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Empirical Approach of Leaching Curves for Determining the Efficiency of Reclaiming Saline-Sodic Soils in Sahl El-Tina, Sinai, Egypt

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Authors' contributions

This work was carried out in collaboration between both authors. Authors MKAF and ESAE designed the study, wrote the protocol, and wrote the first draft of the manuscript. Authors MKAF and ESAE managed the literature searches, analyses of the study performed the laboratory analyses. Both authors managed the experimental process. Both authors read and approved the final manuscript.

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ABSTRACT

Columns experiment was conducted to determine desalinization and desodification leaching curves of a clay saline-sodic soil. Soil samples were collected from Sahl El-Tina plain, Northern Sinai Governorate, Egypt. Soil columns were amended with agricultural normal gypsum "NG", phosphogypsum "PG" and calcium chloride "$CaCl_2.2H_2O$". Gypsum Requirements (GR) were calculated according to USDA equation. Calculated amount of gypsum was mixed with whole soil matrix (30-cm). Leaching was done using intermittent ponding method so as to add portions to the already saturated soil columns; and obtained leachates equal to the added portions. Desalinization and desodification curves showed that all treatments reduced soil salinity and sodicity, with a superiority of calcium chloride in reducing soil salinity and sodicity. In addition, the Hoffman's approach was adopted to estimate the leaching constant (*k*) of amendments. Desalinization and desodification curves showed that application of calcium chloride appears to have a strong effect on (*k*) values. The leaching constants (*k*) of control, NG, PG and $CaCl_2.2H_2O$ gave averaged values of 0.39, 0.27, 0.25 and 0.19 for desalinization and 0.35, 0.28, 0.27 and 0.16 for desodification,

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respectively. The lower values of (*k*) in $CaCl_2.2H_2O$ treatment depicted lower amounts of water required for leaching and reclamation compared to other treatments. This study suggests that Leaching curves represent a very good method to determine the efficiency of amendments and the optimum depth of leaching water needed for successful reclamation.

Keywords: Leaching curves; saline-sodic soil; reclamation; normal gypsum; phosphogypsum; calcium chloride.

1. INTRODUCTION

Globally, it is estimated that 62% (over 800 million ha.) of the total cultivated land in more than 100 countries around the world is classified as salt-affected soils. This problem is extensively spread in the arid and semiarid regions [1,2,3,4]. In Egypt, about one million hectare (33%) of the total irrigated lands is infested with salinity problems and belongs to salt- affected soils that are mostly located in the Northern part of Nile Delta. Saline-soils contain excess soluble salts, and sodic soils contain excess exchangeable sodium. Reclamation and management of these soils require special approaches to maintain their productivity [5]. Leaching process (removal of excess salts) out of the root zone to the drainage system and eliminating sodicity via replacing exchangeable sodium with calcium by using calcium-bearing materials (amendments) are the first steps of reclamation processes.

The amount of leaching water depends on initial soil salinity level, applied water technique, and soil type. Therefore, it is important to have reliable estimates of the required amount of leaching water needed to reduce soil salinity/ sodicity to a desirable level [6]. Chemical amendments used for reclamation process are broadly grouped into three categories: soluble calcium salts, e.g. $CaCl_2$ and gypsum, acids or acid forming substances, e.g. sulfuric acid, iron sulfate, aluminum sulfate, pyrite, etc., and finally calcium salts of low solubility (ground lime stone). The suitability of one or another amendment for sodic soil reclamation largely depends on the nature of the soil and cost consideration [7].

The principle of leaching is very simple; the salts must be washed downwards and away from the root zone by means of flooding and presence of good drainage conditions. In practice, the quantity and quality of drained water are used as an index of the actual amount of leaching water needed to reduce soil salinity/ sodicity to a desirable level. The empirical approach is by far the most suitable way that can be adopted to tackle this problem. This approach involves plotting the decrease in soil salinity in relation to the required amount of leaching water. Therefore, the leaching relationship is considered a useful tool for deciding which amendment is most suitable and economically justified for soil reclamation, taking into account local soil and agricultural conditions [8].

[9] determined Leaching curves with respect to desalinization and desodification of a highly saline-sodic soil. They conluded that these curves were useful in knowing the amount of water of a given composition needed to reduce the harmful levels of salinity and sodicity to the lower desirable values.

[10] reported that application of Phosphgypsum (PG), followed by karnal grass as first crop, resulted in the greatest reduction of soil pH and exchangeable sodium percentage (ESP) followed by PG applied at 10 Mg ha^{-1} alone. Application of PG at 10 Mg ha^{-1} resulted in greater yields of both rice and wheat than other treatments. Phosphogypsum effected greater increase in aggregation, soil organic carbon, microbial biomass carbon, and aggregate associated carbon and decrease in zeta potential, leading to increased hydraulic conductivity and moisture retention capacity in soil over mined gypsum–treated soil. Phosphogypsum (PG), a by-product of phosphate industry, is produced in high quantities. Compared to mined gypsum, PG dissolves faster, produces acidic reaction and develops higher electrolyte leaching solution, promotes particle aggregation and therefore improves soil hydraulic conductivity [11,12].

[13] determined the efficiency of calcium chloride and phosphogypsum (PG) in reclaiming saline sodic soil using moderately saline canal water. 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. Phosphogypsum has lower total costs than calcium chloride and it represents an efficient amendment.

[14] in large outdoor lysimeter column studies found that 1.3 pore volume (PV) of applied water or 1 PV of drainage water removed nearly all chlorides from sandy loam and clay loam soils. However, total salt removal, including dissolving soil gypsum, required considerable amounts by a single curve, as: $(C/C_0)\ (d_1/d_s\theta) = 0.8$, for all treatments, where C is salt concentration in effluent, C_0 is initial salt in soil water, d_1 and d_s are depth of water applied and depth of leached soil, respectively, and θ is soil volumetric water content. In this case, about 60 and 80% of total salt removal occurred by applying 2 and 4 PV equivalents of leaching water, respectively. As a rule of Thump (i.e. a practice based upon experience), one may apply the following relationship [15] described the leaching constant by the following equation: $k = (C/C_0) \times (D_w/D_s)$; where C/C_0 is the fraction of the initial salt concentration remaining in the soil profile (C: salt concentration after reclamation; C_o: salt concentration before reclamation); and D_w/D_s is the amount of water per unit depth of soil (D_w: total amount of applied water in terms of water-depth; D_s: the depth of soil to be reclaimed, i.e., the soil depth). The constant (*k*) varies with soil type and method of water application. For flooding conditions, using continuous leaching, Hoffman assumed that the appropriate value of (*k*) is equal to 0.45, 0.3 and 0.1 for peat, clay loam and sandy loam soils, respectively; using intermittent leaching, the efficiency of salt removal is enhanced and (*k*) value was assumed to be 0.1 irrespective to soil type.

The main objectives of this work were: (1) to estimate the efficiency of desalinization and desodification using leaching curves approach, (2) to determine the optimum depth of leaching water required for reclaiming saline-sodic soils, and (3) to determine the effectiveness of some chemical amendments ($CaCl_2$, normal gypsum, phosphogypsum) in reclaiming saline sodic soils.

2. MATERIALS AND METHODS

2.1 Soil Sample Preparation and Description

Before setting up the experiment, soil samples were collected from Sahl El-Tina plain, Northern Sinai Governorate, Egypt. El-Tina plain is of flat or almost flat surface with low-lying terrain, Morphotectonic depression, and a parent material of a mixture of Nile alluvial and lacustrine deposit which may contain some aeolian sediments [16]. Soil structure is weak fine sub-angular blocky. The area locates between (31.037778 - 31.0138409 N) latitudes and (32.589167 - 32. 34692 E) longitudes and is exaggerated by salinization and sodification. Soil was air dried, crushed and sieved through a 2-mm sieve and analyzed for their physicochemical characteristics (Table 1). Soils of the study area are mostly fine textured (clay loam), with a high amount of salts and high values of cation exchange capacity with a prominent exchangeable sodium. Soil was salty and pH value higher than 8.5.

Table 1. Physical and chemical properties of the studied soil

Property	Soil
- Clay	35.60
- Silt	31.90
- Sand	32.50
- Texture class	Clay loam
- Saturation percent	62.13
- Bulk density, $Mg.m^{-3}$	1.42
- Total porosity, %	46.42
- Organic matter, g kg^{-1}	3.80
- $CaCO_3$, g kg^{-1}	15.0
- EC, dSm^{-1} [Soil paste extract]	24.90
- pH [Soil suspension 1:2.5]	8.78
- Soluble ions, $mmol_c\ L^{-1}$	
▪ Na^+	195.85
▪ K^+	4.83
▪ Ca^{2+}	15.59
▪ Mg^{2+}	95.75
▪ Cl^-	240.25
▪ HCO_3^-	2.18
▪ SO_4^{2-}	66.576
▪ SAR	26.25
Exchangeable cations, $cmol_c\ kg^{-1}$	
▪ Na^+	10.38
▪ K^+	2.86
▪ Ca^{2+}	4.56
▪ Mg^{2+}	7.99
- CEC, $cmol_c\ kg^{-1}$	25.79
- ESP, %	40.25

2.2 Soil Columns Setup

For establishing the experiment, four groups of 12 soil columns were used; each group was treated with different types of calcium sources (control, NG, PG and $CaCl_2.2H_2O$). Polyvinyl chloride (PVC) cylindrical tubes of 40-cm height and 16-cm inside diameter were used for this purpose. The bottom of each tube was sealed with a perforated mesh nylon screen and glass wool. Acid-washed inert sand was placed on the tube bottom to make a 5-cm layer of the column to ease the filtration. Such arrangement allowed for 5-cm on top of soil column to give sufficient space for addition of water for the leaching process. The tubes were packed with air-dried soil to a total depth of 30 cm to obtain a homogeneous bulk density of 1.42 $Mg.m^{-3}$. The experimental design was a randomized complete block design in a factorial arrangement three replicates.

2.3 Amendments Application and Leaching Processes

Three calcium-bearing amendments were used in the experiment, Normal gypsum (NG), phosphogypsum (PG), and calcium chloride. Gypsum requirements (GR) were calculated to reducing the initial exchangeable sodium percentage (ESP) in the investigated soil from an initial value of 40.25% to a typical acceptable value of 10% for the 30-cm depth soil matrix according to [17]. The equivalent amount of GR was calculated for calcium chloride "$CaCl_2.2H_2O$" and phosphogypsum according to [7]. The treatment, purity degree of the amendment, and calculated quantity for each were as follows: control (untreated soil), normal gypsum (NG) with purity of 98% at 32.6 Mg ha^{-1}, phsphogypsum (PG) with purity of 65% at 49.14 Mg ha^{-1}, and calcium chloride ($CaCl_2.2H_2O$) with purity of 99% at 27.97 Mg ha^{-1}.

Calculated amount of each amendment was homogeneously mixed with the whole soil matrix (30-cm). After mixing, the soils were exposed to leaching with moderate saline water having EC value of 1.5 dSm^{-1}. The amount of water used in leaching was delivered to saturated soil column under an intermittent ponding mode with a water head of 5-cm above soil surface. Intermittent method is to add equal portions of water to the already saturated soil columns and obtain leachates equal to the added portions. The leachate from each soil column, equal to the added water leachate (1005 ml per column = 1/3 PV), was collected. Six collections were performed in all, and all leachates were chemically analyzed. Leaching process was terminated after reaching to steady state condition. Following termination of leaching, each soil column was sectioned into three depth-identical segments (0-10 cm, 10-20 cm, and 20-30 cm). Soil of each segment was air dried, crushed, sieved through a 2-mm sieve and analyzed for cations, anions, and exchangeable cations.

2.4 Physiochemical Analyses

Particle size analysis was determined by the pipette method, bulk density [18], pH and EC were measured in saturated paste extracts [19], Determination of Ca and Mg was done by atomic absorption spectrophotometry and K and Na by flame emission spectrophotometry, cation exchange capacity (CEC) by the method of [19], exchangeable sodium percentage (ESP) by the ammonium acetate method [20], and soil organic matter by wet oxidation [20].

3. RESULTS AND DISCUSSION

3.1 Desalinization Curves

Desalinization leaching curves were constructed to relate the soil salinity after leaching to effective leaching water. The depth of effective leaching water is expressed as ratio to the depth of the soil layer leached Dw/Ds where D_w represents the depth of effective leaching (drainage) water, which can be obtained by adding the total depth of percolated water, to the depth of water needed for moistening the soil layer or layers beneath, Ds is the depth of leached soil layer.

Desalinization curves (Fig. 1) show that all treatments reduced soil salinity, with a superiority of calcium chloride in reducing soil salinity, increasing soil permeability and speed of reclamation. Using $CaCl_2$ can appreciably improve the time and water efficiency such as when sufficient water intake cannot be achieved. The control was less efficient in reducing soil salinity when comparing with the amendments. Desalinization curves also show that salinity was considerably decreased with leaching. Soils amended with NG and PG required higher amounts of water to reduce soil salinity compared to those amended with calcium chloride.

3.2 Desodification Curves

Desodification leaching curves were constructed in relation to the residual ESP after leaching expressed as ESP/ESP_o to effective leaching water expressed as Dw/Ds. The ESP_o refers to the initial exchangeable sodium. Desodification leaching curves were illustrated in Fig. 2. Desodification leaching curves take the same trend as that of desalinization curves where all treatments reduced soil sodicity, with a superiority of calcium chloride. The ESP curves for $CaCl_2$ and PG were more effective than $CaSO_4$ and control. The efficiency of leaching is influenced by the solubility of amendment. Calcium chloride is more soluble therefore supplies a source of calcium ions and produces high electrolyte solution mostly at the early stages of reclamation. The high electrolyte concentration produced is efficient in replacing exchangeable Na only with high ESP [21,22]. For such conditions, the overall time and water required for reclamation are significantly lower than for NG and PG.

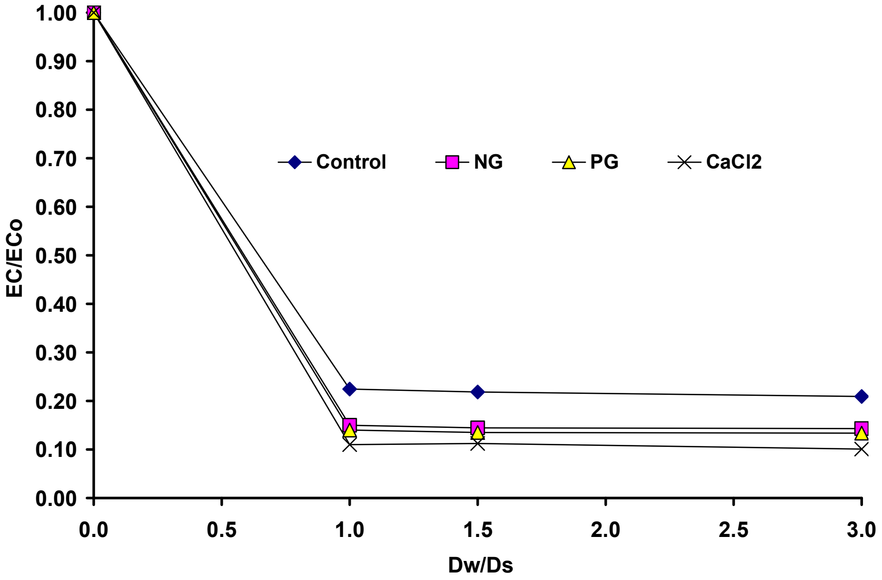

Fig. 1. Desalinization leaching curves, residual EC (EC/EC_o) in the soil columns vs. relative depth of effective leaching water (Dw/Ds)

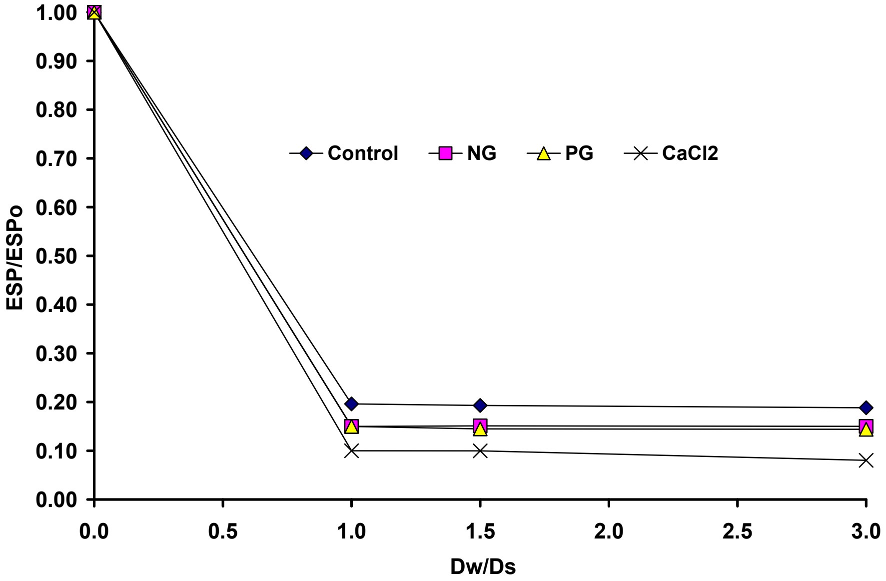

Fig. 2. Desodification leaching curves, residual ESP (ESP/ESP_o) in the soil columns vs. relative depth of effective leaching water (Dw/Ds)

In contrast, NG and PG have relatively low solubility, more time and water are required than with other amendments [23]. However, as the soil exchangeable sodium percentage ESP is reduced, the electrolyte concentration (EC) of soil solution becomes increasingly more desirable, therefore, reducing the amount of amendment is needed.

As shown in Figs. 1 and 2, calcium chloride was more efficient than NG and PG and required substantially lower amounts of leaching water.

3.3 Empirical Constant

[15] described the leaching constant by the following equation: k = (C/Co)*(Dw/Ds), where k is an empirical coefficient that differs with soil type. The constant k varies with soil type and method of water application. Larger k values indicate more water is required for leaching. The leaching constant (k) was calculated and averaged per each treatment and depth of leached water (Table 2). The leaching constants (k) of control, NG, PG and $CaCl_2.2H_2O$ averaged 39, 27, 25 and 19% for desalinization and 35, 28, 27 and 16% for desodification, respectively. The lower values of k in $CaCl_2.2H_2O$ treatment depicted lesser amounts of water required for leaching and reclamation compared to other treatments. Relationships between the leaching constants (k) and Dw/Ds under different effect of amendments were illustrated in Figs. 3 and 4.

Table 2. Leaching constants (*k*) for soil desalinization and desodification

Treatments	$k = (C/C_0) \times (D_w/D_s)$	
	Desalinization	Desodification
Control	0.39	0.35
NG	0.27	0.28
PG	0.25	0.27
$CaCl_2.2H_2O$	0.19	0.16

An attempt was made to fit an empirical relationship to the experimental data, the best model was found as: $(EC/EC_o) = a + b\ (Ds/Dw)$ for desalinization curve, and $(ESP/ESP_o) = a + b\ (Ds/Dw)$ for desodification curve. A fitting model was plotted for control, NG, PG, and $CaCl_2.2H_2O$ with the desalinization and desodification, respectively, as it is shown in Table 3 and Figs. 3 and 4.

The desalinization leaching curves for various treatments are shown in Figs. 1 and 2. Using the above equation and the corresponding empirical constants presented in Table 3, it is possible to estimate the depth of leaching water required to reduce soil salinity or sodicity to a particular ESP-value or EC-value to a certain fraction in a given depth of soil and vice versa.

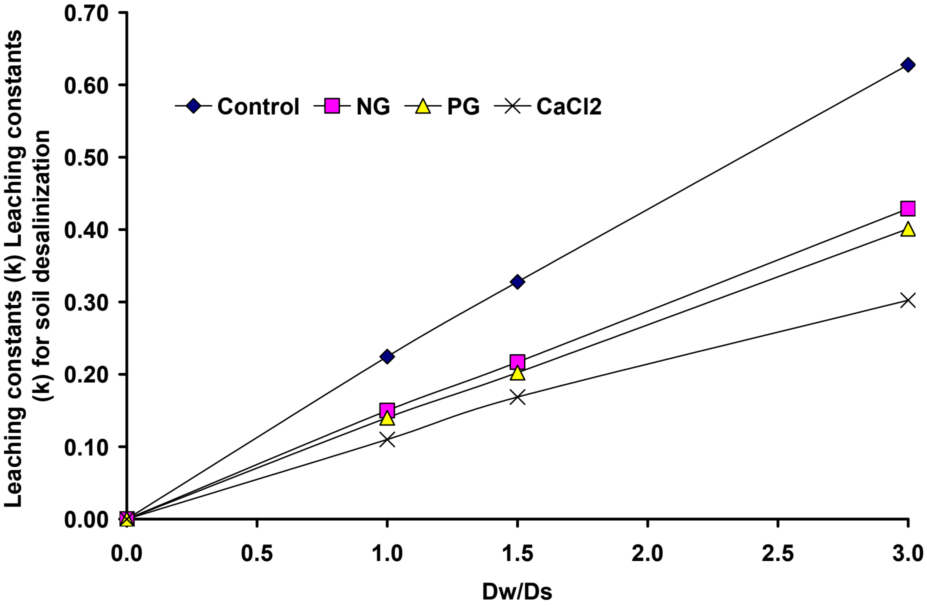

Fig. 3. Leaching constants (*k*) for soil desalinization vs. Dw/Ds

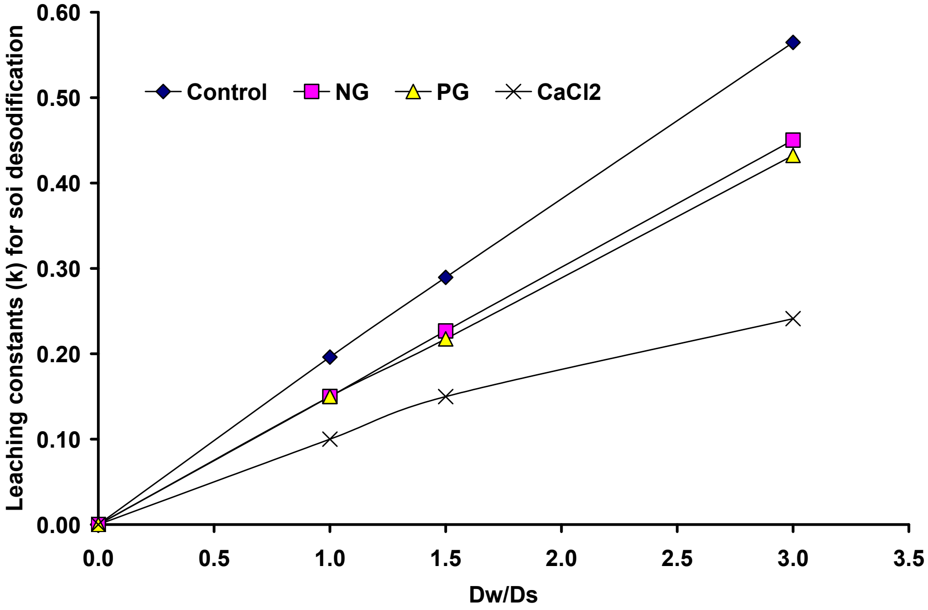

Fig. 4. Leaching constants (*k*) for soil desodification vs. Dw/Ds

Table 3. Empirical constant (a and b) of the regression equation relating the residual salinity fraction (EC/EC_o) or residual sodicity fraction (ESP/ESP_o) to the effective leaching water (Dw/Ds)

Treatments	Desalinization		Desodification	
	Equation	R^2	Equation	R^2
Control	y = -0.2329x + 0.7333	0.55	y = -0.2386x + 0.7224	0.55
NG	y = -0.2519x + 0.7058	0.54	y = -0.2493x + 0.7056	0.54
PG	y = -0.2546x + 0.7022	0.54	y = -0.2515x + 0.7056	0.54
$CaCl_2.2H_2O$	y = -0.2642x + 0.6941	0.55	y = -0.2708x + 0.6924	0.56

Notes: y refers to EC/EC_o or ESP/ESP_o and x refers to Dw/Ds

4. CONCLUSION

Desalinization and desodification curves showed that all treatments have reduced soil salinity and sodicity, with a superiority of calcium chloride in reducing soil salinity and sodicity. In addition, the Hoffman's approach was adopted to determine the leaching constant (*k*) for each amendment. Desalinization and desodification curves showed that application of calcium chloride seems to have a strong effect on *k* values. The leaching constants (*k*) for control, NG, PG and $CaCl_2.2H_2O$ gave average values of 0.39, 0.27, 0.25 and 0.19 for desalinization and 0.35, 0.28, 0.27 and 0.16 for desodification, respectively. The lower values of *k* in $CaCl_2.2H_2O$ treatment showed lower amounts of water required for leaching and reclamation compared to other treatments. Thus, leaching curves represent a very good method to determine the efficiency of amendments and the optimum depth of leaching water needed for successful reclamation of saline-sodic soils. However, the value of leaching constant (*k*) depends mainly on soil type and initial soil depth to be reclaimed, initial salt content of soil, quality and quantity of leaching water, mode of leaching (intermittent or continuous), type of chemical amendment and its solubility, and physical and chemical properties of soils. Therefore, the empirical approach of leaching relationship is considered a useful tool for deciding which amendment is the most appropriate and economically acceptable for soil reclamation, considering prevailing local soil and agricultural conditions. Further extended studies are needed in the future to cover the whole conditions that may affect leaching curve constant approach.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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