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Potential Use of Halophytes in Combination with Gypsum to Reclaim and Restore Saline-Sodic Soils in Egypt

Abdel-Fattah, M.K.

Soil Science Department, Faculty of Agriculture, Zagazig University, Egypt

ABSTRACT

A pot experiment was conducted under greenhouse conditions to assess the impact of three halophyte species, *Atriplex halimus, Atriplex lentiformis,* and *Atriplex amnicola*, coupled with or without gypsum, on salt accumulation from excessive saline-sodic soil from the Sahl El-Tina plain, North West coast of Sinai, Egypt. All halophyte species ameliorated the soil at the end of their growth. Soil salinity and sodicity decreased particularly when combined with gypsum. Soil salinity decreased from 51.2 (initial soil salinity) to 8.10, 12.10, 10.14, 4.10, 7.10 and 5.14 mS/cm using *A. halimus, A. amnicola, A. lentiformis, A. halimus + gypsum, A. lentiformis + gypsum,* and *A. amnicola* + gypsum, respectively. Sodium adsorption ratio (SAR) decreased from 31.1 to 4.10, 5.01, 4.58, 2.91, 3.84 and 3.26, whilst exchangeable sodium percentage (ESP) decreased from 35.9 to 4.83, 6.19, 5.56, 3.07, 4.44 and 3.59 using *A. halimus, A. amnicola, A. lentiformis, A. halimus + gypsum, A. lentiformis + gypsum,* and *A. amnicola* + gypsum, respectively. The most efficient treatments that enhanced soil characteristics were A. halimus + gypsum, followed by *A. amnicola* + gypsum, *A. lentiformis* + gypsum, *A. halimus, A. amnicola,* and *A. lentiformis.*

Keywords: **Greenhouse study, gypsum halophytes, greenhouse study, reclamation, phytoremediation, saline-sodic soil**

INTRODUCTION

Soil salinity, a widespread environmental problem, particularly in arid and semi-arid regions of the world, affects a quarter to a third of all crop producing agricultural land on earth (Szabolcs, 1989; Rengasamy, 2010). Salt-affected soils occupy more than 20% of global irrigated cropping areas (Szabolcs, 1994; Ghassemi *et al.*, 1995).

Adding gypsum is the most common amendment used to overcome soil sodicity hazards due to its low cost, availability, and ease of handling (Siyal *et al.*, 2002). Miyamoto and Enriquez (1990) pointed out that gypsum decreased sodicity and salinity in a percolating solution and allowed the maintenance of a relatively uniform hydraulic gradient throughout the soil profile. Abdurrahman *et al*. (2004) found that the application of gypsum followed up with the application of municipal solid compost restored degraded sodic soils. The application of

*Corresponding author : E-mail: mohammedkamal8@yahoo.com

gypsum also decreased pH, electrical conductivity (EC), exchangeable sodium percentage (ESP), and bulk density (Manzoor *et al*., 2001). Conversely, the addition of gypsum increased soil hydraulic conductivity and infiltration rate (Abdel-Fattah, 2011). These results are consistent with the findings of Gupta *et al.* (1988) who state that gypsum application to a sodic vertisol at different rates and frequencies decreased soil pH, EC and ESP. Furthermore, Abou Yuossef (2001) stated that using phosphogypsum (PG) decreased pH, EC, ESP and decreased bulk density with increasing PG supply, but increased soil hydraulic conductivity, total porosity, mean weight diameter of soil aggregates, geometric mean diameter, and water stable aggregates.

A halophyte is a hydrophobic plant that is capable of surviving in a highly saline environment. Halophytes can grow in salt marshes, live on cliffs and dunes near the oceans, and adapt to the desert environments. Nevertheless, Custódia Gago et al. (2011) found that 20% of halophytic plant species, mainly glycophytes, cannot survive in saline environments. Halophytes adopt salinity tolerance mechanisms such as salt exclusion, uptake, compartmentalisation and extrusion (Holly, 2004). While the physiological uniqueness of halophytes is often expressed in morphological features such as salt glands, salt hairs, and succulence, they evolve different mechanisms to deal with excess sodium and other salts in their environments (Holly, 2004; Naidoo and Naidoo, 1999). Some vascular halophytes accumulate high levels of salts in their above-ground parts (Gorham *et al*., 1987). Thus, functioning halophytes are ion accumulators and ion excreters, to be able to phytoremediate excess soil salinity and sodicity. Rush and Epstein (1981) found that, as an adaptation mechanism to saline environments, ion accumulators (hyperaccumulators) absorb high amounts of ions. The accumulation of salts reduces the requirements for increased wall extensibility, leaf thickness, and water permeability required to maintain positive growth and turgor at low soil water potentials. The objective of this study was to examine amelioration of a saline-sodic soil in Egypt using halophyte plants and gypsum.

MATERIALS AND METHODS

A pot experiment was conducted under greenhouse conditions using clay saline-sodic soil collected from the 0-30 cm topsoil of the Sahl El-Tina plain, north-west coast of Sinai, Egypt. Closed bottom plastic pots of internal dimensions 25 × 20 cm were filled with 10 kg of the collected soil. The experiment assessed the reclamation of soil using three halophyte Atriplex species of *A. halimus, A. lentiformis, A. amnicola* and the combination of each with gypsum. Therefore, there were six treatments executed in a randomised complete block design, and the three replicates were as follows: *A. halimus, A. amnicola, A. lentiformis, A. halimus + gypsum, A. lentiformis + gypsum,* and *A. amnicola* + gypsum. Images and classifications of *A. halimus, A. lentiformis* and *A. amnicola* are shown in *Figure 1*. Gypsum was added until its final concentration was 33.5 g kg^{-1}. This was calculated to adapt the ESP of the soil to 10% in line with the United States

Image of halophyte plant	Classification of halophyte plant
 *Atriplex halimus*	Kingdom Plantae – Plants Subkingdom Tracheobionta – Vascular plants Superdivision Spermatophyta – Seed plants Division Magnoliophyta – Flowering plants Class Magnoliopsida – Dicotyledons Subclass Caryophyllidae Order Caryophyllales Family Chenopodiaceae – Goosefoot family Genus Atriplex L. – saltbush Species *Atriplex halimus* L. – saltbush
 *Atriplex lentiformis*	Kingdom Plantae – Plants Subkingdom Tracheobionta – Vascular plants Superdivision Spermatophyta – Seed plants Division Magnoliophyta – Flowering plants Class Magnoliopsida – Dicotyledons Subclass Caryophyllidae Order Caryophyllales Family Chenopodiaceae – Goosefoot family Genus Atriplex L. – saltbush Species *Atriplex lentiformis* (Torr.) S. Watson – big saltbush
 *Atriplex amnicola*	Kingdom Plantae – Plants Subkingdom Tracheobionta – Vascular plants Superdivision Spermatophyta – Seed plants Division Magnoliophyta – Flowering plants Class Magnoliopsida – Dicotyledons Subclass Caryophyllidae Order Caryophyllales Family Chenopodiaceae – Goosefoot family Genus Atriplex L. – saltbush Species *Atriplex amnicola* Paul G. Wilson – swamp saltbush

Sources:http://plants.usda.gov/java/ClassificationServlet?source=profile&symbol=ATRIP&display=31
https://commons.wikimedia.org/wiki/Category:Atriplex

Figure 1: Images and classification of studied A. halimus, A. lentiformis and A. amnicola

of America's Department of Agriculture's (USDA) (1954) guidelines. Gypsum application was done by mixing it with soil before filling the pots. Seedlings were transplanted in the pots. Water supplied to plants in the pots was maintained at water holding capacity of the soils. After 6 months, at the end of the experiment, the plants and soils were analysed according to the methods described by the USDA (1954) and the studies of Van Reeuvijk (2002) and Piper (1950).

RESULTS AND DISCUSSION

Initial Soil Properties

The physical and chemical properties of soil are presented in Table 1. In accordance with the guidelines of the USDA (1954), the soil was classified as saline-sodic as (i) the EC of its saturation extract exceeded 4 mS cm^{-1}; (ii) ESP exceeded 15; and (iii) pH was 8.40. This may be attributed to the extremely high soluble Mg^{2+} and Na^+ contents. Soluble sodium was the dominant cation, constituting approximately half of the soluble cations. Cations found, listed in the order of decreasing propotion, were $Na^+ > Mg^{2+} > Ca^{2+} > K^+$. On the other hand, chloride was the major anion. Anions found, listed in the order of decreasing proportion were $Cl^- > SO_4^= > HCO_3^-$. Exchangeable cations found, listed in the order of decreasing proportion, were $Na^+ > Mg^{2+} > Ca^{2+} > K^+$. The soil had a clay texture, was low in organic matter and contained 94 g $CaCO_3$ kg^{-1}.

TABLE 1
Physical and chemical properties of studied soil

Property	Value
Texture class	Clay
Organic matter [g kg^{-1}]	5.3
$CaCO_3$ [g kg^{-1}]	94
Soluble ions, EC_e and pH:	
▪ EC (mS cm^{-1})**	51.2
▪ pH [Soil suspension 1:2.5]	8.68
Soluble ions ($mmol_c$ L^{-1})	
▪ Na^+	588.9
▪ K^+	26.4
▪ Ca^{++}	151.9
▪ Mg^{++}	564.0
▪ Cl^-	1126.1
▪ HCO_3^-	9.7
▪ $SO_4^=$	195.4
▪ SAR	31.1
Exchangeable cations and CEC ($cmol_c$ kg^{-1})	
▪ Na^+	11.3
▪ K^+	2.8
▪ Ca^{++}	7.4
▪ Mg^{++}	10.0
▪ CEC ($cmol_c$ kg^{-1})	31.5
▪ ESP	35.9

** measured in soil paste extract

Soil Properties at the End of the Experiment

Halophytes with or without gypsum decreased soil salinity, soil pH, soluble ions, SAR and ESP (Table 2). Electric conductivity decreased from 51.2 (initial soil salinity) to a range between 4.10 to 12.10 mS cm^{-1}. These results were obtained for *A. halimus, A. amnicola, A. lentiformis, A. halimus* + gypsum*, A. lentiformis* + *gypsum,* and *A. amnicola* + gypsum with reduced ECs of 8.10, 12.10, 10.14, 4.10, 7.10 and 5.14 mS cm^{-1} respectively with a p value of < 0.05. Thus the efficiency of *A. halimus* + gypsum*, A. amnicola* + gypsum*, A. lentiformis* + gypsum*, A. halimus, A. amnicola, A. lentiformis* at decreasing soil salinity were 92, 90, 86, 84, 80 and 76 %, respectively. These results agreed with the findings of Le Hou´erou (1992) who stated that A. halimus is a highly drought resistant and salt tolerant crop, which can be used to ameliorate saline soils and provide periodical removal of extracted salts. *A. halimus* is characterised by the presence of vesiculated hairs (trichomes) on the leaf surface, which collect water from the atmosphere and secrete salts, and upon bursting, the water and salts can be seen on the surface of its leaves (Mozafar and Goodin, 1970). Combining the halophytes with gypsum enhanced the soil's characteristics by liberating adsorbed Na^+ on the soil exchange complex, which leave the exchange sites due to the Ca^{2+} from applied gypsum. As for the other soluble sodium and chloride, the same trend was observed.

TABLE 2

Some chemical soil properties of soil at the end of experiment

Treatment	EC_e ± SE	pH ± SE	Cations ($mmol_c$ L^{-1}) ± SE				Anions ($mmol_c$ L^{-1}) ± SE			SAR ± SE	ESP ± SE
			Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	HCO_3^-	$SO_4^=$		
T1	8.10c ±0.04	8.63a ±0.05	19.94c ±0.22	13.69c ±0.13	31.17c ±0.05	16.20c ±0.05	69.73c ±0.21	3.89c ±0.06	7.38bc ± 0.62	4.10c ±0.05	4.83c ±0.07
T2	12.10a ±0.02	8.65a ±0.01	29.78a ±0.18	20.45a ±0.08	46.56a ±0.51	24.20a ±0.02	104.16a ± 0.12	5.81a ±0.05	11.02a ± 0.39	5.01a ±0.05	6.19a ±0.07
T3	10.14b ±0.09	8.63a ±0.02	24.96b ±0.25	17.14b ±0.05	39.02b ±0.57	20.28b ±0.03	87.29b ± 0.02	4.87b ±0.05	9.24ab ±0.94	4.58b ±0.02	5.56b ±0.03
T4	4.10f ±0.08	7.88c ±0.06	10.09f ±0.32	6.93f ±0.05	15.78f ±0.36	8.20f ±0.03	35.29f ± 0.03	1.97d ±0.00	3.74e ± 0.73	2.91f ±0.07	3.07f ±0.10
T5	7.10d ±0.03	8.12b ±0.06	17.48d ±0.02	12.00d ±0.01	27.32d ±0.19	14.20d ±0.12	61.12d ±0.08	3.4c ±0.09	6.47cd ± 0.47	3.84d ±0.02	4.44d ±0.03
T6	5.14e ±0.03	8.10b ±0.02	12.65e ±0.01	8.69e ±0.06	19.78e ±0.18	10.28e ±0.03	44.25e ± 0.49	2.47d ±0.57	4.68de ± 0.78	3.26e ±0.01	3.59e ±0.02

Notes: Means with the same letter are not significantly different, T1 = *A. halimus*, T2 = *A. lentiformis*, T3 = *A. amnicola*, T4 = *A. halimus* + gypsum, T5 = *A. lentiformis* + gypsum, T6 = *A. amnicola* + gypsum, and SE refers to Standard Error

With regard to soil pH, soils treated with gypsum showed lower values. Initial soil pH was 8.68, but by the end of the experiment, this value was reduced to 8.63, 8.65, 8.63, 7.88, 8.12 and 8.1 for treatments of *A. halimus, A. amnicola, A. lentiformis, A. halimus* + gypsum *, A. lentiformis* + gypsum*, A. amnicola* + gypsum, respectively. Gypsum application led to the replacement of Na^+ by Ca^{2+} on the soil exchangeable complex, which decreased pH (Abdel-Fattah, 2011).

Gypsum solubility was enhanced due to the increased activity coefficient of Ca^{2+} and SO_4^{2-} as a result of the increased ionic strength of the soil solution, and the formation of sodium sulphate ion pairs. Additionally, most of the CO_2 would have dissolved in the ground water to form carbonic acid.

With regard to soil sodicity, ESP and SAR at the end of experiment were lower than their initial values. ESP at the end of the experiment varied from 3.59 to 4.83 compared with its initial value of 35.9. The efficiency ranking of treatments, in decreasing order, was *A. halimus* + gypsum*, A. amnicola* + gypsum*, A. lentiformis* + gypsum*, A. halimus, A. amnicola, and A. lentiformis.* These results agreed wih the findings of Robbins (1986), Qadir and Oster (2002) and Qadir *et al.,* (2005) that halophytes increase calcite dissolution through their root activity resulting in adequate Ca^{2+} ions in soil solution, which replace exchangeable Na^+.

Fresh Weight, Dry Weight, Biomass and Ionic Concentration

The significant decrease in soil salinity was reflected in a high amount of soluble ions that were removed through the uptake by halophytes (Table 3) especially for Na^+ and Cl^- ions. Sodium ions removed by halophytes were 13.09, 12.86, 12.97, 13.31, 13.14 and 13.25-gram sodium per kilogram for *A. halimus, A. amnicola, A. lentiformis, A. halimus* + gypsum*, A. lentiformis* + gypsum*, A. amnicola* + gypsum, respectively. Removal of chloride ions showed a similar pattern in the plant tissues, in that their values increased and ranged from 37.5 to 38.41 gram chloride per kilogram.

TABLE 3

Fresh weight, dry weight, biomass and ionic concentration for halophytes species

Treatment	FW	DW	Biomass	Ions removal from soil by plant (g kg^{-1})						
	g pot^{-1}	g pot^{-1}	FW:DW	Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	HCO_3^-	$SO_4^=$
T1	156.80e	40.20f	3.90a	13.09d	0.50d	2.41d	6.57d	37.50d	0.35b	9.02cd
T2	250.85d	71.77d	3.50d	12.86f	0.23f	2.11f	6.48f	36.28f	0.24d	8.85e
T3	283.67b	78.67b	3.56cd	12.97e	0.36e	2.26e	6.52e	36.88e	0.29c	8.94de
T4	159.10e	42.42e	3.75b	13.31a	0.76a	2.72a	6.67a	38.72a	0.47a	9.20a
T5	255.23c	73.12c	3.49d	13.14c	0.56c	2.49c	6.60c	37.81c	0.38b	9.07bc
T6	293.25a	79.98a	3.67bc	13.25b	0.69b	2.64b	6.64b	38.41b	0.44a	9.15ab

Notes: Means with the same letter are not significantly different, FW = Fresh Weight, DW = dry Weight, T1 = *A. halimus*, T2 = *A. lentiformis*, T3 = *A. amnicola*, T4 = *A. halimus* + gypsum, T5 = *A. lentiformis* + gypsum, T6 = *A. amnicola* + gypsum and SE refers to Standard Error

Plants' dry weights at the end of the experiment were 40.20, 71.77, 78.67, 42.42, 73.12 and 79.98 g/pot for *A. halimus, A. amnicola, A. lentiformis, A. halimus + gypsum, A. lentiformis* + gypsum, *A. amnicola* + gypsum, respectively. A. halimus produced more biomass than *A. amnicola* and *A. lentiformis.* The biomass readings at the end of the experiment were 3.9, 3.5, 3.56, 3.75, 3.49 and 3.67 for *A. halimus, A. amnicola, A. lentiformis, A. halimus* + gypsum*, A. lentiformis* + gypsum*, A. amnicola* + gypsum, respectively. These results agreed with Munns (1993) and Munns *et al*. (1995) who found that salts taken up by halophytes do not directly control their growth by affecting turgor, photosynthesis, or the activity of enzymes. It was the build-up of salts in old leaves, which hastened their death, and loss of leaves in turn affected the supply of assimilates or hormones to the growing organs and therefore affected plant growth. Additionally, the efficiency of *A. halimus* in increasing salt removal was reported with increasing salinity, especially for calcareous-sodic soils, as noted by Qadir *et al.* (2005) who found that phytoextraction is driven by: (i) enhanced Na^+ and salt uptake in shoots; and (ii) ability of roots to increase the dissolution rate of calcite, resulting in enhanced levels of Ca^{2+} in soil solution to replace Na^+ from the cation exchange complex. This process was enhanced by the pressure of CO_2 within the root zone.

CONCLUSIONS

Halophytes were effective for ameliorating saline sodic soils. Combining gypsum with halophytes helped to decrease soil salinity and sodicity by absorbing salts and liberating Na^+ on the soil exchange complex as a result of Ca^{2+} emanating from applied gypsum. The efficiency of the treatments in decreasing order was *A. halimus + gypsum, A. amnicola* + gypsum, *A. lentiformis* + gypsum*, A. halimus, A. amnicola, and A. lentiformis.*

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