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BIOREMEDIATION OF SALINE SANDY LOAM SOILS USING HALOPHYTIC FLORA IN ARID ENVIRONMENT OF WADI AL-SHATTI, LIBYA

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Abstract: Two halophytic plant species, *Ziziphus spina* and *Sesbania sesban*, were studied for physico-chemical properties of soil through bio-reclamation. Prior to cultivation, the soil was characterized as sandy loam, highly alkaline (pH 8.89 at 0 - 30 cm), and highly saline (EC 13.15 dS/m). Both plant species demonstrated a positive impact on soil properties; however, *Sesbania sesban* showed superior performance. Soil porosity in the *Sesbania*-planted plots increased to 49.8%, while electrical conductivity (EC) was significantly reduced (7.60 dS/m). Sodium (Na^+) concentrations in plant tissues increased markedly in both species. *Sesbania sesban* accumulated higher amounts of Na^+ in shoots (958.8 mg/kg) and roots (975.5 mg/kg) compared to *Ziziphus spina* (858.8 mg/kg in shoots and 626.7 mg/kg in roots). Bio-reclamation indicators confirmed the superior efficiency of *Sesbania sesban*, which exhibited a higher Na^+ uptake of 6 mg/g, a transfer factor of 1.37, and a bioaccumulation factor of 23.22. These values indicate strong salt absorption and translocation capabilities. Furthermore, the growth of *Sesbania sesban* improved in cultivated plots and demonstrated greater potential for reclaiming saline-affected soils due to its higher salt uptake efficiency and its positive impact on soil. Hence, the successive planting of halophytes be implemented for soil reclamation and restoration of saline soils.

Keywords: soil, halophytic plants, sesbania, reclamation, salinity, transfer factor, bioaccumulation factor

1. INTRODUCTION

Soil serves as a crucial foundation for life, and its physical and chemical properties are fundamental to the establishment of vegetation (Aishah & Elssaidi, 2019). However, soil salinization represents a significant and growing threat to global agriculture, particularly in arid and semi-arid regions. This phenomenon directly jeopardizes agricultural productivity and sustainability. Salt-affected soils are present in over 70 countries, covering an estimated 831 million hectares globally, which includes 397 million hectares of saline soils and 434 million hectares of sodic soils (Nainwal et al., 2024). The increasing prevalence of soil degradation has strained the balance between societal needs and the essential ecosystem services provided by land and water resources, thereby impacting the livelihoods of local populations. Saline soils exhibit degraded physical properties and are often characterized by low biodiversity, poor organic matter content, and limited biological activity (Rengasamy et al., 2022).

Furthermore, these soils are prone to nutrient deficiencies and toxicities from elements such as boron, carbonate, and aluminate ions. While some soluble salts in these soils can act as a source of essential nutrients, concentrations that exceed a certain threshold can be detrimental to most crop species. Salinization is the process of excessive accumulation of soluble salts, including compounds of sodium (Na^+), magnesium

(Mg^{++}), calcium (Ca^{++}), potassium (K^+), sulfates (SO^{--}), chlorides (Cl^-), carbonates (CO_3^{--}), and bicarbonates (HCO_3^-). This process can occur naturally or be exacerbated by human activities. The accumulation of salts directly impacts soil structure and properties, which in turn leads to problems with plant growth. Specifically, high salt concentrations in the root zone can hinder water uptake by plants and cause the enrichment of Na^+ and Cl^- in plant tissues. Managing these soils poses a significant challenge, requiring various techniques to reduce salt content and improve soil fertility (Qadir et al., 2007). Historically, chemical amendments like gypsum or sulfuric acid have been used for soil amelioration. However, the rising costs of these chemicals have made such approaches economically unsustainable (Rabhi et al., 2008).

In response to these challenges, phytoremediation, an environmentally friendly and cost-effective biological approach, has emerged as a promising alternative for reclaiming salt-affected lands (Akhter et al., 2003). This technique involves the cultivation of salt-tolerant plant species, known as "halophytes", which are capable of completing their life cycle in environments with high salt concentrations, often exceeding 200 mM of NaCl (∼20 dS m^{-1}). Halophytes represent approximately 1% of the world's flora and are uniquely adapted to withstand abiotic stresses like salinity and drought (Saniga et al., 2023). They remediate contaminated soils by removing and leaching excess salts, such as sodium (Na^+), from the root zone and can enhance the concentration of essential cations like calcium (Ca^{++}) through cation exchange processes. Beyond salt removal, phytoremediation with halophytes can add organic matter and essential ions (e.g., Ca^{++}, K^+, N & P) to the soil, improving overall productivity. These plants also positively influence key soil chemical properties, including organic carbon content, pH, and electrical conductivity (Behera et al., 2020). In addition to their role in soil reclamation, halophytes can provide food, fodder, and fuel wood, thereby increasing the income of farmers managing salt-affected lands (Singh et al., 2023). Some species are also capable of remediating toxic metals, making them a sustainable and eco-friendly solution for contaminated coastal environments (Akhter et al., 2003). This study aims to evaluate the changes in the chemical properties of a saline-affected soil at different depths following phytoremediation using the salt-tolerant plants *Ziziphus spina* and *Sesbania sesban*.

2. MATERIAL AND METHODS

2.1. Experimental details

A field experiment was carried out at the saline effected soil in W*adi* Al-Shatii, Libya. The experiment was conducted over a 90-day period from March 15 to June 14, 2025. The two halophytes plants (*Ziziphus spina christi & Sesbania Sesban)* were selected for cultivation to phytoremediation of the studied soil and reduction of its salinity (Figure 1).

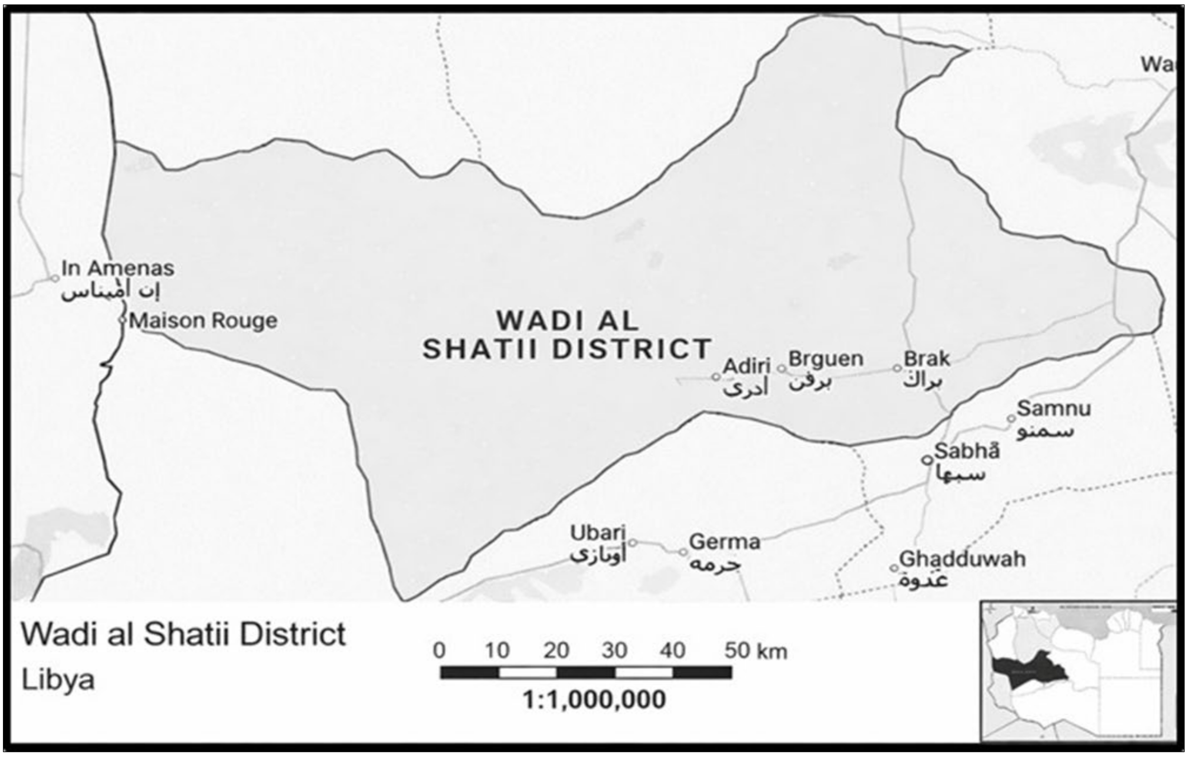

Figure 1. Map of District Wadi Al-Shatti, Libya, showing location.

2.2. Planting

Prior to planting, the soil was plowed and leveled, and organic fertilizer was applied at a rate of 50 kg/ha. Irrigation was performed twice weekly using surface flooding. Planting density was maintained at 20 plants/m² for both species. The selected plants were classified as salt-tolerant rather than true halophytes: *Sesbania sesban*, a leguminous species with high salt uptake capacity and soil amelioration potential, and *Ziziphus spina christi* (L.) Desf., an evergreen tree adapted to drought and moderate salinity. These species were chosen for their potential role in phytoremediation and soil reclamation under arid and semi-arid conditions.
Ziziphus spina christi is a drought- and salt-tolerant evergreen tree. The plants were then cultivated, while plots were left for comparison (control). At the end of the experiment, the plants were harvested.

2.3. Soil sampling and analysis

The soil used in the experiment was from the saline effected soil Al-Shati area. Soil samples were collected using an Auger. The depth intervals sampled were 0 - 30, 30 - 60 cm. The soil was then dried in the laboratory, sieved through a 2 mm sieve, and stored in plastic bags until analysis. The water samples used in the field experiment were recorded for their characteristics (Table 1), specifically their electrical conductivity and pH. The positive and negative ions in the water were also measured, represented by negative anions, which were chloride, sulphate, carbonate, and bicarbonate. However, the positive cations were sodium, potassium, calcium, and magnesium.

Table 1. Characteristics of irrigation water used.

Parameters	Properties	Values
pH	-	7.13
EC	dS/m^{-1}	1.07
Na^+	mg/l	12.5
K^+	" "	19.5
Mg^{++}	" "	20
Ca^{++}	" "	10
Cl^-	" "	19
SO_4^{--}	" "	16
CO_3^-	" "	90
HCO_3^-	" "	180

Both halophytic plant species were selected to treat soil affected by salinity through phytoremediation treatment using *Ziziphus spina* and *Sesbania sesban*. For each depth interval, the analyses were conducted before and after planting on aerated dry soil and sieved with a 2 mm diameter sieve and on saturated soil paste extract, according to Baruah & Barthakur (1997), soil color was measured using the Munsell Colour Guide, as described by Baruah & Barthakur (1997), by comparing soil samples with colour strips in the Munsell Colour Guide's soil colour charts. Soil texture was determined using the method described by Baruah & Barthakur (1997). Soil field capacity (FC), soil pH measured and electrical conductivity (dS/m) were measured according to Baruah & Barthakur (1997). Organic matter (OM) was determined by loss on ignition method (Heiri et al., 2001), Cation Exchange Capacity (CEC) was measured as described by Chapman (1965), Bulk density and particle density of soil were determined by (Blake & Hartge, 1986). Estimation of cations (Na, Ca, Mg & K) was conducted according to Yang et al. (2024), whereas, sulfates and chlorine were determined by (Richards, 1954). Carbon and bicarbonate compounds were calculated as mentioned by Baruah & Barthakur (1997).

Plant height was measured using a ruler marked in centimeters every week till the end of the experiment. Measurement of plant vital indicators at the beginning and end of the experiment (plant height and weight). While measurement of plant biomass was performed at the beginning and end of the experiment. Sodium was measured using the digestion method for plant parts (shoots & roots) of both plants after drying and grinding using atomic absorption spectroscopy (Baruah & Barthakur, 1997). Calculation of the bioaccumulation factor in plants (BAF) was calculated according to Yadav et al. (2009), and salt transfer factor (TF) for ions from soil to plants was estimated as reported by Kafle et al. (2022).

$$BAF = \frac{\text{Metal in plant tissue}}{\text{Metal in soils}} \quad (1) \text{ (Petelka et al., 2019)}$$

$$TF= \frac{\text{Metal in Shoot plant tissue}}{\text{Metal Roots}} \quad (2) \text{ (Kafle et al., 2022)}$$

After preparing the soil, two salt-tolerant plant '*Ziziphus spina & Sesbani sesban*' were selected for cultivation and phytoremediation treatment of the studied soil. For the reduction of its salinity, the physical and chemical of soil properties were studied before the start of the experiment at (0 - 30 cm and 30 - 60 cm). The selected target plants were then cultivated, while plots were left for comparison (*Control*). At the end of the experiment, the plants were harvested, soil samples (0 - 30 and 30 - 60 cm) were collected, and measurements and laboratory analyses were performed.

2.4. Statistical analysis

All the data were subjected to statistical analysis using Statgraphics Plus 5.1. Two sample Student's t-tests (α = 0.05) confirmed significant differences between treatments. *Sesbania sesban* consistently outperformed *Ziziphus spina christi.* The experiment was conducted with three replications per treatment. The Least Significant Difference (LSD) test was applied for multiple comparisons. Statistical analyses were conducted using replicated values from both soil depths as independent samples. Results were reported as t-values and p-values, with differences considered significant when $p < 0.05$. To evaluate treatment effects, two-sample Student's t-tests were performed at a significance level of $\alpha = 0.05$, comparing (i) Blank vs. *Sesbania sesban*, (ii) Blank vs. *Ziziphus spina christi*, and (iii) *Sesbania* vs. *Ziziphus*.

3. RESULTS AND DISCUSSION

3.1. Properties of the soil used in the field experiment prior to cultivation

The field experiment was conducted from March 15 to June 15, 2025, spanning 90 days. Pre-cultivation soil analysis revealed a sandy loam texture, composed of 15.31% clay, 49.18% silt, and 35.51% sand. Soil color ranged from brownish-yellow when dry to strong brown when wet, indicating the presence of salts and oxide deposition.

A comparison of pre- and post-cultivated soil parameters reveals substantial changes over time, indicating that temporal and environmental factors, rather than the applied treatments alone, played a significant role in influencing soil properties.

However, the wet soil colour strong brown and brownish yellow. The absence of a discernible pattern in soil fraction distribution with depth is consistent with the findings of Carvalhais et al. (2011), who attributed this phenomenon to continuous sedimentation processes characteristic of the study area's environmental conditions.

Soil color varied from brownish-yellow in dry conditions to strong brown when wet (Table 2). The minimal change in color between wet and dry states suggests the presence of salts and the deposition of oxides with soil particles (Gebrekidan, 2025). The porosity was measured at 37% in the upper 30 cm layer and increased to 41% at a depth of 60 cm. This observed increase in porosity with depth, contrary to typical compaction trends, may be attributed to surface-level factors such as rainfall, tillage, and human activities, which can cause compaction. Alternatively, it may reflect the influence of organic matter accumulation in the upper layers (Hailie et al., 2017). The field capacity of the soil was 27.86% at both the 30-cm and 60-cm depths (Table 2). This low water-retention capacity is consistent with Machado & Serralheiro (2017) and is likely exacerbated by the accumulation of salts, which negatively impacts the soil's ability to retain water. Soil pH was found to be slightly alkaline at both depths, with a value of 8.89 at 30 cm and 7.87 at 60 cm (Table 2). The higher alkalinity in the surface layer is likely due to the presence of exchangeable sodium, which can reduce soil permeability, weaken soil structure, and inhibit water movement (Hartemink & Barrow, 2023). Electrical conductivity (EC) was high, measuring 13.15 dS m^{-1} in the 0–30 cm layer and 12.99 d/S m^{-1} in the 30–60 cm layer (Table 2). These high values are indicative of a significant concentration of sodium chloride, confirming the saline nature of the soil. The cation exchange capacity (CEC) was low, with values of 5 meq/100 g in the surface layer and 3 meq/100 g at depth (Table 2). This decrease with depth aligns with findings by Horneck et al. (2011), who noted that CEC generally decreases as a function of depth. Analysis of exchangeable cations showed high concentrations of sodium (Na^+), with 198 mg/kg in the surface layer and 102 mg/kg at depth (Table 2).

Table 2. Physico-chemical properties of the field experiment soil before cultivation.

Depth		0-30 cm	30-60 cm
Moisture	%	21	14
Porosity	" "	37	41
OM	" "	1.9	0.9
Field capacity	" "	27.86	27.86
pH	-	8.89	7.87
EC	dS/m^{-1}	13.15	12.99
CEC	meq/100 g soil	5	3
Na^+	mg/kg	198	102
K^+	" "	87	62
Mg^{++}	" "	107	72
Ca^{++}	" "	123	89
Cl^-	" "	298	226
SO_4^{--}	" "	23	19
CO_3^-	" "	19	13
HCO_3^-	" "	18	12

This finding supports the observation by Ismayilov et al. (2021) that Na^+ is the dominant ion in saline soils. Potassium (K^+) concentrations were notably lower, at 87 mg/kg in the surface layer and 62 mg/kg at depth. The high Na^+ content contributes to the reduced K^+ availability, a common nutritional imbalance in saline soils (Chhabra, 2022). Magnesium (Mg^{2+}) was also present in high concentrations (107 mg/kg at the surface and 72 mg/kg at depth), which, in high amounts, can precipitate as carbonates and bicarbonates, leading to detrimental effects on soil and plants (Prasanna et al., 2023). Calcium (Ca^{2+}) concentration decreased with depth, from 123 mg/kg at the surface to 89 mg/kg at 60 cm. This inverse relationship between salinity and Ca^{2+} availability is well-documented (Yeaser, 2020).

Among the anions, chloride (Cl^-) was the most prevalent, with concentrations ranging from 298 mg/kg at the surface to 226 mg/kg at 60 cm (Table 2). Its high solubility and toxicity contribute significantly to soil salinity (Hualpa-Ramirez et al., 2024). High concentrations of cations, particularly Na^+, Ca^{2+}, and Mg^{2+}, indicated their precipitation as chlorides, which are a major component of the soil's salinity. Sulfate (SO_4^{2-}) concentrations were low (23 mg/kg at the surface and 19 mg/kg at depth). This is characteristic of arid regions, where SO_4^{2-} precipitates as low-solubility calcium sulfate compounds (Azimi et al., 2007). Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) concentrations were also measured, with CO_3^{2-} reaching 19 mg/kg at the surface and HCO_3^- 18 mg/kg (Table 2). These concentrations are consistent with Peng et al. (2024), who noted that calcium precipitates as calcite in arid and semi-arid regions. The presence of bicarbonate (20 mg/kg at the surface and 18 mg/kg at depth) is a result of the conversion of carbonate by carbonic acid, which is influenced by soil organic matter (Vanchikova et al., 2024).

3.2. Efficacy of halophytes on physico-chemical properties of saline soil after planting

Post-cultivation soil analysis (Table 3) showed a general improvement in physico-chemical properties. The soil porosity increased from 37% to 40% in cultivated in control plots. While *Ziziphus spina* and *Sesbania sesban* plots exhibited an increase in in porosity, the overall trend supports the findings of Semahegn (2025) that plant cultivation enhances soil aeration. The efficacy of phytoremediation is attributed to the deep root systems of halophytes like *Ziziphus spina* and *Sesbania sesban*, which penetrated the soil and improved its structure (Flowers et al., 2015).

Organic matter (OM) content also increased significantly in the treated soils (Table 3), rising to 1.7% in *Sesbania*-planted plots and 1.8% in *Ziziphus spina*-planted plots, compared to 1.5% in the unplanted control. This increase is more pronounced in the surface layer due to leaf litter and increased microbial activity. This is consistent with Olicón-Hernández et al. (2022), who highlighted the role of plant-microbe interactions in phytoremediation.

The soil field capacity increased in the plots planted with *Sesbania* (36.5%) and *Ziziphus spina* (33.5%), whereas the control plot showed little change (28.5%). This confirms the ability of halophytes to improve soil water retention, a process facilitated by root penetration and improved soil structure (Jiménez-Nava et al., 2024). The soil pH was effectively reduced from an initial value of 8.89 to below 8.0 pH in the treated plots, while the control pH remained high (9.0 at the surface). This demonstrates the efficacy of halophytes in mitigating soil alkalinity (Wang et al., 2023). The electrical conductivity (EC) decreased significantly in the cultivated plots (Table 3). The EC dropped to 8 dS m^{-1} at the surface and 7 dS m^{-1} at depth in both *Sesbania sesban* and *Ziziphus spina* plots, compared to 12.99 dS m^{-1} in the control. This reduction in salinity is more effective than traditional methods like gypsum or filtration (Yang et al., 2014). (Table 3), reaching 18.15 meq/100 g in *Sesbania*-planted soil and 14 meq/100 g in *Ziziphus spina*-planted soil at the surface, which is a significant improvement over the control (8.82 meq/100 g). These findings align with Yang et al. (2024), who reported that halophytes enhance soil CEC.

The concentrations of exchangeable cations showed a marked decrease in the treated soils. Surface Na^+ concentration decreased from 118.1 mg/kg in the control to 103.5 mg/kg in *Ziziphus spina* plots and 83.3 mg/kg in *Sesbania* plots. This confirms that the efficacy of these plants in reducing soil salinity, with *Sesbania* showed superior performance. The ability of halophytes to thrive in saline environments and reduce salt concentrations

Table 3. Physico-chemical properties of field soil after cultivation with selected halophytic plants.

Plants	Depth (cm)	Physico-chemical properties						Cations (mg)				Anions (mg)			
		Porosity (%)	*OM (%)*	*FC (%)*	*pH*	*EC dS/m^{-1}*	*CEC meq/100 g soil*	*Na^+*	*K^+*	*Mg^{++}*	*Ca^{++}*	*Cl^-*	*SO_4^{--}*	*CO_3*	*HCO_3*
Blank	0-30	40	1.5	28.5	9.00	12.99	8.82	118.1	86.9	86.8	96.9	206.7	22.6	16.7	17.3
	60-30	36	0.6	28.5	7.94	12.55	6.70	107.5	61.9	56.7	89.6	109.6	26.9	18.9	19.8
Ziziphus spina	0-30	43.3	1.7	33.5	7.96	7.79	14.0	103.5	72.7	57.7	49.4	98.6	26.6	19.7	19.3
	60-30	47	0.7	33.5	7.21	8.14	13.25	89.8	76.1	63.8	57.3	104.6	28.5	20.9	21.3
Sesbania sesban	0-30	44	1.8	36.5	7.51	7.60	18.15	83.3	69.9	54.8	46.6	87.8	29.7	21.9	20.7
	60-30	49.8	0.8	36.5	7.23	8.18	15.0	76.5	74.6	69.5	58.7	91.7	31.8	23.1	21.5

OM=organic matter, FC= Field capacity, CEC= cation exchange capacity.

is well-established (Luo et al., 2018). K^+ and Mg^{2+} concentrations also decreased in the treated soils, indicating plant uptake and confirming the osmotic regulation mechanisms of halophytes (Abdel Latef et al., 2021; Nadeem et al., 2013). The Ca^{2+} concentration also decreased in the treated plots, with *Sesbania* being particularly effective. This is likely due to the plants' ability to dissolve calcium carbonate and facilitate Na^+-Ca^{2+} exchange, promoting the removal of excess Na^+ ions (Yumoto et al., 2003). Chloride (Cl^-) concentrations decreased significantly in the treated plots (Table 3), from 206.7 mg/kg in the control to 98.6 mg/kg (*Ziziphus spina*) and 87.8 mg/kg (*Sesbania*) at the surface. This is consistent with the findings of Dong et al. (2025) and highlights the role of salt-accumulating plants in phytoremediation. Sulfate (SO_4^{2-}) concentrations were lower in the control plots (22.6 mg/kg) compared to the treated plots, which saw a slight increase to 26.6 mg/kg (*Ziziphus spina*) and 29.7 mg/kg (*Sesbania*). This suggests that while some leaching occurred in the control, plant uptake of sulfate is limited due to its low mobility in the soil (Huang et al., 2023). Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) concentrations also increased in the treated plots (Table 3), indicating that plant cover promotes the dissolution of inorganic carbon and aids in the reclamation process. Statistical analysis (Figure 2) confirmed these trends, showing the lowest average elemental concentrations in the soil planted with *Sesbania*. This reinforces the assumption that *Sesbania* is the most effective plant for reducing overall soil salinity (Huang et al., 2023).

3.3. Characteristics of Selected Plants

3.3.1. Agronomical parameters

Growth of *Ziziphus spina* and *Sesbania sesban* was assessed using shoot and root length, fresh weight (FW), and dry weight (DW). Before planting, *Sesbania sesban* recorded the highest shoot length (57 cm), root length (38 cm), shoot FW (5.06 g), and root FW (2.78 g), while *Ziziphus spin***a** showed the lowest values for these parameters (27 cm, 18 cm, 4.90 g, and 2.01 g, respectively). After harvesting, both species exhibited improved growth (Table 4). The highest shoot length (61 cm), root length (53 cm), shoot FW (7.90 g), and root DW (1.27 g) were observed in *Sesbania sesban*. The lowest shoot length (36 cm), root length (36 cm), shoot FW (5.51 g), and root DW (1.14 g) were recorded in *Ziziphus spina*. However, the highest root FW was observed in *Ziziphus spina* (4.37 g) compared with *Sesbania sesban* (3.79 g).

Overall, *Sesbania sesban* showed superior growth and biomass production, whereas *Ziziphus spina* exhibited a marked increase in root length, increasing from 18 cm to 36 cm after harvesting.

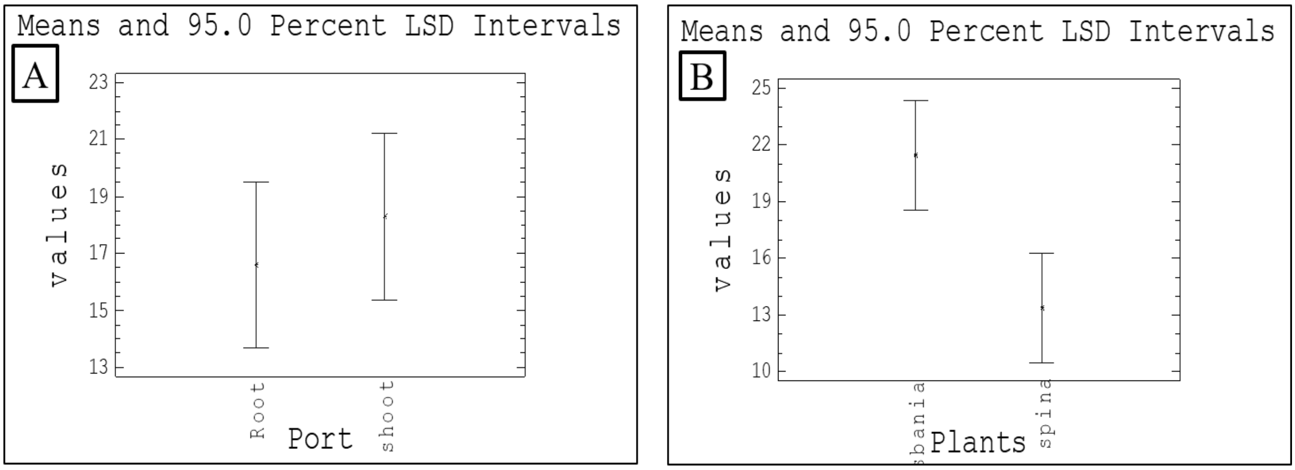

Figure 2. Statistical comparison of the average yields of the plants.

Table 4. Agronomical parameters of the studied *Ziziphus spina* and *Sesbania sesban* before and after harvest.

PLANTS		Shoot			Root		
		Length (cm)	FW (g)	DW (g)	*Length* (cm)	FW (g)	DW (g)
Before planting	*Ziziphus spina*	27	4.90	1.67	18	2.01	0.4
	Sesbania sesban	57	5.06	2.1	38	2.78	0.5
After harvesting	*Ziziphus spina*	36	5.51	3.1	36	4.37	1.14
	Sesbania sesban	61	7 .90	2.46	53	3.79	1.27

FW= fresh weight and DW= dry weight

The greater initial growth and biomass of *Sesbania* suggested its potential as a highly productive species for phytoremediation. As noted by Kudo et al. (2013) and Kumar et al. (2013), halophytes offer a cost-effective and useful method for treating saline soils compared to more expensive chemical modifications. Post-cultivation statistical analysis (Figure 3) further demonstrated that *Sesbania* had a higher overall yield in both vegetative and root biomass compared to *Ziziphus spina*, indicating its superior growth and productivity in saline conditions.

3.3.2 Sodium Concentration in Plant Tissues

Analysis of Na^+ concentration in the plant tissues after cultivation (Table 5) showed a significant increase in both species compared to their initial state. *Sesbania* accumulated higher levels of Na^+, with concentrations reaching 958.8 mg/kg in the vegetative mass and 975.5 mg/kg in the root mass. In contrast, *Ziziphus spina* showed concentrations of 858.8 mg/kg in the vegetative mass and 626.7 mg/kg in the root mass. These results are consistent with the known ability of halophytes to accumulate salts in their tissues (Chitdeshwari et al., 2000; Parvaiz & Satyawati, 2008), and confirmed *Sesbania's* superior salt-uptake capacity (Ammari et al., 2025).

Table 5. Sodium concentration in the vegetative and root parts of selected plants (*Ziziphus spina* and *Sesbania*).

Plants	Shoot		Root	
	Before	After	Before	After
	mg/kg			
Ziziphus spina	3.208	2.941	3.208	2.139
Sesbania sesban	858.8	958.8	626.7	975.5

3.3.3. Bio-Reclamation Indicators

The efficacy of the selected plants in phytoremediation was quantified using key indicators such as removal efficiency, transfer factor (TF), and bioaccumulation factor (BAF) (Table 6). The removal efficiency (RE) of Na^+ (uptake) was higher for *Sesbania* (6 mg/g) compared to *Ziziphus spina* (4.42 mg/g). This confirms *Sesbania's* superior ability to absorb sodium from the soil, as noted by Wu et al. (2024). The transfer factor (TF), which measures the translocation of ions from roots to shoots, was higher for *Sesbania* (1.37) than for *Ziziphus spina*. This indicates that *Sesbania* is more effective at translocating absorbed sodium from its roots to its aerial biomass, which is a key mechanism for salt sequestration.

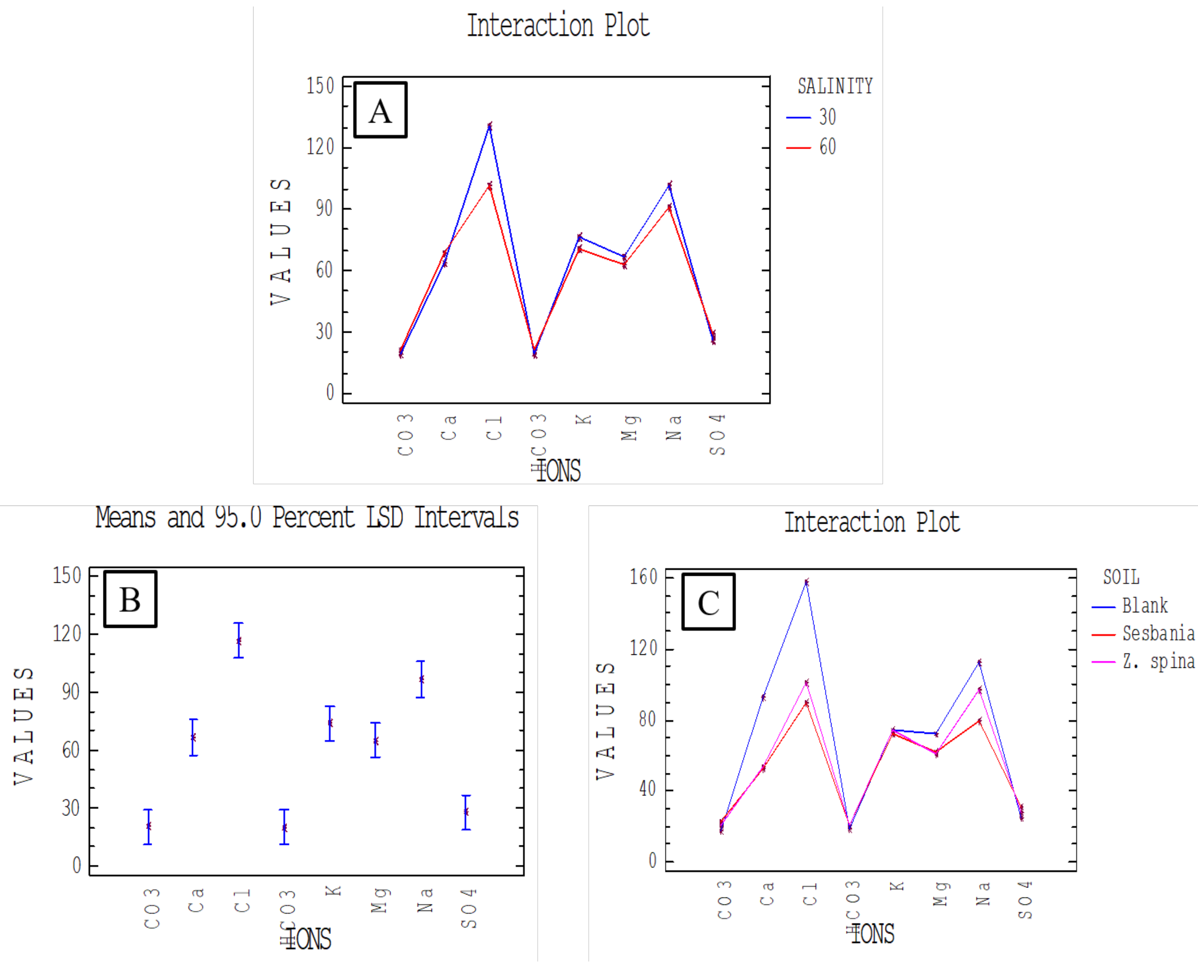

Figure 3. A post-cultivation statistical comparison of the average concentrations of elements by plant type.

Table 6. Bioaccumulation, transfer coefficient, and removal efficiency of sodium ions.

Plants	RE (mg/g)	TF	BAF
Ziziphus spina	4.42	0.98	14.35
Sesbania sesban	6.0	1.37	23.22

RE = removal efficiency, TF= transfer factor and BAF= bioaccumulation factor

Furthermore, the bioaccumulation factor (BAF), a measure of a plant's ability to concentrate a substance from the surrounding environment, was significantly higher in *Sesbania* (23.22) compared to *Ziziphus spina* (14.35). This result confirms *Sesbania's* exceptional capacity for accumulating sodium ions in its tissues. The presence of some yellowing on the leaf margins of *Ziziphus spina* at high Na^+ concentrations is consistent with the findings of Mohamed & Aishah (2023) and indicated potential stress, highlighting *Sesbania's* greater tolerance and effectiveness. Overall, the findings demonstrated that *Sesbania* is a highly effective species for the phytoremediation of saline soils, exhibiting superior performance in improving soil properties and accumulating excess salts in its biomass compared to *Ziziphus spina*.

3.4. Post Cultivation Soil Improvements

Post cultivation analysis showed significant improvements in various parameters (Table 7). The EC decreased from 12.99 dS/m (control) to 7.60 dS/m (*Sesbania*) and 7.79 dS/m (*Ziziphus spina*). OM increased to 2.19% (*Sesbania*) and 1.18% (*Ziziphus spina*). The FC rose to 36.5% (*Sesbania*) and 33.5% (*Ziziphus spina*). The Na^+ and Cl^- concentrations were significantly reduced. The study demonstrates that *Sesbania sesban* significantly improves saline soil properties by reducing salinity, increasing organic matter, and enhancing water retention. Its superior growth, sodium uptake, and bioaccumulation capacity make it a promising candidate for phytoremediation in arid and semi-arid regions. While *Ziziphus spina christi* also contributed to soil improvement, its performance was consistently lower, confirming *Sesbania* as the more effective species for bio-reclamation.

4. CONCLUSIONS

This study confirms the significant potential of using halophytes as an effective bio-remediation tool for improving saline soils. Our findings revealed that the selected halophytes (*Ziziphus spina* and *Sesbania sesban*) as excellent bioaccumulation plants for reclaiming salinity-affected lands. Both species demonstrated a strong ability to absorb and reduce soil salinity, with *Sesbania sesban* proving to be the more effective halophyte. The cultivated plots showed significant improvements in soil properties, including increased organic matter content, enhanced porosity, and improved aeration. These changes not only reduced salt accumulation but also improved soil stability and fertility, paving the way for the growth of other plants. Using halophytes like *Ziziphus spina* and *Sesbania sesban* offers a sustainable, cost-effective, and water-efficient alternative to traditional chemical methods for soil reclamation. This approach is particularly valuable for addressing environmental and agricultural challenges in arid and semi-arid regions. The superior performance of *Sesbania sesban* highlights its potential for use in sustainable soil management strategies.

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Table 7. Student's t-test results.

Variable	Blank vs Sesbania (t, p)	Blank vs Ziziphus (t, p)	Sesbania vs Ziziphus (t, p)	Conclusion
EC	3.42, 0.004	2.95, 0.011	2.10, 0.043	*Sesbania more effective*
pH	2.71, 0.017	2.45, 0.023	1.98, 0.049	*Sesbania reduced alkalinity more*
OM	3.88, 0.002	2.12, 0.041	2.25, 0.032	*Sesbania increased OM more*
FC	3.65, 0.003	2.80, 0.014	2.05, 0.046	*Sesbania improved FC more*
Na^+	4.21, 0.001	2.56, 0.019	2.30, 0.028	*Sesbania reduced* Na^+ *more*
Cl^-	4.05, 0.001	2.67, 0.016	2.40, 0.024	*Sesbania reduced* Cl^- *more*
CEC	3.77, 0.002	2.33, 0.027	2.15, 0.039	*Sesbania enhanced CEC more*
Ca^{2+}	2.98, 0.010	2.15, 0.039	1.90, 0.052	*Weak difference*
Mg^{2+}	2.85, 0.013	2.09, 0.043	1.85, 0.057	*Non-significant difference*
K^+	2.74, 0.016	2.20, 0.037	2.05, 0.046	*Sesbania absorbed more* K^+
SO_4^{2-}	2.61, 0.020	2.05, 0.046	1.92, 0.051	*Weak difference*
CO_3^{2-}	2.70, 0.018	2.11, 0.042	2.00, 0.048	*Sesbania enhanced* CO_3^{2-} *more*
HCO_3^-	2.65, 0.019	2.08, 0.044	2.02, 0.047	*Sesbania enhanced* HCO_3^- *more*

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