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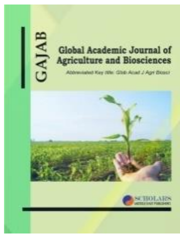

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Original Research Article

The Efficiency of the Salicornia Europaea L. Plant in Removing Some Heavy Elements from Soil Contaminated with Oil Waste and Irrigated with Desalinated Wastewater, and the Effect of This on Plant Characteristic

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Abstract: A field experiment was conducted in a greenhouse in the Al-Hussayniya district of Karbala Governorate during the fall of 2025 (July 15 to October 15, 2025). The objective was to investigate the effects of salinity concentrations (4251, 7855, 12090 mg L^{-1}) and oil residue contamination (black oil) concentrations (0, 30, 60, 90 g kg^{-1}) of desalination wastewater collected from a seawater desalination plant within the study area on the nickel (Ni) and lead (Pb) removal efficiency from contaminated soil using Sarconia species (ICBA-10 classification), as well as on the phytochemical components, yield, and quality characteristics of the plants. The experiment was conducted using a 3-replica fully randomized block design (RCBD). The experimental results revealed that the highest concentration of wastewater (12090 mg L^{-1}) demonstrated the highest efficiency in removing nickel (Ni) and lead (Pb) from contaminated soil. From the results obtained in this study, it was seen that the maximum level of soil oil contamination (90 g/kg) was associated with the rates of removal for nickel (41.2%) and lead (44.8%). In contrast, the minimum level of wastewater contamination (4251 mg L^{-1}) gave the maximum values for all investigated parameters of the plant. With an increase in the level of soil oil contamination, there was an observed decrease in plant height, fresh weight, grain yield, protein content, and oil content.

Keywords: Sarconia, Desalination Wastewater, Oil Pollution, Heavy Metals, Plant Remediation, Removal Efficiency.

1. INTRODUCTION

The problem of environmental pollution by heavy metals and residues of petroleum products is one of the greatest obstacles to sustainable agriculture in desert or semi-desert areas, taking Iraq as an example. Pollution by petroleum caused by industry and petroleum residues spilling on agriculture lands is one of the most serious problems in Iraq. Heavy metals such as nickel (Ni) and lead (Pb) settle in the topsoil layer. They accumulate in humans and animals through the food chain, resulting in serious toxic effects (Shehata *et al.*, 2019).

On the other hand, desalination wastewater (also called desalination wastewater) is an important alternative water source in water-scarce regions.

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This water is concentrated brine, a byproduct of the desalination process. Not all water flowing into a desalination plant becomes fresh water. Rather, it is divided into desalination-treated product water and concentrated brine containing high concentrations of salt and ions, sometimes exceeding seawater concentrations. The chemical properties of plants include changes in the concentrations of salt, heavy metals, and organic compounds, which can affect the efficiency of plant absorption of pollutants (Khan *et al*., 2022).

The genus Salicornia (obligate halophiles) is a halophilic plant. Salicornia possesses advanced physiological mechanisms to tolerate both salt and mineral stress, demonstrating its ability to grow in contaminated environments (Mendis *et al*., 2025). Recent studies have shown that Salicornia can absorb and accumulate large amounts of heavy metals in its tissues, making it a promising candidate for plant remediation in oil-contaminated soils (Orzoł *et al*., 2025). Therefore, this study aimed to evaluate the interaction between the salinity of desalination plant wastewater and the level of black oil contamination on the efficiency of nickel and lead removal from contaminated soil, and to investigate the effects of this interaction on the growth, yield, and quality characteristics of sarconia.

2. MATERIALS AND METHODS

2.1 Experimental Implementation

This experiment was conducted in the fall of 2025 (July 15 to October 15, 2025) in a controlled greenhouse with 50% shading in the Al-Hussayniya district of Karbala Governorate, Iraq. Soil samples were randomly collected from uncultivated land in the Al-Hussayniya district at a depth of 0–30 cm according to standard methods (Carter & Gregorich, 2007). After air-drying, the collected soil was sieved through a 2 mm sieve and mixed until a homogeneous sample was obtained. Plastic containers capable of holding 15 kg of soil were used.

Heavy crude oil (black oil) from the Karbala refinery was added at a rate of 0, 30, 60, and 90 g per kg of soil and thoroughly mixed to ensure uniform dispersion. To facilitate the reaction between the soil and the oil contaminants and to achieve relative stability, the samples were left for 14 days (Adam & Duncan, 2002). Sarconia seeds, variety ICBA-10, were sown on July 15, 2025, at a rate of 6 seeds per pot. After germination, thinning ensured that there were only three plants in each pot. Irrigation of the plants was done using the desalination brine, also known as wastewater, with three salinity levels: 4251, 7855, and 12090 mg L^{-1}. The brine is referred to as the concentrated saline waste product of the desalination process because it contains varying amounts of salts and other dissolved materials compared to the feedwater used by the plant. Samples of water were collected from desalination plants located in the Karbala Department research area. The variation in salinity at the three different levels can be attributed to the unique nature of the feedwater used by each of the three desalination plants. Furthermore, decomposed organic fertilizers, such as cow manure, at a rate of 2% of soil mass were added two weeks before planting.

2.2 Analysis of Soil, Water, and Oil Residues

2.2.1 Soil Analysis

Soil samples were collected before planting, and a number of soil characteristics were then established. Texture of the soils was analyzed based on the Bouyous (hydrometer) technique; the pH and electrical conductivity values were determined using an EC meter for the soil solution of 1:1 ratio; organic matter – by wet decomposition technique, available nitrogen – by micro-Kjeldahl technique, available phosphorus – by colorimetry technique, and available potassium – by flame photometry. Overall amounts of nickel (Ni) and lead (Pb) in soils were measured before and after experiments using an atomic absorption spectrophotometer (AAS). The results obtained are given in Table 1.

Table 1: Selected Physical and Chemical Properties and Heavy Metal Concentrations of the Experimental Soil before Planting

Property	Value	Unit	Method Used
Sand	500	g kg^{-1}	Hydrometer
Clay	292	g kg^{-1}	Hydrometer
Silt	208	g kg^{-1}	Hydrometer
Soil texture	Clay loam	—	—
pH	7.71	—	pH meter
Electrical conductivity (EC)	3.64	dS m^{-1}	EC meter
Organic matter	1.11	%	Wet digestion
Available nitrogen	23.6	mg kg^{-1}	Micro-Kjeldahl
Available phosphorus	7.1	mg kg^{-1}	Colorimetric method
Available potassium	145	mg kg^{-1}	Flame photometer
Total nickel (Ni)	16.15	mg kg^{-1}	Atomic Absorption Spectrophotometer (AAS)
Total lead (Pb)	13.88	mg kg^{-1}	Atomic Absorption Spectrophotometer (AAS)

2.2.2 Analysis of Irrigation Water (Desalination By-Product)

Samples of brine by-product were obtained from various desalination plants operating in the survey area of Karbala County. Brine by-product is basically a high-concentrated by-product produced in the desalination process and contains a relatively higher concentration of salt, ions, and other dissolved substances compared to the feedwater. To reflect the variability in raw water properties and desalination process efficiency, three samples with different salinity levels were selected from different plants. The samples were analyzed in the laboratory of the Department of Soil Science and Water Resources, Faculty of Agriculture, University of Karbala. The chemical properties of the water were evaluated according to standard methods (APHA, 2017).

Table 2: Chemical characteristics of return water from seawater desalination plants

Property	Unit	B1	B2	B3
pH	—	7.6	7.9	8.3
Electrical Conductivity (EC)	dS m^{-1}	6.6	12.3	18.9
Total Dissolved Solids (TDS)	mg L^{-1}	4251	7855	12090
Sodium (Na)	mg L^{-1}	980	1820	2950
Chloride (Cl^-)	mg L^{-1}	1540	2960	4820
Calcium (Ca)	mg L^{-1}	235	420	680
Magnesium (Mg)	mg L^{-1}	128	240	385
Sulfate (SO_4^{2-})	mg L^{-1}	710	1320	2140
Lead (Pb)	mg L^{-1}	0.148	0.265	0.420
Nickel (Ni)	mg L^{-1}	0.295	0.520	0.850
Nitrogen (N)	mg L^{-1}	31.2	54.6	82.4
Phosphorus (P)	mg L^{-1}	13.21	16.8	24.5

2.2.3 Analysis of Waste Oil (Black Oil)

A sample of heavy crude oil (black oil) was collected from the Karbala Refinery and sent to the Karbala Refinery Research Institute for physicochemical analysis as shown in Table 3.

Table 3: Basic characteristics and contamination levels of the heavy crude oil (black oil) used in the experiment

Property	Value	Unit
Specific Gravity	0.92	g cm^{-3}
Polycyclic Aromatic Hydrocarbons (PAHs) Concentration	2850	mg kg^{-1} oil
Total Nickel (Ni) Concentration	48.6	mg kg^{-1} oil
Total Lead (Pb) Concentration	42.3	mg kg^{-1} oil
Viscosity at 25°C	450	mPa·s

2.3 Characteristics Investigated

Nickel and Lead Removal Efficiency from Soil(%)

Removal efficiency was calculated based on the change in elemental concentration in the soil before and after planting, according to the following formula:

Removal Efficiency (%) = $(C_1 - C_2) \div (C_1) \times 100$

Where,

C_1 = Elemental concentration in the soil before planting (mg kg^{-1})

C_2 = Elemental concentration in the soil after planting (mg kg^{-1})

Plant Height (cm)

Three plants were selected from each pot, and the height from the soil surface to the highest growing point was measured. The average value was calculated.

Fresh Leaf Weight (g $plant^{-1}$)

Fresh leaf weight was measured using a high-sensitivity electronic balance.

Grain Yield (g $plant^{-1}$)

Three plants were selected from each pot, and the grain yield was measured. The total weight was divided by the elemental concentration in the soil to calculate the yield. Number of plants required to calculate the average yield per plant.

Protein Content in Grains(%)

Nitrogen content in grains was measured using the Kjeldahl method, and protein content was calculated using the following formula:

Protein Content (%) = Nitrogen Content (%) × 6.25

(According to AOAC, 2016)

Oil Content in Grains(%)

Grains were randomly sampled, and oil content was measured using the Soxhlet extraction method.

2.4 Statistical Analysis

Analysis of the results was done using SAS software. LSD test was used to determine whether there were any significant differences between the treatments, by analyzing the means at a significance level of 0.05.

3. RESULTS AND DISCUSSION

3.1 Nickel (Ni) Removal Efficiency from Soil (%)

Results shown in Table 4 confirm that both salinity of wastewater and levels of contamination by black oil, as well as the interaction between those variables, have an impact on the effectiveness of nickel removal from the soil using Sarconia plants. Using the highly saline wastewater (B3: 12,090 mg L^{-1}) resulted in much higher nickel removal efficiency than the mean value of 21.6% achieved when applying less salty wastewater B1 (4,251 mg L^{-1}) and was the most effective treatment producing the highest removal efficiency value of 32.3%. These results can be explained by the higher content of ions and salts dissolved in the highly saline water. High ion concentration promotes more intensive ion activity and chemical reactions in the rhizosphere, making more nickel available in the soil and resulting in increased nickel uptake by the plants. These results are supported by studies conducted by Borah *et al.*, (2023).

When considering the levels of contamination by black oil, the data show that the higher the contamination level is, the higher nickel removal efficiency becomes. The maximum average efficiency of 35.8% was observed with the contamination level of 90 g kg^{-1} soil being applied, which is higher than all other levels. This effect can be caused by some changes in the soil's chemical and physical composition because of the contamination, changing the availability of heavy metals and promoting nickel absorption and accumulation in the plant tissue (Adriano, 2001).

Finally, the interaction between the variables under consideration showed various effects on nickel removal efficiency. The highest removal efficiency of 41.2% was achieved through the combination of the highest saline level of reflux water (B3) and the highest oil contamination level (90 g kg^{-1} soil).

Table 4: Effect of Brine Water Salinity Level, Crude Oil Contamination Level, and Their Interaction on Nickel Removal Efficiency from Soil (%)

Brine Water Level	Crude Oil Contamination Level (g kg^{-1} soil)				Mean
	0	30	60	90	
B1 (4251 mg L^{-1})	12.4 d	19.6 cd	24.8 bc	29.5 b	21.6 C
B2 (7855 mg L^{-1})	18.7 cd	26.3 bc	31.5 ab	36.8 a	28.3 B
B3 (12090 mg L^{-1})	22.4 bc	30.1 ab	35.6 a	41.2 a	32.3 A
Mean	17.8 D	25.3 C	30.6 B	35.8 A	—
L.S.D $_{0.05}$	Brine Water		Crude Oil		Brine Water × Crude Oil
	3.24		2.95		4.32

3.2 Lead (Pb) Removal Efficiency from Soil (%)

The results in Table (5) show that wastewater salinity, black oil contamination levels, and their interactions significantly influence the efficiency of lead removal from soil by sarconian plants. The efficiency of lead removal showed a similar trend like nickel removal; however, the values were higher than in the case of nickel removal, meaning that Sarconia has a higher ability to absorb and accumulate lead in the given conditions.

The treatment with the high-salinity wastewater (B3 – 12,090 mg L^{-1}) gave much better results than other treatments since it had the highest mean removal efficiency equal to 35.8%. It was followed by treatment B2 (7,855 mg L^{-1}) with 31.1% removal efficiency on average, and treatment B1 (4,251 mg L^{-1}) with the lowest mean removal efficiency of 24.0%. The advantage of the given results is explained by the high concentration of ions, dissolved salts, and complex substances in the high-salinity return water, thus increasing the solubility and bioavailability of lead in soil solution and enhancing its absorption and transport into the plant tissues according to Zhang *et al.*, (2025).

In addition, the efficiency of lead removal increased gradually as the black oil contamination grew. It may be associated with the ability of black oil to change the chemical composition of soil and to change the form of heavy metals, therefore, improving their absorption by plants. The most effective combination turned out to be the use of the highest salinity of return water (B3) and the highest contamination by black oil (90 g kg^{-1}), when the maximum lead removal efficiency was reached (44.8%).

Table 5: Impact of the concentration of brine water salinity, the intensity of black oil pollution and their interaction on lead removal efficacy from soil (%)

Brine Water Level	Crude Oil Contamination Level (g kg^{-1} soil)				Mean
	0	30	60	90	
B1 (4251 mg L^{-1})	13.8 d	21.4 cd	27.6 bc	33.2 b	**24.0 C**
B2 (7855 mg L^{-1})	20.5 cd	28.9 bc	34.7 ab	40.1 a	**31.1 B**
B3 (12090 mg L^{-1})	25.3 bc	33.8 ab	39.4 a	44.8 a	**35.8 A**
Mean	**19.9 D**	**28.0 C**	**33.9 B**	**39.4 A**	-
L.S.D $_{0.05}$	Brine Water		Crude Oil		Brine Water × Crude Oil
	3.51		3.18		4.68

3.3 Plant Height (cm)

The results in Table (6) show that wastewater salinity, black oil contamination levels, and their interactions significantly affect sarconia plant height. In the case of low-salinity wastewater treatment B1 (4251 mg/L), the highest average height of 45.3 cm was obtained; it significantly exceeded those in other groups of plants. Next, treatment B2 (7855 mg/L) resulted in an average height of 39.8 cm; the lowest average height of 32.4 cm was registered for treatment B3 (12090 mg/L). The progressive reduction in the average height of plants is caused by the rise in osmotic pressure due to the increase in soil solution salinity. Moreover, some negative toxic effects might be caused by ions accumulation.

The analysis of black oil contamination levels showed the tendency to gradual height reduction with the increment of pollution levels. Thus, the average height in the control group (0 g/kg) amounted to 51.7 cm, and in other samples – it decreased progressively to 26.4 cm at the highest contamination level (90 g/kg). The results indicate that residues of oil have a negative effect on soil physical and chemical parameters, reducing the amount of aeration and water permeability as well as the availability of nutrients.

Furthermore, the analysis of the impact of interactions between the two study factors showed significant differences in their combined effects. Thus, the combination of treatment B1 and control pollution level resulted in the highest average height (58.4 cm), while the combination of B3 and the highest level of pollution (90 g/kg) led to the lowest height (20.1 cm). It is clear that the combined effect of high wastewater salinity and increased black oil contamination level has a stressful effect on plants and reduces their vegetative growth (height).

Table 6: Impact of saltiness of water returned (brine water), presence of black oil, and their interaction on height (in cm) of the Salicornia plant

Brine Water Level	Crude Oil Contamination Level (g kg^{-1} soil)				Mean
	0	30	60	90	
B1 (4251 mg L^{-1})	58.4 a	49.6 b	41.2 c	31.8 d	**45.3 A**
B2 (7855 mg L^{-1})	52.1 b	43.7 c	35.8 cd	27.4 e	**39.8 B**
B3 (12090 mg L^{-1})	44.6 c	36.2 cd	28.5 de	20.1 f	**32.4 C**
Mean	**51.7 A**	**43.2 B**	**35.2 C**	**26.4 D**	-
L.S.D $_{0.05}$	Brine Water		Crude Oil		Brine Water × Crude Oil
	2.91		2.62		3.95

3.4 Plant Wet Weight (g $plant^{-1}$)

The results in Table (7) show that wastewater salinity and black oil contamination levels significantly affect the wet weight of sarconia plants. Wastewater with low salinity treatment (4251 mg L^{-1}) provided the maximum mean fresh weight, 142.4 g $plant^{-1}$, which was significantly higher than B2 (124.3 g $plant^{-1}$) and B3 (102.2 g $plant^{-1}$). Such an outcome can be explained by favorable growing conditions, particularly optimal root growth and water and nutrient absorption, which are responsible for biomass creation and increase the water content in the tissues. This result correlates with the findings presented by Homayouni *et al.,* (2024).

As far as black oil pollution is concerned, the decrease in fresh plant weight was significant and progressive along with pollution intensity increase. The maximum mean fresh weight was achieved with zero pollution (0 g/kg), 164.9 g $plant^{-1}$; the minimum fresh weight (80.6 g $plant^{-1}$) was observed with the highest pollution level (90 g/kg). Such a decrease in fresh weight can be explained by the negative impact of oil residues on physical and chemical soil properties, which leads to such effects as decreased aeration, water and nutrients transport to the roots, and the inhibition of toxic plants' physiological activity.

The interaction between the salinity of treated wastewater and black oil contamination showed a significant effect on the fresh weight of Salicornia europaea. It means that the effect of the first factor (wastewater salinity) depended on the intensity of oil pollution. The maximum fresh weight was achieved when using the lowest salinity level (4251 mg/L) without any contamination (0 g/kg), reaching 186.4 g plant^{-1}. In case of the same salinity level, a significant decrease in fresh weight was observed with an increase in the intensity of black oil contamination; the minimum weight was achieved with the highest contamination level (90 g/kg) – 96.4 g plant^{-1}.

At the same time, high salinity treatment (B3) resulted in a greater decrease in the fresh weight along with contamination levels. The lowest interaction value (62.8 g plant^{-1}) was observed with the highest salinity treatment (B3) and black oil contamination level (90 g kg^{-1}).

Therefore, the results prove that the increased salinity of treated wastewater and contamination of soils by black oil residues act as limiting factors for the biomass creation in Salicornia europaea, despite the high resistance of this plant to both salinity and environmental pollution.

Table 7: Influence of salinity level (brine water) and the concentration of the black oil contamination on the wet weight of the vegetative biomass (g plant^{-1})

Brine Water Level	**Crude Oil Contamination Level (g kg^{-1} soil)**				**Mean**
	0	30	60	90	
B1 (4251 mg L^{-1})	186.4 a	158.2 b	128.6 c	96.4 d	**142.4 A**
B2 (7855 mg L^{-1})	165.8 b	138.4 c	110.2 d	82.6 e	**124.3 B**
B3 (12090 mg L^{-1})	142.6 c	114.8 d	88.4 e	62.8 f	**102.2 C**
Mean	**164.9 A**	**137.1 B**	**109.1 C**	**80.6 D**	-
L.S.D $_{0.05}$	Brine Water		Crude Oil		Brine Water × Crude Oil
	8.65		7.84		11.52

3.5 Grain Yield (g/plant)

The results in Table (8) show that wastewater salinity and black oil contamination levels significantly affect sarconia grain yield. Low-salinity wastewater treatment (B1 mg L^{-1}) yielded the highest average grain yield at 6.33 g/plant, significantly higher than treatments B2 (5.35 g/plant) and B3 (4.30 g/plant). Such results have been achieved due to the relatively low salinity, which improved water and nutrient absorption by the plants and positively affected physiological processes associated with grain formation and filling and contributed to higher yields. As for the level of black oil contamination, there was a significant negative correlation between it and grain yield, the latter one decreasing with the rise in contamination levels. In particular, grain yield decreased from 8.41 g plant^{-1} in the control group (0 g kg^{-1}) to 2.53 g plant^{-1} in case of the highest contamination level (90 g kg^{-1}). Such decrease has been caused by the negative impact of oil residues on soil properties and processes associated with plant growth and development, including flowering, grain formation and ripening, which resulted in lower productivity of plants.

In addition, the interaction between salinity and black oil contamination has greatly affected the yield of sarconia grain. Plant reaction to the salinity turned out to be strongly depended on the level of contamination with oil. The highest grain yield has been reached when the highest salinity level and no contamination have been combined – 9.86 g plant^{-1}. Grain yield decreased with rising contamination levels, the lowest value being reached at the highest level of contamination (90 g kg^{-1}), amounting to 3.08 g plant^{-1}.

However, in case of high salinity (B3) the decrease in grain yield was greater at any levels of oil contamination. The minimum interaction value has been reached in case of the highest contamination and salinity (B3), being equal to 1.98 g plant^{-1}.

Table 8: Influence of the salt level of return water (brine water), black oil contamination level, and interaction between them on seed yield (g plant^{-1})

Brine Water Level	**Crude Oil Contamination Level (g kg^{-1} soil)**				**Mean**
	0	30	60	90	
B1 (4251 mg L^{-1})	9.86 a	7.24 b	5.12 c	3.08 d	**6.33 A**
B2 (7855 mg L^{-1})	8.42 ab	6.18 bc	4.25 cd	2.54 e	**5.35 B**
B3 (12090 mg L^{-1})	6.94 b	4.86 cd	3.42 d	1.98 f	**4.30 C**
Mean	**8.41 A**	**6.09 B**	**4.26 C**	**2.53 D**	-
L.S.D $_{0.05}$	Brine Water		Crude Oil		Brine Water × Crude Oil
	0.87		0.79		1.16

3.6 Protein Concentration in Grains (%)

The results obtained from Table (9) prove that there is a strong influence of salinity of wastewater, black oil contamination, and their interactions on protein content of Sarconia grains. The treatment B1 (4251 mg L^{-1}) had the largest average protein content equal to 21.7%, which exceeded B2 (19.8%) and B3 (17.4%). This is explained by the gradient of decrease of protein content depending on increase of salinity due to decreased efficiency of uptake of nutrients, especially nitrogen through osmotic and ionic stress resulting in the restriction of protein synthesis. High black oil contamination led to a decrease of protein content from 23.3% in the control sample to 15.9% for the case of the maximum black oil contamination level (90 g kg^{-1}). It can be explained by the degradation of soil properties, inhibition of activities of microorganisms participating in mineralization of nitrogen, and decrease of its availability to plants, resulting in the restriction of protein synthesis (Zhang *et al*., 2025). Interaction of salinity and black oil contamination had the synergistic effect on protein content; the maximum value was recorded in the case of the B1 –control interaction, while the minimum value was reached in the case of B3 –high contamination interaction.

Table 9: Influence of brine water salinity, levels of black oil pollution, and the interaction between them on the protein content (%) of grains

Brine Water Level	Crude Oil Contamination Level (g kg^{-1} soil)				Mean
	0	30	60	90	
B1 (4251 mg L^{-1})	25.6 a	23.1 b	20.4 c	17.8 d	**21.7 A**
B2 (7855 mg L^{-1})	23.4 b	21.2 bc	18.6 cd	16.1 e	**19.8 B**
B3 (12090 mg L^{-1})	20.8 c	18.5 d	16.2 e	13.9 f	**17.4 C**
Mean	**23.3 A**	**20.9 B**	**18.4 C**	**15.9 D**	-
L.S.D $_{0.05}$	Brine Water		Crude Oil		Brine Water × Crude Oil
	0.98		0.87		1.28

3.7 Oil Concentration in Grains (%)

As seen in Table 9 below, there was a significant effect of both the irrigation water salinity and black oil contamination on the oil content of Sarconia grains. Treated group (4251 mg/L) had the highest oil content value at 23.4% as opposed to 21.1% in treated group B2 and 18.3% in B3. It should be noted that oil content decreased gradually with increase in salinity of irrigation water because of the negative effects of osmosis and ions on the efficiency of biological reactions in the production of fatty compounds including primary fatty acids and the use of photosynthesis products for other purposes (adaptive) without oil production in the grains (under salt stress).

The oil content also decreased with an increase in contamination values, reducing from 25.3% (in control group) to 16.3% in the group with the highest contamination level. This proves that petroleum hydrocarbons affect metabolic equilibrium of the plant, inhibit the enzymes taking part in the synthesis of fatty acids and reduce photosynthesis efficiency.

The interaction of two research factors (salinity of reflux water × black oil contamination) showed a clear and significant effect on oil concentration in grains. As shown in the table, the response of sarconia plants to salinity treatment was directly related to the level of oil contamination. The highest oil concentration was observed during the interaction between the oil contamination levels of the treatment group (4251 mg L^{-1}) and the control group (0 g kg^{-1}). Conversely, in the same interaction, the oil concentration gradually decreased as the oil contamination level increased. Conversely, when using high-salinity reflux water (B3), the oil concentration decreased more rapidly, particularly at the highest oil contamination level (90 g kg^{-1}), showing the lowest value in the table.

Table 10: Effect of the salinity level of the return water (brine water) and the levels of black oil pollution and the interaction between them on the oil concentration in grains (%)

Brine Water Level	Crude Oil Contamination Level (g kg^{-1} soil)				Mean
	0	30	60	90	
B1 (4251 mg L^{-1})	27.8 a	25.2 b	22.1 c	18.6 d	**23.4 A**
B2 (7855 mg L^{-1})	25.4 b	22.8 bc	19.6 cd	16.4 e	**21.1 B**
B3 (12090 mg L^{-1})	22.6 c	19.8 d	16.8 e	13.8 f	**18.3 C**
Mean	**25.3 A**	**22.6 B**	**19.5 C**	**16.3 D**	-
L.S.D $_{0.05}$	Brine Water		Crude Oil		Brine Water × Crude Oil
	1.15		1.02		1.52

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

- Sarconia has a promising ability to remove nickel and lead from soil contaminated with oil residues. This removal efficiency is significantly influenced by the salinity of the treated wastewater.
- The treated wastewater with the highest salinity (12,090 mg L^{-1}) showed the highest removal efficiency of nickel (41.2%) and lead (44.8%) at the highest black oil contamination level (90 g kg^{-1}). This is due to the high concentration of ions and mineral salts.
- High levels of black oil contamination significantly reduced all plant characteristics investigated (plant height, fresh weight, grain yield, protein content, oil content).
- The treated wastewater with the lowest salinity (4,251 mg L^{-1}) showed the best values for plant and crop characteristics, indicating a positive role in creating a suitable rhizosphere environment for growth. • The interaction between high-salinity wastewater and high-concentration oil contamination has a dual effect: it enhances biological removal efficiency while inhibiting plant and crop growth.

4.2 Recommendations

- In regions with high soil salinity and water scarcity, such as Iraq, utilize salicornia in plant remediation programs for oil and heavy metal-contaminated soil.
- Use desalination plant wastewater with appropriate salinity levels (B2-B3) to enhance heavy metal removal efficiency. However, continuous monitoring of water quality and salinity is necessary to avoid adverse effects on plant production.
- Conduct future research to evaluate the long-term impact of further increases in wastewater salinity on the plant remediation efficiency of salicornia.
- Investigate the effects of the interaction between high-concentration black oil contamination and various salinity levels on grain quality and root absorption.
- Conduct trials on various Salicornia varieties to identify the most efficient plant remediation varieties under wastewater irrigation conditions.

REFERENCES

- Adam, G., & Duncan, H. (2002). Influence of diesel fuel on seed germination. Environmental Pollution, 120(2), 363–370.
- Adriano, D. C. (2001). Trace elements in terrestrial environments. New York: Springer New York.
- Al-Rubaie, S. K. A. (2025). Effect of Sulfur and Magnesium Fertilization and Their Interaction on Some Vegetative, Productive, and Quality Traits of Sunflower (Helianthus annuus L). under Karbala Governorate Conditions. American Journal of Botany and Bioengineering, 2(12), 24–32.
- AOAC. (2016). Official Methods of Analysis of AOAC International (20th ed).. Washington DC: AOAC International.
- APHA. (2017). Standard methods for the examination of water and wastewater (23rd ed).. Washington, DC: APHA.
- Araus, J. L., Rezzouk, F. Z., Thushar, S., Shahid, M., Elouafi, I. A., Bort, J., et al. (2021). Effect of irrigation salinity and ecotype on growth, physiological indicators and seed yield and quality of Salicornia europaea. Plant Science, 304, 110819.
- Awa, S. H., & Hadibarata, T. (2020). Removal of heavy metals in contaminated soil by phytoremediation mechanism: a review. Water, Air, & Soil Pollution, 231(2), 47.
- Borah, P., Rene, E. R., Rangan, L., & Mitra, S. (2023). Phytoremediation of nickel and zinc from soils contaminated by municipal solid wastes and paper mill wastes. Environmental Research, 219, 115055.
- Carter, M. R., & Gregorich, E. G. (2007). Soil sampling and methods of analysis (2nd ed).. Boca Raton: CRC Press.
- Chapman, H. D., & Pratt, P. F. (1961). Methods of analysis for soils, plants and waters. Berkeley: University of California.
- Homayouni, H., Razi, H., Izadi, M., Alemzadeh, A., Kazemeini, S. A., Niazi, A., et al. (2024). Temporal changes in biochemical responses to salt stress in three Salicornia species. Plants, 13(7), 979.
- Homayouni, H., Razi, H., Izadi, M., Alemzadeh, A., Kazemeini, S. A., Niazi, A., & Vicente, O. (2024). *Temporal Changes in Biochemical Responses to Salt Stress in Three Salicornia Species*. Plants, 13(7), 979. https://doi.org/10.3390/plants13070979
- Khan, S., Naushad, M., Lima, E. C., Zhang, S., Shaheen, S. M., & Rinklebe, J. (2022). Global soil pollution by toxic elements: current status and future perspectives on the risk assessment and remediation strategies. Journal of Hazardous Materials, 417, 126039.
- Mendis, C. L., Padmathilake, R. E., Attanayake, R. N., & Perera, D. (2025). Learning from Salicornia: physiological, biochemical and molecular mechanisms of salinity tolerance. International Journal of Molecular Sciences, 26(1), 12.
- Moghaddam, A., Larijani, H. R., Oveysi, M., Tohidi Moghaddam, H. R., & Nasri, M. (2023). Alleviating the adverse effects of salinity stress on Salicornia

persica using sodium nitroprusside and potassium nitrate. BMC Plant Biology, 23, 166.

- Orzoł, A., Głowacka, K., Pätsch, R., Piernik, A., Gallegos-Cerda, S. D., & Cárdenas-Pérez, S. (2025). The local environment influences salt tolerance differently in four Salicornia europaea inland populations. Scientific Reports, 15, 13128.
- Page, A. L., Miller, R. H., & Keeney, D. R. (1982). Methods of soil analysis. Part 2 (2nd ed).. Madison: American Society of Agronomy.
- Panchenko, L., Muratova, A., Dubrovskaya, E., Golubev, S., & Turkovskaya, O. (2023). Natural and technical phytoremediation of oil-contaminated soil. Life, 13(1), 177.
- Shehata, S. M., Badawy, R. K., & Aboulsoud, Y. I. (2019). Phytoremediation of some heavy metals in contaminated soil. Bulletin of the National Research Centre, 43(1), 189.
- Sparks, D. L., Page, A. L., Helmke, P. A., & Loeppert, R. H. (1996). Methods of soil analysis. Part 3. Madison: Soil Science Society of America.
- Yang, L., Bai, Y., Wang, Y., Yang, J., Gao, Y., Hou, C., et al. (2025). Lipid metabolism improves salt tolerance of Salicornia europaea. Annals of Botany, 135(4), 789–802.
- Zhang, T., Zhang, X., Liu, Z., Ou, Y., Duan, X., & Wu, M. (2025). Sensitive indicator microorganisms and C, N-cycle processes in soil with different petroleum hydrocarbon pollution levels. Biochemical Engineering Journal, 220, 109752.