82 mg kg^{-1}) but, its availability is very low in saline environments. The data presented in **Table 2** showed that the mean DTPA zinc content in the zinc control (Zn_0) was 0.41 mg kg^{-1} which is below the critical level. With application of nano zinc, the mean DTPA zinc content was significantly (≤ 0.05) increased by 319% over zinc control.

In our study, the application of nano zinc fertilizer has a positive effect on the available phosphorus, potassium and zinc in the soil. Similar results were observed by El-Sharkawy *et al.* (2022). They found that Zn application to rice enhanced P and K availability, reduced the soil sodium concentration and sodium adsorption ratio and balanced the cationic ratio, which improved the rice yield. Ibrahim and Faryal (2014) demonstrated that Zn application increased the Zn availability in soil which increased salt tolerance by improving antioxidant activities and hormone synthesis.

Available Sodium

The initial available sodium content of soil was 1449 kg ha^{-1} and reduced by 38% after 64 days of growth with normal water irrigation. This might have happened due to the leaching of soluble sodium from the root zone or diffusion of sodium from the surface of porous earthen pots. On the other hand, application of brackish water (SW_1 - 8 dS m^{-1}) significantly (≤ 0.05) increased the available sodium content by 250% over SW_0. Addition of phosphorus and zinc did not have any impact on reduction of available sodium in soil.

Effect of salinity on root characteristics

Out of 16 treatments, 8 treatments were selected for study of root characteristics such as root length, root weight, root volume and root density. The length of roots in SW_0 treatments ranged from 80.7 to 83.0 cm and in SW_1 treatments from 49 to 58 cm (**Table 3**). Application of brackish water reduced the root length by 36% over normal water irrigation indicating that the growths of roots were severely affected under saline environment. However, application of the phosphatic fertilizer reduced the adverse effect of salinity by improving crop growth and increasing root length. The root length in P_1 (50% P) treatment was 51cm which was increased by 6% in P_4 with brackish water irrigation (**Plate 1** and **2**).

Similar beneficial effects of zinc fertilization were observed on root length. Under brackish water irrigation (SW_1), nano zinc application increased the root length by 12% over zinc control. The findings of Bouras *et al.* (2023) corroborated with our results. They demonstrated that as the EC of the irrigation water increases, the length of the root system (LRS) decreased. Application of P fertilizer under saline condition significantly increased the root length, the wheat biomass yield and reduced the negative effect of salinity.

The root weight ranged from 5.8 to 5.9 g in SW_0 and from 3.65 to 3.96 in SW_1 treatments. The mean root weight was decreased by 37% in SW_1 treatment over SW_0. However, with application of higher dose of P (P_4) and nano zinc fertilizer there was marginally increased in root weight. The mean root volume of maize ranged from 14 to 18 cm^3 in SW_0 treatment and from 10 to 12 cm^3 in SW_1 treatment. Application of brackish water (SW_1) decreased the root volume by 29% over SW_0 treatment. On the other hand, application of higher dose of phosphorus (P_4) reduced the adverse effect of salinity with an increase in the root volume by 17% in SW_0 and 5% in SW_1 over P_1 treatment. Similarly, application of nano zinc increased the root volume by 10% in SW_0 treatment and by 14% in SW_1 treatment over zinc control.

The mean root density of maize varied from 0.328 to 0.414 g cm^{-3} in SW_0 treatments and from 0.304 to 0.368 in SW_1 treatments. There was decrease in root density by 12% in SW_1 over SW_0 treatment. Higher dose of phosphatic fertilizer (P_4) application did not have any impact on root density rather; there was a decline in root density by 13% both in SW_0 and SW_1 treatments. Similarly, application of nano zinc fertilizer reduced the root volume by 8% in SW_0 and 13% in SW_1 over the Zinc control.

Table 2. Fertility status of soil after harvest

Treatments		**Available P (kg ha^{-1})**	**Available K (kg ha^{-1})**	**Available Ca (meq 100g^{-1})**	**Available Mg (meq 100g^{-1})**	**DTPA Zn (mg kg^{-1})**	**Available Na (kg ha^{-1})**
SW$_0$P$_1$Zn$_0$		46.000^{g}	459.243^{cd}	10.800^{bcd}	8.500^{abc}	0.593^{d}	929.733^{c}
SW$_0$P$_1$Zn$_1$		50.000^{g}	470.937^{bcd}	10.950^{bcd}	8.800^{ab}	1.940^{a}	939.100^{c}
SW$_0$P$_2$Zn$_0$		55.000^{fg}	466.293^{cd}	11.200^{bcd}	9.400^{a}	0.433^{de}	925.847^{c}
SW$_0$P$_2$Zn$_1$		61.000^{f}	534.803^{abc}	11.433^{abcd}	9.833^{a}	1.583^{c}	1032.173^{c}
SW$_0$P$_3$Zn$_0$		62.000^{f}	554.920^{ab}	13.767^{a}	9.600^{a}	0.373^{de}	785.463^{c}
SW$_0$P$_3$Zn$_1$		80.000^{e}	465.620^{cd}	12.367^{abc}	9.800^{a}	1.630^{bc}	903.273^{c}
SW$_0$P$_4$Zn$_0$		92.000^{d}	459.503^{cd}	12.500^{ab}	8.300^{abc}	0.347^{e}	824.227^{c}
SW$_0$P$_4$Zn$_1$		91.000^{d}	558.810^{a}	12.400^{abc}	8.500^{abc}	1.807^{ab}	854.387^{c}
SW$_1$P$_1$Zn$_0$		90.000^{d}	517.880^{abcd}	10.300^{bcd}	6.900^{bc}	0.340^{e}	2920.267^{b}
SW$_1$P$_1$Zn$_1$		100.000^{c}	493.667^{abcd}	10.500^{bcd}	6.950^{bc}	1.557^{c}	2973.733^{ab}
SW$_1$P$_2$Zn$_0$		110.000^{b}	500.340^{abcd}	11.533^{abcd}	6.800^{c}	0.407^{de}	3161.573^{ab}
SW$_1$P$_2$Zn$_1$		112.000^{b}	482.497^{abcd}	11.400^{abcd}	6.933^{bc}	1.967^{a}	3232.693^{ab}
SW$_1$P$_3$Zn$_0$		114.000^{b}	497.017^{abcd}	9.600^{d}	8.333^{abc}	0.380^{de}	3166.427^{ab}
SW$_1$P$_3$Zn$_1$		118.000^{b}	475.590^{abcd}	9.933^{cd}	8.267^{abc}	1.777^{abc}	3352.627^{a}
SW$_1$P$_4$Zn$_0$		130.000^{a}	436.903^{d}	9.500^{d}	8.400^{abc}	0.423^{de}	3281.213^{ab}
SW$_1$P$_4$Zn$_1$		140.000	464.567^{cd}	9.300^{d}	8.500^{abc}	1.560^{c}	3111.053^{ab}
ANOVA							
Sources of Variation	**df**	**Significance**	**Significance**	**Significance**	**Significance**	**Significance**	**Significance**
Factor SW	1	*	ns	*	*	ns	*
Factor P	3	*	ns	ns	*	ns	ns
Interaction SW x P	3	ns	ns	*	*	*	ns
Factor Zn	1	*	ns	ns	ns	*	ns
Interaction SW x Zn	1	ns	ns	ns	ns	ns	ns
Interaction P x Zn	3	ns	*	ns	ns	ns	ns
Interaction SW x P x Zn	3	*	ns	ns	ns	*	ns
Error	32						
Total	47						

Note: Means followed by the same letter are not significantly different according to Duncan's multiple range test ($p \leq 0.05$), ns- not significant, * $p \leq 0.05$

Effects of brackish water irrigation on root CEC

The uptake of plant nutrients by roots is controlled by root CEC. Application of brackish water adversely affects the root CEC. It varied from 20-24 meq 100 g^{-1} in SW$_0$ treatments and from 15-20 meq 100 g^{-1} in SW$_1$ treatments (**Table 4**). There was a decline in root CEC by 21% in SW$_1$ over SW$_0$. However, application of phosphorus through P$_4$ treatment increased the root CEC by about 12% over P$_1$ both in SW$_0$ and SW$_1$ treatments. A similar beneficial effect of zinc fertilization was observed in root CEC. Application of nano zinc increased the CEC by 7% in SW$_0$ and by 19% in SW$_1$ over zinc control.

Dogra *et al.* (2017) revealed that, the beneficial role of Zn in increasing CEC of roots helped in increasing adsorption of nutrients from the soil. Further, the beneficial role of Zn in chlorophyll formation, regulating auxin concentration and its stimulatory effect on most of physiological and metabolic process of plant, might have helped to plants in absorption of greater amount of nutrients from the soil.

Table 3. Effects of treatments on root characteristics

Treatments	Root length (cm)	Root weight (g)	Root volume (cm^3)	Density ($g\ cm^{-3}$)
$SW_0P_1Zn_0$	80.7	5.8	14	0.414
$SW_0P_1Zn_1$	81.5	5.8	15	0.387
$SW_0P_4Zn_0$	82.4	5.8	16	0.363
$SW_0P_4Zn_1$	83.0	5.9	18	0.328
$SW_1P_1Zn_0$	49.0	3.68	10	0.368
$SW_1P_1Zn_1$	53.0	3.65	12	0.304
$SW_1P_4Zn_0$	50.0	3.68	11	0.335
$SW_1P_4Zn_1$	58.0	3.69	12	0.308

Note: Each value is the mean of two observations

Nutrient content of maize roots

Application of brackish water @ 8 dS m^{-1} (SW_1) reduced the content of P and K by 5 and 14%, respectively, over normal water irrigation (SW_0) (**Table 4**). However, the accumulation of Ca, Mg, Zn and Na was increased by 24, 23, 4 and 56% respectively, in SW_1 over SW_0 treatment. A similar trend was observed in SW_1 treatment although the magnitudes were lower than SW_0 treatments. In SW_1 treatments, accumulation of K, P, Zn, Ca and Mg in P_4 was increased by 1, 17, 2, 11 and 9% respectively, over P_1.

Application of P_4 (45 mg kg^{-1}) improved the accumulation of K, P, Zn and Mg by 24, 19, 1 and 24% respectively, over P_1 (15 mg kg^{-1}) in SW_0 treatment. However, there was a reduction in Na content by 30% in P_4 over P_1 treatment. Beneficial effects of Zinc fertilization were recorded in both SW_0 and SW_1 treatments. With the application of nano zinc fertilizer, accumulation of K, P, Zn, Ca and Mg was increased by 20, 4, 22, 4 and 8% in SW_0 and by 4, 7, 16, 19 and 14% in SW_1 treatments, respectively.

Effects of Zn fertilizer on sodium accumulation in maize roots were found promising and beneficial for maize crop. There was a reduction in Na accumulation by 10-11% with nano zinc fertilization both under normal water and brackish water irrigation treatment.

Effect of salinity, phosphorous and zinc on biomass yield of maize

The mean biomass yield in normal water irrigation (SW_0) treatments ranged from 110.3 to 150.33 g pot^{-1} and brackish water irrigation (SW_1) treatments from 100.0 to 130.0 g pot^{-1} with C.V. 9.31% (**Figure 4**). Brackish water application reduced the biomass yield in all treatments. The mean biomass yield in SW_0 treatment was 121.25 g pot^{-1} and reduced by 4% in SW_1 treatment. This showed that the salinity developed due to brackish water irrigation resulted in a reduction in biomass yield because of water stress and ionic imbalance (**Plate 1 and 2**).

Plate 1. Photographs showing growth of maize roots in different treatments irrigated with normal water (S_0). (P_1- 15 mg P kg^{-1} soil, P_4- 45 mg P kg^{-1} soil in 2 splits, Zn_0- zinc control, Zn_1- nano zinc 1.25 mg Zn kg^{-1} soil)

Plate 2. Photographs showing growth of maize roots in different treatments irrigated with brackish water (S_1- 8 dS m^{-1}). (P_1- 15 mg P kg^{-1} soil, P_4- 45 mg P kg^{-1} soil in 2 splits, Zn_0- zinc control, Zn_1- nano zinc 1.25 mg Zn kg^{-1} soil)

Table 4. Effect of treatments on nutrient composition of maize root

Treatments	CEC (meq 100 g^{-1})	K (%)	Na (%)	P (%)	Zn (mg kg^{-1})	Ca (%)	Mg (%)
$SW_0\ P_1\ Zn_0$	20.0	1.24	0.40	0.21	55.1	0.22	0.72
$SW_0\ P_1\ Zn_1$	22.0	1.35	0.36	0.22	67.4	0.24	0.75
$SW_0\ P_4\ Zn_0$	23.0	1.39	0.28	0.25	56.0	0.23	0.86
$SW_0\ P_4\ Zn_1$	24.0	1.82	0.25	0.26	68.0	0.23	0.96
$SW_1\ P_1\ Zn_0$	15.0	1.19	0.58	0.20	58.1	0.24	0.84
$SW_1\ P_1\ Zn_1$	18.0	1.28	0.49	0.21	68.0	0.30	1.10
$SW_1\ P_4\ Zn_0$	17.0	1.24	0.48	0.23	60.0	0.28	1.06
$SW_1\ P_4\ Zn_1$	20.0	1.26	0.45	0.25	69.0	0.32	1.06

These results were in consistence with Wang *et al.* (2023). They reported that the grain yields of summer maize significantly decreased when EC_{iw} reached 7.1 dS m^{-1}. Saline water could raise soil ECe and SAR, which can lessen the concentration difference between soil solution and root cell cytosol and inhibit the water absorption of root system. Additionally, the soil structure deterioration caused by sodification, such as increasing soil BD, decreasing porosity and decreasing macro aggregates, demonstrated the decrease of soil permeability and hydraulic conductivity, which could reduce water infiltration, impair growth of crop root and cause the yield reduction. The adverse effect of salinity on plant growth was reported by Ali *et al*. (2023) for sunflower, Alomar and Jena (2022) for maize crop.

The adverse effect of salt stress was reduced by the application of different doses and methods of P fertilization. The mean (averaged over salinity and zinc) biomass yield in the P_1 treatment was 110.67 g pot^{-1} and increased significantly (≤ 0.05) by 4, 7 and 18 % in P_2, P_3 and P_4 treatments, respectively over P_1 treatment. Similar results were reported by Ding *et al.* (2020). They observed that, soil salinity decreased yield and quality of wheat, due to its negative impact on soil available water and nutrients. The combined application of P fertilizers and organic amendments could alleviate the negative impacts of salinity and improved soil physical and chemical properties and thus enhanced wheat yield and quality.

In saline environments, many plants suffer because of zinc deficiency. Zinc helps in crop growth by influencing enzymatic activity. In this study application of nano Zn @ 1.25 mg kg^{-1} (2.5 kg ha^{-1}) significantly (≤ 0.05) increased the biomass yield by 11% over zinc control. Similar results were reported by Izadi *et al*. (2014). They observed that Zn application to the crops in saline soil increases root extension, providing many effective root hairs that increase nutrient and water uptake and thus improving photosynthetic efficiency, grain and biological yield. Ali *et al.* (2023) revealed that spraying of nano-zinc fertilizer to sunflower irrigated with saline water increased seed yield significantly and this can be attributed to its role in enhancing plant growth and increasing the efficiency of the photosynthesis process. Similarly, Iqbal *et al.* (2014) found that, Zn application significantly reduced Na concentration in maize shoots, thus improved salinity tolerance. This can be attributed to positive effects of Zn application on membrane stability and increased plant growth on Zn deficient and Na stressed plants.

K^+/Na^+ ratio in soil

The K^+/Na^+ ratio in soil varied between 0.292 and 0.436 in SW_0 and between 0.079 and 0.105 in SW_1 treatment (**Figure 5**). The mean K^+/Na^+ ratio in SW_0 treatment was 0.333 and decreased by 73% in SW_1 treatment. With P fertilization, the ratio was increased by16% in P_3 and 13% in P_4 treatment over P_1 (0.198). On the other hand, with nano zinc application the ratio was decreased by 5% over zinc control (0.217). According to Bouras *et al.* (2021), the appropriate P-fertilization under saline conditions contributed to minimize the effect of salinity and improved wheat growth and production and that may associate to a rise of essential plant nutrients uptake and concentrations, decrease in concentrations of toxic ions i.e., sodium (Na^+) and chloride (Cl^-) and thus expansion of Ca^{2+}/Na^+ and K^+/Na^+ ratios. The P applied rates through the rooting medium inhibits accumulation of Na^+ and Cl^- in leaves and roots, while increasing leaf and root K^+, P with Ca^{2+} (Naheed *et al.*, 2008).

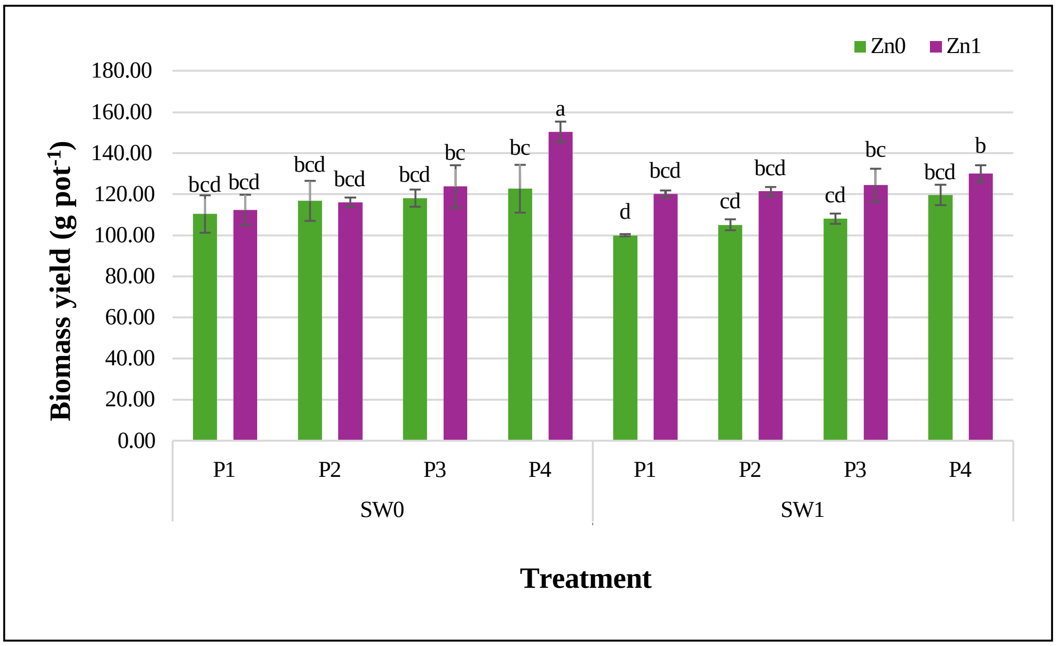

Figure 4. Effect of phosphorous and nano zinc on biomass yield (g pot^{-1}) of maize irrigated with brackish water. Each value is mean of 3 replications ± SE. Means followed by the same letter are not significantly different according to Duncan's multiple range test (p≤0.05).

Note: (SW_0 - normal water, SW_1 - brackish water EC 8 dS m^{-1}, P_1-15 mg P kg^{-1} basal, P_2- 30 mg P kg^{-1} basal, P_3- 30 mg P kg^{-1} two splits, P_4- 45 mg P kg^{-1} two splits, Zn_0-zinc control, Zn_1- nano zinc- 1.25 mg kg^{-1} soil)

Correlation of ECe with biomass yield

Soil salinity developed with brackish water irrigation resulted in reduction of plant growth, biomass yield, nutrient accumulation and uptake. In this study attempts were made to understand the relationship between electrical conductivity of saturated soil paste (ECe) with maize biomass yield both under brackish water (SW_1) and normal water (SW_0) irrigation treatments. The polynomial curve fitting was applied to correlate ECe with biomass yield (**Figure 6).** Better correlationship with high R^2 was obtained through polynomial curve fitting as compared to linear relationship between two variables (ECe and biomass yield). The co-efficient of regression curve for ECe x biomass yield in SW_0 and SW_1 treatment was found to be 0.2168 and 0.5645, respectively (**Figure 6**). The regression value in SW_0 was very low whereas better relationship exists with high regression value (R^2 = 0.5645) in SW_1. As per the shape of curve in SW_0, the biomass yield increased with increase in ECe values when the maize was irrigated with normal water. The ECe values in all points were below the level of critical limit (< 4 dS m^{-1}). However, with application of brackish water irrigation, the ECe increased above the critical limit of salinity which varied between 15 and 20 dS m^{-1}. With increase in ECe above the critical limit, the biomass yield decreased significantly with R^2 – 0.5645. Higher coefficient value indicates a close relationship between ECe and biomass yield when the ECe values are above the critical level of salinity (**Figure 6**).

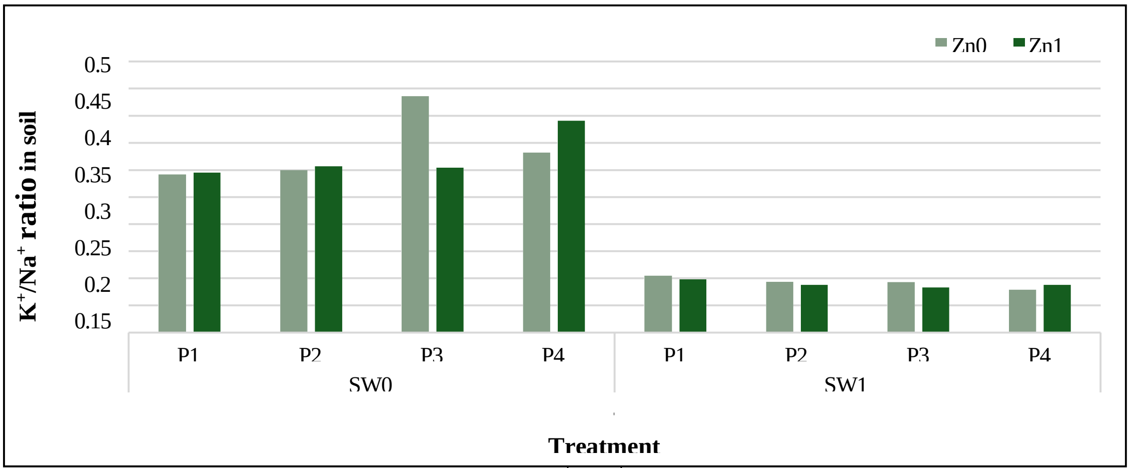

Figure 5. Effect of phosphorous and nano zinc on K^+/Na^+ ratio in soil irrigated with brackish water. Each value is mean of 3 replications

Note: (SW_0 - normal water, SW_1 - brackish water EC 8 dS m^{-1}, P_1-15 mg P kg^{-1} basal, P_2- 30 mg P kg^{-1} basal, P_3- 30 mg P kg^{-1} two splits, P_4- 45 mg P kg^{-1} two splits, Zn_0-zinc control, Zn_1- nano zinc- 1.25 mg kg^{-1})

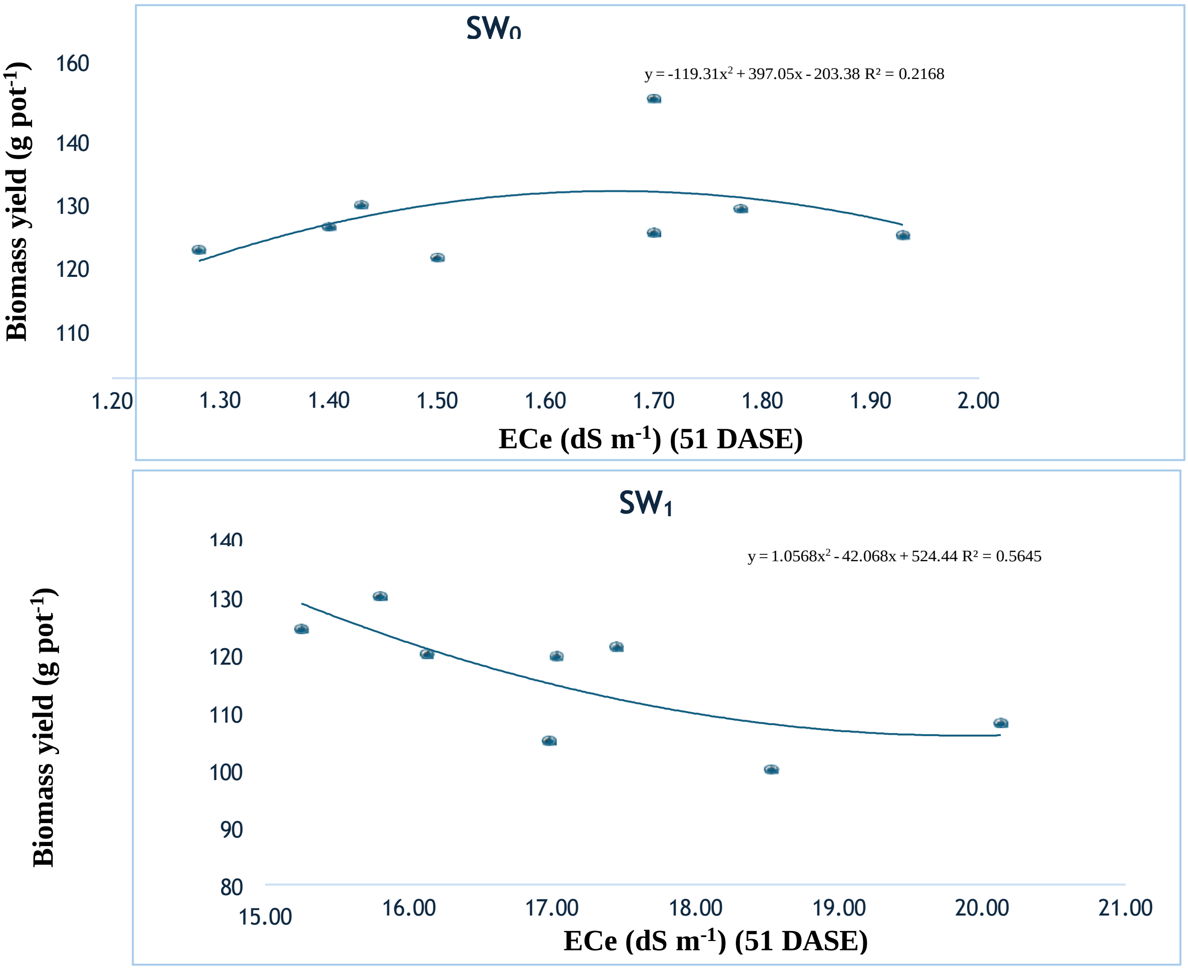

Figure 6. Correlation between ECe (51 DASE) and biomass yield in normal water (SW_0) and brackish water (SW_1) irrigated soil

CONCLUSION

Brackish water irrigation increased the soil salinity (ECe) by 212% over normal water irrigation. The buildup in ECe ranged from 5.81 – 8.54 dS m^{-1} which are above the critical limit of salinity (>4 dS m^{-1}). Brackish water irrigation @ 8 dS m^{-1} affects nutrient availability by decreasing organic carbon content (18%), available potassium (3%), calcium (14%), magnesium (16%) and DTPA zinc (3%) in soil whereas, the available sodium increased by 250%. The root length, root mass, root density, root CEC and biomass yield of maize were reduced with brackish water irrigation. However, there was improvement in yield with application of P and nano zinc fertilizer by 4 – 18% and 11% respectively. Finally, it is concluded that brackish water irrigation up to 8 dS m^{-1} combined with P and zinc fertilizer is recommended for different crops during winter and summer season in coastal saline soil.

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