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Effect of Irrigation Water Salinity and Soil Amendments on Leaching Efficiency of Salts and Sodium Under Lysimetrs Condition

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SALT leaching is considered one of the fundamental pillars in the reclamation of salt-affected soil. In the study area, the quality of irrigation water poses a challenge to this process, as it is classified as moderately to highly saline water. Therefore, this study aims to improve soil leaching processes and the efficiency of salts and sodium removal using some chemical and organic soil amendments. The study was conducted in lysimeters over nine months from Oct. 15, 2022 to July 15, 2023. The experiment followed a factorial design with four replicates in clay-saline soil. The first factor was the salinity levels of the irrigation water used for leaching, which were 0.8, 1.5, 2, and 3 dS m^{-1}. The second factor consisted of different soil amendments: a control group with no amendments, gypsum applied at a rate of 2.8 tons per feddan, compost tea applied at a rate of 58 L per feddan, and a combination of gypsum and compost tea.The results of this study highlighted that the water required for leaching varied with different levels of irrigation water salinity: 121.48, 126.08, 129.58, and 137.21 L per lysimeter were applied for salinity levels of 0.8, 1.5, 2, and 3 dS m^{-1}, respectively. Irrigation with water at 3 dS m^{-1} resulted in a 35.11% reduction in the removal of salts and a 13.29% reduction in sodium removal compared to initial soil values. However, these percentages increased to 54.48% and 36.76%, respectively, when gypsum was combined with compost tea. These findings demonstrate that applying gypsum alone or in combination with compost tea significantly enhances the removal of salts and sodium from the soil, regardless of the salinity level of the irrigation water used.

Keywords: Compost tea, Gypsum, Leaching, Salt-affected soil, Salt and Sodium removable, Water salinity.

1. Introduction

Salt-affected soils are widespread in most parts of the world to a large extent. They pose a significant problem for food security, especially in developing countries (Negacz et al., 2022). The Nile Delta in Egypt is considered the most important land resource for the production of strategic crops (Fishar, 2018). According to the results presented by Negacz, (2021) and Aboelsoud et al., (2022), they showed that the percentage of salt-affected soils represents approximately 60%, 25% and 20% of the total farmed land in the Lower Delta, the Middle Delta, and the Upper Delta of Egypt. It is a result of climatic influences and suboptimal soil management practices. Principal contributors include irrigation water, waterlogging and intrusion of saline water from the Mediterranean Sea (Mohamed, 2016). Relying on non-traditional water sources for irrigation in the Northern Delta is essential due to the evident shortage of suitable water resources for irrigation throughout the year in these areas (El-Ghannam et al., 2019). Furthermore, the reuse of over 10 billion cubic meters of saline drainage water intensifies the accumulation of salinity and sodicity in these soils (Fleifle and Allam, 2016). The main characteristic of this type of soil is the high level of salinity and exchangeable sodium percentage. They affect soil permeability aeration and water infiltration due to soil structure deterioration, which hinders plant growth and reduces crop productivity (El-Ramady et al., 2022; Donald et al., 2024).

Salt leaching is a fundamental process for eliminating accumulated soil salts within the soil profile (Donald et al., 2024). Numerous studies highlight the importance of soil leaching to rid the soil of excessive salts from re-entering the root zone via capillary rise and reintroducing salts (Navarro-Torre et al., 2023; Yang et al., 2023). However,

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leaching carry adverse environmental effects. The water utilized in these processes can elevate salinity levels, thereby jeopardizing aquatic ecosystems and water quality (Leng et al., 2021). Moreover, essential plant nutrients such as potassium, calcium, and magnesium can also be leached from the soil (Stavi et al., 2021); leading to nutrient depletion and potentially impacting crop yields and ecosystem vitality.

Therefore, the addition of agricultural gypsum and organic matter is considered important to mitigate this degradation (dos Santos et al., 2019; Roy and Nasrin, 2020; Yahya et al., (2022). They found that adding gypsum combined with organic amendments during soil leaching enhances the efficiency of the leaching process by improving soil structure and consequently activating salt leaching. Additionally, the addition of organic matter plays a crucial role in improving the efficiency of soil leaching, as scientists clarified in their researches in Chaganti et al., (2015); Yue et al., (2016); Premanandarajah et al., (2017); Hoshan et al., (2023). They found that having a source of organic matter in the soil enhances soil structure and the efficiency of the leaching process.

Previous studies have demonstrated the role of gypsum in improving and restoring deteriorated lands affected by salinity and sodicity (Bayoumy et al. 2019; Mary et al., 2020; Gonçalo et al., 2020; Farid et al., 2020; Aiad et al., 2021; Abate et al., 2021; El-Sharkawy et al., 2022; Khalifa et al., 2022). They indicated that gypsum and organic source modified the chemical and physical properties of salt-affected soils. Carrascosa et al. (2023) stated that using compost increased organic matter in the soil and enhanced the activity of microorganisms, which helped improve soil structure and aggregates. This, in turn, enhances soil salt leaching processes.

So, this research aims to narrow the gap in the research process by highlighting the role of gypsum and compost tea in improving the efficiency of soil leaching, considering the salinity of irrigation water used in salt leaching

2. Materials and methods

2.1 Water and amendments sources

The different irrigation water salinity levels_used in the experiment were selected based on the salinity of irrigation water used in Kafr El-Sheikh Gov. The water salinity levels (0.83, 1.50 and 2.00 dS m^{-1}) were diluted from water with a salinity of 3 dS m^{-1} (pH 7.35 and SAR 5.48 from Shalama canal) according to following equation:

$$C1\,V1 = C2\,V2 \qquad (1)$$

Where C1 and C2 are the initial water salinity concentration and the desired water salinity concentration, and V1 and V2 are the initial water volume and the final water volume, respectively.

Gypsum was sourced from the Executive Authority for Land Improvement Projects at Kafr El-Sheikh Gov., Egypt

The gypsum requirement was determined according to **FAO and IIASA (2000)** guidelines to achieve a target reduction in the initial exchangeable sodium percentage (ESP) of the soil layer (0-60 cm) to 14% at each lysimeters.

$$GR = (ESP_i - ESP_f) \times CEC \times 1.72 \qquad (2)$$

Where GR: gypsum requirement (ton/fed), ESPi and ESPf is the initial soil ESP and the desired soil ESP, and CEC: Cation exchange capacity (cmolc /kg). The gypsum requirement for each lysimeter was calculated and it was applied in two doses namely (30%, before setting up the experiment was meticulously blended into the surface soil layer, and 70% after 3 month).

Compost tea was sourced from the Agricultural Microbiology Departments at SWERI, ARC, Egypt. It was administered at a rate of 58 liters per faddan and diluted at a 1:5 (v/v) ratio with water (**Omara et al., 2022**). This mixture was applied four times during the experimental period. The primary composition of the compost tea is outlined in Table1.

Table 1. Main composition of compost tea.

pH	EC dS m^{-1}	Total N (ppm)	Ava. P (ppm)	Ava. K (ppm)
6.8	2.88	110.77	44.5	129.11

TBC Log CFU ml^{-1}	TFC Log CFU ml^{-1}
7.88	4.55

2.2 Experiment location and description

The experiment was conducted in lysimeters within the greenhouse of the Soil Improvement and Conservation Research Department at the Agricultural Research Station in Sakha, Kafr El-Sheikh, Egypt. It spanned nine consecutive months, from October 15, 2022, to July 15, 2023. The aim was to assess the efficacy of the leaching method, water quality, and the incorporation of soil amendments in removing salts and sodium from a saline-sodic soil system. The soil properties were determined using the methods described **Carter and Gregorich (2006)** and it’s outlined in Table 2. These lysimeters were irrigated by water mixed with seawater for 3 seasons, and 64 lysimeters with similar soil salinity were selected, with salinity ranging from 9.41 to 10.16 dS m^{-1}, SAR ranging from 15.80 to 18.70 and ESP ranging from 19.12 to 22.81 (Table 3).

Table 2. Physical and chemical properties of studied soil.

Property	Value	Property	Value
pH (1:2.5)	8.34	Sand (g kg^{-1})	183.1
EC (dS m^{-1})	9.83	Silt (g kg^{-1})	286.2
SAR	16.87	Clay (g kg^{-1})	530.7
ESP (%)	19.10	Texture	Clayey
Na (meq l^{-1})	77.10	Bulk density (g cm^{-3})	1.38
K (meq l^{-1})	3.50	Porosity (%)	47.92
Ca (meq l^{-1})	28.21	CEC ($Cmol_c$ kg^{-1})	38.24
Mg (meq l^{-1})	23.58	Organic matter (g kg^{-1})	2.86
HCO_3 (meq l^{-1})	4.75	Saturation percentage (%)	72.90
Cl meq l^{-1})	87.46	Field Capacity (%)	36.68
SO_4 (meq l^{-1})	40.17	Wilting point (%)	20.04

EC, cation and anion in soil paste extract

Table 3. The main initial values of soil salinity, sodicity and gypsum requirements in soil with treatments

Irrigation water salinity levels	Amendments	EC(dS m^{-1})	SAR	ESP (%)	GR (ton fed^{-1})
0.83 dS m^{-1}	Control	9.79	16.88	19.12	3.37
	Gypsum	9.71	17.12	19.35	3.52
	Compost tea	9.91	17.02	19.25	3.45
	Gypsum + Compost tea.	9.57	17.56	19.77	3.79
1.50 dS m^{-1}	Control	9.73	15.90	18.16	2.74
	Gypsum	9.90	17.10	19.33	3.51
	Compost tea	9.82	16.66	18.91	3.23
	Gypsum + Compost tea.	9.75	17.30	19.52	3.63
2.00 dS m^{-1}	Control	9.77	15.98	18.24	2.79
	Gypsum	9.71	16.69	18.93	3.25
	Compost tea	10.04	17.03	19.26	3.46
	Gypsum + Compost tea.	9.90	17.01	19.25	3.45
3.00 dS m^{-1}	Control	9.80	16.21	18.47	2.94
	Gypsum	9.81	17.60	19.81	3.82
	Compost tea	10.16	17.27	19.49	3.61
	Gypsum + Compost tea.	9.98	16.54	18.78	3.14

2.3 Experimental design

The lysimeter units were divided into 4 groups for the salinity of irrigation water used in salt leaching, 16 units for each (0.64 m² for each unit), and meticulously prepared following a factorial design with four replicates (Diagram 1). The design factors are outlined as follows:

Factor A: Water salinity

- Water salinity = 0.83 dS m^{-1}
- Water salinity =1.5 dS m^{-1}
- Water salinity =2.0 dS m^{-1}
- Water salinity =3.0 dS m^{-1}

Factor B: Soil Amendments

- Control (untreated soil).
- Gypsum
- Compost tea.
- Gypsum + Compost tea.

2.4 Leaching experiment

The leaching requirement (LR) proposed the following equation for **Rhoades (1996):**

$$\text{LR (\%)} = \frac{\text{EC}_\text{w}}{5\ \text{EC}_\text{e} - \text{EC}_\text{w}} \times 100 \qquad (3)$$

Where EC_w: the water salinity and EC_e: as measured by saturated paste extract, that a crop can tolerate (4.0 dS m^{-1}, as a better salinity for the most crop).

The amount of water (IW) was determined based on soil moisture contents before each leaching and according to the following equation **(Kovda et al., 1973):**

$$IW = (FC_i - SM_f) \times BD \times D \times A \qquad (4)$$

Which: FC_i is the of moisture content at field capacity (%), SM_f is the moisture content before the next leaching (%), BD is the bulk density of soil (g cm^{-3}), D is the soil depth (cm) and A is the plot area (m^2). After obtaining the result of equation (3), it is further modified by multiplying it with the leaching percentage and subsequently added to the total amount of water.

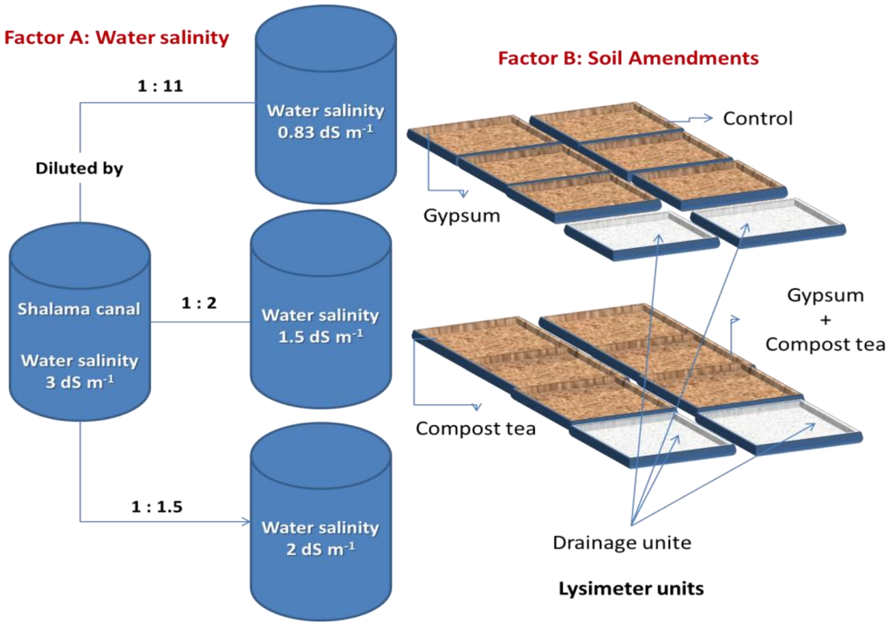

Diagram 1. Illustrated the experimental design.

2.5 Prepare and analyze soil samples

Soil samples were systematically collected from each lysimeter using a soil auger, ensuring five replicates, for monthly analysis of EC, SAR, and ESP at depths ranging from 0-30 cm and 30-60 cm. Perform chemical analyses to determine Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), and Exchangeable Sodium Percentage (ESP) using the methodologies outlined in **Richards, (1985).** The **Kerr and Hanan (1985)** equations were used to compute removable of salts (RS) and sodium (RNa) %:

$$RS = \frac{(EC_i - EC_f)}{(EC_i - LR)} \times 100 \qquad (5)$$

$$RNa = \frac{(ESP_i - ESP_f)}{(ESP_i - LR)} \times 100 \qquad (6)$$

Where: ECi and ECf are the concentration of salt in soil before and after experimental (meq/l = 10 × EC dS m-1), and LR is the leaching requirement.

2.6 Statistical analyses

Utilize the analysis tools in R v.4.4.0 to conduct the required statistical analysis, such as Analysis of Variance (ANOVA) for comparing the effects of treatments and interactions **(Larson–Hall 2015).** After the analysis, the bar plot graphs are used for the data description **(Grömping 2017**).

3. Results

3.1 Irrigation water applied with different water salinity levels and leaching requirements

The results presented in Table 3 display the quantities of water required to be added (12 times), along with the leaching needs, for each type of water used in the current study. Generally, we find that LR increases with higher irrigation water salinity levels. For instance, leaching requirements (LR) ranges from 4.17% at 0.83 dS m^{-1} to 17.65% at 3.00 dS m^{-1}. Furthermore, the total water requirement (AW+LR) shows a substantial increase as salinity levels rise. Specifically, at 3.00 dS m^{-1}, AW+LR increases by 660.30 m^3 fed^{-1} compared to 0.83 dS m^{-1} (Table 3).

Table 3. The water applied and leaching requirements

Water salinity:	LR (%)	IW+LR (m^3 lysimeters $^{-1}$)	IW+LR (m^3 fed^{-1})
0.83 dS m^{-1}	4.17	121.48	5102.34
1.50 dS m^{-1}	8.11	126.08	5295.40
2.00 dS m^{-1}	11.11	129.58	5442.49
3.00 dS m^{-1}	17.65	137.21	5762.64

* The water applied per lysimeter was 9.72 for each irrigation.

3.2 Analysis of variance

Table 4 summarizes the results of an analysis of variance (ANOVA) conducted to assess the significance of the irrigation water salinity used in salt leaching, soil amendments, and their interactions in relation to soil salinity, exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), removable of salt (RS), and sodium (RNa) levels. The ANOVA results indicate that the irrigation water salinity used in salt leaching and soil amendments, as well as their interactions, have a significant effect on these variables.

Table 4. Main and interaction effects of the irrigation water salinity used in salt leaching and soil amendments on various soil parameters, including EC, ESP, SAR, removable of salt (RS), and sodium (RNa).

Variables	EC		SAR		ESP		RS		RNa	
Treatments	F-Value	*P*	F-Value	*P*	F-Value	*P*	F-Value	*P*	F-Value	*P*
Water Salinity (A)	91.35	**	63.55	**	62.87	**	13.39	**	39.71	**
Amendments (b)	42.85	**	262.94	**	258.88	**	39.81	**	184.59	**
A×B	26.99	**	3.07	**	03.10	**	10.97	**	32.99	**

3.2.1 Effect of the irrigation water salinity used in salt leaching on soil properties

The findings presented in Table 5 illustrate a significant impact of irrigation water salinity on studied soil properties during leaching processes. Lower salinity levels of irrigation water (0.8 dS m^{-1}) resulted in notably reduced electrical conductivity (EC) values and exchangeable sodium percentage (ESP) compared to higher salinity levels (3 dS m^{-1}). Specifically, as the salinity of the irrigation water increased: EC values were increased from 4.83 at 0.8 dS m^{-1} to 6.79 at 3 dS m^{-1}. SAR was increased from 13.39 to 14.71. ESP was increased from 15.59% to 16.95%. Moreover, the results also highlight a significant increase in the percentage of salt and sodium removal as salinity levels decrease.

Table 5. Main effect of the irrigation water salinity used in salt leaching and soil amendments on various soil parameters, including EC, ESP, SAR, % removable salt (RS), and sodium (RNa).

Variables	EC	SAR	ESP	RS	RNa
Treatments	(dS m^{-1})		(%)	(%)	(%)
Water salinity					
0.83 dS m^{-1}	4.83c	13.39d	15.59d	54.98a	32.96a
1.50 dS m^{-1}	5.71b	13.86c	16.08c	49.23b	25.76b
2.00 dS m^{-1}	6.04b	14.35b	16.59b	48.57b	20.99c
3.00 dS m^{-1}	6.79a	14.71a	16.95a	45.32b	19.20c
Amendments					
Control	6.45a	15.26a	17.53a	41.35c	09.03d
Gypsum	5.53b	13.31c	15.52c	53.07a	33.76b
Compost tea	6.15a	14.87b	17.13b	46.65b	18.67c
Gypsum + Compost tea	5.24b	12.87c	15.06c	57.03a	37.46a

* In statistical analysis, the means that do not share a common letter are considered significantly different from each other.

3.2.2. Effect of soil amendments

The results presented in Table (5) comparing different soil amendments offer valuable insights into their effects on essential soil properties, particularly in managing soil salinity and sodicity. Among the treatments, the combination of gypsum with compost tea demonstrated notable efficacy in improving soil conditions. Specifically, this combination reduced the soil EC to 5.24 dS m^{-1}, sodium adsorption ratio (SAR) to 12.87, and exchangeable sodium percentage (ESP) to 15.06% compared to the control treatment.

3.2.3 Interaction effect:

The interaction between the irrigation water salinity used in salt leaching and soil amendments shows soil amendments shows different effects different effects on the studied properties, as illustrated in Figures 1 to 3.

Figure (1) showed that the lowest soil EC value (4.22 dS m^{-1}) was obtained with the use of gypsum + compost tea at irrigation water salinity levels of 0.8 dS m^{-1}. Additionally, there were no significant differences in soil EC values with the use of gypsum alone or in combination with compost tea at irrigation water salinity levels of 0.8 or 1.5 dS m^{-1}. Also, the same treatments had a similar effect on SAR, and ESP values. The highest values of SAR and ESP (15.68 and 17.94%, respectively) were recorded with irrigation water salinity of 3 dS m^{-1} (Figs 2 and 3). The highest removal rates of salts and sodium (60.91% and 46.25%, respectively) were observed with the combination of gypsum with compost tea at irrigation water salinity levels of 0.8 dS m^{-1} (Figs 1 and 3). However, it was noted that there were no significant differences in salts removal rates with the use of gypsum alone or in combination with compost tea at different irrigation water salinity of 0.8, 1.5, 2 and 3 dS m^{-1} or in sodium removal rates with gypsum + compost tea at an irrigation water salinity levels of 0.8 and 1.5 dS m^{-1}. The combination of gypsum with compost tea decreased the removal salts and sodium by an average of 57.03% and 37.46%, respectively at different irrigation water salinity levels (Figs 1 and 3).

So, the obtained results indicated that water with different salinity level had significant effects of salts and sodium from soil, but adding gypsum with compost tea increased the efficiency of these leaching. For example, the irrigation with 3 ds m^{-1} caused a reduction in removal of salts and sodium by 35.11% and 4.95% compared to the initial values and these removal rates were increased to 54.48 and 30.02%, respectively with the combination of gypsum with compost tea (Figs 1 and 3).

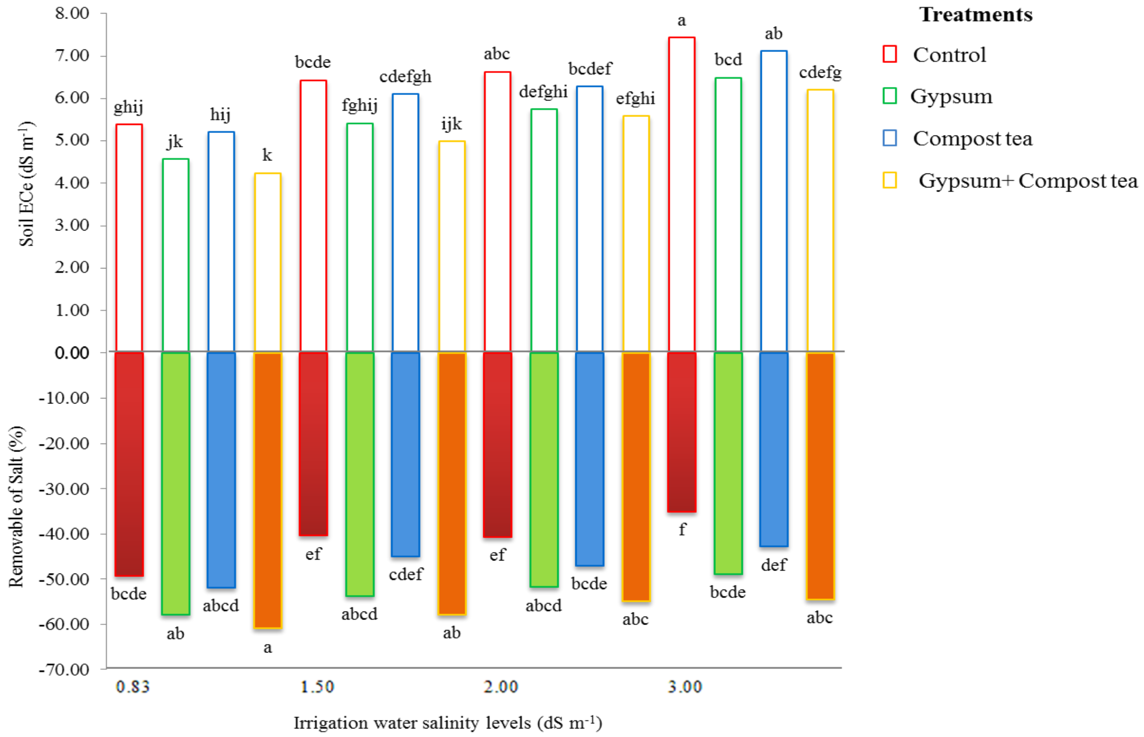

Fig. 1. The interaction effect of irrigation water salinity and soil amendments on the soil electrical conductivity and the removable of salts (%).

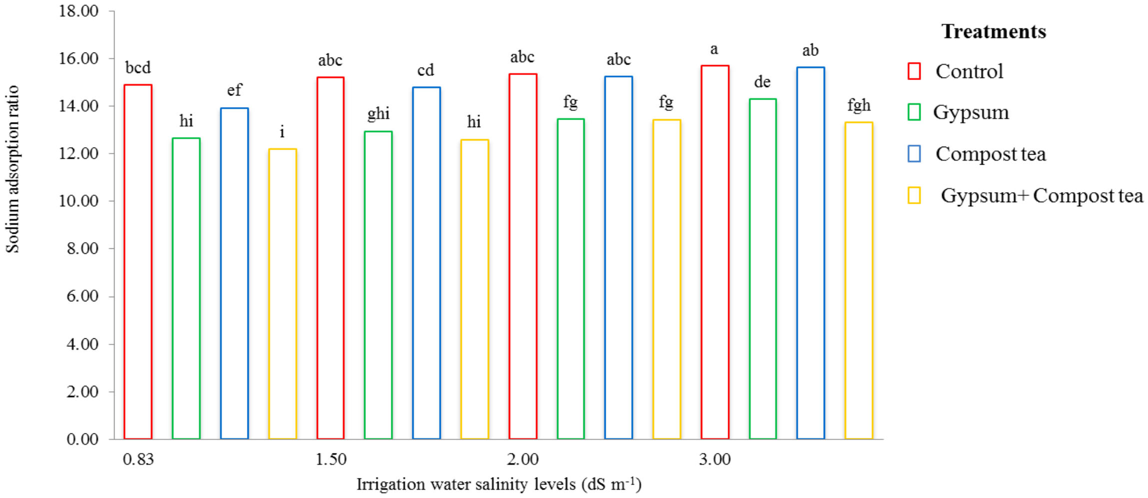

Fig. 2. The interaction effect of irrigation water salinity and soil amendments on the sodium adsorption ratio.

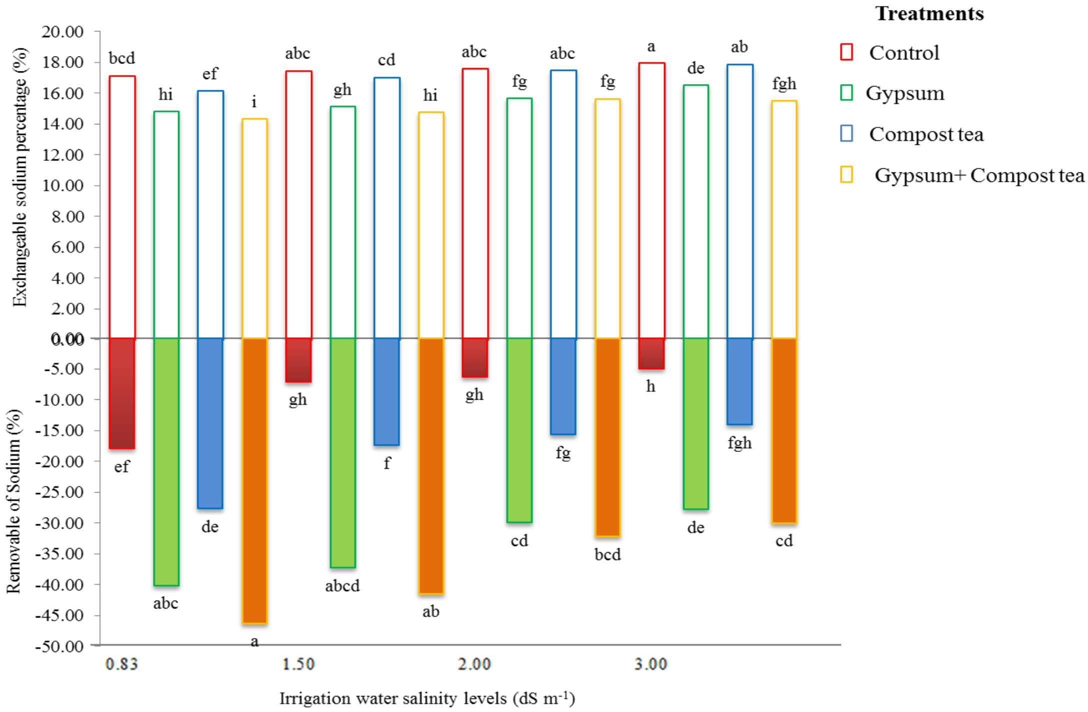

Fig. 3. The interaction effect of irrigation water salinity and soil amendments on the exchangeable sodium percentage and the removable of sodium (%).

4. Discussion

As shown in the Table 3, an increase in irrigation water salinity (from 0.83 dS m^{-1} to 3.00 dS m^{-1}) correlates with a significant rise in the leaching requirement, escalating from 4.17% to 17.65%. This underscores the considerable challenge in managing saline water for agriculture, as higher leaching percentages necessitate greater overall water use. These results are consistent with Chu et al. (2016); Corwin and Grattan (2018); Manzoor et al. (2019);Silva et al. (2019); Ndiaye et al. (2022).

Table 5 reveals a clear trend where higher leaching water salinity corresponds with elevated soil electrical conductivity (EC), sodium absorption ratio (SAR), and exchangeable sodium percentage (ESP) compared to lower salinity levels (0.80 and 1.00 dS m^{-1}). This indicates that the efficacy of salts and sodium removal is influenced by improved leaching processes, likely facilitated by the movement of salts and sodium with the irrigation water. Conversely, the percentage of removable salts (RS) and sodium (RNa) were decreases as irrigation water salinity increased, indicating reduced efficiency in removing salts and sodium from the soil. Lower irrigation water salinity enhances leaching efficiency, thereby reducing the accumulation of salts and exchangeable sodium in the soil. These findings highlight the critical role of managing irrigation water quality to mitigate soil degradation, consistent with studies by Fard et al. (2007), Manzoor et al. (2019), and Yang et al. (2023), which also demonstrate the diminishing efficiency of soil leaching with increased irrigation water salinity.

Using gypsum alone or combined with compost tea consistently resulted in lower EC, SAR, and ESP values compared to other treatments, indicating improved soil quality and reduced sodicity. For instance, irrigation with 3.00 dS m^{-1} resulted in a reduction in salt and sodium removal values by 35.11% and 13.29%, respectively, compared to initial soil values. However, when gypsum was combined with compost tea, these removal percentages increased to 54.48% and 36.76%, highlighting a synergistic effect in managing soil salinity, these suggesting enhanced leaching efficiency and soil remediation capabilities. Also, increasing the efficiency of salts and sodium leaching may be interpreted by that the application of gypsum with compost tea provides calcium, sulfur and organic carbon that, enhances soil aggregation, leading to increased salts and sodium leaching. These improvements have been reported by Rantamo et al. (2022) who demonstrated that applying gypsum in saline soils leads to increased sulfate concentration, which can facilitate the leaching of sodium sulfate. Gypsum also contributes calcium, which helps mitigate sodicity in saline soils. Moreover, combining gypsum application with compost tea has been demonstrated to reduce the soil EC and ESP (Bayoumy et al. 2019). Additionally, studies such as dos Santos et al., 2019; Roy and Nasrin, 2020; Yahya et al., 2022 found that adding gypsum combined with organic amendments during soil leaching enhances the efficiency of the leaching process by improving soil structure and consequently activating salt leaching.

Although compost tea alone did not significantly reduce soil salinity levels, it effectively reduced sodium percentage compared to the control treatment. This indicates that while compost tea may not directly mitigate salinity, it plays a crucial role in managing sodium accumulation in soils, thereby maintaining soil structure. (Cuevas et al., 2019; Khatun et al., 2019).

5. Conclusions

Our research underscores the critical role of soil leaching in reclaiming salt-affected soil, despite challenges posed by saline irrigation water. Through a nine-month lysimeter study employing a factorial design, we evaluated the effectiveness of different amendments. The irrigation water salinity levels ranged from 0.8 to 3 dS m^{-1}, and treatments included gypsum alone, compost tea, and their combination.

Higher salinity levels (3 dS m^{-1}) initially reduced salt and sodium removal efficiencies by 35.11% and 13.29%, respectively, compared to initial soil values. However, the combined application of 100% gypsum requirements and 58 liter of compost tea per Fadden significantly increased removal efficiencies to 54.48% and 36.76%, respectively, highlighting their synergistic effect in mitigating soil salinity.

These results underscore the effectiveness of gypsum and compost tea amendments in improving soil leaching processes and enhancing salt and sodium removal under varying irrigation water salinities. This study provides valuable insights into sustainable soil management practices in saline environments.

While the current study provides valuable insights, it is essential to acknowledge its limitations. The experiment was conducted in controlled lysimeter conditions, which may not fully replicate field conditions. Future research should focus on field-scale trials over multiple growing seasons to assess the long-term effects of gypsum and compost tea amendments on soil health, crop productivity, and microbial communities to further optimize soil remediation strategies.

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