

Article

Reclaiming Tropical Saline-Sodic Soils with Gypsum and Cow Manure

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Abstract: Saline-sodic soils are a major impediment for agricultural production in semi-arid regions. Salinity and sodicity drastically reduce agricultural crop yields, damage farm equipment, jeopardize food security, and render soils unusable for agriculture. However, many farmers in developing semi-arid regions cannot afford expensive amendments to reclaim saline-sodic soils. Furthermore, existing research does not cover soil types (e.g., Luvisols and Lixisols) that are found in many semi-arid regions of South America. Therefore, we used percolation columns to evaluate the effect of inexpensive chemical and organic amendments (gypsum and cow manure) on the reclamation of saline-sodic soils in the northeast of Brazil. Soil samples from two layers (0–20 cm and 20–40 cm in depth) were collected and placed in percolation columns. Then, we applied gypsum into the columns, with and without cow manure. The experiment followed a complete randomized design with three replications. The chemical amendment treatments included a control and four combinations of gypsum and cow manure. Percolation columns were subjected to a constant flood layer of 55 mm. We evaluated the effectiveness of sodic soil reclamation treatments via changes in soil hydraulic conductivity, chemical composition (cations and anions), electrical conductivity of the saturated soil-paste extract, pH, and the exchangeable sodium percentage. These results suggest that the combined use of gypsum and cow manure is better to reduce soil sodicity, improve soil chemical properties, and increase water infiltration than gypsum alone. Cow manure at 40 ton ha⁻¹ was better than at 80 ton ha⁻¹ to reduce the sodium adsorption ratio.

Keywords: salinization; gypsum; manure; sodicity; tropical soils

1. Introduction

The use of brackish water in arid and semi-arid regions is increasing due to the increasing food demand by a growing population and declines in the current and future supply of freshwater [1–3]. However, the increasing use of brackish water in irrigated agriculture and the potential for inadequate drainage lead to salinization due to the low rainfall and high evaporation rate [4,5]. Under these conditions, the soils gradually accumulate soluble salts and alter the physical properties of the soil in the root zone, eventually reducing the potential yield of crops [6].

Soil degradation, caused by increased salinity and sodicity, reduces the soil organic matter and can weaken the soil due to the unstable structure and low water holding capacity. This degradation can also disrupt the soil aggregates, thus affecting the soil water, nutrients, and plant development [7]. Furthermore, organic matter applied to the salt-affected soils can increase the physical properties, such as the water retention capacity [7].

To improve sodic soil, a substantial percentage of the exchangeable sodium needs to be removed by calcium ions. This reaction can be quickly accomplished using chemical soil amendments, such as calcium chloride or calcium sulfate (gypsum), followed by leaching for the removal of salts after the reaction of salts with amendments in an acidic environment. However, adding industrial acids to soils is an expensive alternative for near-subsistence farmers in developing countries. Thus, alternative and readily available acidic substances, such as manure, can also help dissolve calcium compounds in soils. However, there are few guidelines for using manure to reclaim sodic soils. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is the most common amendment to reclaim sodic soils and to reduce sodium from the soil profile [8]. Gypsum is also a source of sulfur and calcium to plants, is moderately soluble in water, and is affordable for farmers in developing countries [9].

Cow manure is a common organic acidic amendment that has been shown to improve the physical properties of soils and increase soluble calcium. Both of these properties are required to reclaim sodic and saline-sodic soils [10]. Prapagar et al. [11] observed that gypsum combined with organic residues, cow manure, and rice husk decreased the pH values of a saline-sodic soil relative to the gypsum-only treatment. This change is mainly because of the acids formed during the decomposition of the organic matter. Combining gypsum with manure accelerated the recovery of sodic soils compared to either 5.2 g gypsum kg^{-1} soil or 50 g manure kg^{-1} soil alone [8]. In northwest India, the combined application of organic and inorganic fertilizers increased the concentrations of nutrients available to plants [12]. Cow manure (20–40 t ha^{-1}) increased soil organic matter, nitrogen (N), phosphorus (P), and soil permeability [13–15]. The advantages of combining gypsum and organic matter have been documented worldwide. They include the stimulation of soil microbiological activity in Chile [16], the enhancement of the infiltration rate in arid soils in Iran [17], decreasing the soil electrical conductivity (EC) and exchangeable sodium percentage (ESP) in South Korea [4], and improvement of the physical-hydric properties of Fluvisols in northeastern Brazil [18].

Despite extensive international research, there is little information in semi-arid tropical regions, which have large areas affected by saline-sodic soils [19]. Tropical semi-arid soils often have significantly different characteristics, including compared to other arid regions, especially in Latin America. These differences include different World Reference Base soil types [20] (e.g., Luvisols and Lixisols) compared to other arid soil types that have been more frequently studied (e.g., Calcisols, Gypsisols, and Durisols). Understanding saline soil reclamation in these lesser-studied soil types will become increasingly important. This importance is due to the likely altered locations and extent of semi-arid areas [21–23] under climate change and the shift of semi-arid climates over soil types that are not historically associated with semi-arid soil development. With specific respect to South America, land use changes are expected to increase the aridity of many regions, including regions that are already water stressed, such as the northeast of Brazil [24,25].

When soils have more organic matter in semi-arid areas, the negative effects of sodium are often reduced, and the water infiltration rate can be improved. Because cow manure and gypsum are widely available and affordable for small, near-subsistence farmers, this study aimed to evaluate if gypsum, applied alone or combined with cow manure, is efficient in the recovery of chemical and physical properties of a saline-sodic soil.

2. Materials and Methods

This experiment was conducted at the Hydraulic Engineering Laboratory of the Federal Rural University of the Semi-Arid Region (UFERSA), Mossoró, Rio Norte (RN), Brazil, in percolation columns from March to April 2013. Each column was made using polyvinyl chloride (PVC) pipes 50 cm in height and 10 cm in diameter (internal diameter = 9.72 cm). These columns were set on a wooden workbench and capped on the bottom. To facilitate drainage, we used a sponge in both ends of the columns and collected the leachate in 2-L plastic soda bottles connected on each cap (Figure 1).

We used an alluvial soil collected from a local irrigation district (Perímetro Irrigado de Paus dos Ferros, RN, Brazil). This soil was classified as a Chromic Luvisol according to the World Reference Base for soils [26]. We collected soil from the field in two layers ranging from 0 to 20 cm and 20 to 40 cm in depth [27]. During the collection, we observed that the soil exhibited signs of salt crusts on the surface. The soils were sandy and eutrophic, with both low cation exchange capacity (CEC) and high concentrations of sodium (Table 1). After collection, the soil material was pounded to break up clods, sieved, and air-dried for physical and chemical characterization. Then, the percolation columns were filled with the soil material, already mixed and uniformly moist to avoid high bulk density [28], up to a depth of 40 cm. There was 10 cm of headspace left in each column to facilitate drainage.

Details of Soil Column

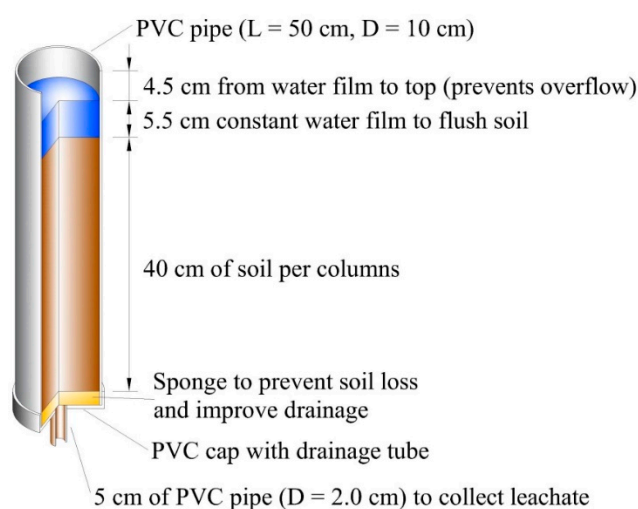


Figure 1. Schematic drawing of the soil columns inside polyvinyl chloride (PVC) pipes.

Table 1. Chemical characteristics of the experimental soil, in layers from 0 to 20 cm and 20 to 40 cm.

Soil Characteristics	Layers (cm)	
	0–20	20–40
pH _{1:2.5}	9.7	8.5
P (Mehlich) (mg kg ⁻¹)	18	23
Exchangeable cations (cmol _c kg ⁻¹)		
Ca ²⁺ (KCl 1 N)	1.50	1.10
Mg ²⁺ (KCl 1 N)	0.50	0.40
K (Mehlich-1)	0.32	0.25
Na ⁺ (Mehlich-1)	0.71	2.44
Exchangeable acidity (H ⁺ and Al ³⁺)	0.17	0.66
ESP (%)	22.2	47.0
Base saturation (V %)	94.7	85.5
Ion composition in the saturated extract 1:5 (cmol _c dm ⁻³)		
Ca ²⁺	0.60	0.60

Mg ²⁺	0.20	0.20
K ⁺	0.19	0.15
Na ⁺	1.88	2.61
CO ₃ ²⁻	0.40	0.00
HCO ₃ ⁻	2.40	1.70
Cl ⁻	1.40	2.00

The dose of gypsum necessary for the recovery of the soil, sufficient to reduce the initial ESP of the soil by 20%, was calculated using the following equation [29]:

$$D = (\text{ESP}_i - 0.8 \text{ESP}_f) \times \text{CEC} \times E \times h \times \rho, \quad (1)$$

where: D = dose of gypsum, $\text{g}\cdot\text{cm}^{-3}$; $(\text{ESP}_i - 0.8 \text{ESP}_f)$ = difference between the desired initial and final ESP (established as 20%); CEC = cation exchange capacity; E = equivalent mass of gypsum (86 g); h = soil depth to be recovered (cm); and ρ = soil density ($\text{g}\cdot\text{cm}^{-3}$).

The composition of the manure used in the experiment is shown in Table 2. The amount of manure followed the recommendation of 20 to 40 $\text{t}\cdot\text{ha}^{-1}$ of fresh manure by [30]. Doses of manure were chosen to provide 43.8, 30, and 15 $\text{g}\cdot\text{kg}^{-1}$ of N with an 8, 11.7, and 23 C/N ratio, respectively. Lower C/N ratios of less than 20 can cause higher N loss [31].

Table 2. Chemical composition and pH of cow manure.

PH and Minerals	
pH _{1:2.5}	7.5
C ($\text{g}\cdot\text{kg}^{-1}$)	334
N ($\text{g}\cdot\text{kg}^{-1}$)	14.0
P ($\text{g}\cdot\text{kg}^{-1}$)	8.68
K ⁺ ($\text{g}\cdot\text{kg}^{-1}$)	9.45
Ca ²⁺ ($\text{g}\cdot\text{kg}^{-1}$)	8.43
Mg ²⁺ ($\text{g}\cdot\text{kg}^{-1}$)	2.50
S ($\text{g}\cdot\text{kg}^{-1}$)	4.20
Cu ($\text{mg}\cdot\text{kg}^{-1}$)	63.1
Mn ($\text{mg}\cdot\text{kg}^{-1}$)	466
Zn ($\text{mg}\cdot\text{kg}^{-1}$)	198.41

The experiment had a completely randomized design with five treatments and three replicates. The treatments included: T_0 = without gypsum or manure (control); T_1 = 38.7 and 116.8 $\text{t}\cdot\text{ha}^{-1}$ of gypsum in the field soil layers of 0 to 20 cm and 20 to 40 cm, respectively; T_2 = 80 $\text{t}\cdot\text{ha}^{-1}$ of cow manure; T_3 = T_1 + 40 $\text{t}\cdot\text{ha}^{-1}$ of cow manure; and T_4 = T_1 + 80 $\text{t}\cdot\text{ha}^{-1}$ of cow manure. We incorporated the amendments in the first 10 cm of the soil layer in the column. We applied water to the upper part of the columns with a constant depth of 55 mm for eight days to leach salts. The water came from a local well, with the ionic composition presented in Table 3.

After the first four days, the percolation was interrupted for nine days to allow the chemical reactions with the soil amendments to occur, and then resumed for four additional days. A constant water depth was maintained in each column individually through narrow siphons from a 100-L plastic reservoir, a constantly replenished tank, with the water level controlled by a fixed float valve (Figure 2).

The following soil parameters were measured: pH, Ca, Mg, K, Na, P, ESP, E_{Ce}, SAR, hydraulic conductivity, and water infiltration rate in the soil. The water infiltration rate (T_i) was modeled as a response to the five treatments to the recovery of the sodic soil, according to the Green–Ampt equation [32]:

$$T_i = K_0 \left(1 + \frac{\psi_f(\theta_s - \theta_i)}{l} \right), \quad (2)$$

where T_i = infiltration rate ($\text{mm}\cdot\text{h}^{-1}$), K_0 = saturated soil hydraulic conductivity ($\text{mm}\cdot\text{h}^{-1}$), Ψ_f = matric potential in the moisture front (mm), θ_s = saturated soil water content ($\text{m}^3\cdot\text{m}^{-3}$), θ_i = initial soil water content ($\text{m}^3\cdot\text{m}^{-3}$), and I = water infiltration stemflow (mm). The variables measured in each treatment were evaluated considering two layer depths in each column (0–20 cm and 20–40 cm). Statistical tests included a comparison of means by the Tukey test at the 0.05 probability level, and analyses were conducted using the program 'Sistema para Análises Estatísticas (System for Statistical Analyses)' [33].

Table 3. Composition of irrigation water used in the percolation leaching experiments.

pH	EC	Na ⁺	Ca ²⁺	Mg ²⁺	Cl ⁻	K ⁺	CO ₃ ²⁻	HCO ₃ ⁻	SAR	(Richards, 1969)
	dS·m ⁻¹	mmol·L ⁻¹								
8.5	0.57	3.90	0.90	0.30	2.40	0.26	0.89	2.70	5.06	C ₂ S ₁

Experimental Hydraulic System

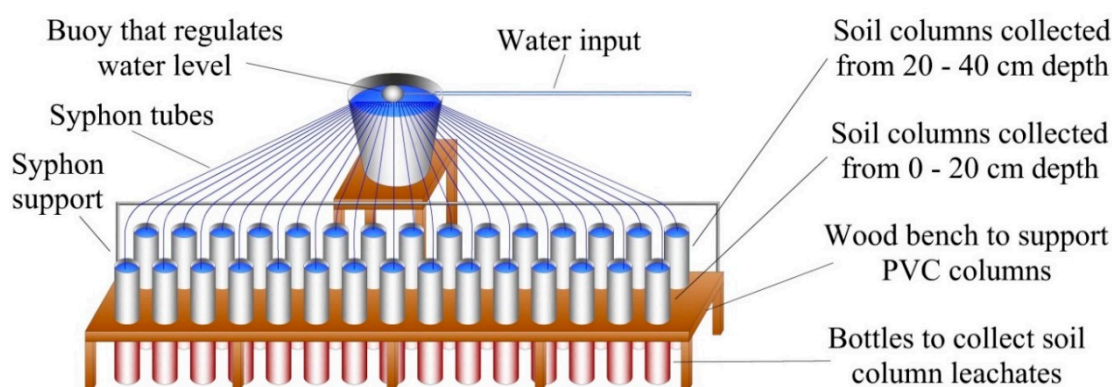


Figure 2. Schematic drawing of the soil columns inside polyvinyl chloride (PVC) pipes.

3. Results and Discussion

3.1. Effect on Soil Exchangeable Sodium Percentage (ESP)

Data analysis confirmed the efficacy of both gypsum and cow manure, combined or individually, in reducing soil sodicity. The reductions observed in SAR reiterate the positive effect obtained by the combined use of gypsum and manure as the manure treatments containing gypsum were more efficient than the manure-only treatments (Tables 4 and 5). The substitution of sodium by calcium can explain this reduction in sodicity in the soil exchange complex and due to gypsum being a rich source of soluble calcium.

We also observed that the combination of gypsum with cow manure was more efficient at 40 Mg than at 80 Mg per hectare. This effect is probably because cow manure also contains Na⁺, and its excessive use may go against the desired effect of improving soil chemistry. Although cow manure also contains Ca²⁺, this cation is not as available due to its adsorption to organic compounds, such as citric acid and humic acid, that are also present in the cow manure [34,35]. Thus, the addition of cow manure as a source of organic matter can improve the physical characteristics of the soil, facilitating the release of salts present in the soil solution. The low ESP values in the top layer (0–20 cm) of the percolation column for T₂, T₃, and T₄ illustrate the importance of organic matter in the redistribution of Na in the soil profile (Tables 4 and 5).

Table 4. Physical and chemical analysis of sodic soils (collected at the 0–20 cm depth in the field) following laboratory column leaching in the district of Perímetro Irrigado de Paus dos Ferros, Rio Grande do Norte, Brazil.

Treatments	Column Layer (cm)	pH _{1:2.5}	Soil Sorption Complex						Saturated Soil Extract					
			Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	H ⁺	T	V	ESP ²	P	pH	EC	SAR ¹
			cmol·kg ⁻¹						%		mg·kg ⁻¹			
T ₀	0–20	8.3 a	2.33 a	0.53 a	0.24 a	0.29 a	0.20 a	3.59 a	94.5 a	8.02 a	13.7 a	7.3 a	0.10 a	2.20 a
	20–40	8.3 a	1.90 a	0.60 a	0.22 a	0.26 a	0.38 b	3.37 a	88.64 b	7.74 a	21.3 a	7.3 a	0.24 b	2.39 a
	Mean	8.3 A	2.11 B	0.56 AB	0.23 B	0.27 B	0.29 B	3.48 B	91.57 C	7.88 AB	17.5 B	7.3 B	0.17 C	2.29 A
T ₁	0–20	8.1 a	2.67 a	0.53 a	0.24 a	0.29 a	0.11 a	3.84 a	97.23 a	7.48 a	15.3 a	7.5 a	0.53 a	2.17 a
	20–40	8.3 a	2.30 b	0.40 a	0.21 a	0.28 a	0.08 a	3.26 b	97.65 a	8.48 a	24.6 a	7.5 a	0.33 b	1.85 a
	Mean	8.2 A	2.48 B	0.46 B	0.22 B	0.28 B	0.09 C	3.55 B	97.44 A	7.98 A	20.0 B	7.5 A	0.43 B	2.01 A
T ₂	0–20	8.3 a	4.13 a	1.17 a	0.30 a	0.38 a	0.21 a	6.19 a	96.68 a	6.22 a	113.3 a	7.6 a	0.75 a	2.12 a
	20–40	8.2 a	1.90 b	0.73 a	0.83 b	0.27 b	0.20 a	3.33 b	93.99 a	8.11 b	23.3 b	7.3 a	0.43 b	2.35 a
	Mean	8.2 A	3.01 A	0.95 A	0.26 AB	0.32 A	0.20 BC	4.76 A	95.35 AB	7.16 ABC	68.3 A	7.4 B	0.59 A	2.24 A
T ₃	0–20	8.0 a	3.40 a	0.93 a	0.30 a	0.35 a	0.17 a	5.15 a	96.70 a	6.82 a	138 a	7.3 a	0.62 a	1.96 a
	20–40	8.3 a	2.80 b	0.37 b	0.21 b	0.26 b	0.22 a	3.86 b	94.22 a	6.66 a	25.8 b	7.4 a	0.32 b	1.8 a
	Mean	8.1 A	3.10 A	0.65 B	1.75 AB	0.30 B	0.19 BC	4.50 A	95.46 AB	6.74 BC	81.8 A	7.3 B	0.47 B	1.88 A
T ₄	0–20	8.1 a	3.87 a	0.87 a	0.34 a	0.34 a	0.22 a	5.64 a	96.07 a	6.08 a	116.3 a	7.2 a	0.54 a	1.92 a
	20–40	8.4 a	2.47 b	0.47 a	0.22 b	0.27 b	0.42 b	3.83 a	89.16 b	6.96 a	24.3 b	7.6 b	0.32 b	2.19 a
	Mean	8.2 A	3.17 A	0.67 B	0.28 A	0.30 B	0.32 A	4.73 A	92.61 BC	6.52 C	70.3 A	7.4 AB	0.43 AB	2.05 A
HSD	Column	0.41	0.45	0.43	0.047	0.034	0.109	0.56	2.82	1.198	13.58	0.19	0.09	0.53
	Treatment	0.42	0.46	0.44	0.048	0.035	0.111	0.57	2.87	1.22	13.86	0.19	0.09	0.55
	CV (%)	2.91	9.35	37.85	10.98	6.71	28.64	7.67	1.72	9.53	15.2	1.49	2.41	14.85

¹ SAR = Sodium Adsorption Ratio (mmol·L⁻¹)^{0.5}. ² ESP = Exchangeable Sodium Percentage. Lower case letters are for comparison of means between soil layers in each column, while upper case letters show comparison of means inside each treatment. T₀ = Control without gypsum or manure (control), T₁ = 38.7 e 116.8 t ha⁻¹ of gypsum applied to soil layers ranging from 0 to 20 cm and 20 to 40 cm, respectively; T₂ = 80 t·ha⁻¹ of cow manure; T₃ = T₁ + 40 t·ha⁻¹ of cow manure; T₄ = T₁ + 80 t·ha⁻¹ of cow manure. HSD = honestly significant difference.

Table 5. Physical and chemical analysis of sodic soils (collected at the 20–40 cm depth in the field) following laboratory column leaching in the district of Perímetro Irrigado de Paus dos Ferros, Rio Grande do Norte, Brazil.

Treatments	Column Layer (cm)	pH _{1:2.5}	Soil Sorption Complex							Saturated Soil Extract				
			Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	H ⁺	T	V	ESP ²	P	pH	EC dS·m ⁻¹	SAR ¹
			cmolc kg ⁻¹							%				
Soil Samples Collected from 20 to 40 cm														
T ₀	0–20	7.8 a	1.50 a	0.33 a	0.22 a	0.29 a	0.41 a	2.76 a	85.43 a	10.82 a	13.3 a	7.1 a	0.03 a	2.42 a
	20–40	8.4 a	0.83 a	0.47 a	0.23 a	0.42 ab	0.28 a	2.23 a	87.71 a	19.02 a	23.00 b	6.8 a	0.12 a	3.41 a
	Mean	8.1 A	1.16 C	0.40 B	0.22 AB	0.35 A	0.34 A	2.49 C	86.57 B	14.92 A	18.16 C	6.9 B	0.07 A	2.91 A
T ₁	0–20	7.6 a	16.4 a	1.50 a	0.18 a	0.26 a	0.22 a	18.65 a	98.37 a	1.51 a	13.00 a	7.4 a	1.66 a	1.20 a
	20–40	7.7 a	2.47 b	0.30 b	0.16 a	0.21 a	0.57 b	3.72 b	84.78 b	5.83 b	10.66 a	7.3 a	0.31 b	1.32 b
	Mean	7.6 C	9.45 B	0.9 AB	0.17 C	0.23 AB	0.42 A	11.16 B	91.57 AB	3.67 B	11.83 C	7.3 A	0.99 B	1.76 C
T ₂	0–20	7.8 a	4.13 a	1.87 a	0.27 a	0.36 a	0.49 a	7.13 a	92.93 a	5.10 a	261 a	7.2 a	1.65 a	2.25 a
	20–40	8.0 a	1.16 a	1.10 a	0.24 a	0.20 a	0.49 a	3.21 a	84.74 b	6.57 a	24.0 b	7.2 a	0.26 a	2.28 a
	Mean	7.9 AB	2.64 C	1.48 A	0.25 A	0.28 A	0.49 A	5.17 C	88.83 AB	5.83 B	142.5 A	7.2 AB	0.95 B	2.26 B
T ₃	0–20	7.6 a	17.6 a	2.10 a	0.22 a	0.36 a	0.41 a	20.73 a	98.02 a	1.74 a	129.6 a	7.5 a	3.21 a	1.44 a
	20–40	7.8 a	2.3 b	0.43 b	0.17 b	0.18 b	0.52 a	3.66 b	85.34 b	4.88 a	22.33 b	7.3 a	0.86 b	1.81 b
	Mean	7.7 BC	9.98 B	1.26 B	0.19 BC	0.27 A	0.48 A	12.19 B	91.53 A	3.31 B	76.00 B	7.4 A	2.03 B	1.63 CD
T ₄	0–20	7.6 a	27.7 a	1.03 a	0.22 a	0.31 a	0.22 a	29.61 a	99.02 a	1.04 a	224.0 a	7.4 a	3.57 a	1.39 a
	20–40	7.8 ab	2.53 a	0.37 a	0.17 b	0.29 a	0.46 a	3.82 b	87.91 b	7.15 b	33.0 b	7.3 a	0.78 b	1.66 b
	Mean	7.7 BC	15.1 A	0.70 AB	0.18 C	0.30 A	0.37 A	16.71 A	93.46 A	4.09 B	128.5 A	7.3 AB	2.17 B	1.53 D
HSD	Column	0.2	3.82	0.88	0.03	0.14	0.26	4.16	4.94	4.24	37.64	0.39	1.75	0.19
	Treatment	0.21	3.88	0.89	0.03	0.14	0.27	4.25	5.04	4.33	38.4	0.4	1.74	0.19
	CV (%)	1.5	28.72	53.52	9.06	27.88	36.29	25.19	15.15	38.48	28.82	3.16	34.91	5.45

¹ SAR = Sodium Adsorption Ratio (mmolc L⁻¹)^{0.5}. ² ESP = Exchangeable Sodium Percentage. Lower case letters are for comparison of means between soil layers in each column while upper case letters show comparison of means inside each treatment. T₀ = Control without gypsum or manure (control), T₁ = 38.7 e 116.8 t·ha⁻¹ of gypsum applied to soil layers ranging from 0 to 20 cm and 20 to 40 cm, respectively; T₂ = 80 t·ha⁻¹ of cow manure; T₃ = T₁ + 40 t·ha⁻¹ of cow manure; T₄ = T₁ + 80 t·ha⁻¹ of cow manure. HSD = honestly significant difference.

3.2. Effect of Treatments on Soil Reaction (PH)

In both layers, soil pH (pH_e and $pH_{1.2.5}$) decreased compared to values before the application of treatments (Table 2). After leaching with well water, soil $pH_{1.2.5}$ from the 20 to 40 cm layer decreased from 9.7 to 7.6 in T₁ (116.80 t·ha⁻¹ of gypsum), 7.9 in T₂ (80 t·ha⁻¹ of manure), 7.7 in T₃ (combination of gypsum + 40 t·ha⁻¹ of manure), and 7.7 in T₄ (combination of gypsum + 80 t·ha⁻¹ of manure) (Table 5).

We observed the lowest significant pH values ($p < 0.05$) in T₄, followed by T₂ and T₃. These values represented reductions of 6%, 4.9%, and 4.9%, respectively, compared to the control. Even with the most effective gypsum plus manure treatments (T₃ and T₄), the pH values are still above what would be considered ideal for crop development and yield [36]. Additional acidifiers may be required for optimal growth. The main advantage of gypsum and cow manure is that gypsum supplies Ca²⁺ to substitute the adsorbed Na⁺ while manure increases the content of CaCO₂ in the soil, also releasing more Ca²⁺ for the substitution of Na⁺ [37]. Our results are similar to those of Tiwari and Jain [38] and Izhar-ul-Haq et al. [39]. These studies found that the best results came from the combined use of gypsum and manure to reduce soil pH. Islam et al. [40] mentioned that gypsum and organic manure should be the right choices for managing silty-loam soils in Bangladesh. However, Buckley and Wolkowski [41] did not find any improvement after gypsum application in soil properties in an experiment in Wisconsin, USA.

Furthermore, the pH_e increased with increased depth of the layer in the soil column (Tables 5 and 6). This is due to the movement of bases inside the column, caused by the constant inundation from the water. Also, the applied CaSO₄ may have translocated, being positively correlated with pH_e (Tables 5 and 6). Compared to the control, the pH reduction caused by the combined treatment (gypsum + manure) was due to the acidifying effect of the organic acids produced during the decomposition of organic matter. Prapagar et al. [11] compared gypsum alone with the application of gypsum combined with cow manure and rice husk and reported that the application of the combined treatment decreased the pH values of a saline-sodic soil. Our results disagree with those of Rani and Khetarpaul [42], who grew tomatoes under a sodic condition with gypsum and farmyard manure. They found that treatment with gypsum and 20 t·ha⁻¹ of manure was enough to raise the pH and neutralize 100% of the sodium in sodic soils of India.

3.3. Treatment Effect on Electrical Conductivity and Sodium Absorption Ratio (SAR)

In both soil layers, the EC_e decreased in all treatment combinations and the control, compared with the initial EC_e of the soil (1.92 and 3.28 dS·m⁻¹ for the layers of 0 to 20 cm and 20 to 40 cm, respectively). The control was more effective in the reduction of soil EC_e , in comparison to the combination of gypsum or gypsum + manure. The decrease in the original soil EC_e may have resulted from the beneficial action of the organic matter, which improved the physical properties of the soil, facilitating the leaching of excess salts. Organic matter also decreased EC_e , ESP, and accelerated the leaching of Na⁺ [4]. Concerning the percolation column, there was a greater accumulation of salts in the layer of 15 to 30 cm, compared with the superficial layer in all treatments, except for the treatment without gypsum or manure (control).

Compared to the control, SAR values decreased in all treatments that had amendments, with significant decreases in the layer of 20 to 40 cm. The combination of manure in the high dose (80 t·ha⁻¹) with gypsum (20% of ESP) showed a better result in comparison to gypsum only (difference of 0.23 SAR units—Table 5). The decrease in SAR in the control treatment was probably due to the weathering and leaching of the soil [43] with the application of the leaching water depth. The reduction in SAR occurs because of the increase of the divalent cations (Ca²⁺ and Mg²⁺) or decrease of the monovalent cation (Na⁺), provided in the reaction of gypsum with the soil and the decomposition of the organic residues. The mean values of the cations (Tables 5 and 6) indicated that Na⁺ decreased while Ca²⁺ + Mg²⁺ increased in the sorption complex after the application of organic and inorganic amendments followed by the application of the leaching water depth. These results agree with [13,44,45] in showing that the combination of organic matter with gypsum was more effective in reducing soil ESP because of the replacement of exchangeable sodium ions with calcium ions.

High pH, EC, and ESP values have a profound impact on the chemical and physical properties of soils [46]. These results agree with Mahmoodabadi and Heydarpour [47]. This study observed a decrease of EC and ESP following the addition of organic matter in an arid area of the Kerman province, central Iran. In South Korea, Kim et al. [46] also observed that the combined application of gypsum and organic matter was more effective in reducing soil salinity and sodicity. Combined application of gypsum and organic matter resulted in lower pH values, resulting in good soil reclamation in Lucknow, India [13].

Table 6. Infiltration rate of percolating water, according to treatment, from soil collected at 0 to 20 cm and 20 to 40 cm.

Treatment	Days After Treatment (Days)								Average
	1	2	3	4	14	15	16	17	
	Infiltration Velocity (mm h ⁻¹)								
	(Soil from the 0 to 20 cm Layer)								
T ₀	19.7	13.0	14.6	21.1	22.5	21.7	17.6	6.0	17.05 C
T ₁	40.4	33.2	27.4	38.2	42.1	29.7	19.0	88.8	29.85 B
T ₂	33.0	29.6	24.0	33.6	32.3	26.0	22.6	32.5	29.21 B
T ₃	35.0	43.7	52.0	53.2	44.3	12.1	8.7	85.4	41.80 A
T ₄	52.0	44.6	47.8	105.4	45.3	47.3	37.9	25.7	50.76 A
HSD	-	-	-	-	-	-	-	-	11.45
CV (%)	-	-	-	-	-	-	-	-	42.1
	(Soil from the 20 to 40 cm Layer)								
T ₀	10.5	5.3	3.4	1.8	0.8	0.2	0.4	0.3	2.84 B
T ₁	27.4	49.4	28.4	10.7	33.6	19.0	11.7	20.4	25.09 A
T ₂	13.6	9.0	7.0	5.6	5.3	5.3	3.4	3.0	6.52 B
T ₃	33.0	26.9	26.0	24.4	34.5	29.9	19.9	18.1	26.62 A
T ₄	32.7	16.5	27.4	22.5	20.5	16.3	19.8	25.7	22.70 A
HSD	-	-	-	-	-	-	-	-	4.45
CV (%)	-	-	-	-	-	-	-	-	32.87

T₀ = Control without gypsum or manure (control), T₁ = 38.7 and 116.8 t·ha⁻¹ of gypsum applied to soil layers ranging from 0–20 cm and from 20–40 cm, respectively; T₂ = 80 t·ha⁻¹ of cow manure; T₃ = T₁ + 40 t·ha⁻¹ of cow manure; T₄ = T₁ + 80 t·ha⁻¹ of cow manure. HSD = honestly significant difference.

3.4. Effect of Amendments on Soil Physical Properties

The water infiltration rates increased significantly with gypsum alone and gypsum plus manure for both studied soil layers (Table 6). The treatments with organic and inorganic conditioners (gypsum + cow manure), regardless of the applied dose of manure, led to higher water infiltration rates in the soil profile, with maximum values of 41.80 and 50.76 mm·h⁻¹ in the layer of 0 to 20 cm, for the combination of 116.8 t·ha⁻¹ + 40 t·ha⁻¹ of manure and 116.8 t·ha⁻¹ + 80 t·ha⁻¹ of cow manure, respectively. In the layer of 20 to 40 cm, the maximum water infiltration rates were equal to 26.6 and 22.7 mm·h⁻¹ for the combination of 116.8 t·ha⁻¹ + 40 t·ha⁻¹ of manure and 116.8 t·ha⁻¹ + 80 t·ha⁻¹ of cow manure, respectively. Gypsum was fundamental to improve the water flow in the soil since the treatment that received only manure at the dose of 80 t·ha⁻¹ did not differ statistically from the control.

These observations indicate that the presence of gypsum was important to displace sodium from the exchange complex, improving the physical conditions for water movement. Also, the treatments may have induced an increase in aggregate stability, facilitating water infiltration and movement in the soil, because gypsum provides Ca²⁺ to replace the adsorbed Na⁺, which might reduce the dispersion, improving the soil physical properties [13,48].

The application of organic matter and gypsum combined was more effective in reducing the soil pH, ESP, and SAR as compared to the treatment using gypsum alone. This added efficacy may be because organic matter from manure and other sources supports rich micro-flora and has a

nutritional quality by improving soil C storage [13,49]. However, soil application of organic matter would not improve plant nutrition by itself. Therefore, the application of cow manure + gypsum is recommended as an efficient soil amendment for reclaiming sodic soil in combination with chemical fertilizers.

From previous experiments performed in Brazil, we assumed that cow manure doses above 40 t·ha⁻¹ were needed to improve the chemical quality of sodic soils in combination with gypsum. These experiments reported that manure doses below 40 t·ha⁻¹ were insufficient to reduce ESP in alluvial saline-sodic soils [50]. Although a dose of 40 t·ha⁻¹ of cow manure reduced the ESP in a fluvial soil, it did not reduce pH, EC, or Na⁺ [18].

4. Conclusions

Saline-sodic soils hinder agricultural production in many semi-arid regions of the world, including regions with relatively lesser studied soil types. Nevertheless, many farmers in drylands cannot afford the costly amendments that can be used to reclaim their soils. In this experiment, we used gypsum and cow manure to evaluate how they affected both the physical and chemical properties of a saline-sodic soil irrigated with local groundwater in the northeast of Brazil. We found that gypsum combined with manure provided the greatest improvement, leading to the largest reductions in sodium saturation percentage, sodium adsorption rate, and pH, and to the greatest increase in the infiltration rate. The lower dose of manure (40 t·ha⁻¹) was equally effective at reducing the sodium adsorption ratio (SAR) as a higher dose (80 tons/hectare). Applying enough gypsum to substitute 20% of the exchangeable sodium percentage was enough for the reclamation of the soil under study. Despite the clear benefit of combining gypsum and manure, the pH of the soil was still above the optimal range (6.0–6.8) to make macro and micronutrients fully available to most plants. Future work should focus on testing additional, low-cost acidifying agents to enhance soil reclamation of saline/sodic soils in semi-arid regions.

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