

Reclamation of highly calcareous saline-sodic soil using low quality water and phosphogypsum

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Abstract The efficiency of two amendments in reclaiming saline sodic soil using moderately saline (EC) and moderate sodium adsorption ratio (SAR) canal water was investigated. Phosphogypsum (PG) and reagent grade calcium chloride were applied to packed sandy loam soil columns and leached with canal water (SAR = 4, and EC = 2.16 dS m⁻¹). Phosphogypsum was mixed with top soil prior to leaching at application rates of 5, 10, 15, 20, 25, 35, 40 Mg ha⁻¹, whereas calcium chloride was dissolved directly in water at equivalent rates of 4.25, 8.5, 12.75, 17.0, 21.25, 29.75, and 34 Mg ha⁻¹, respectively. Both amendments efficiently reduced soil salinity and sodicity. Calcium chloride removed 90 % of the total Na and soluble salts whereas PG removed 79 and 60 %, respectively. Exchangeable sodium percentage was reduced by 90 % in both amendments. Results indicated that during cation exchange reactions most of the sodium was removed when effluent SAR was at maximum. Phosphogypsum has lower total costs than calcium chloride and as an efficient amendment an application of 30 Mg ha⁻¹ and leaching with 4 pore volume (PV) of canal water could be recommended to reclaim the studied soil.

Keywords Phosphogypsum · Reclamation · Saline · Sodic · Leaching · Canal water

Introduction

Salt-affected soils are a widespread problem in arid and semiarid regions. Globally, it is estimated that 62 % of total land in more than 100 countries around the world is saline-sodic or sodic (Tanji 1990; Szabolcs 1994). Reclamation and management of these soils require special approaches to maintain their productivity (McWilliams 2003).

Reclamation involves supply of calcium ions (Ca²⁺) to replace sodium ions (Na⁺) from exchange sites. To avoid resodification, replaced Na⁺ has to be leached away from the root zone with adequate amount of water. The most commonly used chemical amendments are gypsum (CaSO₄·2H₂O), calcium chloride (CaCl₂·2H₂O), and sulphuric acid (H₂SO₄). Gypsum and calcium chloride provide a direct source of Ca²⁺ to replace Na⁺, while sulphuric acid increases calcite dissolution (Gupta and Abrol 1990; Mace et al. 1999; Qadir et al. 2001). Recently, Gharaibeh et al. (2010) showed that phosphoric acid can be used to reclaim saline-sodic soils.

Several studies indicate that highly soluble calcium chloride may be preferred over gypsum for reclaiming severely sodic soils, because high electrolyte concentrations overcome the dispersing effect of sodium (Prather et al. 1978). Shainberg et al. (1982) pointed out that the effect of CaCl₂ is short-term, and permeability of non-calcareous soils may decline below that obtained with gypsum, when leached with distilled water. In calcareous soils, which could release calcium through dissolution of native CaCO₃, the authors (Shainberg et al. 1982) found non-significant differences between gypsum and CaCl₂ amendments.

Phosphogypsum (PG) a by-product of the Jordanian phosphate industry is produced in high quantities. Compared to mined gypsum, PG dissolves faster, produces acidic reaction and develops higher electrolyte leaching

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solution, promotes particle aggregation and therefore improves soil hydraulic conductivity (Keren and Shainberg 1981; Oster 1982). Moreover, PG has lower costs than all other amendments and could be used for soil reclamation.

The use of PG in agriculture may raise significant environmental concerns because this material contains relatively high levels of natural uranium-series radionuclides and other impurities such as fluoride, sulfate and trace elements (Rutherford et al. 1994; Burnetta and Elzermanb 2001). However, Zielinski et al. (2011) showed that Jordanian PG contained low levels in trace elements. The use of PG may lead to serious chemical and radioactive contamination to the surrounding soil, water and air and therefore, the use of PG has been banned in most countries (Tayibia et al. 2009).

The world's range of uranium levels in soils is 17–60 Bq kg⁻¹ (average 32 Bq kg⁻¹). According to Canadian soil quality guidelines for the protection of environmental and human health for agricultural land use; the recommended limit for uranium (²³⁸U) is 23 ppm equivalent to 280 Bq kg⁻¹ (CCME, 2007).

The latest available data for uranium levels in Jordanian PG was reported to range 14–37 Bq kg⁻¹ with an average of 22 Bq kg⁻¹ (Al-Jundi et al. 2008). This value falls within the recommended limits by the Canadian and European guidelines.

Little work had been done to evaluate the use of low-quality water in salt-affected soil reclamation (Abrol et al. 1988; Mace and Amrhein 2001). The productivity of agricultural soils in Jordan is impaired by many form of soils degradation such as salinity, sodicity, loss of nutrients, and water and wind erosion (Mashali 1989). In the Jordan valley, more than one-third of the agricultural land (~0.5 Mha) is salt-affected soil. Around 75 % of which has an electrical conductivity (ECe) exceeding 16 dS m⁻¹, 12 % with an ECe of 4–8 dS m⁻¹, and 13 % with an ECe of 8–16 dS m⁻¹ (Mashali 1989). It is expected that salinity and sodicity problems in Jordan are likely to be increased in the future since most of the water sources available for irrigation are of poor quality (Gharaibeh et al. 2009).

The main objectives of this study are to determine the reclamation efficiency of PG and calcium chloride using moderate saline and moderate sodic canal water, and to determine the optimum gypsum quantities required to reduce soil sodicity and salinity to levels promoting good crop production.

Materials and methods

Methods of soil analysis

Surface soil sample (0–20 cm) was collected from agricultural fields in the southern parts of the Jordan Valley,

20 km north of the Dead Sea. The soil is sandy loam, classified as loamy, mixed, hypothermic Typic Xerochrept soil type (MINAG 1993). The soil sample was air-dried, gently broken up to pass through a 2 mm sieve and mixed thoroughly for soil analysis. Particle size analysis was determined by the pipette method (Gee and Bauder 1986), bulk density by the core method (Blake and Hartge 1986), pH and EC were measured in saturated paste extracts (McLean 1982; Rhoades 1982), cation exchange capacity (CEC) by the method of Palemion and Rhoades (1977), exchangeable sodium percentage (ESP) by the ammonium acetate method (Thomas 1982), and soil organic carbon (SOC) by wet oxidation (Nelson and Sommers 1982). Soil physical and chemical properties are shown in Table 1.

Column experiments

Forty-five plexiglass columns (25 cm height and 11 cm internal diameter) were packed with 1.3 kg of air-dried soil (<2 mm) to a total depth of 10 cm to obtain a uniform bulk density of 1.4 Mg m⁻³. Columns were packed with subsamples of the same soil.

Phosphogypsum, a by-product of the phosphate industry (80 % pure) and reagent grade calcium chloride were applied to soil columns. The gypsum consisted mainly of CaSO₄·2H₂O and contained some impurities mainly CaO (variable), P₂O₅ (1–1.3 %), SiO₂ (1–1.2 %). Gypsum particle size distribution was: 2 % <53 μm, 24 % 53–106 μm, 44 % 106–300 μm, 19 % 300–500 μm, and 11 % 500–1,000 μm. Gypsum was mixed with upper 1 cm of soil column prior to leaching at application rates of 0, 5, 10,

Table 1 Chemical and physical properties of used soil

Property	Value
pH	8.5
ECe (dS m ⁻¹)	4.8
Sand %	68
Silt %	20
Clay %	12
Bulk density (Mg m ⁻³)	1.4
CaCO ₃ %	16
Organic carbon %	0.5
Exchangeable cations (cmole ₍₊₎ kg ⁻¹)	
Na ⁺	4.3
Ca ²⁺	1.2
K ⁺	0.9
Mg ²⁺	1
Cation exchange capacity (CEC)	7.4
Exchangeable sodium percent (ESP)	58

15, 20, 25, 35, and 40 Mg ha⁻¹ (Mg ha⁻¹ is mega grams or metric ton per hectare), whereas calcium chloride was dissolved directly in irrigation water and applied at equivalent application rates of 0, 4.25, 8.5, 12.75, 17.0, 21.25, 29.75, and 34 Mg ha⁻¹. All treatments were in triplicate. Gypsum rates represented 25 % of total amount of gypsum required (GR) to reduce the ESP to 6, while calcium chloride rates were obtained by multiplying GR by a factor of 0.85. This factor is based on an amount equivalent to 1 ton of pure gypsum. Leaching water was supplied using circulating pumps to attain soil hydraulic conductivity value similar to that in the field.

Irrigation water from King Abdullah Canal (KAC) was used for soil leaching. Five pore volumes (PV) were

allowed to pass through soil columns and leachates were collected in successive 30 mL aliquots. The PV is the volume of water required to saturate all soil pores. Average PV was about 460 mL, average porosity was 0.48, and flow velocity ranged 2.2–2.4 cm h⁻¹. The experiment was terminated when salinity (EC) of effluent approached that of canal water. Soil samples were taken out from columns, dried and analyzed for EC, pH, exchangeable Na, Ca, Mg, and K. Moreover, in separate column experiments a known PV was added to each packed column (e.g. 1 PV), then the leachate was collected once. After that soils were taken out and analyzed for exchangeable Na and ECe. Data per each percolated PV (exchangeable Na and ECe) were graphed against PV.

Table 2 Chemical properties of King Abdullah Canal (KAC) water used in this experiment

EC (dS m ⁻¹)	pH	Na ⁺ (mg L ⁻¹)	Ca ²⁺ (mg L ⁻¹)	K ⁺ (mg L ⁻¹)	Mg ²⁺ (mg L ⁻¹)	HCO ₃ ⁻ (mg L ⁻¹)	CO ₃ ⁻² (mg L ⁻¹)	SAR
2.16	8.08	252	144	470	39	470	3	4.8

Fig. 1 Effect of amendment rates (Mg ha⁻¹) and volumes of leaching water (PV) on relative Na removal (Na/Na₀)

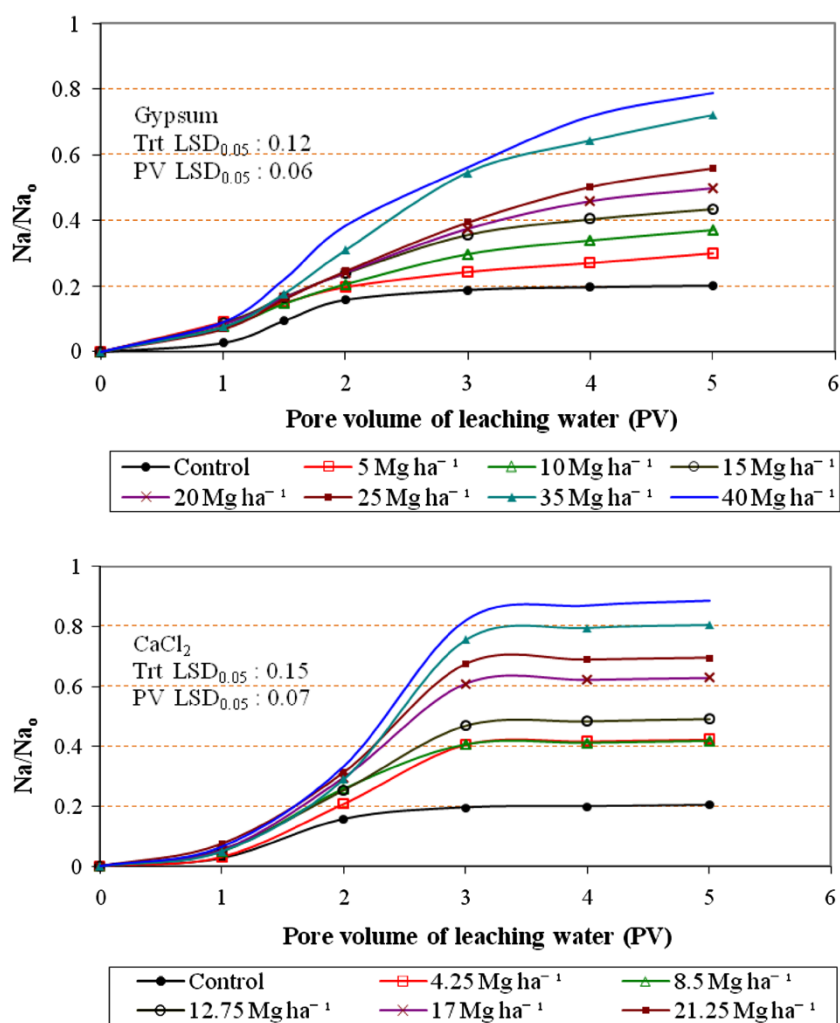
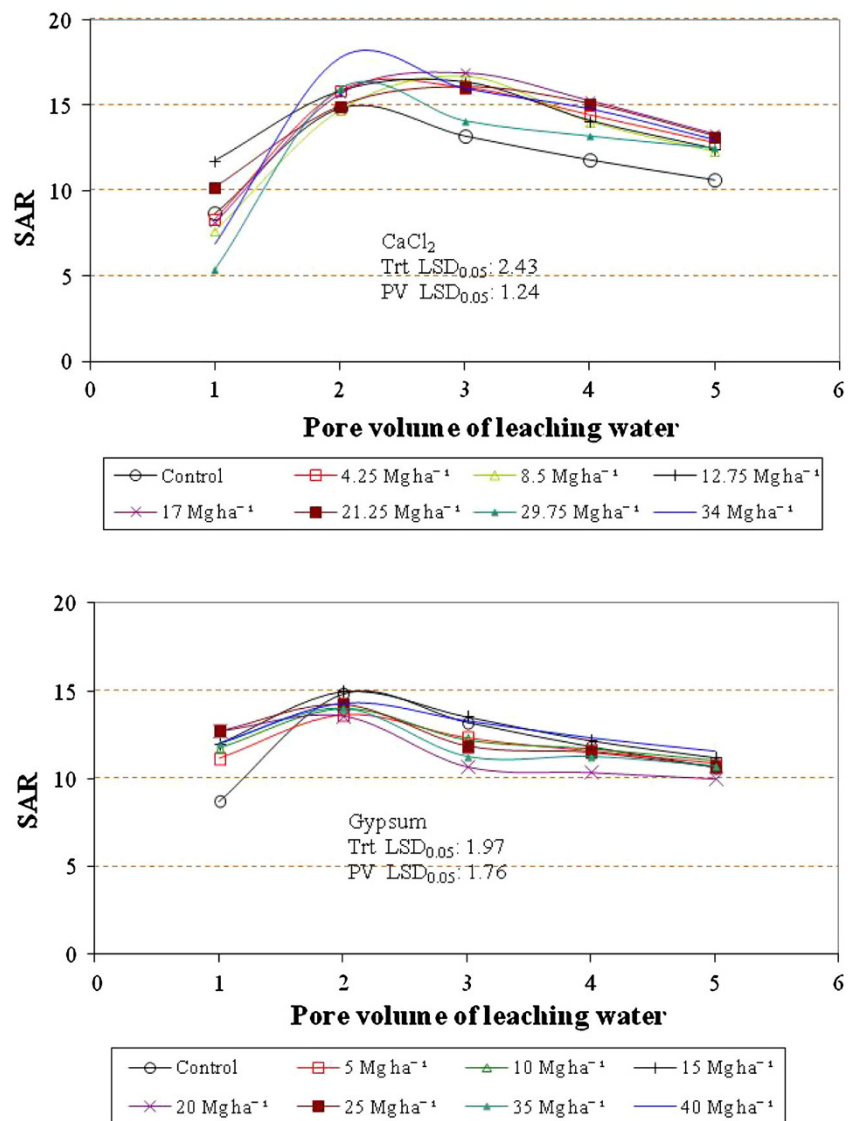


Fig. 2 Effect of amendment rates (Mg ha^{-1}) and volumes of leaching water (PV) on average sodium adsorption ratio (SAR) of effluent



Significance was tested using two-way ANOVA between treatments with subsequent mean separation by Student's LSD test using the John Macintosh Product (JMP) 5.1.2 (SAS 2003) program.

Irrigation water analysis

Water from the southern parts of KAC in the Jordan Valley was applied to leach soil columns (Table 2). Water analysis was performed according the methods in US Salinity Laboratory Staff (1954). Soil EC and pH were measured using conductivity and pH meter (WTW 720), Ca^{2+} and Mg^{2+} by EDTA titration method, Na^+ and K^+ using flame photometer (BWB Xp), and HCO_3^- and CO_3^{2-} by acid titration. Irrigation water is classified as moderate saline according to Rhoades et al. (1992) and moderate SAR according to Shainberg and Letey (1984).

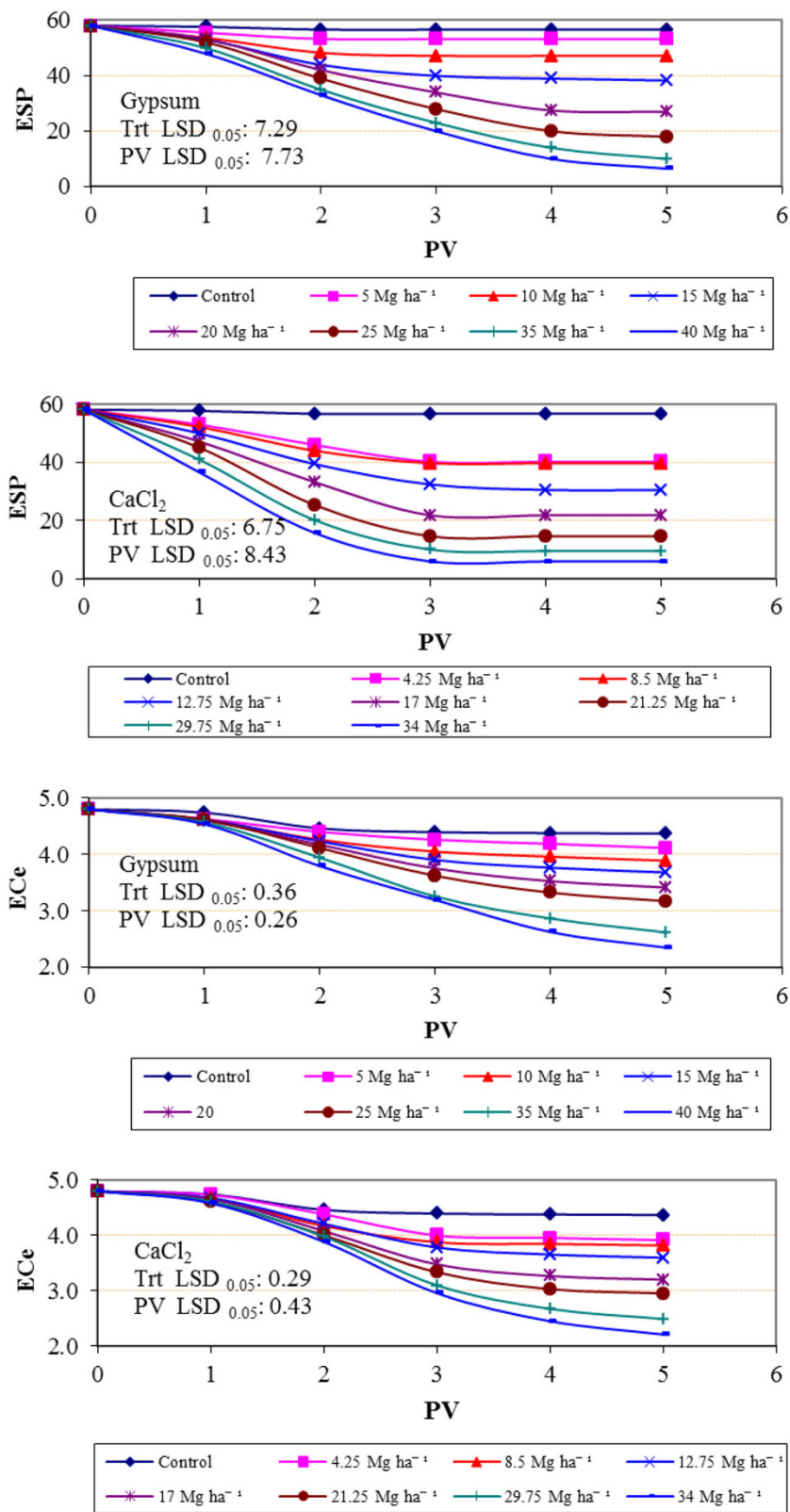
Results and discussion

Sodium removal in leachate

Sodium concentration in effluent (Na) relative to total Na in system was expressed as (Na/Na_0) and plotted against PV of collected effluent (Fig. 1). The ratio of (Na/Na_0) was <0.2 at the early stages of leaching and increased to above 0.8 at the final stages of leaching. This can be attributed to the tendency of leaching water to move mostly through the larger pores, and to lesser extent through the smaller ones. Consequently, the fluid in small pores cannot be removed completely and therefore, the effluent will not be totally displaced.

Results indicated that sodium in effluent was increased with increasing amendment rate and PV of leaching water. Both amendments removed similar quantities of Na during

Fig. 3 Effect of amendment rates (Mg ha^{-1}) and volumes of leaching water (PV) on exchangeable sodium percent (ESP) and soil salinity (ECe)



the passage of the first two PVs, and most of Na removal was observed after 3 and 4 PV of water using both amendments (Fig. 1). Relative Na removal in both

amendments shows significant differences with increasing application rates and PV of leaching water. No significant differences were observed above 3 PV with CaCl_2

treatments. This could be attributed to uniformity of ionic strength of CaCl_2 solutions during leaching stages, whereas gypsum produces higher ionic strength solutions during early stages and would decrease at later ones.

Effluent composition was also evaluated by plotting SAR versus PV of leached water (Fig. 2). Both amendments showed similar increase in SAR with maximum value occurring at 2 PV; indicating that most of the exchange reactions had taken place at this stage. SAR profiles were similar in shape and character demonstrating that both amendments have comparative efficiency in Na removal with favorable conditions to CaCl_2 treatments.

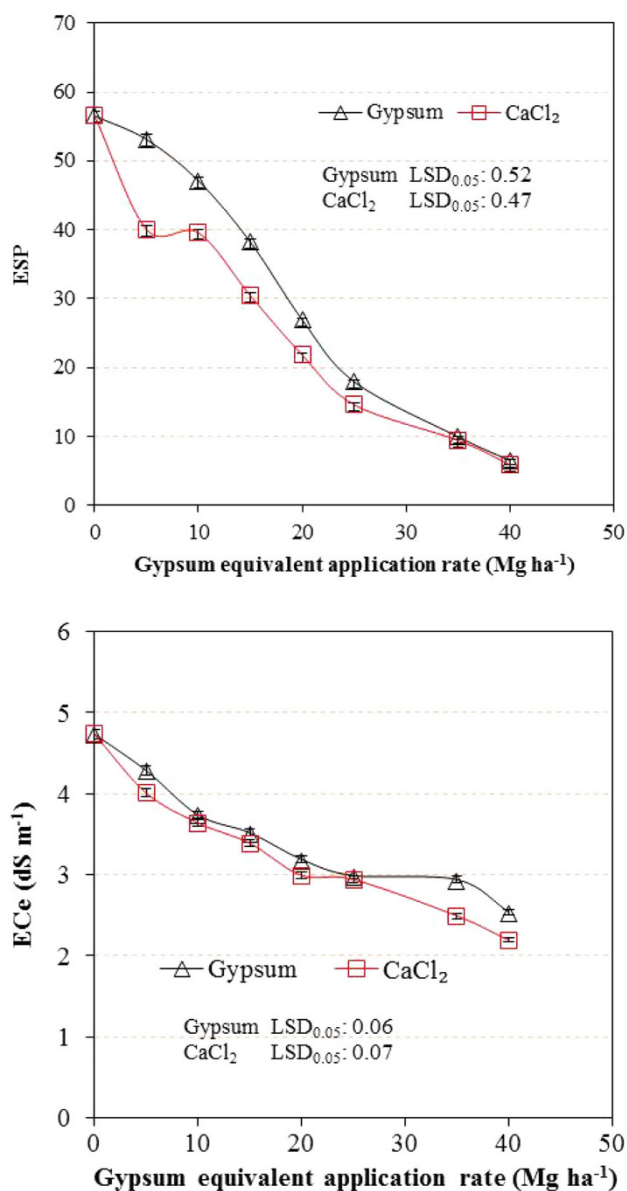


Fig. 4 Effect of amendment rates (Mg ha^{-1}) on final exchangeable sodium percent (ESP) and soil salinity (ECe)

Soil reclamation

The effect of increased application rate on soil ECE and ESP is shown in Fig. 3. Soil ECE and ESP were significantly decreased with increasing application rate, the highest decrease was observed in the highest rate. A Salinity level of $<4 \text{ dS m}^{-1}$ was achieved with application rates exceeding 5 Mg ha^{-1} .

Application rates greater than 35 Mg ha^{-1} of equivalent gypsum produced no significant benefits. Both amendments showed that application of more than 3 PV of canal water has no additional significant benefits on ECE (Fig. 3).

To reclaim the top 30–60 cm of soil to desirable ESP (<10); an application rate of 35 Mg ha^{-1} of gypsum is recommended. Gypsum is generally applied and mixed with the top layer, with average soil bulk density of 1.4 Mg ha^{-1} ; the resultant dilution factor for uranium will be 0.1–0.2 of the original value (3.5 kg of gypsum per $\text{m}^2 \times$ average uranium level 22 Bq/kg to reclaim $420\text{--}840 \text{ kg}$ soil). The resultant dilution is equivalent to 0.15 Bq/kg for intended average depth of reclamation. The dilution concept here applies for all other radionuclides, metals, and anions (chlorides and sulfates) in amending material. Therefore, using PG is considered safe from environmental and agricultural point of view.

The reduction in soil salinity (desalination) in all treatments is attributed to the leaching of soluble salts. Due to the high content of sand in reclaimed soils; more than 3 PV of leaching water were needed to reach an acceptable salinity level for crop production ($<4 \text{ dS m}^{-1}$). Such soils mainly have macro-pores which allow water to move through quickly, therefore the contact time between soluble salts and percolating water will be short.

Significant reductions in ESP (desodification) were also observed with increasing application rate (Fig. 3). No additional benefit on ESP ($P < 0.05$) was observed at equivalent gypsum rate $>35 \text{ Mg ha}^{-1}$. Statistical analysis

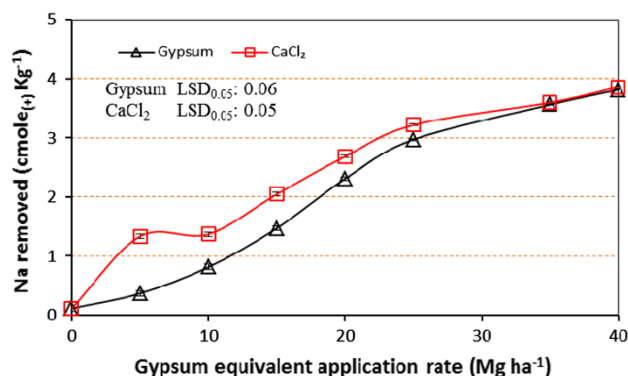


Fig. 5 Effect of amendment rates (Mg ha^{-1}) on exchangeable sodium removed ($\text{cmole}_e \text{ kg}^{-1}$)

Table 3 Final values of soil exchangeable Ca, K (cmole₍₊₎ kg⁻¹) and pH for both amendments (Mg ha⁻¹)

Rate	Ex. Na	Phosphogypsum			Rate	Ex. Na	CaCl ₂		
		Ex. Ca	Ex. K	pH			Ex. Ca	Ex. K	pH
Control	4.2	1.25a	0.90a	7.85a	Control	4.20a	1.25a	0.90a	7.85a
5	3.95a	1.30a	1.10b	7.75b	4.25	2.98b	2.38b	1.00a	7.66b
10	3.50b	1.70b	1.15b	7.62c	8.50	2.93b	2.21b	1.20b	7.54c
15	2.84c	2.21c	1.30c	7.55c	12.75	2.26c	2.56c	1.53c	7.50c
20	2.00d	2.85d	1.50d	7.45d	17.00	1.62d	2.93d	1.80d	7.42d
25	1.33e	3.22e	1.80e	7.30e	21.25	1.1e	3.47e	1.80d	7.20e
35	0.74f	3.60f	2.00f	7.20f	29.75	0.70f	3.65e	2.00e	7.20e
40	0.48g	3.87g	2.00f	7.10g	34.00	0.44g	3.91d	2.00e	7.02f
LSD	0.05	0.23	0.12	0.08	0.05	0.26	0.18	0.06	

Letter following numbers indicate significant differences ($P < 0.05$) between treatments

showed that CaCl₂ and gypsum treatments had no significant benefits on ESP when more than 2 and 3 PV of canal water were applied to soil, respectively (Fig. 3).

Results indicated that ESP was reduced to <10 % when at 35 Mg ha⁻¹ of equivalent gypsum was applied. It is worthwhile to mention that soils with ESP above 10 often have unstable aggregates and exhibit low infiltration rates that can cause damage to crops (Sumner 1993). The decrease in ESP is attributed to the exchange reactions with calcium ions in the system.

The final values of ESP and ECe were plotted as a function of application rate (Fig. 4). Gypsum and Calcium chloride had similar effect in decreasing soil ECe, while calcium chloride decreased efficiently ESP at equivalent application rates below 15 Mg ha⁻¹. Our results showed that the highest addition of both amendments decreased exchangeable sodium to 0.46 cmole_c kg⁻¹ (ESP = 6). This finding was in consistence with earlier works of Shainberg and Lety (1984), and Oster and Frenkel (1980).

The removal of exchangeable sodium does not indicate the actual “per equivalent” efficiency of amendments since all the applied gypsum was not necessarily brought into solution. A direct comparison of the removal efficiency between amendments can be evaluated by the cumulative sodium removal (Fig. 5). Plotting cumulative sodium removal versus application rate showed that the efficiency of calcium chloride was almost similar at all application rates (Fig. 5). Calcium chloride removed relatively higher amounts of exchangeable sodium compared to gypsum treatments with application rates <10 Mg ha⁻¹. Both amendments had almost similar removal efficiency with applications rates >10 Mg ha⁻¹.

Exchangeable Ca, Na, K and pH were determined after the termination of experiments (Table 3). Exchangeable calcium increased significantly with increasing application rate and this is mainly due to the replacement of Na with Ca.

The highest rate of gypsum and CaCl₂ increased exchangeable Ca from 1.25 (control) to 3.87 and 3.91 cmole₍₊₎ kg⁻¹ (equivalent to 52 % exchangeable calcium percent, ECP), respectively. Exchangeable K was increased from 0.9 (control) to 2.0 cmole₍₊₎ kg⁻¹ (equivalent to 27 % exchangeable calcium percent, ECP) with the highest rate of both amendments. The increase in exchangeable K may be coming from soluble K in irrigation water (Table 2). Statistical analysis shows significant increase in exchangeable K with increasing application rate, no significant increase above 35 Mg ha⁻¹ of equivalent of gypsum application. Soil pH was decreased from 8.5 to 7.1 and 7.02 with highest application treatments of gypsum and CaCl₂, respectively. Increasing application rate significantly reduced soil pH in both amendments. The highest decrease was associated with the highest application rate in both amendments. The reduction in soil pH may be due replacement of Na from exchangeable sites and subsequent leaching. The reduction in soil pH is generally linked to the reduction in sodium hazard (Abrol et al. 1988).

Summary and conclusions

Water shortage is a serious problem in many regions of the world. The use of low quality water and industrial by products for soil reclamation is found to be an efficient alternative for traditional soil water management and development of agriculture areas. Results of this study showed that moderate saline-sodic canal water and PG can be effective in reducing the sodicity and salinity of highly calcareous saline-sodic soil. Taking into account that phosphogypsum has lower costs than calcium chloride; application of 30 Mg ha⁻¹ and leaching with 4 PV of canal water could be recommended for reclaiming studied soil.

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