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Reclamation of a saline-sodic soil as a function of incubation time with chemical amendments

Recuperação de um solo salino-sódico em função do tempo de incubação com corretivos químicos

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Highlights

Chemical amendments efficiently reduced soil sodicity within 20 days.
Gypsum yielded the greatest soil structure and clay flocculation gains.
Sulfuric acid reduced soil pH and hydraulic conductivity fastest.
Longer treatment time produced greater soil chemical and physical gains.

Abstract

Soil salinization and sodification pose threats to agricultural sustainability in the São Francisco Valley, a semi-arid region of the Middle-Lower São Francisco River. This study evaluated the efficiency and reaction time of four soil amendments (agricultural gypsum, calcium chloride, sulfuric acid, and elemental sulfur) in the recovery of saline-sodic soils. Conducted at IFSertãoPE – Campus Petrolina Zona Rural, the laboratory experiment used soil columns incubated for 20, 40, and 60 days. The variables analyzed included pH, electrical conductivity, exchangeable cations (sodium [Na^+], potassium [K^+], calcium [Ca^{2+}], and magnesium [Mg^{2+}]), percentage of exchangeable sodium (PST), hydraulic conductivity, and the degrees of clay dispersion and flocculation. The results showed that, at 100% field capacity, all treatments effectively reduced PST and exchangeable Na^+ within 20 days. Th agricultural gypsum

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treatment was the most efficient in promoting clay flocculation. Treatment with sulfuric acid led to the fastest increase in hydraulic conductivity and decrease in pH, although caution is required due to its corrosive nature. Consequently, gypsum is the most suitable longer-term treatment, while sulfuric acid is effective for immediate chemical correction of saline-sodic soils.
Key words: Salinity. Semiarid region. Sodicity. Soil amendments. Soil reclamation.

Resumo

A salinização e a sodificação do solo representam ameaças à sustentabilidade agrícola no Vale do São Francisco, região semiárida do Médio-Baixo Rio São Francisco. Este estudo avaliou a eficiência e o tempo de reação de quatro corretivos de solo (gesso agrícola, cloreto de cálcio, ácido sulfúrico e enxofre elementar) na recuperação de solos salino-sódicos. Conduzido no IFSertãoPE – Campus Petrolina Zona Rural, o experimento em laboratório utilizou colunas de solo incubadas por 20, 40 e 60 dias. As variáveis analisadas incluíram pH, condutividade elétrica, cátions trocáveis (Na^+, K^+, Ca^{2+}, Mg^{2+}), porcentagem de sódio trocável (PST), condutividade hidráulica e graus de dispersão/floculação da argila. Os resultados mostraram que, a 100% da capacidade de campo, todos os tratamentos reduziram efetivamente a PST e o sódio trocável em 20 dias. O gesso agrícola foi o mais eficiente na promoção da floculação da argila. O ácido sulfúrico proporcionou a resposta mais rápida no aumento da condutividade hidráulica e na redução do pH, embora seja necessário cautela devido à sua natureza corrosiva. Consequentemente, O gesso é a alternativa mais adequada para o período de avaliação de 60 dias, enquanto o ácido sulfúrico é eficaz para a correção química imediata.
Palavras-chave: Salinidade. Região semiárida. Sodicidade. Corretivos de solo. Recuperação de solo.

Introduction

In Brazil, the Northeast Region stands for fruit production, particularly in the irrigated agricultural hub of the Lower São Francisco Valley. This region has a semi-arid climate characterized by high temperatures, with a mean above 25 °C, high annual evapotranspiration (near 2,000 mm), low rainfall, and an irregular distribution of precipitation (Costa et al., 2023; Tavares et al., 2026). These climatic conditions, combined with local geological characteristics and inadequate irrigation and drainage management, may favor salt accumulation and soil sodification, constituting an important constraint to agricultural production.

Salinization and sodification are associated with the accumulation of soluble salts and an increase in the proportion of sodium (Na^+) on the soil exchange complex, respectively. Under conditions of limited leaching, ions such as Na^+, chloride (Cl^-), calcium (Ca^{2+}), and magnesium (Mg^{2+}) may accumulate in soil, altering its chemical and physical properties (Paiva et al., 2016; Pedrotti et al., 2015). In soils affected by excess Na, particle dispersion may reduce aggregate stability, infiltration, and hydraulic conductivity (K_0), and also restrict root development. These effects, combined with the high salt concentrations in the soil solution, may impair the water that is available to plants and, consequently, agricultural productivity (Patel et al., 2026).

In this context, appropriate management of soil salinity and sodicity is essential for maintaining the productive capacity and sustainability of agricultural systems. The reclamation of Na-affected soils depends, among other factors, on reducing salt concentrations and removing Na^+ from the exchange complex, processes that require adequate water availability, drainage, and leaching conditions. The application of chemical amendments is one of the strategies used to modify soil chemical conditions and promote reclamation, particularly when combined with appropriate water management.

Among the products used or investigated for this purpose, gypsum ($CaSO_4 \cdot 2H_2O$) stands out as a traditional source of soluble Ca^{2+} for sodic soils. Other products, such as calcium chloride ($CaCl_2$), sulfuric acid (H_2SO_4), and elemental sulfur (S^0), have more limited use under field conditions but are of experimental interest because of the different chemical mechanisms through which they can modify the soil environment (Pedrotti et al., 2015). $CaCl_2$ is a readily soluble source of Ca^{2+}, whereas H_2SO_4 promotes acidification and may enhance the dissolution of carbonates and the release of Ca^{2+} present in the soil. S^0 depends on microbial oxidation to form acidifying compounds and therefore may have a potentially more gradual effect (Yi et al., 2023). Thus, these amendments can be compared based on their effects, even though they differ in solubility and in how they affect soil chemical properties. This comparison does not imply that the amendments are equally suitable for all agricultural applications or would be used at the same frequency.

Despite the established use of agricultural gypsum for the reclamation of sodic soils, how soils respond to different amendments may vary according to their chemical characteristics, the application rate, and the treatment time. There has been limited comparison of how the chemical properties of saline-sodic soils subjected to different amendments change over time, along with the mechanisms of action responsible for these changes. Therefore, this study hypothesized that the application of different chemical amendments to saline-sodic soils alters the concentrations of soluble and exchangeable cations and the exchangeable sodium percentage (ESP), with responses depending on the type of amendment, application rate, and treatment time. Based on this hypothesis, the objectives were to evaluate the effects of different chemical amendments, applied at practical rates, on the chemical properties of a saline-sodic soil and to analyze how these properties change over time. Soil responses were characterized as a function of amendment type, application rate, and treatment time.

Material and Methods

The experiment was conducted at the Soil, Water, and Plant Analysis Laboratory of the Federal Institute of the Sertão Pernambucano (IFSertãoPE), Petrolina Zona Rural Campus (9°20'12"S, 40°41'21"W). The soil, classified as saline-sodic, was collected from the 0-0.20 m soil layer in an area representative of Fazenda Barreiras, Riacho Seco community, Curaçá, Bahia, Brazil, in the Lower São Francisco Valley region. Approximately 100 kg of soil was

collected from the established depth. It was first characterized and then used to fill the percolation columns.

After collection, the soil was transported to the laboratory, prepared according to the analytical procedures adopted, and subjected to chemical and physical characterization, with the results presented in Tables 1 and 2. The analyses were performed according to the methods described by Teixeira et al. (2017), with the specific analytical procedure used to evaluate each physical and chemical attribute described below.

Table 1
Chemical attributes of the soil used in this study

pH (1:1.25)	EC (1:5)	OM	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	ESP
H_2O	dS m^{-1}	g kg^{-1}	mg dm^{-3}	----------cmol$_c$ dm^{-3}----------						
7.30	37.97	9.10	90.16	1.02	14.17	27.70	11.90	0.00	0.00	25.85

EC, electrical conductivity of the saturated soil extract; P, available phosphorus; OM, organic matter; K^+, potassium; Na^+, sodium; Ca^{2+}, calcium; Mg^{2+}, magnesium; Al^{3+}, aluminum; H+Al hydrogen plus aluminum; ESP exchangeable sodium percentage.

Table 2
Physical attributes of the soil used in this study

Sand	Silt	Clay	Bd	Pd	Tp	K_0	WDC	DF
	g kg^{-1}		g cm^{-3}		m^{-3} m^{-3}	cm h^{-1}	g kg^{-1}	%
445.35	428.75	125.90	1.32	2.45	0.46	1.09	61.85	50.88

Bd, bulk density; Pd, particle density; TP, total porosity; K_0, hydraulic conductivity; WDC, water-dispersible clay; DF, degree of flocculation.

Figure 1 presents a diagram of the experimental procedure, from the collection of saline-sodic soil in Curaçá, Bahia, through sample preparation and treatment, filling of the percolation columns, and leaching, during which water flow displaced ions from the exchange complex and the resulting leachate was evaluated.

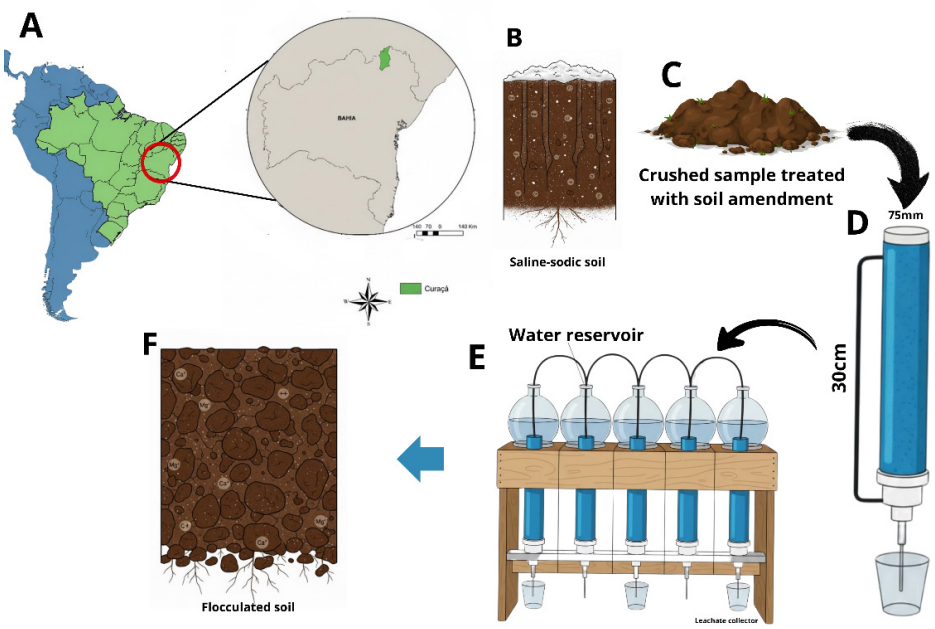


Figure 1. (A) Sampling location in Curaçá, BA. (B) Saline-sodic soil profile. (C) Sample preparation with amendments. (D and E) Assembly of columns and leaching system. (F) Representation of flocculated soil after treatment.

In the experimental setup, a completely randomized design was adopted in a 5 × 3 factorial scheme, with four replications, totaling 60 experimental units. The factors comprised:

1. Four chemical amendments, namely agricultural gypsum ($CaSO_4 \cdot 2H_2O$), $CaCl_2$, H_2SO_4, and S^0, alongside untreated soil (no chemical amendment);

2. Three treatment times, namely 20, 40, and 60 days after application.

The theoretical amendment rate (Dt) required to reduce the final exchangeable sodium percentage (ESPf) to 10% was calculated according to Pizarro (1985), as shown in Equation 1:

$$Dt = \frac{(ESPf - ESPi) x CEC x h x Ds x Pe}{100} \frac{kg}{ha} \qquad eq\ (1)$$

where:

Dt = theoretical amendment rate (kg ha^{-1});

ESPf and ESPi = final and initial exchangeable sodium percentage (%), respectively;

CEC = cation exchange capacity ($cmol_c\ dm^{-3}$);

h = depth of the soil profile to be corrected (cm);

Ds = soil bulk density (kg dm^{-3});

Pe = equivalent weight of the amendment (86 for gypsum, 73 for $CaCl_2$, 49 for H_2SO_4, and 16 for S^0).

The practical rate (Dp) was adjusted using correction factors (f): 1.2 for gypsum and S^0, and 1.1 for $CaCl_2$, H_2SO_4, and sulfates (Pizarro, 1985), according to Equation 2:

$$Dp = Dt\ x\ f \qquad eq\ (2)$$

The experimental units consisted of polyvinyl chloride (PVC) columns with a diameter of 75 mm and a height of 30 cm. The base of each column was sealed with a custom-designed slotted cap (CAP), produced using a three-dimensional (3D) printer (Bambu Lab) at the INOVE-Sertão laboratory, aiming to optimize drainage and the collection of leachate.

The soil was air-dried, gently disaggregated, sieved, and homogenized. Subsequently, 1.750 kg of soil was weighed for each column, and the amendment was incorporated at the following rates: 27.3 t ha^{-1} for agricultural gypsum, 23.2 t ha^{-1} for $CaCl_2$, 15.6 t ha^{-1} for H_2SO_4, and 5.1 t ha^{-1} for S^0, calculated according to a previously presented equation.

The amount of soil packed into the columns was calculated based on the internal volume of the columns (1,357.36 cm^3) and the natural bulk density of 1.32 g cm^{-3}. During filling, the columns were gently compacted using a glass rod to obtain a uniform bulk density of 1.32 g cm^{-3} across all columns.

The water-holding capacity was previously determined using test columns through saturation followed by drainage of free water. The retained volume of water was used to determine the amount of water applied to the experimental columns. Moistening was performed only once by capillary action until 100% of the water-holding capacity was reached. After the application of water, the columns were sealed with plastic film and covered with a plastic cap, preventing water loss through evaporation during the experimental period.

During the incubation and leaching procedure, the columns containing the untreated soil (control) remained under the same experimental conditions throughout the established experimental period. However, due to the high Na content and elevated ESP, the control soil exhibited low K0 and reduced percolation capacity, resulting in an insufficient volume of leachate for collection and analysis of the eluate. Therefore, after the treatment time, the control soil was collected and analyzed for the evaluated soil attributes, following the same analytical procedures used for the other treatments. To analyze the eluate, only data from treatments that showed percolation and allowed leachate collection were considered.

After the treatments times, the columns were saturated in the upward direction until a 2-cm layer of water formed on the surface. Then, the columns were incubated for 24 h with the system closed to establish equilibrium between the solution and the solid phase before elution began (Caron et al., 2015). Subsequently, leaching was performed using a water volume equivalent to twice the pore volume (PV), maintained under a constant hydraulic head using the Mariotte bottle method.

The time required to collect this volume was recorded to calculate K_0, according to Equation 3:

$$K_0 = \frac{Q\ x\ L}{A\ x\ h\ x\ t} \qquad eq\ (3)$$

Where:

K_0 = hydraulic conductivity (cm h^{-1});

Q = volume of percolate (mL);

L = height of the soil column (cm);

h = total hydraulic head (sum of soil height and water layer height) (cm);

A = cross-sectional area of the cylinder (cm^2);

t = time elapsed for percolation (h).

At the end of each collection, a sample of the leachate solution was stored for analysis of Na^+, K^+, Ca^{2+}, Mg^{2+}, pH, and electrical conductivity (EC). The remaining soil in the columns was air-dried, gently crushed, and subjected again to the abovementioned chemical analyses, including the degree of clay dispersion and the degree of clay of flocculation, according to Teixeira et al. (2017).

The data were analyzed with two-way analysis of variance (ANOVA), followed by Tukey's test for pairwise comparisons. For all tests, $p < 0.05$ was considered to be statistically significant. The analyses were performed using Sisvar software, version 4.1

Results and Discussion

Table 3 presents the amendment × day interaction effect, which was significant for pH, the available phosphorus (P) content ($p < 0.001$), the K^+ content ($p < 0.001$), the Mg^{2+} content ($p < 0.001$), the degree of clay dispersion ($p < 0.001$), the degree of clay flocculation ($p < 0.001$), the Na^+ content ($p < 0.01$), K_0 ($p < 0.01$), and ESP ($p < 0.05$). However, the interaction was not significant for EC and the Ca^{2+} content ($p > 0.05$).

Table 1
Summary of the analysis of variance for pH, electrical conductivity (EC); the phosphorus (P), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) contents; exchangeable sodium percentage (ESP), hydraulic conductivity (K_0), the degree of clay dispersion (°Dis), and the degree of clay flocculation (°Flo), as a function of the amendment and treatment time

SV	df	pH	EC	P	Na^+	K^+	Ca^{2+}	Mg^{2+}	ESP	K^0	°Dis	°Flo
Treatment	4	***	***	***	***	***	***	***	***	***	***	***
Days	2	***	*	***	*	***	***	***	*	**	***	***
Treatment * days	8	***	ns	***	**	***	ns	***	*	**	***	***
CV (%)		1.59	10.70	8.41	9.22	3.81	5.05	2.46	23,19	30.25	3.18	3.13

SV, source of variation; df, degrees of freedom; CV (%), coefficient of variation; ns, not significant; *** $p < 0.001$; $p < 0.01$; * $p < 0.05$.

At 20 days, treatment had a significant effect on soil pH (Figure 2A), with the highest pH recorded for the $CaCl_2$ (8.2) and gypsum (8.0) treatments, which did not differ from each other. pH was 7.7 for the S0 treatment, 7.3 for the untreated soil, and 5.8 for the H_2SO_4 treatment, indicating an acidifying effect for the latter. The pH trend was similar at 40 days: It was again highest for the gypsum (8.0) and $CaCl_2$ (7.9) treatments, with no significant difference between them, followed by untreated soil (7.3), the S^0 treatment (7.2), and the H_2SO_4 treatment (5.8). Finally, at 60 days, pH was 7.8 for the gypsum and $CaCl_2$ treatments, 7.3 for the untreated soil, 6.7 for the S^0 treatment, and 5.7 for the H_2SO_4 treatment.

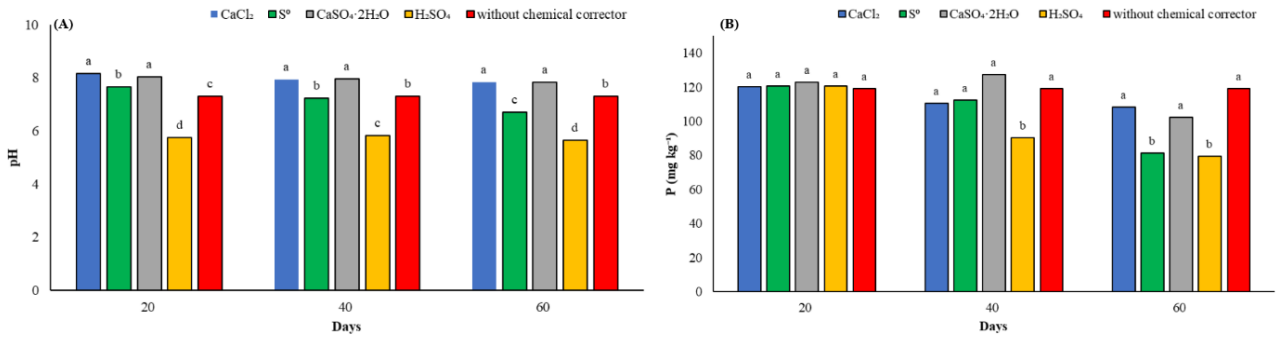


Figure 2. Soil pH (A) and exchangeable phosphorus (P) content (B) in saline-sodic soil subjected to different chemical amendments over the 60-day experimental period. Columns with the same letter do not differ according to Tukey's test ($p < 0.05$).

Variations in soil pH may be associated with the application of chemical amendments and changes in the equilibria between the solid phase and the soil solution. Agricultural gypsum and $CaCl_2$ are sources of Ca^{2+}, albeit with different solubility characteristics. In solution, gypsum can be represented by the equilibrium $CaSO_4 \cdot 2H_2O \rightleftharpoons Ca^{2+} + SO_4^{2-} + 2H_2O$, whereas $CaCl_2$ is highly soluble and dissociates according to $CaCl_2 \rightarrow Ca^{2+} + 2Cl^-$. The release of Ca^{2+} increases the concentration of this cation in the soil solution and may promote changes in cation-exchange equilibria, displacing Na^+ from the soil exchange complex into the solution. Subsequently, Na+ present in the solution may be removed by leaching, particularly under conditions of water flow.

In the case of gypsum, the SO_4^{2-} released during dissolution remains in the solution and may interact electrostatically with Na^+, potentially forming Na^+–SO_4^{2-}(aq) ion pairs that can be transported with the percolating water. Similarly, Cl^- released from $CaCl_2$ dissociation remains predominantly in solution and may accompany Na^+ during the leaching process.

Under equilibrium conditions, the high Ca^{2+} concentration in the solution may alter cation-exchange equilibria between the solution and the soil exchange complex, favoring the replacement of adsorbed cations and the consequent redistribution of ionic species between the solid and liquid phases. Thus, the observed changes in pH should be interpreted by considering the combined acid-base and cation-exchange equilibria established among the soil solution, colloids, and mineral constituents of the soil.

The pH reduction associated with the H_2SO_4 treatment is consistent with its direct acidifying effect, resulting from increased hydrogen ion (H^+) activity in the soil solution. The additional H^+ may react with carbonates in soil, promoting their neutralization and facilitating the dissolution of carbonate minerals, with the consequent release of Ca^{2+} into the soil solution. This mechanism is consistent with the reduction in pH observed in the H_2SO_4 treatment and with its greater acidifying capacity compared with the other treatments (Daba, 2025).

The reduction in pH observed with the S0 treatment is associated with the biological oxidation of S^0 in the soil by sulfur-oxidizing microorganisms, including *Acidithiobacillus* spp., promoting acid generation in the soil (Ibáñez et al., 2023). Unlike H_2SO_4, whose acidifying effect occurs directly after application, oxidation of S^0 depends on microbial activity and environmental conditions such as soil moisture, temperature, and oxygen availability. Thus, the progressive reduction in pH observed throughout the 60-day experimental period is consistent with the gradual nature of S^0 oxidation (Chaudhary et al., 2023; Yi et al., 2023).

At 20 days, there were no significant differences among the treatments in terms of the P content (Figure 2B). At 40 days, the H_2SO_4 treatment had the lowest P content (90 mg kg^{-1}), differing significantly from the other treatments, which did not differ from each other. The gypsum treatment resulted in the numerically highest P content (127 mg kg^{-1}), followed by the untreated soil (119 mg kg^{-1}), the S0 treatment (112 mg kg^{-1}), and the $CaCl_2$ treatment (111 mg kg^{-1}). At 60 days, the P content was highest for the untreated soil (119 mg kg^{-1}), followed by the $CaCl_2$ treatment (109 mg kg^{-1}). Those samples differed from the S^0 (81 mg kg^{-1}), gypsum (102 mg kg^{-1}), and H_2SO_4 (79 mg kg^{-1}) treatments.

P dynamics in the soil may also be influenced by its vertical movement through the soil profile. In sandy soils or soils with low adsorption capacity, such as Quartzipsamments and Regosols, the lower abundance of surface charges and iron (Fe) and aluminum (Al) oxides reduces P retention, favoring its mobility and redistribution to deeper layers, particularly under irrigation conditions (Santos et al., 2024). This process may contribute to a reduction in the P content in the surface layers over time.

The presence of carbonates and a high pH is common in soils with a high Na content. In these systems, the application of H_2SO_4, as well as its formation through the oxidation of S^0, promotes carbonate dissolution, releasing Ca^{2+} into the soil solution (Albuquerque et al., 2018). This Ca^{2+} may react with P, favoring the formation of Ca phosphates with limited solubility and thereby reducing P availability.

Furthermore, the reduction in pH may increase the solubility of Fe and Al oxides, increasing the number of P adsorption sites. Thus, P availability becomes controlled by precipitation and adsorption reactions involving Ca^{2+}, Fe^{3+}, and Al^{3+}, which may explain the lower P content observed in the acidifying treatments (Hu et al., 2023; Islam et al., 2024).

Figure 3A shows that at 20 days, the K^+ content differed among the treatment. The untreated soil had the highest value (1.3 $cmol_c$ kg^{-1}), significantly different from the four treatments. The S^0 and $CaCl_2$ treatments had a similar K^+ content (1.2 $cmol_c$ kg^{-1}). The gypsum and H_2SO_4 treatments had the lowest K^+ content (1.0 $cmol_c$ kg^{-1}), indicating a possible effect of these amendments in reducing exchangeable K^+. At 40 days, there was a general reduction in the K^+ content compared with the values recorded at 20 days. The untreated soil maintained the highest value (1.3 $cmol_c$ kg^{-1}), differing significantly from the four treatments, followed by the gypsum (0.9 $cmol_c$ kg^{-1}), $CaCl_2$ (0.8 $cmol_c$ kg^{-1}), and S0 (0.8 $cmol_c$ kg^{-1}) treatments, which did not differ from each other. The H_2SO_4 treatment again had the lowest K^+ content

(0.7 $cmol_c\ kg^{-1}$). This pattern persisted at 60 days. The untreated soil again showed the highest K^+ content (1.3 $cmol_c\ kg^{-1}$), indicating stability over the 60-day experimental period. The $CaCl_2$ (0.8 $cmol_c\ kg^{-1}$) and gypsum (0.8 $cmol_c\ kg^{-1}$) treatments did not differ from each other, followed by the S^0 (0.7 $cmol_c\ kg^{-1}$) and H_2SO_4 (0.6 $cmol_c\ kg^{-1}$) treatments.

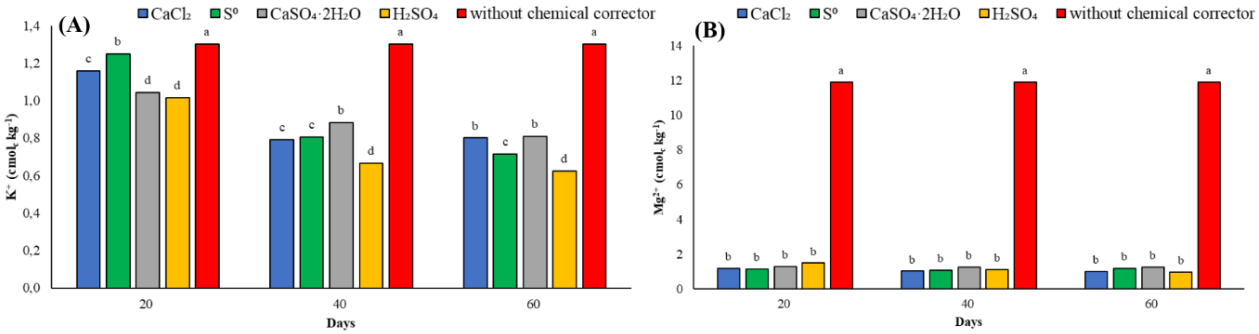


Figure 3. The exchangeable potassium (K^+) (A) and magnesium (Mg^{2+}) (B) contents in saline-sodic soil subjected to different chemical amendments over the 60-day experimental period. Columns with the same letter do not differ according to Tukey's test ($p < 0.05$).

The reduction in the K^+ content can be explained by cation exchange processes and changes in soil chemical equilibrium. The application of H_2SO_4 decreases soil pH and favors their dissolution, releasing Ca^{2+} into the soil solution. This increase in the Ca^{2+} content, combined with higher H^+ availability, intensifies the displacement of basic cations from exchange sites, especially K^+ and Na^+, promoting their movement into the soil solution and possible leaching (Han et al., 2023; Pedrotti et al., 2015). This behavior is supported by recent evidence showing that changes in pH and cation concentrations, particularly Ca^{2+}, directly influence K availability and mobility in the soil, potentially resulting in reduced exchangeable K^+ due to increased leaching and redistribution within the soil profile (Shabtai et al., 2023).

The effect of S^0 on K^+ is more gradual, as its biological oxidation depends on microbial activity for in situ formation of H_2SO_4 (Ibáñez et al., 2023). This slower process explains why the reduction in K^+ becomes more pronounced over time, accompanying the progressive acidification of the soil.

For the $CaCl_2$ and gypsum treatments, the reduction in exchangeable K^+ is associated with increased Ca^{2+} saturation in the exchange complex. The addition of large amounts of Ca^{2+} promotes the displacement of adsorbed K^+, moving it into the soil solution and increasing its susceptibility to leaching (Pedrotti et al., 2015). An increase in Ca^{2+} in the soil can enhance K^+ mobility, especially in soils with lower retention capacity (Doulgeris et al., 2023).

The untreated soil showed a markedly higher Mg^{2+} content over the experimental period (15.7 $cmol_c\ kg^{-1}$) compared with the four treatments (Figure 3B). At 20 days, the Mg^{2+} content was 1.5 $cmol_c\ kg^{-1}$ for

the H_2SO_4 treatment, 1.3 $cmol_c$ kg^{-1} for the gypsum treatment, 1.2 $cmol_c$ kg^{-1} for the $CaCl_2$ treatment, and 1.1 $cmol_c$ kg^{-1} for the S^0 treatment. At 40 days, the H_2SO_4 treatment decreased the Mg^{2+} content to 1.1 $cmol_c$ kg^{-1}; this value wax similar to the S^0 treatment (1.1 $cmol_c$ kg^{-1}). At 60 days, the Mg^{2+} content was again reduced for the H_2SO_4 treatment (1.0 $cmol_c$ kg^{-1}) and was similar to the $CaCl_2$ treatment. Overall, gypsum treatment led to greater stability in Mg^{2+} during the 60 days, with a content ranging from 1.2 to 1.3 $cmol_c$ kg^{-1}.

The reduction in the Mg^{2+} content for the treatments with soluble sources of Ca^{2+} (gypsum and $CaCl_2$) can be explained by cation exchange processes in the exchange complex. The additional Ca^{2+} competes for exchange sites and displaces previously adsorbed cations such as Mg^{2+} and Na^+, promoting their transfer into the soil solution (Westhoff et al., 2024). The greater affinity of Ca^{2+} for soil colloids compared with Mg^{2+} is associated with its smaller hydrated radius and stronger electrostatic adsorption, favoring its retention in the exchange complex and the displacement of Mg^{2+} into the liquid phase (Zhang et al., 2025). This effect is particularly relevant in saline-sodic soils, where the application of gypsum promotes ionic exchange between Ca^{2+} and Mg^{2+}, followed by leaching of the displaced Mg^{2+}, especially in soils with low retention capacity or under irrigation conditions (Westhoff et al., 2024).

The untreated soil showed the highest Na^+ content throughout the entire experimental period (18.7 $cmol_c$ kg^{-1}), differing significantly from the four treatments at 20, 40, and 60 days (Figure 4A). At 20 days, the H_2SO_4 treatment produced the highest Na^+ content (1.5 $cmol_c$ kg^{-1}), followed by the $CaCl_2$ and S^0 treatments (each at 0.7 $cmol_c$ kg^{-1}) and the gypsum treatment (0.3 $cmol_c$ kg^{-1}). At 40 and 60 days, all treatments presented an Na^+ content below 1 $cmol_c$ kg^{-1}, indicating high efficiency in removing exchangeable Na^+.

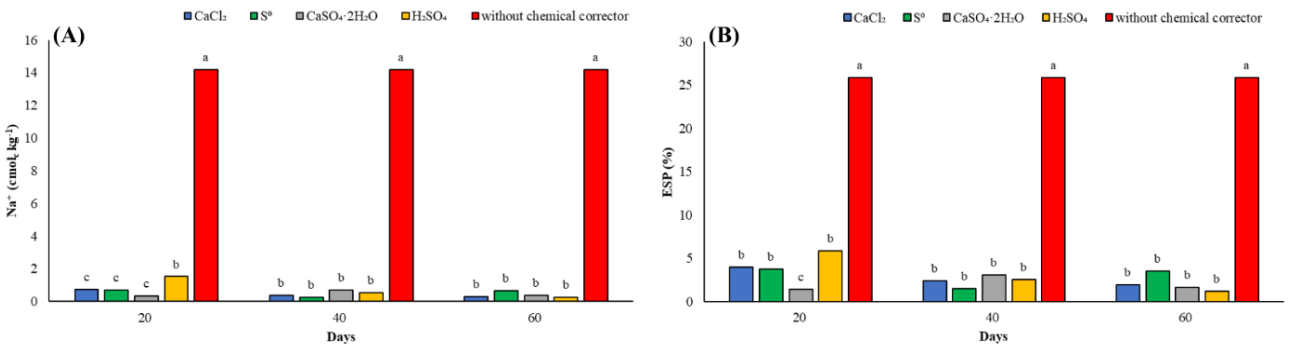


Figure 4. The exchangeable sodium (Na^+) content (A) and exchangeable sodium percentage (ESP) in saline-sodic soil subjected to different chemical amendments over the 60-day experimental period. Columns with the same letter do not differ according to Tukey's test ($p < 0.05$).

The significant reduction in Na^+ is associated with the ion exchange mechanism between Ca^{2+} and Na^+ in the soil exchange complex. The amendments supply Ca^{2+}, which has a higher affinity for exchange sites, displacing previously adsorbed Na^+ and promoting its transfer to the soil solution, where it can be removed by leaching (Elmeknassi et al., 2024). In the case of gypsum and $CaCl_2$, this effect occurs directly through the supply of soluble Ca^{2+}, which replaces Na^+ on soil colloids, forming salts such as sodium sulfate (Na_2SO_4) and sodium chloride (NaCl), both highly soluble and easily leached (Elmeknassi et al., 2024). In contrast, acid-type amendments such as H_2SO_4 and S^0 act indirectly by reducing soil pH and dissolving carbonates, thereby releasing Ca^{2+} into the soil solution and enhancing Na^+ replacement (Zhang et al., 2025).

The untreated soil presented the highest ESP for the entire experimental period (25.9%), differing significantly from the four treatments (Figure 4B). At 20 days, the ESP was higher for the H_2SO_4 treatment (5.8%), followed by the $CaCl_2$ (4.0%), S^0 (3.7%), and gypsum (1.4%) treatments. At 40 days, ESP ranged from 2.4% to 3.1% for the $CaCl_2$, S0 and H_2SO_4 treatments, and was 1.5% for the gypsum treatment. At 60 days, ESP was 3.5% for the S^0 treatment, 2.0% for the $CaCl_2$ treatment, 1.6% for the gypsum treatment, and 1.2% for the H_2SO_4 treatment.

Changes in ESP are directly related to cation exchange processes and Ca dynamics in the soil. In the $CaCl_2$ and gypsum treatments, the predominant mechanism is the replacement of Na^+ by Ca^{2+} in the exchange complex, promoting the release of Na^+ into the soil solution and subsequent removal by leaching (Elmeknassi et al., 2024). The variations in ESP are directly associated with the exchangeable Na^+ content, indicating a proportional relationship between these variables. Because ESP represents the fraction of Na^+ relative to the soil's CEC, its reduction reflects a decrease in Na adsorbed by the exchange complex, confirming the effectiveness of the amendments in mitigating sodicity (Green et al., 2023).

The degree of clay flocculation was highest for the gypsum treatment at all treatment times: 70% at 20 days, 74% at 40 days, and 82% at 60 days. It differed significantly from the other treatments at each time (Figure 5A). At 20 days, the untreated soil presented the next highest degree of clay flocculation (51%), significantly higher that of the $CaCl_2$ (41%) and H_2SO_4 (43%) treatments. At 40 days, the degree was of clay flocculation was 45% for the S^0 treatment, 42% for the $CaCl_2$ treatment, and 40% for the H_2SO_4 treatment. At 60 days, the degree of clay flocculation was 42% for the $CaCl_2$ and H_2SO_4 treatments.

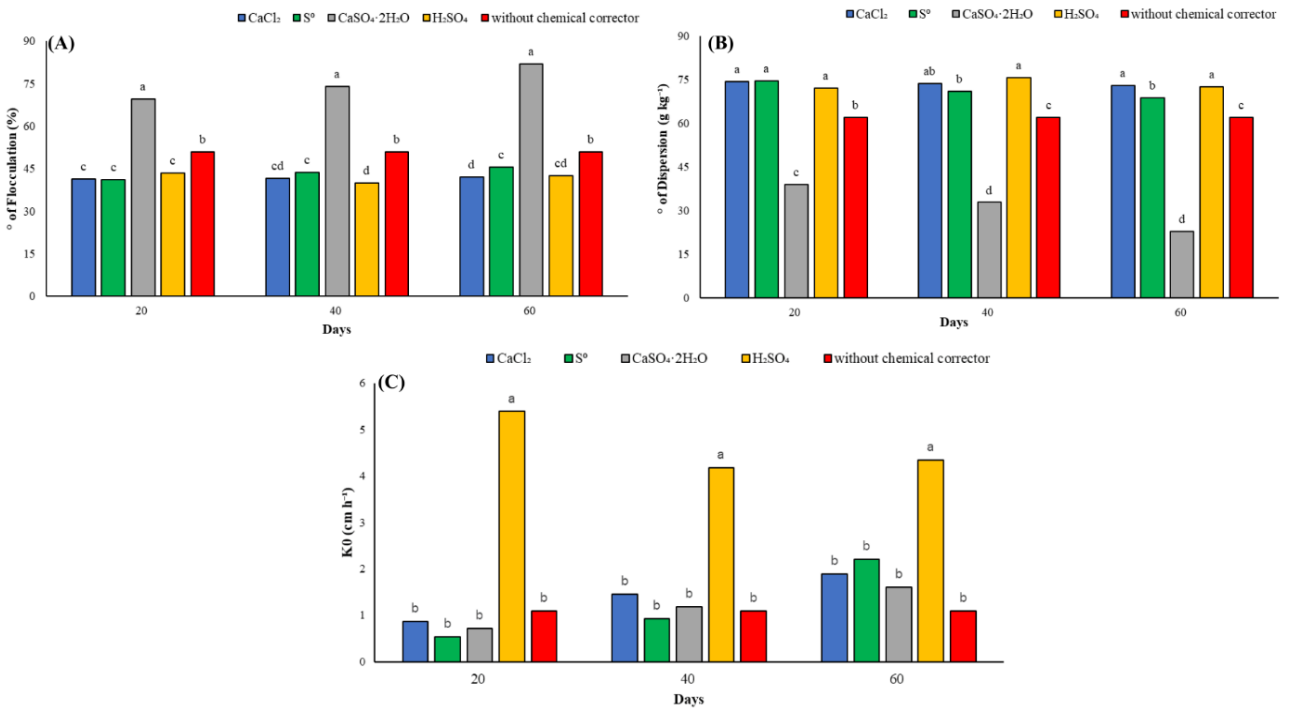


Figure 5. The degree of clay flocculation (A), the degree of clay dispersion (B), and hydraulic conductivity (K_0) in saline-sodic soil subjected to different chemical amendments over the 60-day experimental period. Columns with the same letter do not differ according to Tukey's test ($p < 0.05$).

The degree of clay dispersion was lowest for the gypsum treatment at 20 days (39 g kg^{-1}), 40 days (33 g kg^{-1}), and 60 days (23 g kg^{-1}), significantly lower than the other treatments (Figure 5B). At 20 days, the degree of clay dispersion was highest for the $CaCl_2$ (74 g kg^{-1}), S^0 (74 g kg^{-1}), and H_2SO_4 (72 g kg^{-1}) treatments, followed by the untreated soil (62 g kg^{-1}). At 40 days, the trend was similar, with the H_2SO_4 treatment showing the highest value (76 g kg^{-1}) and a slight reduction for the S0 treatment (71 g kg^{-1}). In saline-sodic soils, excess Na^+ promotes clay particle dispersion, reducing aggregation, porosity, and water infiltration (Niaz et al., 2022). The application of gypsum supplies Ca^{2+} to the soil solution, which replaces Na^+ at exchange sites, promoting the formation of soluble salts and their subsequent removal by leaching, thereby contributing to clay flocculation (Zhang et al., 2025).

In addition, the increase in the Ca^{2+} content reduces the thickness of the diffuse double layer around colloidal particles, favoring particle approximation and promoting soil aggregation, resulting in improved structure and K_0 (Zhang et al., 2025). Although amendments such as S^0 and H_2SO_4 promote soil acidification, they have an indirect effect on structural recovery, as they depend on the solubilization of Ca sources present in the soil. Therefore, their efficiency in reducing clay dispersion depends on Ca^{2+}

availability in the system, which explains the higher dispersion values observed in these treatments throughout the experimental period (Westhoff et al., 2024).

Figure 5C shows the relationship between the different treatments and K_0. At 20 days, the H_2SO_4 treatment increased K_0 to 5.4 cm h^{-1}, markedly higher than the untreated soil (1.1 cm h^{-1}). The other treatments reduced K_0: 0.9 cm h^{-1} for the $CaCl_2$ treatment 0.7 cm h^{-1} for the gypsum treatment, and 0.5 cm h^{-1} for the S^0 treatment; there were no significant difference between those treatments and the untreated control. At 60 days, K_0 was reduced to 4.3 cm h^{-1} for the H_2SO_4 treatment while it was increased for the S^0 (2.2 cm h^{-1}), $CaCl_2$ (1.9 cm h^{-1}), and gypsum (1.6 cm h^{-1}) treatments. The change in K_0 associated with the H_2SO_4 treatment is related to rapid action of this amendment on soil chemical properties. It immediately reduces soil pH and enhances the solubilization of minerals, especially carbonates, with the consequent release of Ca^{2+} into the soil solution. These changes reduce sodicity and improve soil structure (Westhoff et al., 2024; Zhang et al., 2025).

As shown in Table 4, the amendment × incubation time interaction effect in the leachate was significant for EC ($p < 0.001$), the Ca^{2+} content ($p < 0.001$), the Na^+ content ($p < 0.01$), and the K^+ content ($p < 0.05$), but not the Mg^{2+} content ($p > 0.05$).

Table 2
Summary of the analysis of variance for pH; electrical conductivity (EC); and the sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) contents in the leachate as a function of the amendment and treatment time

SV	df	pH	EC	Na^+	K^+	Ca^{2+}	Mg^{2+}
Treatment	3	***	***	ns	**	***	*
Days	2	***	***	***	***	***	***
Treatment * Days	6	**	***	**	*	***	ns
CV (%)		2.89	10.95	34.15	15.49	10.42	11.56

FV, source of variation; df, degrees of freedom; CV (%), coefficient of variation; ns, not significant; *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

The pH of the soil leachate (Figure 6A) differed significantly among the treatments throughout the experimental period, with the $CaCl_2$ and gypsum treatments leading to higher pH compared with the S^0 and H_2SO_4 treatments. Nevertheless, the variation in pH among treatments was relatively small, suggesting that the system was highly resistant to changes in acidity during the leaching process. This behavior may be related to the soil's buffering capacity, resulting from interactions between the soil solution and solid-phase components, which tend to limit more pronounced changes in the H^+ concentration.

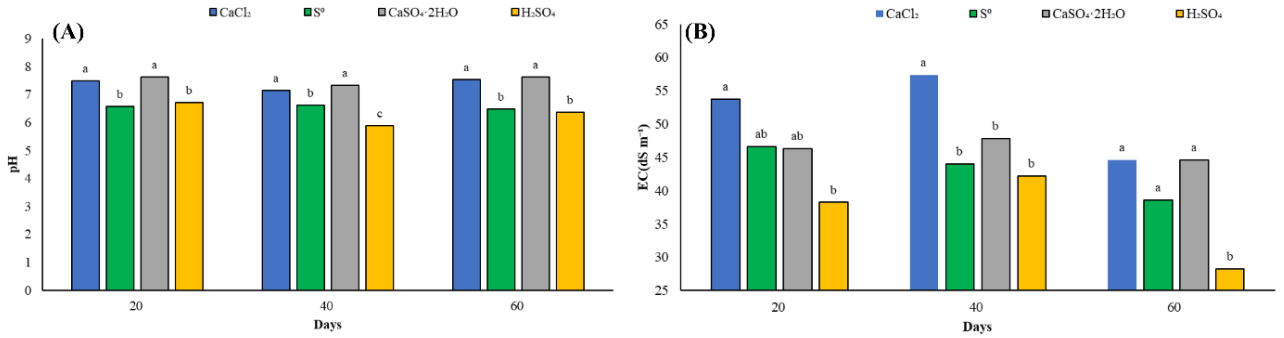


Figure 6. pH (A) and electrical conductivity (EC) (B) in the soil leachate of saline-sodic soil subjected to different chemical amendments over the 60-day experimental period. Columns with the same letter do not differ according to Tukey's test ($p < 0.05$).

EC of the leachate showed significant differences among the treatments at all treatment times (Figure 6B). EC was highest for the $CaCl_2$ treatment, followed by the gypsum treatment, while the H_2SO_4 treatment led to the lowest EC. EC tended to decrease over the experimental period, indicating progressive leaching of salts (Zhang et al., 2025). This behavior is directly related to the solubility of the amendments: $CaCl_2$ is highly soluble and responsible for greater ion release into the soil solution, gypsum dissolves more gradually, and H_2SO_4 tends to react with soil constituents, reducing the concentration of free ions in the leachate (Elmeknassi et al., 2024; Green et al., 2023).

Among the treatments, at 20 days, the Na^+ content was higher for the $CaCl_2$ and gypsum treatments and lower for the H_2SO_4 treatment. At 40 and 60 days, there was a marked reduction in the Na^+ content, with no significant differences among treatments (Figure 7A). The Ca^{2+} content was higher for the $CaCl_2$ treatment, followed by the gypsum treatment, while it was lower for the S^0 and H_2SO_4 treatments (Figure 7B). The K^+ content was low at 20 days, followed by an increase at 40 days and a subsequent decrease at 60 days, with the H_2SO_4 treatment producing the lowest values (Figure 7C).

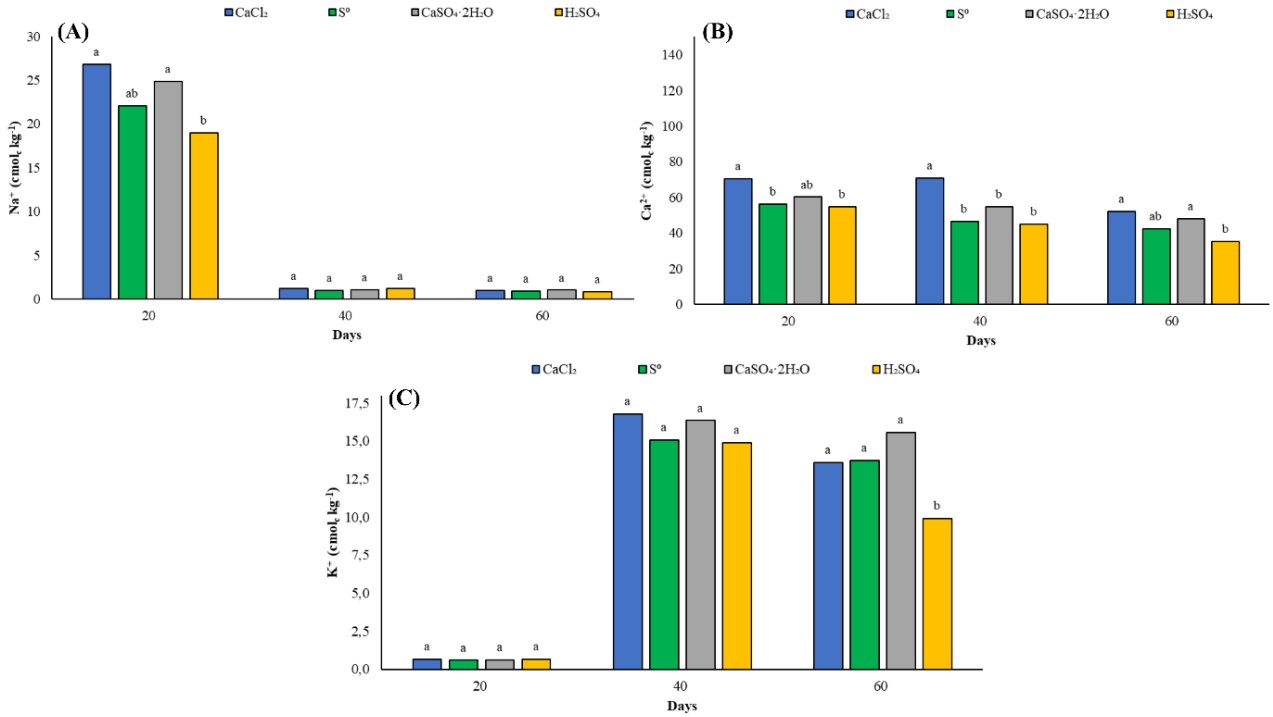


Figure 7. The sodium (Na^+) (A), calcium (Ca^{2+}) (B), and potassium (K^+) (C) contents in the soil leachate of saline-sodic soil subjected to different chemical amendments over the 60-day experimental period. Columns with the same letter do not differ according to Tukey's test ($p < 0.05$).

The application of amendments, especially Ca^{2+} sources, promotes the replacement of Na^+ at exchange sites, initially increasing its concentration in the soil solution, followed by a reduction over time due to leaching (Daba, 2025; Elmeknassi et al., 2024). The efficiency of this process depends on the solubility of the amendments: It is faster when highly soluble sources such as $CaCl_2$ are applied, intermediate for gypsum, and slower for H_2SO_4 and S^0, which depend on soil reactions (Green et al., 2023; Zhang et al., 2025).

Leaching acts as an essential step in salt removal, reflected in the reduction of Na^+ and EC over time (Niaz et al., 2022; Westhoff et al., 2024). In addition, the increase in Ca^{2+} enhances ionic competition, promoting the mobilization of other cations such as K^+, which may be temporarily elevated in the leachate and subsequently leached (Doulgeris et al., 2023; Shabtai et al., 2023). In this context, the reclamation of saline-sodic soils depends on Ca^{2+} availability, the nature of the amendments, and the efficiency of leaching factors that also influence nutrient dynamics within the system.

Conclusion

The application of chemical amendments was effective in reclaiming

saline-sodic soil, promoting a significant reduction in the exchangeable Na^+ content and ESP with treatment for as little as 20 days. The treatment time significantly influenced the efficiency of the amendments, with more pronounced improvements in soil structure after 40 and 60 days.

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