Studying the efficiency of *Suaeda maritima* (L.) Dumort in phytoremediation of saline soil

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Abstract

The true halophyte, *Suaeda maritima* grows naturally at the Mediterranean coast. Terminal shoots and roots of *S. maritima* and its associated soil were taken from two sites across the Damietta- Port Said coastal road, Egypt through winter and summer, 2019. Soil physical and chemical properties were investigated in details. In addition to heavy metals, water content, phenols content, total ash, Na, K, Ca, Mg, and Cl were determined in both shoots and roots. Also, translocation factor and bioconcentration factor for heavy metals were assessed. Soil near the *S. maritima* rhizosphere was highly saline and had lower concentration of most metals (Al, Ba, Cd, Cu, Fe, Mo, Pb, Si) and total heavy metals during summer. The heavy metal intake by roots were high and more sequestered in shoots and roots in summer. Water and ash contents were higher in winter season while the reverse was observed in total phenols and Na in both shoots and roots. Ca content accumulated highest at site 2 during summer for shoots and those growing at site 1 for roots either in winter or summer. Concerning Mg, the maximum value was recorded in plants at site 1 through summer in shoots and roots. Cl content had the greatest accumulation in *S. maritima* at site 1 in summer shoots and at site 2 in winter roots.

Keywords heavy metals, inorganic, salinity, solutes, *Suaeda maritima*, total phenols

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Introduction

Suaeda maritima is an annual species included in Amaranthaceae family that grows in salt marshes and flooding habitats. The optimum photosynthesis and growth rate in *S. maritima* were noticed at 200 mM NaCl, but the optimum concentration for growth extended to 450 mM NaCl (Alhdad and Flowers, 2021). Its leaf ethanolic extract has high antibacterial and antioxidant activities (Beulah et al., 2021), whereas hexan extract among other extracts shows the highest antibacterial activity with the potential to treat infectious diseases owing to the presence of high bioactive compounds (Bilal and Hussain, 2019).

Soil salinity is a disruptive agent that significantly decreases plant progress and yield. In the last decade, huge areas of tillage in semiarid and arid regions have been impacted by salinity and harmful heavy metals. Halophytes are the best

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nominee for bioremediation of heavy metal polluted saline soils (Liang et al., 2016). The majority of salt marsh plants restore high levels of metals in their aerial organs and/or stabilize them in the rhizosphere (Nawaz et al., 2017; Wiszniewska et al., 2018). *Aeluropus lagopoides*, *Arthrocnemum macrostachyum*, *Atriplex stocksii*, *Avicennia marina*, *Cressa cretica*, and *Suaeda fruticosa* have been shown to be capable of cleaning metals (Mn, Zn, Pb, and Cr) from polluted soil (Mujeeb et al., 2021). Wang et al. (2021) recommended *Suaeda salsa* cultivation with drip-irrigation as an effective strategy for saline soil reclamation, where its shoot contained more than one fifth of its dry weight as ash, and Cl^- and Na^+ were the major contributions.

Heavy metals are elements with high mass number and a density higher than 5 g/cm^3. Some of them in low concentrations are essential in many biological processes while the other (non-essential) are toxic even at low concentrations (Shah, 2021). They are non-expendable, can enter the food chain via crop plants, and ultimately may concentrate inside human body through bio-amplification. Thus, remediation of land contamination is of the highest priority (Yan et al., 2020). The heavy metals (Pb, Cr, Cd, Zn, and Cu) were accumulated in *Suaeda maritima* and *Sesuvium portulacastrum* cultivated in the soil treated with tannery sewage water (Samundeeswari and Lakshmi, 2018). *S. maritima* retained high inorganic ions under saline conditions and hypoxia related to osmotic stress (Behr et al., 2017). In plants, total phenolic content increases in response to heavy metals exposure depend upon metals type and their concentration (Kisa et al., 2016; Sharma et al., 2019). They are electrons-donors and vital antioxidants combined with metals (Sharma et al., 2019).

This study aims to investigate some physiological characters of *S. maritima* as affected by seasonal variations, in addition to studying the possibility of using *S. maritima* as phytoremediator.

Materials and Methods

Terminal shoots and roots of *Suaeda maritima* were fetched from two sites across the Damietta-Port Said coastal road in late February (winter season) and late June (summer season), 2019. Soil samples from (0-20 cm depth) was also collected. The GPS reading for the first site was 31° 12.222 N, 32° 17.117 E, and that for the second was 31° 22.722 N, 32° 57.975 E. Soil samples were air dried and sieved with ≥ 1mm screen. Mechanical analysis was done using hydrometer method (Bouyoucos, 1951). Electrical conductivity (EC) and cations and anions were checked in soil water extract (1:1). Soil moisture content, EC, K^+, Na^+, Mg^{++}, and Ca^{++} were measured using the protocol described in Rowell (1994). Chlorides were assessed using volumetric titration (standardized $AgNO_3$ in the presence of 5% potassium chromate as indicator (Skoog et al., 2012). Sulphates were determined using turbidity method (Rainwater and Thatcher, 1960). Bicarbonate was titrated with sulphuric acid 0.01N (Reitemeier, 1943).

Shoots and roots were dried in an oven at 55 ℃ for one week, then ground to fine powder to start analyses. Water content percentage of plant shoots and roots was calculated as TWC = 100 (Fw-Dw)/ Fw). Heavy metals in soil, shoots, and roots. Ca^{++} and Mg^{++} in both shoots and roots were calculated in acid digested samples using ICP (POEMSIII, thermo Jarrell elemental company USA), using 1g/l (Merck) stock solution to prepare standard. Both Na^+ and K^+ in shoots and roots were determined in wet ash samples using flame emission spectrophotometry as indicated by Harris (2007). Dry plant material was burned to ash at 550 ℃ in a muffle furnace for 6 hours to calculate total ash as (wt of ash/wt of sample) × 100 (Ismail, 2017). Chloride contents were estimated in ashes dissolved in nitric acid (Jackson and Thomas, 1960). Total phenols were extracted with 95% methanol and calculated against gallic acid standard using Folin-Ciocalteu reagent according to Ainsworth and Gillespie (2007). Translocation factor (TF) and bio-concentration factor (BCF) for heavy metals as average in *S. maritima* were calculated following Zabergja-Ferati et al. (2021) as following:

TF = metal concentration in shoots / metal concentration in roots

BCF = metal concentration in roots / metal concentration in soil

where the unit of measuring metals in shoots, roots and soil was mg kg^{-1}

Statistical Analysis

Data of each season were subjected to ANOVA (Casella, 2008) using Costate software program, Version 6.303, 2004 ($p<0.05$). Duncan test was used for distinguishing among the treatment means.

Results

Soil characters supporting *S. maritima*

The soil supporting *Suaeda maritima* was saline, alkaline, loamy sand at site 1 and sandy at site 2 (Table 1). In general, EC, soluble anions, and cations were higher in summer than in winter, recording higher values in those growing at site 1. Generally, soil moisture content increased in winter season to record the highest value in site 1.

Spatiotemporal dissemination of heavy metals in soil supporting *S. maritima*

Heavy metal sediments varied not only between sites but between seasons as well (Table 2). In general, Fe level was the highest (more than half of the total heavy metals) reaching up to 757 and 704 mg kg^{-1} at site 2 and site 1, respectively, in winter while the other detected metals were in the following order Fe > Al > Si > Mn > Zn > Cu > Cr > Ba > Mo > Pb > Co > V > Ni > Cd at site 1 and Fe

Table 1
Soil characters substantiating *S. maritima*

a. Soil particle distribution

Seasons	Sites	Sand %	Silt %	Clay %	Texture
Winter	Site 1	86	6	8	Loamy sand
	Site 2	90	2	8	Sandy
Summer	Site 1	84	8	8	Loamy sand
	Site 2	88	4	8	Sandy

b. Soil chemical properties

Seasons	Sites	$HCO3^{-}$ Meq/l	$SO4^{--}$ Meq/l	Cl^{-} Meq/l	Mg^{++} Meq/l	Ca^{++} Meq/l	K^{+} Meq/l	Na^{+} Meq/l	EC ds m^{-1}	pH	Moisture %
Winter	Site 1	2.50^{a}	53.88^{a}	117.5^{b}	10.00^{b}	31.5^{a}	7.16^{a}	125.22^{b}	16.44^{b}	7.66^{a}	11.38^{a}
	Site 2	1.55^{b}	22.56^{b}	56.0^{c}	5.25^{c}	11.5^{d}	2.44^{c}	60.87^{c}	7.51^{c}	7.59^{a}	5.92^{b}
Summer	Site 1	2.50^{a}	42.00^{a}	182.0^{a}	17.50^{a}	27.0^{b}	6.70^{a}	174.84^{a}	21.14^{a}	7.61^{a}	10.20^{a}
	Site 2	1.50^{b}	27.96^{b}	159.0^{a}	12.75^{b}	16.0^{c}	4.50^{b}	155.26^{a}	17.50^{ab}	7.85^{a}	4.99^{b}

Table 2
Heavy metals (mg kg^{-1}) in soil substantiating *S. maritima*

Items	Site 1		Site 2	
	Winter	Summer	Winter	Summer
Al	539.85^{a}	423.20^{b}	374.75^{b}	390.00^{b}
Ba	6.285^{a}	5.465^{a}	6.445^{a}	2.310^{b}
Cd	0.370^{a}	0.001^{b}	0.001^{b}	0.001^{b}
Co	0.670^{c}	2.560^{b}	1.745^{b}	5.755^{a}
Cr	9.795^{ab}	9.340^{b}	11.220^{ab}	12.595^{a}
Cu	17.795^{a}	12.120^{c}	13.830^{bc}	14.355^{b}
Fe	704.55^{ab}	624.15^{bc}	757.00^{a}	516.55^{c}
Mn	27.570^{bc}	25.990^{c}	30.540^{b}	35.035^{a}
Mo	3.500^{b}	2.730^{b}	16.170^{a}	0.001^{c}
Ni	0.266^{c}	1.645^{b}	0.010^{c}	5.190^{a}
Pb	4.305^{b}	2.280^{b}	19.185^{a}	17.850^{a}
Si	51.985^{b}	50.510^{b}	95.235^{a}	46.380^{b}
V	10.80^{a}	2.15^{d}	5.44^{b}	3.38^{c}
Zn	21.935^{d}	22.930^{c}	32.260^{a}	23.550^{b}
Total heavy	1388.612^{a}	1185.071^{b}	1363.832^{a}	1072.952^{c}

Table 3
Heavy metals (mg kg^{-1}) in shoots and roots of *S. maritima*

Items	Shoots				Roots			
	Site 1		Site 2		Site 1		Site 2	
	winter	summer	winter	Summer	Winter	summer	Winter	Summer
Al	2443.0^{c}	3401.0^{b}	1767.0^{d}	4638.5^{a}	1281.0^{c}	3748.5^{a}	2283.0^{b}	2042.5^{b}
Ba	22.360^{a}	12.035^{b}	3.185^{d}	5.940^{c}	10.385^{b}	30.850^{a}	2.615^{c}	3.680^{c}
Cd	2.580^{a}	0.370^{b}	0.390^{b}	0.001^{c}	0.001^{b}	0.001^{b}	0.450^{a}	0.001^{b}
Co	9.480^{c}	13.030^{a}	9.220^{c}	10.005^{b}	7.445^{d}	15.585^{a}	13.350^{b}	9.190^{c}
Cr	12.395^{d}	17.880^{c}	40.540^{b}	57.070^{a}	12.185^{d}	25.110^{c}	38.505^{b}	56.595^{a}
Cu	19.770^{c}	43.085^{a}	13.075^{d}	24.745^{b}	33.095^{b}	54.540^{a}	15.980^{c}	12.180^{d}
Fe	3253.5^{c}	4475.0^{b}	3441.0^{c}	7185.5^{a}	1678.5^{d}	5648.5^{a}	4756.5^{b}	4147.5^{c}
Mn	245.55^{c}	426.40^{a}	197.05^{c}	310.45^{b}	274.45^{b}	442.50^{a}	213.80^{c}	254.05^{b}
Mo	2.800^{b}	3.780^{a}	2.800^{b}	0.030^{c}	3.330^{b}	8.420^{a}	0.001^{c}	0.001^{c}
Ni	32.81^{c}	54.53^{a}	34.54^{c}	43.99^{b}	49.80^{b}	73.06^{a}	31.81^{c}	24.91^{d}
Pb	12.810^{a}	2.970^{b}	0.001^{c}	0.001^{c}	25.400^{a}	13.000^{c}	16.895^{b}	24.905^{a}
Si	106.10^{b}	199.50^{a}	104.99^{b}	187.75^{a}	163.05^{a}	139.77^{b}	122.35^{bc}	105.76^{c}
V	43.85^{c}	68.73^{b}	50.01^{c}	91.645^{a}	57.13^{b}	100.41^{a}	49.505^{c}	62.17^{b}
Zn	34.385^{c}	65.86^{a}	32.3^{c}	54.54^{b}	48.785^{b}	79.82^{a}	23.85^{d}	29.815^{c}
Total	6241.39^{c}	8784.17^{b}	5696.10^{d}	12610.17^{a}	3644.56^{d}	10380.07^{a}	7568.61^{b}	6773.25^{c}

> Al > Si > Mn > Zn > Pb > Cu > Cr > Mo > Ba > Co > V > Ni > Cd at site 2. As compared seasonally, total heavy metals and most of them turned to increase in winter.

Heavy metals concentration in shoots and roots of *S. maritima*

Metal concentrations in shoots and roots are presented in Table 3. The highest levels of five metals in either shoots or roots of the plants in both two sits were Fe, Al, Mn, Si, and V in that order. Unlike soil, metal concentrations were higher in summer than in winter in shoots and roots. The highest accumulation in shoots was recorded in *S. maritima* growing at site 2 in summer while the highest accumulation in roots was recorded in plants growing at site 1 in summer. Indeed, the roots of *S. maritima* growing at site 1 in summer sequestered the highest Ba (30.85 mg kg^{-1}), Co (15.59 mg kg^{-1}), Mn (442.5 mg kg^{-1}), Mo (8.42 mg kg^{-1}), Ni (73.06 mg kg^{-1}), V (100.41 mg kg^{-1}), and Zn concentration (79.82 mg kg^{-1}). *S. maritima* had high Pb up to 25.4 mg kg^{-1} in roots at site 1 during winter. Cd was detected with low concentration in roots and shoots except in shoots at site 1 in winter (2.58 mg kg^{-1}).

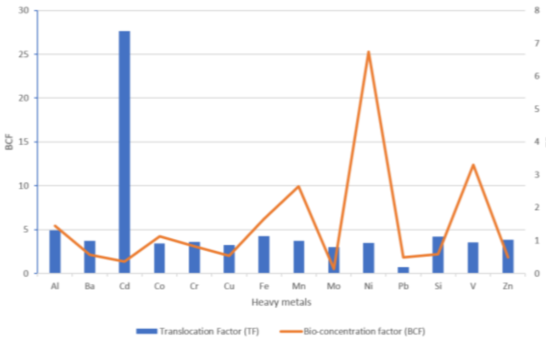

Fig. I. Translocation factors and bio-concentration factors of heavy metals in *S. maritima*

Translocation and bio-concentration factors of heavy metals

Translocation factor as average in *S. maritima* as >1 in Al (1.31), Cd (7.38), Fe (1.13), Si (1.13), and Zn (1.03) while it was <1 in Ba, Co, Cr, Cu, Mn, Mo, Ni, Pb, Si, and V (Fig. I).

Regarding bio-concentration factor, all detected metals were >1 except Mo. The BCF can be arranged in descending order as Ni (25.25) > V (12.36) > Mn (9.94) > Fe (6.23) > Al (5.41) > Co (4.25)> Cr (3.08)> Si > Ba > Cu > Pb > Zn > Cd > Mo.

Table 4
Water content%, Na%, K%, Ca%, Mg%, Cl%, total ash%, and total phenols (mg $100g^{-1}$) in shoots and roots of *S. maritima*

Items	Shoots				Roots			
	Site 1		Site 2		Site 1		Site 2	
	winter	summer	Winter	summer	winter	summer	Winter	Summer
Water content	75.46^{b}	68.01^{d}	81.54^{a}	71.20^{c}	53.39^{a}	48.30^{c}	49.48^{b}	48.32^{c}
Na	6.18^{b}	6.03^{bc}	5.35^{c}	7.23^{a}	0.49^{c}	0.95b^{c}	1.09^{b}	2.18^{a}
K	0.405^{a}	0.431^{a}	0.412^{a}	0.334^{a}	0.284^{a}	0.219^{b}	0.279^{a}	0.133^{c}
Ca	3.859^{ab}	4.230^{ab}	1.798^{b}	4.590^{a}	4.129^{a}	4.451^{a}	1.215^{b}	1.318^{b}
Mg	0.639^{ab}	0.952^{a}	0.225^{b}	0.690^{ab}	0.709^{b}	1.320^{a}	0.216^{c}	0.177^{c}
Cl	5.11^{b}	5.70^{a}	4.12^{d}	4.47^{c}	0.99^{c}	0.55^{d}	1.55^{b}	2.77^{a}
Total ash	22.31^{a}	21.08^{b}	23.05^{a}	20.41^{b}	6.67^{c}	6.25^{c}	23.07^{a}	14.37^{b}
Total phenols	333^{c}	1129^{b}	270^{c}	1347^{a}	329^{c}	358^{b}	184^{d}	495^{a}

Water, phenols, and ash contents, and major elements in shoots and roots

Generally, water content tended to increase in winter shoots and roots of *S. maritima* with the highest values recorded in plants at site 2 for shoots and plants at site 1 for roots (Table 4).

On the opposite side, total phenols were higher in summer with the highest accumulation recorded in *Suaeda* at site 2 (1347.33 and 494.67 mg $100g^{-1}$) in shoots and roots, respectively.

Ash content was higher in winter season in shoots and roots, recording the greatest value in plants growing at site 2. Sodium attained the highest sequestration in shoots and roots of *Suaeda* growing at site 2 in summer (7.23 and 2.184%), respectively. Potassium was not affected significantly in shoots while in roots the highest value was recorded in plants at site 1 in winter. Calcium content was not affected seasonally in roots, recording higher accumulation in those at site 1 while in shoots the highest amount (4.59%) was in plants at site 2 in summer. Regarding Mg, the highest values were observed in plants at site 1 during summer in shoots (0.952%) and roots (1.32%). In general, Cl tended to increase in summer in both shoots and roots. The highest values were (5.70%) in summer shoots at site 1 and (2.77%) in summer roots at site 2.

Discussion

Suaeda maritima naturally grows at saline alkaline soils, either sandy or loamy sand, in the northern border of Egypt. Higher levels of EC value in summer were due to higher evaporation that concentrates salts in upper soil surface. These results are in line with those obtained by Abd El-Maboud (2021). The reduction in total heavy metals and most of them in soil during the summer resulted in their higher uptake by roots and accumulation in both shoots and roots in this season. Similar results were obtained by Mujeeb et al. (2021) on some halophytes *viz*., *Suaeda fruticosa* and *Cressa cretica*. Heavy metals are imperishable, can potentially enter the food chain via crop plants, and subsequently may accumulate in the human body through biamplification. Due to their dangerous nature, heavy metal contaminants pose a serious risk to human health and the ecosystem (Yan et al., 2020). Thus, remediation of land contamination deserves further attention all over the world. Possibility of manipulating green plants in phytoremediation relies on their ability to suck up metals from rhizosphere and conduct to shoots. In our study, *S. maritima* was highly efficient to accumulate high ash content, Na, Cl, and other metals in its shoots and roots, and they may be highly endorsed as effective phytoremediators. Despite low concentration of Cd in soil at site 1 during winter, it is toxic for plants. The presence of Pb at high concentrations up to 19.185 mg kg^{-1} indicates soil contamination. The metals Cd, Co, and Pb still lack any physiological activity, so their presence even at low concentrations is highly toxic. In this respect, Vadyanitskii (2016) classified Cd, Pb, and Zn as highly hazardous elements and Ni, Co, Cr, and Mo as moderately hazardous. Lifelong exposure to Cd is associated with renal dysfunction in human. In fact, high exposure can cause disruption in kidney functions, heart disease, and Alzheimer's disease (Satarug et al., 2020). The high translocation factor for Cd in *S. maritima* reflects its danger as it is easily absorbed by roots and is translocated to shoots fast. Cr (VI) is hazardous even at low amounts which disperse via the epidermis and reduces to Cr (III) that impacts on nuclear enzymes, nucleotides, proteins, and DNA (Kojima and Machida, 2020). In China, the highest permitted concentrations of Cd, Cr, and Pb in vegetables are 0.2, 0.5, and 0.2 mg/kg (Pan et al., 2016). In the current paper Cr reached > 56 mg kg^{-1} in shoots and roots of *S. maritima* at site 2 in summer, indicating that the studied species has phytoremediation power for Cr. The presence of Fe, Al, and Si with high concentrations in soil is attributed to their wide range of industrial applications. Fe has been reported as an essential nutrient which has some physiological functions such as respiration, DNA synthesis, and photosynthesis. Also, it is required for the upkeep of chloroplast structure and function (Rout, 2015). Si can be used in agriculture due to its useful effects via improved quality, increased productivity, response to exogenous stresses (Hoffmann et al., 2020) and motivation of K uptake under salt stress (Yan et al., 2021). Despite high concentrations of Al present in *S. maritima* and associated soil, it has no established biological function and is considered as a non-essential metal (Chang et al., 1996). Most of the heavy metals in *S. maritima* have higher concentrations in roots than shoots. Similar finding has been reported by Mukherjee et al. (2021). They found Mn, Pb, and Cu were accumulated more in roots of *Suaeda maritima* and *Salicornia brachiata* than in shoots and leaves and ordered them as Mn > Cu > Pb. In the current research, *S. maritima* had TF and BCF > 1 in Al, Cd, Fe, Si, and Z. Hence, *S. maritima* is capabale of being used for phyto-extraction of these metals.

The increase in water contents of shoots and roots during winter is associated with high soil moisture content and low salinity level. Similar conclusion was reported by Abd El-Maboud (2021). The stability of ash content in shoots in the two study sites indicates that *S. maritima* can accumulate ash by salinity in their shoots to reach optimum value under certain saline degree and keep stability whenever salinity increases more. While roots were negatively affected by salinity in terms of ash content, Na and Cl in shoots of *S. maritima* responded positively to soil salinity. This result agreed with Abd El-Maboud (2021) who observed powerful positive relation between EC and both Na and Cl contents in shoots of *Salicornia europaea*. On the other hand, Na and Cl accumulation in roots are not associated with salinity degrees. Both Ca and Mg play significant roles in adaptation strategies to salinity either in shoots or in roots of *S. maritima*. Our results are in line with those obtained by Abd El-Maboud and Abdelbar (2020) who declared Ca and Mg were greater in *Limoniastrum monopetalum* leaves growing in salt marshes to reduce the damaging effect of NaCl.

Total phenols are highly responsive to drought and/or salinity in *S. maritima* either in shoots or roots. This means they play a significant role in defense mechanism against abiotic stress. Phenols do not only act as secondary metabolites but antioxidant compounds as well. Our results are in line with those recorded by many authors (Abd El-Maboud, 2019; Abd El-Maboud and Abdelbar, 2020; Abd El-Maboud and Elsharkawy, 2021). In the current paper, total phenols are fit in with total heavy metals accumulation in shoots (the highest values of both at site 2 in summer) that support the pivotal role of phenolic compounds in restricting reactive oxygen result in heavy metals stress. In this trend, Kisa et al. (2016) reported that total phenolic compounds increased significantly as heavy metals increased; nevertheless, these increases depend on heavy metal types and their level. Also, Chen et al. (2019) observed that phenolic compounds in leaves and roots of *Kandelia obovata* are affected positively by increasing Zn or Cd concentrations.

Conclusion

S. maritima is capable of sequestering multiple metal ions and major elements in their shoots and roots, which can be recommended as a promising candidate used in phytoremediation of saline soil tainted with heavy metals. It has the potential to be a phytostabilizer to Ba, Co, Cr, Cu, Mn, Ni, Pb, and V and phytoextractor to Al, Cd, Fe, Si and Z. Total phenols show vital role in abiotic stress tolerance in *S. maritima*.

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