Comparative Effects of Different Soil Amendments on Amelioration of Saline-Sodic Soils

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Abstract: A greenhouse experiment was conducted to test the potential of different soil amendments in saline-sodic soils reclamation; to affect the growth response of alfalfa (*Medicago sativa* L.) plants grown on two saline-sodic soils; and to evaluate the comparative efficiency of different soil amendments for their effects on salinity, sodicity, and pH levels of the soils. To achieve these objectives, two highly saline-sodic soils were selected (Abees, *Typic torrifluvents* and Elhammam, *Typic calciorthids*). Different soil amendments were used (compost, anthracite coal powder, water treatment residuals, ferrous sulphate, and a combination of them). The results of the study indicated that pH of Elhammam soil was less affected than pH of Abees soil after the amendment application because of the high calcium carbonate content which acted as a buffer and resisted any appreciable change in soil pH in the alkaline range. The positive effects of all treatments followed the order: T16 > T12 > T13 > T14 = T5 > T11 = T15 > T7 > T8 > T4 = T6 > T9 = T10 > T2 >T3> T1 >T0. The most effective amendment in reducing SAR_e in the experimental soils was T16. This was due to the presence of Al in WTRs and Fe in ferrous sulphate which enhanced the leaching process, and the presence of high adsorptive capacity materials like WTRs and compost which adsorb more sodium. The positive effects of all treatments for reducing SAR_e in Abees soil followed the order: T16 > T15 > T14 > T13 > T11 > T12 .While, in Elhammam soil, the order was: T16 > T15 > T14 > T13 = T11>T12 = T5. The removal sodium efficiency (RSE) or percentage of Na-removed from the soils at the end of the experiment was significantly reduced after the application of the amendments. RSE of T16 proved the highest value (76%) among the treatments for the two soils used, followed by T15 and T14. The yield of biomass at T16 significantly increased, the increase being 959% in comparison with T0 in Abees soil, while the increase in biomass yield was 1452% in comparison with T0 in Elhammam soil. However, field tests are necessary to draw the final conclusions.

Keywords: amendments; plant semi-colon salinity; sodicity; soil; yield

The reclamation of problem soils is a very important goal throughout the world, especially with saline or saline-sodic soils. Sodic and saline-sodic soils possess poor physical properties and fertility problems that adversely affect the growth and yield of most crops (Sumner 1993; Curtin & Naidu 1998; Grattan & Grieve 1999). The worldwide occurrence of such soils on 560 × 10^6 ha emphasises the need for efficient, inexpensive, and environmentally acceptable management. These soils can be ameliorated by providing a source of calcium (Ca^{2+}) to replace excess sodium (Na^+) from the cation exchange sites (Oster 1982; Shainberg & Letey 1984). The replaced Na^+ is leached from the root zone through leaching irrigation. Many sodic and saline-sodic soils, however, contain a source of Ca^{2+}, i.e. calcite ($CaCO_3$), at varying depths (Kovda *et al.* 1973). Owing to its extremely low solubility, this Ca^{2+} source does not contribute significantly to soil amelioration. The amelioration of saline-sodic and sodic soils with chemical amendments is an established technology (Shainberg *et al.* 1989; Gupta & Abrol 1990). Some amendments supply Ca^{2+} directly to the soil which then replaces excess exchangeable Na^+ while others help increase dissolution of calcite in calcareous sodic soils (Oster *et al.* 1999; Qadir *et al.* 2001).However, chemical strategies have become costly for subsistence farmers in the developing countries during the last two decades. Amendment costs have increased because of the increased use by industry and reductions in government subsidy to farmers for their purchase (Qadir & Oster 2002).

Saline-sodic soils reclamation is one of the main problems for humans in the future (Szabolcs 1994). The reclamation of saline soils uses many different methods such as physical amelioration (deep ploughing, subsoiling, sanding, profile inversion), chemical amelioration (amending of soil with various reagents: gypsum, calcium chloride, limestone, sulphuric acid, sulphur, iron sulphate), electro-reclamation (treatment with electric current). The most effective methods are based on the removal and exchange of soluble sodium and changing the ionic composition of soils by added chemicals with simultaneous leaching of sodium salts out of the soil profile (Chhabra 1994). The biological amelioration methods using living or dead organic matter (crops, stems, straw, green manure, barnyard manure, compost, sewage sludge) (Wang & Li 1990; Matsumoto *et al.*1994) – missing in References) have two principal beneficial effects on the saline and alkaline soils reclamation: the improvement of the soil structure and permeability, thus enhancing salt leaching, reducing surface evaporation, and inhibiting salt accumulation in the surface layers; and the release of carbon dioxide during respiration and decomposition. For saline or sodic soils, the addition of organic matter (OM) can accelerate the leaching of Na, decrease the ESP and electrical conductivity (EC), and increase water infiltration, water-holding capacity, and aggregate stability (Lax *et al.* 1994; Qadir *et al.* 2001). This is particularly important for agricultural soils deficient in OM, such as those in the Egypt region (1–3% OM). It seems that, by amending saline soil with a chemically stable organic material, effective as a permanent source of the organic matter of a high humification degree, the positive amelioration effects mentioned above can be reached in a single reclamation step. Such material of high CEC can adsorb part of soluble salts, decrease pH, and promote aggregation. The drop of pH below 8 can cause positive edge charging of clay minerals and electrostatic adsorption of the organic compounds. The physical adsorption and polyvalent cations bridging of high molecular weight compounds on inorganic surfaces can additionally stabilise the newly formed aggregates. The selection of reclamation agents should take into account not only their influence on the soil itself, but also their price and environmental hazard. It seems that black or brown coal powders can be satisfactory agents. The synergic reclamation effect can possibly be reached by combining the coal with Al or Fe sulphate additions. Also, water treatment residuals (WTRs) are by-products of drinking water clarification using alum ($Al_2(SO_4)_3 \cdot 14H_2O$).

The purposes of the present work were: (1) to test the potential of different soil amendments in saline-sodic soils reclamation; (2) to compare the growth response of alfalfa plants grown on two saline-sodic soils; and (3) to evaluate the comparative efficiency of different soil amendments for their effects on salinity, sodicity, and pH levels of the soils.

MATERIALS AND METHODS

Soil and amendments

Two soil types were selected for this study: The soils were collected from a depth of 0–20 cm at each sampling location. One of the selected soils was collected from a farm at Almowazafeen, in the region of Abees (*Typic torrifluvents*), Alexandria, Egypt. The second one was collected from Elhammam farm (*Typic calciorthids*), Mersa Matrouh, Egypt. Both samples were saline-sodic soils. The samples were air-dried and sieved through a 2-mm sieve prior to the greenhouse experiment and soils analysis. Sub-samples of the air-dried soil were used for the following chemical parameters: pH and electrical conductivity (EC) was determined in soil-paste extract (Richards 1954). The organic matter content was determined by dichromate oxidation method (Nelson & Sommers 1982). Exchangeable sodium and cation exchange capacity (CEC) was determined by IM NaOAc method (Rhoades 1982). The particle size distribution was determined by the hydrometer method (Day 1965). Calcium carbonate content was determined using calcimeter (Nelson 1982). The main properties of the soils are shown in Table 1.

The compost consisted of animal wastes and plant residues and was obtained from the Soil Salinity and Alkalinity Research Laboratory, Elsabahia, Alexandria, Egypt. The characteristics of the compost used were determined according to the standard procedures described by Bertran-Kehres and Andrease (1994) and El-Kouny (1999).

Table 1. Physio-chemical characteristics of the soils and amendments used

Parameter	Abees	Elhammam	Compost	Coal	WTRs
pH (H_2O)	8.75 ± 0.09	8.62 ± 0.33	6.88 ± 0.54	4.72 ± 0.28	7.45 ± 0.06
EC (dSm^{-1})	5.11 ± 0.34	4.03 ± 0.55	7.24 ± 0.86	3.26 ± 0.22	1.67 ± 0.04
CEC (Cmol/kg)	25.26 ± 1.45	19.54 ± 1.56	190.00 ± 8.12	201.00 ± 6.34	34.78 ± 0.34
Clay (g/kg)	341.20 ± 9.22	159.00 ± 3.50	nd	nd	nd
Silt (g/kg)	104.90 ± 4.23	101.00 ± 1.89	nd	nd	nd
Sand (g/kg)	553.90 ± 5.87	740.00 ± 3.70	nd	nd	nd
Texture	SCL	SL	nd	nd	nd
$CaCO_3$ (g/kg)	62.30 ± 3.33	181.30 ± 11.12	nd	nd	nd
SAR	29.21 ± 1.11	22.31 ± 2.78	nd	nd	nd
ESP (%)	37.04 ± 2.00	33.64 ± 2.33	nd	nd	nd
OC (g/kg)	11.95 ± 0.99	5.30 ± 0.88	402.50 ± 9.23	290.10 ± 5.44	33.06 ± 0.11
OM (g/kg)	20.60 ± 0.78	9.12 ± 0.66	693.90 ± 12.11	500.11 ± 11.12	57.00 ± 2.00
Total N (g × kg)	nd	nd	27.50 ± 1.07	8.23 ± 0.87	4.20 ± 0.13
Total P (g × kg)	nd	nd	17.50 ± 0.99	15.65 ± 0.44	1.90 ± 0.15
Total K (g × kg)	nd	nd	19.00 ± 1.05	13.98 ± 0.95	2.20 ± 0.21
C/N	nd	nd	14.64 ± 0.97	35.25 ± 1.55	7.87 ± 0.52

Means of three samples ± SD; EC – electrical conductivity; CEC – cation exchange capacity; SAR – sodium adsorption ratios; ESP – exchangeable sodium percentage; OC –organic carbon; WTRs – water treatment residuals; OM – organic matter; SCL – sandy clay loam; SL – sandy loam; nd – not determined

The alum-WTRs were collected from the drinking water treatment plant in Kafr El-Dawar, Elbohera Governorate, Egypt.The general physico-chemical properties of the soils, compost, anthracite coal powder, and WTRs are summed up in Table 1.

Experimental set-up

The greenhouse experiment was conducted with alfalfa (*Medicago sativa* L.) as a test plant in polyethylene pots, each containing 5 kg of soil. Soil amendments were well-mixed with the soil two weeks before the cultivation. The application of different soil amendments to the soil yielded a total of seventeen treatments, T0–T16:

T0: soil (control)
T1: soil + NPK (0.20g N, 0.20g P and 0.25 g K per kg soil)
T2: soil + NPK + anthracite coal powder (20 g/kg)
T3: soil + NPK + $FeSO_4{\cdot}7H_2O$ (6 g/kg)
T4: soil + NPK + WTRs (40 g/kg)
T5: soil + NPK + compost (10 g/kg)
T6: soil + NPK + anthracite coal powder + $FeSO_4{\cdot}7H_2O$
T7: soil + NPK + anthracite coal powder + WTRs
T8: soil + NPK + anthracite coal powder + compost
T9: soil + NPK + WTRs + $FeSO_4{\cdot}7H_2O$
T10: soil + NPK +compost + $FeSO_4{\cdot}7H_2O$
T11: soil + NPK +compost + WTRs
T12: soil + NPK + compost + anthracite coal powder + WTRs
T13: soil + NPK + anthracite coal powder + WTRs + $FeSO_4{\cdot}7H_2O$
T14: soil + NPK + anthracite coal powder + compost + $FeSO_4{\cdot}7H_2O$
T15: soil + NPK + compost + WTRs + $FeSO_4{\cdot}7H_2O$
T16: soil + NPK + compost + anthracite coal powder + WTRs + $FeSO_4{\cdot}7H_2O$

The soils were equilibrated with the respective amendments at 50% water holding capacity (WHC). The anthracite coal powder was used as a soil conditioner; it is chemically stable organic material and a permanent source of organic matter. The compost was used as a diverse source of organic matter. Drinking water treatment residuals (WTRs) were used as the source of Al from the by-products (alum-sludge containing aluminum sulphate). Sulphates of Al or Fe have also been reported to be effective in reclaiming Na-affected soils (Helalia & Letey 1988).

Seventy alfalfa plants per pot were seeded. At the 3rd leaf stage, some of the plants were removed for thinning to 50 plants per pot. Pots were then left in a greenhouse, receiving only natural light, for 10 weeks, and were watered weekly with distilled water to obtain 70% WHC after drainage of excess water. The experimental design was completely randomized, with four replicates in each treatment (136 pots). At 1, 37, and 75 days of the soil amendments application, the leachates from the pots were analyzed for EC and sodium. The over-ground plant material was harvested 10 weeks after sowing and the biomass yield was recorded. At the harvest, the soil in each pot was mixed and a sample was taken for the analysis of pH, EC, soluble cations, soluble anions, Exchangeable Na and CEC.

Sodium adsorption ratio (SAR)

Sodium adsorption ratio (SAR) was calculated by the following equation using the concentrations of Na^+, Ca^{+2}, and Mg^{+2} cations in meq/l:

$$SAR = C_{Na}/[(C_{Ca} + C_{Mg})/2]^{0.5}$$

Exchangeable sodium percentage (ESP)

Exchangeable sodium percentage was calculated as follows:

ESP = (exchangeable sodium concentration (cmol/kg)/cation exchange capacity (cmol/kg)) × 100

Removal sodium efficiency (RSE)

Removal sodium efficiency in percentage of Na-removed from soils at end of the experiment was calculated as follows:

$$RSE = \frac{(ESP_i - ESP_F) \times 100}{ESP_i}$$

where:

ESP_i – exchangeable sodium percentage before the soil amendments application

ESP_F – exchangeable sodium percentage after the soil amendments application at the end of the experiment

Statistical analysis

The one-way analysis of variance (ANOVA) was carried out to determine the statistical significance of the treatment effects on the crop yield, soil salinity, sodicity, and pH with the Fisher's least significant difference procedure at a significance level of 0.05 (SAS Institute 1994). Regression analysis was employed to determine the relationship between the soil salinity, ESP, and CEC in soils and crop yield.

RESULTS AND DISCUSSION

Characterisation of soils and amendments used

The soils used were: sandy clay loam (*Typic torrifluvents*) with moderate OM and calcium carbonate contents (Table 1). The soil was alkaline (pH = 8.75) and was classified as saline sodic-soil (EC > 4 dSm^{-1}, SAR > 13, ESP > 15) .The cation exchange capacity (CEC) was 25.26 $cmol_{(+)}$/kg. The other soil was sandy loam (*Typic calciorthids*), with a low OM and a high calcium carbonate contents (Table 1).The soil was alkaline (pH = 8.62) and was classified as saline sodic-soil. The cation exchange capacity (CEC) was 19.54 $cmol_{(+)}$/kg.

The compost had an EC value of 7.24 dSm^{-1} and CEC value of 190 cmol/kg. The EC of the compost was well below 10 dSm^{-1} and the CEC of the compost indicated its ability to supply cationic nutrients for the plant growth. In addition, the available amounts of macronutrients (N, P, and K) and organic matter were high. C/N ration was below 20 indicating that more released nutrients would be available during the experiment (Mosara & Roy 2008).

The anthracite coal powder used as a soil conditioner contained 29.10% carbon and moderate amounts of N, P, and K (Table 1). The C/N ratio was high, a chemically stable organic material, being a permanent source of the organic matter of a high humification degree, consequently, positive amelioration effects could be reached during this reclamation step.

The WTRs were slightly alkaline (7.45). The salinity of WTRs was well below 4 dSm^{-1} and the cation exchange capacity was 34.78 $cmol_{(+)}$/kg which indicated its ability to supply cationic nutrients for the plant growth (Bohn *et al.* 1985). Its organic matter content was greater than the typical levels in the soils studied (57.00 g/kg).

Changes in soil properties

Soil pH. Soil pH has a considerable impact on controlling the plant nutrients, particularly the availability of micronutrients (Naidu & Rengasamy 1993). The use of saline-sodic water on soils for agriculture without an amendment application, in general, tends to increase the soil pH that impacts the soil nutrient availability, rendering plants with malnutrition (Curtin & Naidu 1998). In this study, the data (Table 2) obtained after the harvest of alfalfa revealed significant differences between the treatments of the soils used. T2, i.e. anthracite coal powder treatment, tended to maintain the soil pH but the rest of the treatments decreased the pH value (Table 2). Cates *et al.* (1982) also reported a decrease in soil pH after the addition of soil amendments, especially gypsum, during reclamation of a calcareous saline-sodic soil. pH of Elhammam soil was less affected than pH of Abees soil after amendments application because of the high calcium carbonate content which acted as a buffer and resisted any appreciable change in soil

Table 2. The pH, exchangeable sodium percentage (ESP), and amount of exchangeable sodium removed following amendments application to the soils used

Treatment	Abees soil (ESP_i = 37.04)			Elhammam soil (ESP_i = 33.64)		
	pH	ESP_F	Na- removed (%)	pH	ESP_F	Na- removed (%)
T0	8.78 ± 0.11	36.90 ± 1.11	0.46	8.61 ± 0.07	33.11 ± 0.65	1.58
T1	8.83 ± 0.13	36.80 ± 0.89	0.65	8.72 ± 0.09	31.10 ± 0.90	7.55
T2	8.78 ± 0.09	28.90 ± 1.23	21.98	8.66 ± 0.12	26.11 ± 0.83	22.38
T3	8.08 ± 0.08	20.04 ± 0.76	45.90	8.47 ± 0.13	19.18 ± 1.15	42.98
T4	8.13 ± 0.14	13.59 ± 0.80	63.31	8.56 ± 0.12	13.10 ± 1.09	61.06
T5	7.92 ± 0.12	11.13 ± 1.12	69.95	8.09 ± 0.08	11.59 ± 1.87	65.55
T6	7.98 ± 0.09	14.81 ± 1.32	60.02	8.21 ± 0.13	13.68 ± 1.98	59.33
T7	7.82 ± 0.06	12.62 ± 0.88	65.93	7.94 ± 0.05	11.56 ± 0.98	65.64
T8	7.90 ± 0.02	13.02 ± 0.65	64.85	8.02 ± 0.14	12.03 ± 0.77	64.24
T9	7.93 ± 0.03	12.00 ± 0.76	67.60	8.06 ± 0.12	11.03 ± 0.76	67.21
T10	7.53 ± 0.09	13.80 ± 0.98	62.74	7.81 ± 0.06	12.12 ± 0.65	63.97
T11	7.61 ± 0.08	11.71 ± 0.23	68.39	7.92 ± 0.08	10.56 ± 0.98	68.61
T12	7.48 ± 0.04	11.01 ± 1.33	70.28	7.80 ± 0.07	9.54 ± 0.66	71.64
T13	7.44 ± 0.05	11.33 ± 1.22	69.41	7.70 ± 0.08	10.05 ± 0.76	70.12
T14	7.44 ± 0.02	10.00 ± 1.09	73.00	7.72 ± 0.05	9.08 ± 0.45	73.00
T15	7.46 ± 0.02	9.83 ± 0.98	73.46	7.75 ± 0.09	8.55 ± 0.97	74.58
T16	7.41 ± 0.06	8.91 ± 0.43	75.94	7.70 ± 0.05	8.11 ± 0.43	75.89
$LSD_{0.05}$	0.05	0.78	2.51	0.06	0.20	3.31

Means of four samples ± SD

pH in the alkaline range. In general, a high EC to SAR ratio tends to lower pH and vice versa (Ayers & Westcot 1985; Abrol *et al.* 1988; Ghafoor *et al.* 2001). Moreover, Miyamoto (1998) concluded that the much-publicised effects of lowering pH of soil and the resulting increase in the crop performance (probably associated with a better availability of some nutrients) are, however, questionable at least in most calcareous soils. The results of the current study coincide with the results of Deverel and Fujii (1990); Leoppert and Suarez (1997); Halvin *et al.* (2002); Anwar *et al.* (2004); Zia *et al.* (2006).

Soil salinity. Soil salinity (indirectly measured through EC) exerts osmotic effects on plants (Maas & Hoffman 1977; Grattan & Grieve 1999) and often causes physiological drought if the salinity levels are greater than the critical limits of the crop. The dissolved salt concentrations measured in leachates of the soils used at the beginning, mid-time, and end of the experiment are shown in Table 3 in terms of electrical conductivity. The dissolved salt concentrations measured in soil paste extract (EC_e) of the used soils at the end of experiments are shown in Figure 1A. Regarding soil salinity, the results from Abees sandy clay loam soil were similar to those of Elhammam soil (Table 3 and Figure 1A). In general, the EC_e (Figure1A) decreased as a result of all the treatments.Control, T0, and T1 soils showed maximum EC_e, which may be attributed to no treatment of soil and water. The EC_e of compost-WTRs-coal-ferrous sulphate-treated soils T16) was as low as that in the untreated soils (T0 and T1), whereas the EC_e in other treatments was higher than the EC_e of T16, but still lower than with the control treatments. The positive effects of all treatments followed the order: T16 > T12 > T13 > T14 = T5 > T11 = T15 > T7 > T8 > T4 = T6 > T9 = T10 > T2 >T3> T1 >T0. Also, salinity of the leachates from both untreated soils was very small at the initial time (0.20–0.25 dSm^{-1}) and reached 0.98–1.98 dSm^{-1} at the mid-time of the experiment, and further increased to 3.98–4.51 dSm^{-1} at the end of the experiment (Table 3). In general, salinity of leachates after the application of different soil amendments increased during the experiment (Table 3).This was due to the effectiveness of the soil amendments for removing salts from soils to leachates. So, the residues of salts in the soils used (EC_e) were lower at T16, the most effective treatment for reducing salinity (Figure 1A).

Based on the results obtained, a new method for saline and saline-sodic soils reclamation can possibly be outlined. The soil should be amended with black or brown coal powder, possibly as waste materials from coal mines, mixed with WTRs and ferrous sulphate and compost. The powder can be applied in the air dry state or as water suspensions. The presence of humus-like substances in the coal materials enriches the soil with stable organic matter of a high cation exchange capacity and aggregation properties. The high stability of coals can enable a slow release of humus-like compounds into the soil. Thus, the coal material may be regarded as a semi-permanent source of humus-like organic matter. Iron II sulphate can be applied simultaneously as water solution in doses equivalent to the doses of gypsum. Its hydrolysis and oxidation can lead to further reductions in the soil pH and the production of amorphous iron hydroxides, which serve as cementing agents. Iron industrial wastes can also be applied. Also, the addition of organic matter (OM) can accelerate the leaching of Na, decrease the ESP and the electrical conductivity (EC), and increase water infiltration, water-holding capacity, and aggregate stability (Lax *et al.* 1994; Qadir *et al.* 2001). Also, the addition of WTRs containing aluminum sulphate has been reported to be effective in reclaiming Na-affected soils or improving infiltration rates coinciding with the field study by Chand *et al.* (1977). Some laboratory studies indicate that the aggregating ability of Fe and Al is not stronger than that of Ca (e.g., Wada *et al.* 1983).

The amendments added should be mixed with the upper layer of the saline soil under reclamation. Further irrigation of the soil is not necessary. The interaction of the added materials with soil minerals and solutes should diminish toxic concentrations of salt and stabilise the aggregation state of the soil.

Soil sodicity. The sodium adsorption ratios of the saturation extracts (SAR_e) of the soils used are shown in Figure 1B). The SAR_e significantly decreased with the application of the amendments to the soils used. The most effective amendment in reducing SAR_e in the used soils was T16 (Figure 1B). This was due to the presence of Al in WTRs, Fe in ferrous sulphate which enhanced the leaching process, and the presence of high adsorptive capacity materials like WTRs and compost which adsorb more sodium. The positive effects of all treatments for reducing SAR_e in Abees soil followed the order: T16 > T15 > T14 > T13 > T11 > T12. While, in Elhammam soil, the order was: T16 > T15 > T14 > T13 = T11 > T12 = T5.

Table 3. Electrical conductivity (EC, dSm^{-1}) and soluble Na^+ (cmol/kg) in the leachates of soils at the beginning, mid-time, and end of the experiments after the application of various amendments

Treatment	Abees soil						Elhammam soil					
	beginning		mid-time		end		beginning		mid-time		end	
	EC	Na^+	EC	Na^+	EC	Na^+	EC	Na^+	EC	Na^+	EC	Na^+
T0	0.20 ± 0.04	1.14 ± 0.11	1.98 ± 0.22	2.18 ± 0.35	4.51 ± 0.12	4.88 ± 0.41	0.25 ± 0.05	0.89 ± 0.12	0.98 ± 0.22	2.11 ± 0.33	3.98 ± 0.54	4.55 ± 0.54
T1	0.43 ± 0.11	1.89 ± 0.23	2.23 ± 0.12	2.46 ± 0.54	4.68 ± 0.23	5.00 ± 0.33	0.34 ± 0.07	1.35 ± 0.33	1.22 ± 0.32	2.38 ± 0.62	4.12 ± 0.73	4.89 ± 0.69
T2	0.38 ± 0.13	1.98 ± 0.33	4.11 ± 0.21	2.50 ± 0.39	6.23 ± 0.34	5.12 ± 0.34	0.39 ± 0.08	1.87 ± 0.54	4.00 ± 0.12	2.41 ± 0.65	5.00 ± 0.36	5.00 ± 0.89
T3	0.50 ± 0.18	2.13 ± 0.43	4.23 ± 0.22	3.12 ± 0.38	6.42 ± 0.15	6.99 ± 0.23	0.45 ± 0.09	2.05 ± 0.45	4.12 ± 0.54	2.93 ± 0.45	5.12 ± 0.61	6.81 ± 0,79
T4	0.37 ± 0.09	2.18 ± 0.85	2.14 ± 0.44	3.34 ± 0.37	4.23 ± 0.51	7.40 ± 0.98	0.38 ± 0.06	2.10 ± 0.44	2.08 ± 0.65	3.19 ± 0.32	4.00 ± 0.72	7.20 ± 0.97
T5	0.28 ± 0.07	2.00 ± 0.44	1.88 ± 0.34	3.17 ± 0.73	4.04 ± 0.45	7.30 ± 0.66	0.26 ± 0.10	1.76 ± 0.65	1.56 ± 0.44	3.00 ± 0.44	3.76 ± 0.53	7.00 ± 0.87
T6	0.40 ± 0.10	2.08 ± 0.98	1.99 ± 0.34	3.48 ± 0.65	4.25 ± 0.54	7.45 ± 0.67	1.86 ± 0.44	1.87 ± 0.56	1.76 ± 0.65	3.32 ± 0.55	4.11 ± 0.73	7.21 ± 0.98
T7	0.46 ± 0.11	2.34 ± 0.88	2.14 ± 0.44	3.55 ± 0.12	4.67 ± 0.22	7.77 ± 0.65	2.00 ± 0.89	2.15 ± 0.77	2.00 ± 0.76	3.35 ± 0.33	4.42 ± 0.52	7.57 ± 0.78
T8	0.52 ± 0.12	2.71 ± 0.09	2.43 ± 0.23	3.76 ± 0.11	4.73 ± 0.56	7.82 ± 0.22	2.11 ± 0.08	2.33 ± 0.08	2.21 ± 0.08	3.45 ± 0.09	4.46 ± 0.33	7.85 ± 0.22
T9	0.97 ± 0.43	1.67 ± 0.96	2.94 ± 0.45	3.39 ± 0.32	4.80 ± 0.27	7.54 ± 0.67	2.87 ± 0/56	1.46 ± 0.66	2.75 ± 0.55	3.26 ± 0.22	4.56 ± 0.25	7.46 ± 0.88
T10	1.36 ± 0.13	3.99 ± 0.17	2.56 ± 0.53	4.15 ± 0.32	4.76 ± 0.33	7.75 ± 0.54	2.34 ± 0.87	1.79 ± 0.55	2.23 ± 0.33	3.02 ± 0.44	3.43 ± 0.52	7.18 ± 0.98
T11	1.07 ± 0.11	2.09 ± 0.08	2.01 ± 0.11	3.56 ± 0.22	3.81 ± 0.25	7.28 ± 0.44	2.18 ± 0.12	1.65 ± 0.09	2.30 ± 0.12	2.89 ± 0.07	4.53 ± 0.34	7.09 ± 0.11
T12	0.98 ± 0.04	1.89 ± 0.05	2.89 ± 0.12	3.22 ± 0.11	4.65 ± 0.53	7.12 ± 0.08	2.12 ± 0.09	1.52 ± 0.08	2.19 ± 0.13	2.80 ± 0.08	4.21 ± 0.23	7.01 ± 0.11
T13	0.88 ± 0.08	1.62 ± 0.07	2.76 ± 0.22	3.02 ± 0.06	4.72 ± 0.22	7.03 ± 0.06	2.75 ± 0.22	1.38 ± 0.08	2.65 ± 0.11	2.55 ± 0.09	4.43 ± 0.43	6.89 ± 0.08
T14	0.66 ± 0.08	1.71 ± 0.07	2.54 ± 0.21	3.22 ± 0.05	4.81 ± 0.34	7.16 ± 0.11	2.33 ± 0.23	1.53 ± 0.05	2.28 ± 0.12	2.73 ± 0.12	4.56 ± 0.45	7.01 ± 0.12
T15	1.12 ± 0.08	1.80 ± 0.06	3.11 ± 0.22	3.39 ± 0.08	4.89 ± 0.43	7.22 ± 0.13	2.39 ± 0.32	1.58 ± 0.04	2.53 ± 0.09	2.91 ± 0.09	4.76 ± 0.43	7.17 ± 0.07
T16	1.23 ± 0.23	2.00 ± 0.34	3.00 ± 0.66	4.11 ± 0.22	4.22 ± 0.31	8.12 ± 0.98	1.11 ± 0.56	1.65 ± 0.87	2.66 ± 0.43	3.98 ± 0.11	4.00 ± 0.28	8.00 ± 0.99
$LSD_{0.05}$	0.07	0.07	0.06	0.08	0.09	0.11	0.05	0.06	0.07	0.09	0.09	0.10

Means of four samples ± SD

The ratio of SARe to EC_e varied considerably with the treatments (Figure 1C). The control treatment manifested the smallest value of SAR_e/EC_e while the T16 treatment the largest one. It is probable that the fastest reclamation is attained when the amendments are chosen and applied so as to yield SAR_e/EC_e ratios below the threshold limit for hydraulic conductivity reduction at any depth of the soil profiles throughout the leaching period.

The exchangeable Na percentage (ESP) measured at the end of the experiment is shown in Table 2. ESP_f showed a significant reduction in the two soils used, especially at T16 (Note that the initial value of ESP was 37.04 and 33.64% in Abees and Elhammam soils, respectively). The ESP_f of the used soils reached a value lower than the critical value for saline-sodic soils (> 13) with T16, T15, T14, T13, T12, T11, T7, and T5, but with the other treatments, the values were higher than the critical value (Table 2). Also, the removal sodium efficiency (RSE) or percentage of Na-removed from the soils at end of the experiment in used soils was significantly reduced with the soils used after the application of the amendments (Table 2). RSE of T16 revealed the highest value

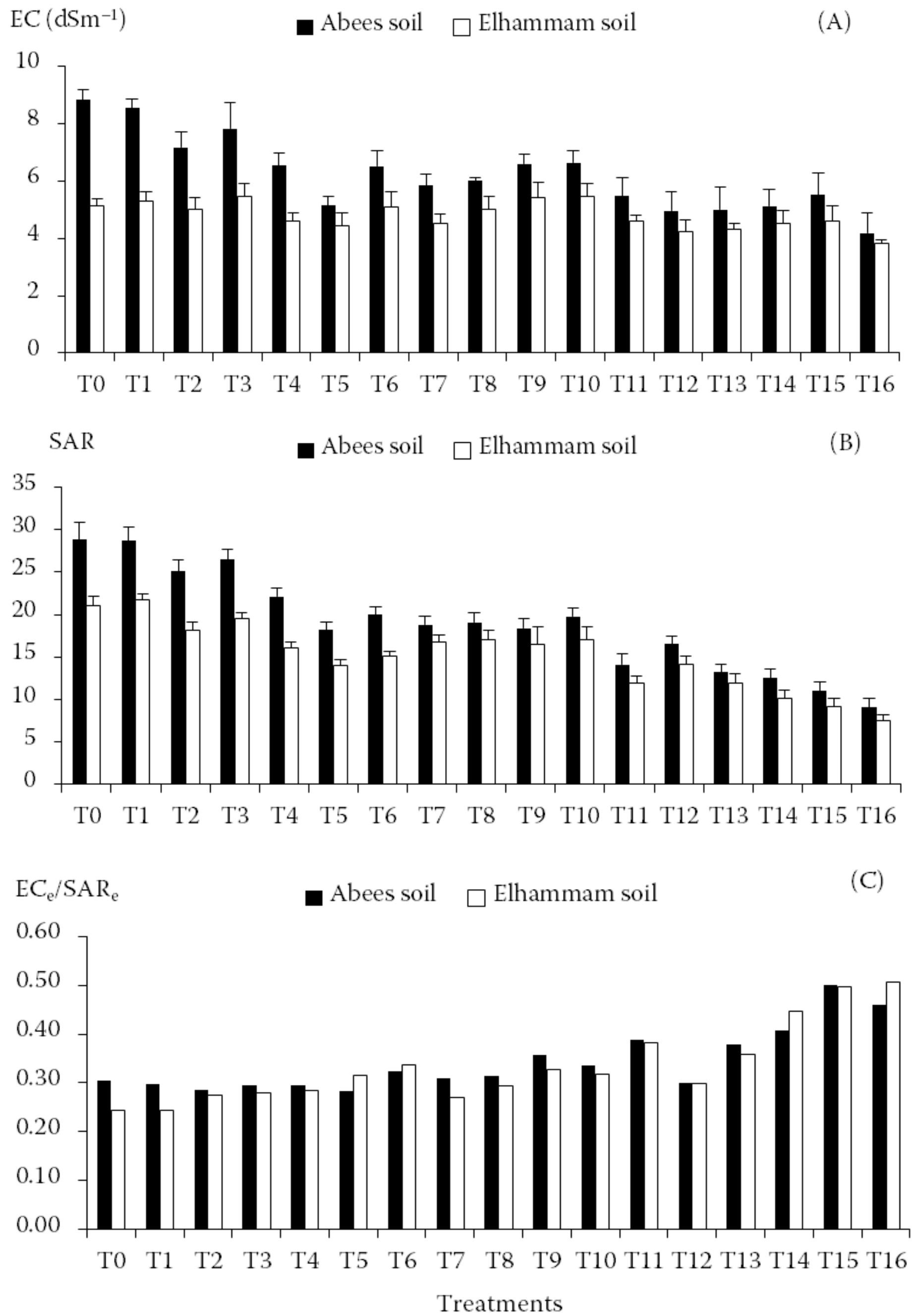

Figure 1. Salinity (EC_e), Sodicity (SAR_e) and their ratio (EC_e/SAR_e) measured in the saturation extract of soils at the end of the experiment

(76%) among the treatments for the two soils used, followed by T15 and T14 (Table 2).

The type of amendments that is best suited for the reclamation of saline-sodic soils has been the subject of debate. According to the data reported here, the coal and ferrous sulphate amendments tested separately seem to have a limited value for reclamation. While the organic amendments co-applied with chemical amendments seem to have a high value for reclamation (Table 2). This study also indicated that sulphates of Fe and A1 performed well, in agreement with the field study by Chand *et al.* (1977). It appears that the strong aggregating action of Fe and A1 claimed by the product distributors was not reflected in an improved soil structure or a better water intake in comparison with gypsum. Some laboratory studies indicate that the aggregating ability of Fe and A1 is not stronger than that of Ca (e.g., Wada *et al.* 1983).

This study also indicates that the efficiency of replacing exchangeable Na differ greatly between the amendments. This finding is in agreement with a general view given in USDA Handbook 60 and field data of Chand *et al.* (1977), but in apparent disagreement with the data obtained in severely Na-affected soils (e.g., Overstreet *et al.* 1951; Prather *et al.* 1978). In these cases, the quantity of the leaching water passed was not adequate to dissolve large quantities of gypsum applied. This study also indicated that Al or Fe applied to the calcareous soils replaced large amounts of exchangeable Na. This is an unusually high efficiency, and may have been caused by large amounts of Ca initially present in the soils.

Plant biomass yield and response

The biomass yields of alfalfa plants grown on saline-sodic soils after the application of amendments at the end of the experiment are shown in Figure 2. The most effective was the reclamation variant T16, in which coal powder, iron sulphate, compost, and WTRs were added to the soil. The yield of biomass at T16 significantly increased and the increase was 959% in comparison with T0 in Abees soil, while the increase in biomass yield was 1452% in comparison with T0 in Elhammam soil (Figure 2). This was due to the effective impact of the soil amendments (T16) in amelioration of saline-sodic soils through reducing soluble Na, exchangeable Na, SAR_e, and ESP, and reducing salinity of the soils used. The next most effective was variant T15 with compost, WTRs, and ferrous sulphate addition, where the biomass yield was 788% higher than in the control treatment T0 in Abees soil. Also, the increase in biomass yield in Elhammam soil treated with T15 was 1221% (Figure 2). The third most effective variant was T14 with anthracite coal powder, compost, and ferrous sulphate additions where the biomass yield was 675% in comparison to the control variant in Abees soil. However, the increase in biomass yield in Elhammam soil at T14 was 1100% (Figure 2).

In this study, a significant positive linear correlation was found between CEC and biomass yield ($r = 87$, $P < 0.001$) (Figure 3A).), as well as a significant negative linear correlation between soil salinity and biomass yield ($r = 0.68$, $P < 0.01$) (Figure 3B). Also, a significant negative linear correlation between ESP and biomass yield was observed ($r = 0.45$,

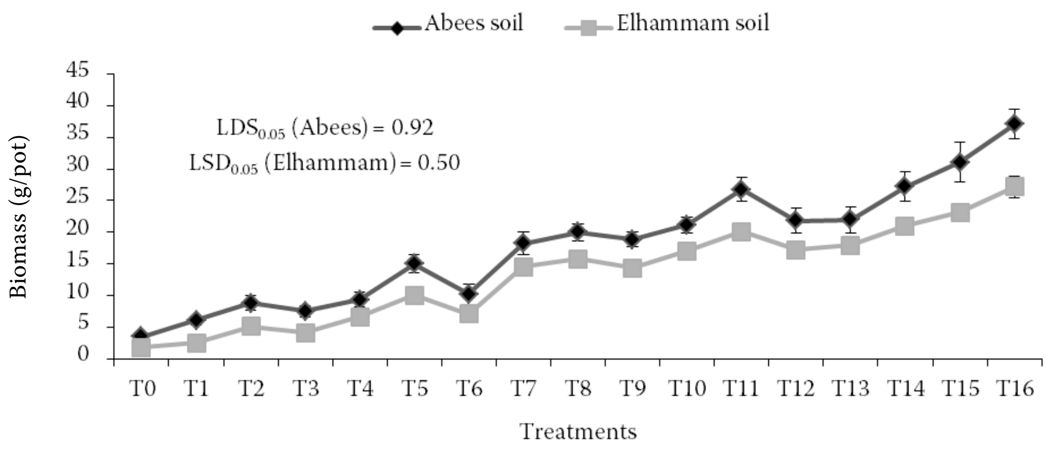

Figure 2. Biomass yield of alfalfa produced from saline-sodic soils after the application of soil amendments; bars indicate standard error ($n = 4$)

P < 0.05) (Figure 3C). The results of the current study coincided with the results of Miyamoto and Enriquez (1990), Raychev *et al.* (2001), Qadir *et al.* (2001), Qadir and Oster (2002); Fathi (2010).

The interaction of the added materials with the soil minerals and solutes should diminish toxic concentrations of the salt and stabilise the aggregation state of the soil. The proposed method has the following advantages: decreasing the soluble salt level and its toxicity for plants, enriching the soil with structure forming organic matter, minimising the environmental pollution hazard, minimising financial input

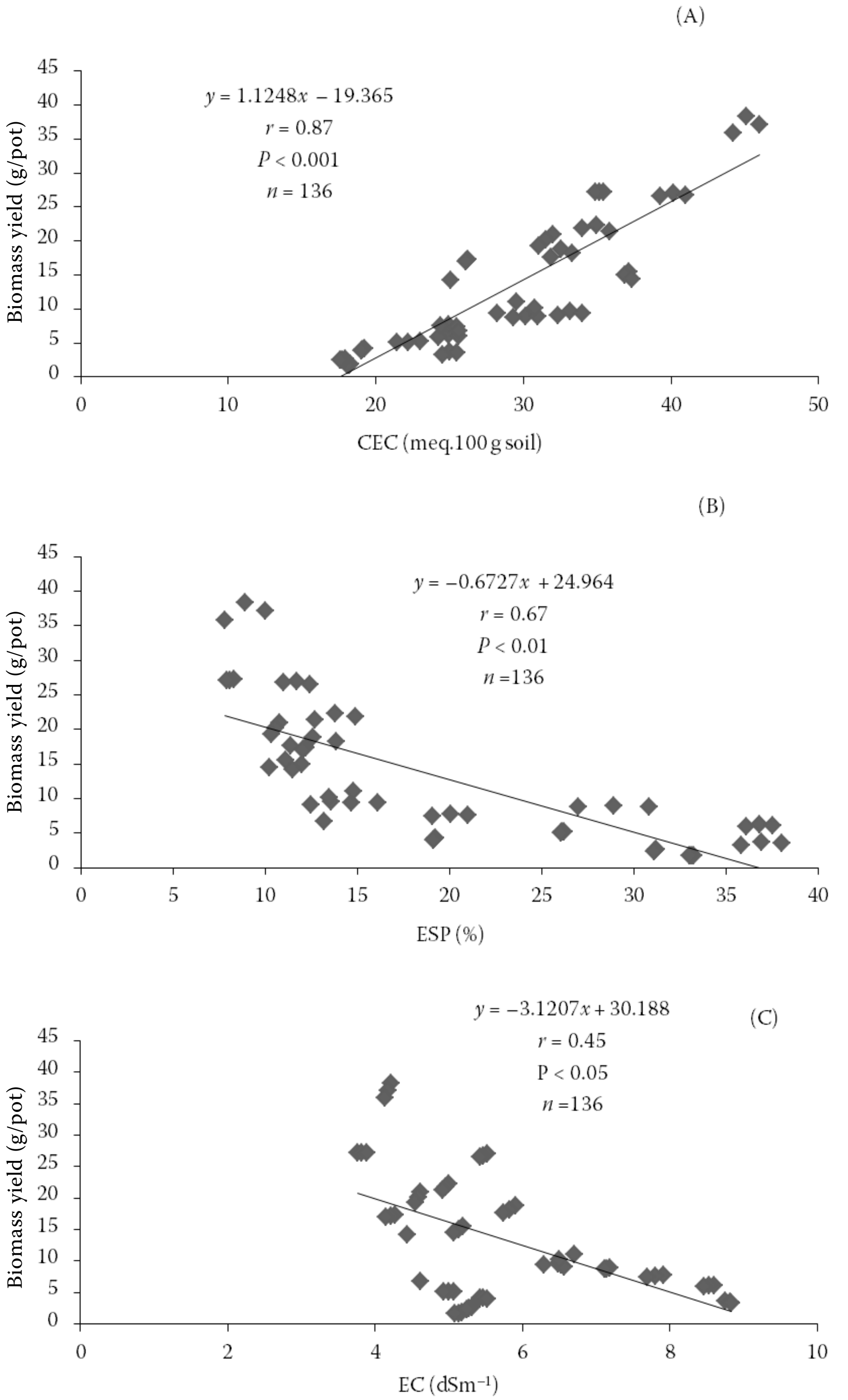

Figure 3. Relationships between cation exchange capacity (CEC), exchangeable sodium percentage (ESP), and electrical conductivity (EC) of soil paste extract of the soils used, and biomass yield of alfalfa grown in saline-sodic soils after the application of soil amendments

(no hydro-technical amelioration), allowing the use of industrial wastes in an ecologically correct way.

CONCLUSION

Saline-sodic soils reclamation will be one of the main problems for humans in the future. The reclamation of saline soils uses many different methods such as physical amelioration (deep ploughing, sub-soiling, sanding, profile inversion), chemical amelioration (amending of soil with various reagents: gypsum, calcium chloride, limestone, sulphuric acid, sulphur, iron sulphate), electro-reclamation (treatment with electric current). The most effective procedures are based on the removal of exchangeable and soluble sodium and modification of the ionic composition of soils by adding chemicals paralleled with leaching of sodium salts out of the soil profile. A method of saline or saline-sodic soils reclamation using a combination of coal powder, WTRs, compost, and ferrous sulphate was evaluated and proved to be the best soil amendment for reducing soil pH, soil salinity, and soil sodicity. The sodium removal efficiency was the highest at T16. Consequently, biomass yield of alfalfa was the highest at the same treatment, T16. However, field tests are necessary to draw final conclusions.

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Received for publication February 7, 2011
Accepted after corrections July 10, 2011

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