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Effect of Saline Irrigation on Maize Productivity, Resource Use Efficiency and Soil Dynamics under Drip Fertigation System

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Abstract

A field investigation was carried out during the Rabi seasons with the primary objective to assess the influence of saline irrigation water on maize performance, specifically focusing on yield, water and nutrient use efficiency, and soil nutrient availability under drip fertigation conditions. The experimental layout comprised eight distinct treatments with four replications, structured using a randomized block design. Maximum grain and stover yield, along with the highest nutrient uptake, were observed under irrigation with high-quality water combined with the recommended fertilizer dose. These results were statistically comparable to those obtained from alternating fresh water and saline water with an electrical conductivity (EC) of 4 dS m^{-1}. Soil pH remained stable across treatments, while the highest soil EC was recorded under continuous saline water irrigation (4 dS m^{-1}) without fertilizer application. Conversely, the lowest nutrient uptake, nutrient use efficiency, and soil nutrient availability were noted under saline irrigation without fertilization. The strategic alternation of fresh and saline water proved effective in mitigating the detrimental effects of salinity, thereby enhancing nutrient utilization efficiency and improving the bioavailability of nutrients in the soil.

Keywords: Drip fertigation, Fresh water, Irrigation, Nutrient use efficiency, Saline water

Introduction

Water is a fundamental component of life on Earth, playing a critical role in sustaining ecological balance, supporting human health, and enabling agricultural productivity. It also contributes significantly to maintaining soil integrity and facilitating livestock rearing. The distribution and density of vegetation across terrestrial landscapes are primarily governed by the availability and quality of water, surpassing the influence of most other environmental parameters.Agricultural systems are intrinsically reliant on water, yet the current supply of high-quality water is insufficient to meet the growing demands of crop cultivation, resulting in extensive areas of uncultivated land. One potential alternative is the use of brackish water for irrigation. However, prolonged application of saline water leads to the accumulation of salts in the soil, posing a major challenge to global agriculture due to its detrimental impact on plant physiological processes. It is estimated that approximately 20% of the world's land area is affected by salinity (Elsiddig *et al.,* 2022). Globally, around 45 million hectares of irrigated land have been degraded by salt intrusion, with an additional 1.5 million hectares rendered unproductive annually due to excessive soil salinity (Ibrahim *et al.,* 2018). Projections suggest that up to 30% of agricultural land may be lost to salt stress within the next 25 years, potentially reaching 50% by 2050 (Hu *et al.,* 2019).

Despite its elevated salt content, saline irrigation water can enhance soil moisture in the root zone and supply trace elements beneficial for crop growth. Drip irrigation has emerged as a particularly effective technique for applying saline water, owing to its low-volume, high-frequency delivery system. This method helps maintain favorable soil matric potential and mitigates the osmotic stress induced by salinity, thereby preserving the overall water potential required for optimal plant development (Kang *et al.*, 2010). Unlike conventional irrigation methods, drip systems localize salt accumulation to the periphery of the wetted zone, where concentrations remain low enough to support healthy crop growth (Yaron *et al.*, 1973). Consequently, drip irrigation is widely recognized as the most suitable approach for utilizing saline water in crop production (Shalhev *et al.,* 1994).

Equally important is the role of nutrient management in maximizing crop yield. Fertigationthe application of fertilizers through irrigation wateroffers a precise and efficient means of nutrient delivery. This technique, compatible with various irrigation systems, ensures uniform distribution of water and nutrients, thereby improving water use efficiencya critical advantage under conditions of increasing water scarcity (Sharma *et al.,* 2017). In the Krishna Western Delta, maize has increasingly replaced pulses during the Rabi season, occupying up to 40% of the cultivated area. Post-monsoon maize cultivation often results in surface salt accumulation. Given the limited availability of surface water during this period, farmers resort to groundwater extraction regardless of its salinity or rely on residual soil moisture. The combined effects of elevated salt concentrations in the root zone, restricted irrigation resources, poor water quality, high ambient temperatures, and reduced osmotic potential have led to declining maize yields in the region. Although maize is a crop of considerable agronomic importance, it exhibits sensitivity to salinity, and current knowledge regarding its tolerance to saline irrigation remains limited. In light of these challenges, a targeted experimental study was initiated to explore viable solutions.

Material and Methods

The field experiment was conducted over three consecutive Rabi seasons 2022-23, 2023-24, and 2024-25 at the Saline Water Scheme, Agricultural College Farm, Bapatla. The soil at the experimental site exhibited a neutral pH of 7.3 and was classified as non-saline, with an electrical conductivity (EC) of 0.3 dS m^{-1}. Soil fertility analysis indicated low levels of available nitrogen (151 kg ha^{-1}), moderate phosphorus content (27 kg ha^{-1}), and high potassium availability (438 kg ha^{-1}). The soil texture was identified as sandy loam. The study employed a randomized block design (RBD) with four replications and eight treatment combinations, as follows:T_1: Irrigation with Best Available Water (BAW), T_2: Irrigation with saline water at 2 dS m^{-1}, T_3: Irrigation with saline water at 4 dS m^{-1}, T_4: BAW + Recommended Dose of Fertilizer (RDF), T_5: T_2 + RDF, T_6: T_3 + RDF, T_7: T_2 + RDF with alternate use of fresh water andT_8: T_3 + RDF with alternate use of fresh water. The RDF applied was 200-80-80 kg ha^{-1} of NPK. Nitrogen was supplied as urea, phosphorus as diammonium phosphate (DAP), and potassium as muriate of potash (MOP). Fertilizers were administered through a venturi injector integrated into the drip fertigation system at designated crop growth stages. Nitrogen was split and applied at the knee-high and flowering stages, while the full dose of phosphorus and half of the potassium was incorporated at sowing. The remaining potassium was applied at flowering. The drip irrigation setup consisted of 16 mm inline laterals equipped with emitters discharging at 2.0 L hr^{-1}, spaced 50 cm apart. Each plot was fitted with individual valve controls to regulate irrigation and fertigation. Screen and disc filters were installed downstream of the pumping and fertigation units to remove particulates from the irrigation water. A venturi injector was positioned upstream of the filtration system to facilitate fertilizer delivery.Saline irrigation water with EC levels of 2 and 4 dS m^{-1} was prepared by diluting seawater (EC 34 dS m^{-1}) with locally available freshwater (EC 0.6 dS m^{-1}) to achieve the desired salinity levels. The maize hybrid ‘Pioneer 3396’ was sown using the dibbling method. Irrigation scheduling was based on pan evaporation replenishment, with water applied at 100% of cumulative pan evaporation every three days. During the crop cycle, a total of 64.6 mm of rainfall was recorded over five days, and irrigation volumes were adjusted accordingly. At harvest, cobs were collected from the net plot area, and plants were sun-dried to determine stover yield. Kernel weight was measured using a mechanical sheller, and the grain yield was calculated by combining the total kernel weight per plot with the kernel yield from five representative plants sampled for post-harvest analysis. Final grain yield was expressed in kilograms per hectare.

Nutrient use efficiency

Nutrient use efficiencies including Agronomic efficiency (AE), Physiological efficiency (PE), Apparent recovery efficiency (ARE) and Utilization efficiency (EU) were worked out for nutrients N, P and K using the following formulas:

Agronomic efficiency (AE) was estimated by using the following formula (kg grain/ kg of applied nutrient).

$$AE = \frac{[\text{Grain yield (kg ha}^{-1}) \text{ in fertilized plot}] - [\text{Grain yield (kg ha}^{-1}) \text{ in control plot}]}{\text{Nutrient applied (kg ha}^{-1})}$$

Physiological efficiency (PE) was estimated by using the following formula (kg biological yield/ kg of nutrient uptake).

$$PE = \frac{[\text{Biological yield (kg ha}^{-1}) \text{ in fertilized plot}] - [\text{Biological yield (kg ha}^{-1}) \text{ in control plot}]}{[\text{Nutrient uptake (kg ha}^{-1}) \text{ in fertilized plot}] - [\text{Nutrient uptake (kg ha}^{-1}) \text{ in control plot}]}$$

Apparent recovery efficiency (ARE) per cent from total nutrient uptake (grain + straw) was estimated by using the following formula

$$ARE = \frac{[\text{Nutrient uptake (kg ha}^{-1}) \text{ in fertilized plot}] - [\text{Nutrient uptake (kg ha}^{-1}) \text{ in control plot}]}{\text{Nutrient applied (kg ha}^{-1})}$$

Utilization efficiency (UE) was estimated by using the following formula (kg biological yield/ kg of nutrient applied).

$$UE = \frac{[\text{Biological yield (kg ha}^{-1}) \text{ in fertilized plot}] - [\text{Biological yield (kg ha}^{-1}) \text{ in control plot}]}{\text{Nutrient applied (kg ha}^{-1})}$$

(or)

$$UE = PE \times ARE$$

Water use efficiency

Water use efficiency in kg ha mm^{-1} for a given treatment was calculated by dividing the kernel yield with the respective total water applied during the crop period.

$$WUE = \frac{\text{Kernel yield (kg ha}^{-1})}{\text{Total water applied (mm)}}$$

The data generated on various parameters during the course of investigation were statistically analyzed by applying the technique of analysis of variance contained in the procedures suggested by Gomez and Gomez (1984).

Nitrogen

Nitrogen content (%) in kernel and stover were estimated by using Modified microkjeldhal method (Piper, 1966). From the Nitrogen content obtained, nitrogen uptake was calculated by using the following formula and expressed in kg ha^{-1}.

$$\text{N uptake in Grain (kg ha}^{-1}) = \frac{\text{N content (\%)} \times \text{Kernel yield (kg ha}^{-1})}{100}$$

$$\text{N uptake in Stover (kg ha}^{-1}) = \frac{\text{N content (\%)} \times \text{Stover yield (kg ha}^{-1})}{100}$$

Phosphorus

The plant samples were digested with diacid mixture consisting of HNO3: HClO4 (9:4) and the digest was made up to 50 ml. The phosphorus content in the diacid digest was determined by Vanadomolybdo phosphoric acid yellow color method (Piper, 1966). The intensity of yellow color developed was measured by using spectrophotometer at 420 nm wavelength. The phosphorus uptake was calculated using the following formula and expressed in kg ha^{-1}.

$$\text{P uptake in Grain (kg ha}^{-1}) = \frac{\text{P content (\%)} \times \text{Kernel yield (kg ha}^{-1})}{100}$$

$$\text{P uptake in Stover (kg ha}^{-1}) = \frac{\text{P content (\%)} \times \text{Stover yield (kg ha}^{-1})}{100}$$

Potassium

The potassium content in the diacid digest was determined by using flame photometer method (Jackson, 1973). The potassium uptake was calculated using the following formula and expressed in kg ha^{-1}.

$$\text{K uptake in Grain (kg ha}^{-1}) = \frac{\text{K content (\%)} \times \text{Kernel yield (kg ha}^{-1})}{100}$$

$$\text{K uptake in Stover (kg ha}^{-1}) = \frac{\text{K content (\%)} \times \text{Stover yield (kg ha}^{-1})}{100}$$

The data generated on various parameters during the course of investigation were statistically analyzed by applying the technique of analysis of variance contained in the procedures suggested by Gomez and Gomez (1984).

Results and Discussion

The yield data clearly demonstrated that both the salinity levels of irrigation water and the applied fertilizer doses exerted a significant influence on kernel and stover yields in maize. Among the treatments, the highest kernel yield was consistently recorded under Treatment 4 (T_4), which involved irrigation with best available water (BAW) combined with the recommended dose of fertilizer (RDF), yielding 5850, 6123, 6523, and 6165 kg ha^{-1} across the respective years and in pooled analysis. This performance was statistically comparable to Treatment 5 (T5: irrigation with 2 dS m^{-1} saline water + RDF) and Treatment 8 (T_8: irrigation with 4 dS m^{-1} saline water + RDF with alternate use of fresh water), but significantly superior to all other treatments throughout the study period. Conversely, the lowest kernel yield values 4135, 4024, 4105, and 4088 kg ha^{-1} were observed under Treatment 3 (T_3), which involved irrigation with 4 dS m^{-1} saline water without any fertilizer application (Table 1). A clear inverse relationship was noted between salinity levels and yield performance, with increasing salinity leading to progressive yield reduction. Previous research has attributed this decline to physiological stress during the kernel filling phase, which impairs endosperm development and amyloplast formation, ultimately reducing grain weight and overall productivity (Jones *et al.,* 1996). These observations align with the findings of Feng *et al.* (2017), Yuan *et al.* (2018), Rodrigues *et al.* (2019), and Shehzad *et al.* (2020).

Regarding stover yield, Treatment 4 again recorded the highest values 9241, 9102, 8475, and 8939 kg ha^{-1} followed closely by Treatments 5 and 8, which were statistically at par. These treatments significantly outperformed the remaining ones across all years and in pooled data. The lowest stover yields7417, 6516, 5875, and 6603 kg ha^{-1} were associated with Treatment 3, reflecting the adverse impact of saline irrigation without nutrient supplementation. The enhanced stover yield under fertilized treatments can be attributed to improved vegetative growth and dry matter accumulation facilitated by adequate nutrient availability. These results are consistent with earlier studies by Tank *et al.* (2006) and Mrudhula *et al.* (2021), which emphasized the role of nutrient management in promoting biomass production. In contrast, the reduced growth and dry matter accumulation observed in unfertilized plots likely contributed to the lower stover yields,

Table 1. Effect of saline water on yield of maize under drip fertigation

Treatments	Grain yield (kg ha^{-1})				Stover yield (kg ha^{-1})			
	2022-23	2023-24	2024-25	Pooled data	2022-23	2023-24	2024-25	Pooled data
T_1	4580	4657	4669	4635	7855	7621	6575	7350
T_2	4510	4362	4421	4431	7614	7043	6250	6969
T_3	4135	4024	4105	4088	7417	6516	5875	6603
T_4	5850	6123	6523	6165	9241	9102	8475	8939
T_5	5600	5720	6241	5854	8954	8819	8405	8726
T_6	4920	4840	5131	4964	8396	8118	7210	7908
T_7	5440	5472	6044	5652	8650	8590	8050	8430
T_8	5400	5071	5955	5475	8524	8312	7975	8270
Sem+	292.5	362	197.7	284	403.2	293	291.9	329
LSD (p=0.05)	860	1064	582	835	1189	862	858	970
CV (%)	11.6	14.4	7.4	11.1	11.7	12.3	7.9	10.6

Treatment combinations: T_1: Irrigation with best available water (BAW), T_2: Irrigation with saline water at 2 dS m^{-1}, T_3: Irrigation with saline water at 4 dS m^{-1}, T_4: BAW + Recommended Dose of Fertilizer (RDF), T_5: T_2 + RDF, T_6: T_3 + RDF, T_7: T_2 + RDF with alternate use of fresh water andT_8: T_3 + RDF with alternate use of fresh water.

Table 2. Effect of saline water on water and nitrogen use efficiencies of maize under drip fertigation

Treatments	Water use efficiency (kg ha mm^{-1})	AE (kg/kg)	PE (kg/kg)	ARE (%)	UE (kg/kg)
T_1	11.7	0.0	0	0	0
T_2	11.1	0.0	0	0	0
T_3	10.3	0.0	0	0	0
T_4	16.3	7.7	85.2	22.5	15.7
T_5	15.6	6.6	82.0	19.6	13.7
T_6	12.9	2.8	52.8	4.4	3.0
T_7	14.9	5.3	72.1	15.3	10.9
T_8	14.7	5.0	67.1	11.4	8.5
Sem+	0.5	0.3	3.91	0.97	0.72
LSD (p=0.05)	1.5	0.7	11.5	2.9	2.1
CV (%)	7.4	14.9	17.4	21.3	22.1

Treatment depictions as in Table 1.

corroborating findings reported by Maryam *et al.* (2013) and Sree Rekha *et al.* (2015).

The analysis of water use efficiency (WUE) in maize revealed a significant impact from both irrigation water salinity and fertilizer application rates. Among the evaluated treatments, the highest WUE was recorded under Treatment 4 (T_4), which involved irrigation with best available water (BAW) combined with the recommended dose of fertilizer (RDF), yielding 16.3 kg ha^{-1} mm^{-1}. This result was statistically comparable to Treatments 5 (T_5), 7 (T_7), and 8 (T_8), yet markedly superior to the remaining treatments. In contrast, the lowest WUE value of 11.7 kg ha^{-1} mm^{-1} was observed under Treatment 3 (T_3), where maize was irrigated with saline water at 4 dS m^{-1} without any fertilizer input.

Nitrogen use efficiency (NUE), assessed through agronomic efficiency, physiological efficiency, apparent recovery, and utilization efficiency, also showed significant variation across treatments. The highest NUE values7.7, 85.2, 22.5, and 15.7 kg/kg, respectively were recorded under T4, with statistical parity observed only with T_5 (Table 2). All other treatments demonstrated significantly lower efficiency metrics.The findings underscore the positive influence of fertilizer application on enhancing WUE in maize, particularly under conditions of saline irrigation. This aligns with earlier research indicating that factors contributing to increased crop yield under optimal fertilization also promote improved water use efficiency (Oner*et al.,* 2002). Additionally, recent studies reported by DivyaSree*et al.* (2024) have confirmed that the combination of freshwater irrigation and recommended fertilizer doses yields the highest WUE in maize cultivation.

The experimental findings indicated that phosphorus use efficiency in maize was significantly influenced by both irrigation water salinity and fertilizer application. Among the treatments, the highest agronomic phosphorus use efficiency was observed under Treatment 4 (T_4), which involved irrigation with best available water (BAW) combined with the recommended dose of fertilizer (RDF), recording a value of 18.7 kg/kg. This was statistically comparable only to Treatment 5 (T_5), while outperforming all other treatments.Physiological phosphorus efficiency reached its peak under T4 as well, with a recorded value of 225.3 kg/kg. This was statistically similar to Treatments 5 (T_5), 7 (T_7), and 8 (T_8), yet significantly superior to the remaining treatments. Apparent physiological phosphorus use efficiency also showed its highest value under T_4 (17 kg/kg), which was on par with T_5 and T_7, but significantly higher than the other treatments. Phosphorus utilization efficiency was maximized under T_4, with a value of 39.1 kg/kg, and was statistically equivalent to T_5, while significantly exceeding the performance of all other treatments (Table 3). In contrast, the lowest values across all phosphorus efficiency metrics were consistently recorded under Treatment 3 (T_3), which involved

Table 3. Effect of saline water on phosphorus use efficiencies of maize under drip fertigation

Treatments	AE (kg/kg)	PE (kg/kg)	ARE (%)	UE (kg/kg)
T_1	0.0	0	0	0
T_2	0.0	0	0	0
T_3	0.0	0	0	0
T_4	18.7	225.3	17.0	39.1
T_5	17.9	222.9	15.4	34.3
T_6	7.5	157.5	5.2	7.6
T_7	8.1	214.5	15.4	27.4
T_8	7.6	210.1	10.3	21.2
Sem+	0.6	12.3	0.65	1.79
LSD (p=0.05)	1.8	36.2	1.9	5.3
CV (%)	15.4	19.1	17.2	22.1

Treatment depictions as in Table 1.

irrigation with saline water at 4 dS m^{-1} without fertilizer application.

The experimental outcomes demonstrated that potassium use efficiency in maize was significantly influenced by the interaction of irrigation water salinity and fertilizer application. Treatment 4 (T_4), which involved irrigation with best available water (BAW) combined with the recommended dose of fertilizer (RDF), recorded the highest values across all potassium efficiency parameters (agronomic, physiological, apparent recovery and utilization efficiency) were recorded with T_4 treatment (18.4, 159.4, 48.7 and 39.1 kg/kg) (Table 4). These results were statistically superior to all other treatments, with the exception of potassium utilization efficiency, which was found to be on par with Treatment 5 (T_5). In contrast, the lowest potassium use efficiency values were consistently observed under Treatment 3 (T_3), where maize was irrigated with saline water at 4 dS m{ ¹ without any fertilizer application. This decline highlights the adverse impact of high salinity and lack of nutrient supplementation on potassium uptake and utilization.

Table 4. Effect of saline water on potassium use efficiencies of maize under drip fertigation

Treatments	AE (kg/kg)	PE (kg/kg)	ARE (%)	UE (kg/kg)
T_1	0	0	0	0
T_2	0	0	0	0
T_3	0	0	0	0
T_4	18.4	159.4	48.7	39.1
T_5	15.8	89.9	41.0	34.3
T_6	2.7	49.9	14.3	7.6
T_7	15.8	78.2	33.5	27.2
T_8	10.6	74.1	26.1	21.1
Sem+	0.78	5.76	1.98	1.79
LSD (p=0.05)	2.3	16.9	5.8	5.3
CV (%)	20.9	20.4	19.3	22.1

Treatment depictions as in Table 1.

Post-harvest analysis of soil nutrient status revealed that the levels of available nitrogen, phosphorus, and potassium were significantly influenced by both the salinity of irrigation water applied through drip systems and the fertilizer treatments administered to the maize crop. The highest concentration of available nitrogen (160 kg ha^{-1}) was recorded under Treatment 4 (T_4), which combined best available water (BAW) with the recommended dose of fertilizer (RDF). This was followed by Treatments 5 (T_5), 6 (T_6), 7 (T_7), and 8 (T_8), all of which demonstrated elevated nitrogen levels compared to the remaining treatments.The observed increase in soil nitrogen availability under RDF treatments may be attributed to enhanced biochemical interactions between applied nitrogen and soil organic matter, facilitating its conversion into plant-accessible forms. These findings are consistent with previous studies that reported similar trends in nitrogen dynamics under fertilized conditionscorroborated with Bera*et al.* (2017) and Ray *et al.* (2020).

Regarding phosphorus, the highest available phosphorus content (47.3 kg ha^{-1}) was also recorded under T4 (Table 5). This treatment showed statistically significant superiority over Treatments 1 (T_1), 2 (T_2), 3 (T_3), 6 (T_6), and 8 (T_8), while remaining on par with T_5 and T_7. The elevated residual phosphorus levels in RDF treatments may be due to direct inorganic inputs and variable uptake rates by maize, as suggested by reported by Kumar *et al.* (2017).

Similarly, the maximum available potassium (350 kg ha^{-1}) was observed under T_4, significantly exceeding the values recorded in T_1, T_2, and T_3. The increased potassium availability is likely a result of higher fertilizer application rates, which not only supplied nutrients for crop uptake but

Table 5. Post harvest soil nutrient status

Treatments	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
T_1	129	36	275
T_2	125	34	254
T_3	120	32	236
T_4	160	47	349
T_5	150	42	327
T_6	132	37	302
T_7	144	39	319
T_8	139	38	306
Sem+	9.4	3.0	24.3
LSD (p=0.05)	28	8.9	71.6
CV (%)	13.7	15.9	16.4

Treatment depictions as in Table 1.

also contributed to residual enrichment in the soil. These outcomes align with findings from prior studies that examined potassium retention under fertilized regimes by Aruna Kumari and Prasad (2016).

Conclusion

The results of the present investigation indicate that irrigating maize with high-quality water via a drip system, in conjunction with the recommended fertilizer dosage, led to optimal outcomes in terms of grain and stover yield, as well as enhanced water and nutrient use efficiency. In contrast, irrigation with saline water at an electrical conductivity of 4 dS m^{-1}, without fertilizer supplementation, resulted in markedly reduced efficiency metrics and diminished availability of essential soil nutrients.

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