



Enhancing Reclamation of Challenging Saline Sodic Soil in EL Abbasa District, EL Sharkia Province, Egypt: Impact of Gypsum Particle Diameters Mixed with Filter Cake

Mohamed H.M.^{1*}, Ali M. A. El-Nagar^{2*}, Omnia F.Amin^{1*} and *. Noha, H. Abdelkader^{2*}

¹Soil, Water and Environment Research Institute Agric., Res. Center, Giza (Egypt) ; Mhahass1370@gmail.com (M.H.M) ; Omniafarouk111@gmail.com (O.F.A.)

²Soil Sci. Dept., Fac. of Agric., Cairo Univ., Giza 12613, Egypt; alimbaba2@yahoo.com (A.M.A) ; noha.abdulkader@agr.cu.edu.eg(N.H.A.)

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The study aimed to evaluate the efficacy of traditional gypsum, and gypsum particle diameters, independently and in conjunction with filter cake, in reclaiming saline-sodic soil. This assessment was conducted through a leaching experiment utilizing column technology, utilizing soil collected from the EL Abbasa region in Egypt's EL Sharkia Province.

The results of the study indicated a significant decrease in electrical conductivity (EC), pH, and exchangeable sodium percentage (ESP), coupled with an increase in hydraulic conductivity (Ks), for all treatments—whether applied individually or in combination—when compared to the control. Notably, the combined treatments demonstrated a higher effectiveness level than individual applications.

Furthermore, the study revealed that the fineness of gypsum particles plays a crucial role in reducing salinity and sodicity. Specifically, the use of fine gypsum particles (<63 µm) in conjunction with filter cake was found to enhance the reclamation process, resulting in more substantial reductions in salinity and sodicity in saline-sodic soil. These findings suggest that the strategic application of fine gypsum, particularly in combination with filter cake, can contribute significantly to soil reclamation efforts.

Keywords: Sodic Saline Soils; Gypsum; Filter Cake; Soil Amendments; Column Leaching Experiment.

Introduction

In arid regions, the annual occurrence of soil salinization poses a challenge, leading to the degradation of productive irrigated lands. Approximately 6% of the world's land, equivalent to more than 800 million hectares (Mha), is affected by soil sodicity or salinity (Khanet *al.*, 2014). While a significant portion of soil salinity and sodicity is naturally occurring, recent human activities such as land clearing and irrigation have contributed to the salinization of developed agricultural land (Munns, 2005). In Egypt, for instance, 3 million hectares of irrigated land have been estimated, with 0.8 million hectares experiencing salt-related soil issues (Oo et al., 2015).

Soil salinization is a prominent environmental issue associated with substantial declines in farmland area, productivity, and quality (Murtaza et al., 2006; Shahbaz and Ashraf, 2013). "Soil salinity" refers to an excess of salt in the soil, while "salt-affected soils" denotes those with significant salt levels impacting water quality, plant health, and land use (Murtaza et al., 2006; Shahbaz and Ashraf, 2013). Salts in soil may result from the weathering of minerals or transportation by water and wind. Typically found in arid and semi-arid climates with minimal precipitation for leaching, salt-affected soils can be categorized as saline or sodic.

Saline soils, characterized by an exchangeable sodium content of less than 15 and a saturation extract conductivity exceeding 4 dS m⁻¹, were formerly known as white alkali soils. The dissolved salts, including NaCl, Na₂SO₄, MgSO₄, CaSO₄, MgCl₂, KCl, and Na₂CO₃, contribute to salinity stress (Yamaguchi and Blumwald, 2005). Despite various salts being present in the soil solution, sodium chloride has been the primary focus of salinity research (Yamaguchi and Blumwald, 2005; Munns and Tester, 2008). Sodic soil, with a saturation extract conductivity below 4 dS m⁻¹ and an exchangeable sodium content exceeding 15, often displays a pH ranging from 8.5 to 10.0. These soils, dominated by carbonate and bicarbonate anions, are informally termed "black saltiness." When moist, high sodicity causes soil overswelling, leading to dispersion and structural collapse upon drying. The clay particles form dense layers, reducing soil aggregation and impeding air and water flow through sodic soils (Seelig, 2000; Rengasamy, 2002).

Gypsum emerges as a widely utilized and cost-effective amendment for sodic soils due to its availability and ease of application. It establishes a consistent hydraulic gradient, reducing sodicity to salinity ratios in percolating solutions (Qadir and Schubert, 2002). By enhancing infiltration rates and lowering pH, electrical conductivity (EC), exchangeable sodium percentage (ESP), bulk density, and hydraulic conductivity, gypsum proves effective (Miyamoto and Enriquez, 1990). However, the amount applied must be carefully considered, taking into account factors such as dissolution rates and crystallinity levels (Abdel-Fattah, 2011).

Organic amendments, well-researched for their positive impact on physical, chemical, and biological aspects, improve soil properties like bulk density, aggregate stability, and permeability. They expedite salt leaching, reducing EC in salt-affected soils. The sugar industry by-product, filter cake, can be composted and used as a natural organic amendment, positively influencing soil structure, nutrient content, and water retention (Chaganti et al., 2015; Premanandarajah, 2017; Dellavalle and Walworth, 2020; Ding et al., 2020; Roy and Chowdhury, 2020).

Leaching, a method to allow dissolved salts to escape the root zone, is effective but often impractical in water-scarce regions. Minimizing water usage while reducing soil salinity is crucial for sustainable crop cultivation (Ayers and Westcot, 1976; Noufal, 2018).

The current study aims to assess the effectiveness of various gypsum treatments, including ordinary gypsum with different sieve diameters (125, 63, and less than 63 μm),

alone or combined with filter cake, for the reclamation of sodic-saline soils in the EL Abbasa district, EL Sharkia Province, Egypt.

Materials and Methods

Soil sampling

Soil samples were obtained from the EL Abbasa district in El-Sharkia Governorate, Egypt, situated at coordinates 30° 33' 26.0" N and 31° 42' 49.6" E. The collected samples, sourced from the top 0–30 cm layer, originate from a region recognized for its saline-sodic soil composition.

Post-collection, the soil samples underwent air-drying, crushing, and sieving through a 2 mm sieve. Subsequently, the physical and chemical attributes of the soils were analyzed using methods outlined in the references (Page, 1982; Klute, 1986; Harker and Mikalson, 1990), with the results presented in Tables 1 and 2.

Soil column experiments were executed at the Soil, Water, and Environment Research Institute in Giza, Egypt. The investigation aimed to assess the impact of applying gypsum with varying particle sizes (125, 63, and 63 μm), either alone or in combination with filter cake, on the chemical and physical properties of saline-sodic soil.

These experiments involved columns filled with soil, to which gypsum or a combination of gypsum and filter cake were added in separate columns. Subsequent measurements were conducted to evaluate the chemical and physical alterations induced by the gypsum application in each soil column.

Table 1. Physical properties of the investigated soil

Parameter	value
Particle size distribution	
Coarse sand	12
Fine Sand (%)	15.3
Silt (%)	24.2
Clay (%)	48.5
Texture*	Clay
Bulk density (g/cm^3)	1.13
Particle density (g/cm^3)	2.82
Porosity (%)	60.28
soil volume (cm^3)	588.75
pore volume (cm^3)	354.90
mass (kg)	0.67
k_{sat} (cm/hr)	0.134

Table 2. Some chemical properties of the investigated soil

Parameter	value
pH*	8.41
EC*(dS m^{-1})	28.14
Soluble ions (meq L^{-1}) (in Saturated soil paste extract)	
Ca^{+2}	61.67
Mg^{+2}	46.69
Na^{+}	172.01
K^{+}	0.9
Cl^{-}	141.45
SO_4^{-2}	138.6
CO_3^{-2}	0

HCO ₃ ⁻	1.22
SAR	23.36
Exchangeable cations meq/100g soil	
Ca ⁺²	20.11
Mg ⁺²	9.18
Na ⁺	10.91
K ⁺	0.32
CEC meq/100g soil	40.58
ESP %	26.9
O.M (%)	0.43
CaCO ₃ (%)	6.2
SP(%)	51.5

Amendments

The agricultural gypsum used in this study was procured from Al-Shafi'i Agricultural Gypsum Company, sourced from quarries in the Sinai Governorate. Table 3 presents specific physical and chemical properties of the gypsum utilized in the experiment.

To prepare granules of gypsum for the experiment, sieving was conducted using the following specifications: Separate calculations were performed for granules with diameters of 1 mm, 500, 250, 125, and 63. The resulting percentages for each diameter are detailed in Table 4.

Table 3 Chemical and physical properties of the agricultural gypsum used in the current study.

Parameter	value
Purity Gypsum	98.28 %
Ca ⁺²	22.6%
SO ₄ ⁺²	25.36 %
S	29.19 %
Powder	46.45 %
Cl ₂	23.46 %
P	0.9 %
pH	2.5

Table 4 The percentage of Gypsum diameters

Gypsum diameters	Ratio
1MM	33%
500 μm	8%
250 μm	17.6%
125 μm	24.6%
63 μm	11.7%
63 > μm	5.01%

In the process of extracting sugar from sugarcane, a by-product known as filter cake is generated. This residual material can be effectively converted into a valuable organic soil amendment through composting. The specific filter cake utilized in this study was acquired from the sugar and distillery factories located in Abu Qurqas, Minya Governorate, Egypt.

Table 5 presents the chemical and physical attributes of the filter cake, as detailed in the reference (Premanandarajah, 2017). The addition rate of filter cake in the experiment was 1% of the total mass of the soil column.

Table 5 Chemical and physical properties of the Filter cake used in the current study.

Parameter	Value
Moisture content (%)	9.65
Bulk density (Mg m ³)	0.27
pH (1-10 Suspension)	6.60
EC(dSm ⁻¹) (1-10Suspension)	4.30
CaCO ₃ (gkg ⁻¹)	115.00
CEC(mmole kg ⁻¹)	451.39
Organic carbon(g kg ⁻¹)	17.67
Organic matter(g kg ⁻¹)	30.39
Total nitrogen (g kg ⁻¹)	2.8
C: N ratio	6.31:1
Total P (g kg ⁻¹)	18.40
Total k (g kg ⁻¹)	10.50

Calculation of gypsum requirements (GR)

Based on Abdel-Fattah et al., (2015), the gypsum requirements (GR) were calculated to reduce the initial Exchangeable Sodium Percentage (ESP) within a 30-centimeter soil matrix from 26.9% to 10%, as outlined below (Eq. 1);

$$GR = \frac{ESP_i - ESP_f}{100} \times CEC \times 1.72 \quad (1)$$

Where

GR: Gypsum requirement (Mg fed⁻¹),

ESP_i: Initial ESP of the soil,

ESP_f: ESP final to be reached by reclamation and

CEC: Cation exchange capacity (cmole kg⁻¹).

Gypsum was added at a rate of 11.65 Mg fed⁻¹ and had a purity of 98.2%.

Experimental setup

Nine groups of 36 soil columns (30 cm in height) each were subjected to specific treatments, as outlined in Table 6. To execute this, cylindrical PVC pipes measuring 5 cm in diameter and 50 cm in height were utilized. These pipes were enveloped in filter paper and textile bandages, and subsequently sealed along the outer surface. The total additive quantity was integrated with the 30 cm soil mixture.

Following the leaching process, the soils underwent thorough drying and subsequent analysis.

Table 6 Applied treatments of different gypsum sources and filter cake.

treatments	
T ₀	initial soil + No treatment (control)
T ₁	initial soil + traditional gypsum
T ₂	initial soil + Gypsum 125 μm
T ₃	initial soil + Gypsum 63 μm
T ₄	initial soil + Gypsum <63 μm
T ₅	initial soil + traditional gypsum + Filter cake
T ₆	initial soil + Gypsum 125 μm + Filter cake
T ₇	initial soil + Gypsum 63 μm + Filter cake
T ₈	initial soil + Gypsum <63 μm + Filter cake

Results and Discussion

Soil Salinity

Figure 1 illustrates the distribution of soil salinity (measured as electrical conductivity, (EC_e dS/m) across various treatments. The EC_e values for T7 and T8 are below 4 dS/m, whereas the EC_e values for T3, T4, T5, and T6 fall within the range of 4 to 10 dS/m. Concurrently, the EC_e values for T0, T1, T2, and the initial condition range from 12 to 29 dS/m.

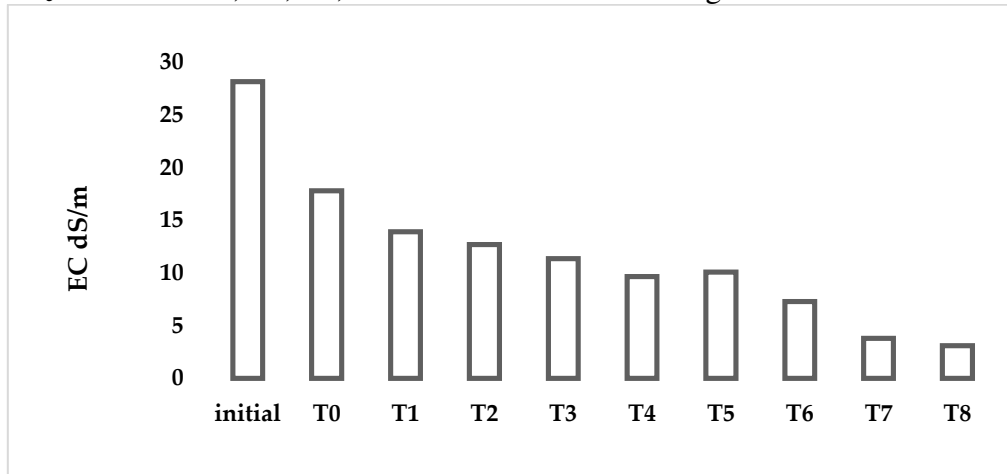


Figure 1. Distribution of EC_e values for the different treatments

Soil Salinity Trend: The progression from initial and early treatments (T0, T1, T2) to later treatments (T7 and T8) reveals a consistent decline in EC_e values. This indicates the success of the implemented remedies in gradually reducing soil salinity. **Categorization of Salinity Levels:** The data, based on EC_e values, can be classified into three salinity levels. The first level (EC_e 10 dS/m) includes treatments T0, T1, and T2. The second level (EC_e 4 to 10 dS/m) encompasses treatments T3, T4, T5, and T6, demonstrating a moderate decrease in salinity compared to the third level ($EC_e < 4$ dS/m), where treatments T7 and T8 have achieved salinity levels suitable for the majority of crops. **Implications:** The observed reduction in salinity is likely a result of the combined effects of the implemented treatments, involving practices such as leaching, amendments, or improved irrigation management. This decrease in salinity carries several positive implications. Overall, the figure provides compelling evidence that the applied treatments successfully mitigated soil salinity. Continuous monitoring and adjustments to the treatment regime may be necessary for maintaining low salinity levels and ensuring the long-term sustainability of soil and agricultural productivity.

Effectiveness of Filter Cake and Biogas Manures: An investigation into the impact of applying filter cake and biogas manures on specific chemical and physical soil properties was conducted (Abdel-Fattah *et al.*, 2015). The researchers (Matsumoto *et al.*, 1994) explored the influence of gypsum, ground to varying fineness levels, on the reclamation of clayey, saline, and sodic soils. Testing three gypsum fineness levels (<0.5, 0.5–1, and 1.0–2.0 mm) revealed that gypsum application, coupled with leaching, enhanced reclamation, and reduced both salinity and sodicity. Finer gypsum particle sizes resulted in greater reductions in salinity and sodicity. According to this study, fine-particle gypsum should be preferred when reclaiming saline-sodic soils for improved reclamation efficiency. **Utilizing Organic Matter in Biological Amelioration:** The use of organic matter, such as filter cake, in biological amelioration techniques offers two main advantages for reclaiming saline and sodic soils. It enhances soil permeability and structure, leading to increased salt leaching, reduced surface evaporation, and prevention of salt buildup in surface layers. Additionally, carbon dioxide is released during respiration and decomposition (Yoram *et al.*, 1994).

Soil Reaction

Figure 2 illustrates the soil pH levels after the experiment. Observable alterations in soil pH occurred across all treatments and soil columns following leaching in comparison to the control (T0). Notably, the application of gypsum resulted in a significant reduction in soil pH relative to leaching alone and the initial soil conditions. T8 and then T7 demonstrated the lowest pH readings. The treatments exhibited an efficiency ranking of T8 > T7 > T5 > T6 > T4 > T2 > T3 > T1.

The decline in soil pH attributed to gypsum application can be attributed to two primary factors: the substitution of calcium for sodium and the formation of neutral salts with SO_4^- . The reduction in sodium concentration as a percentage of cations likely contributed to the soil pH decrease, possibly through the elimination of exchangeable sodium from the soil column. Additionally, the creation of sodium sulfate ion pairs and the heightened ionic strength of the solution resulted in increased activity coefficients of calcium and sulfate, subsequently enhancing gypsum solubility.

Moreover, a substantial release of CO_2 during leaching, with some dissolving in the soil solution, led to the production of carbonic acids.

Concerning filter cake, the lower soil pH reflects both the direct impact of reduced salt content and the indirect influence of organic acids generated during the breakdown of organic matter. The application of filter cake to saline, sodic soils proves beneficial for calcium chelation and pH reduction, thereby increasing CaCO_3 solubility (Bolan *et al.*, 1991).

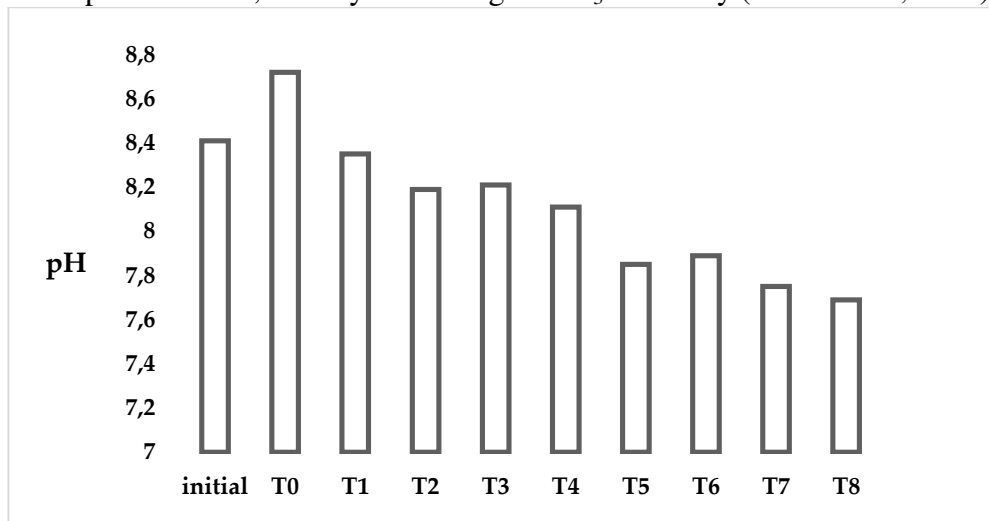


Figure2. Distribution of pH values for the different treatments

Soil Sodicity

Following soil leaching, there was a notable decrease in soil sodicity, as indicated by the Exchangeable Sodium Percentage (ESP) values (Fig 3). In comparison to the control (T0), all treatments consistently led to a significant reduction in ESP, with declines ranging from 15% to 70%. Notably, T8 exhibited the most substantial decrease in sodicity, with a treatment efficiency ranking of T8 > T7 > T4 > T6 > T3 > T2 > T5 > T1.

Furthermore, gypsum-treated soils exhibited a more pronounced reduction in sodicity compared to non-gypsum-treated soils. Research indicated that the extent of sodicity reduction correlated with the size of gypsum particles. Finer gypsum particles, such as those in CaSO_4 , demonstrated increased solubility, resulting in a higher fraction of exchangeable Ca^{2+} in soil colloids and elevated Ca^{2+} release in the soil solution. The enhanced solubility of CaSO_4 led to the presence of more fine colloidal particles in the soil system, contributing to a less sodic soil water system and a decreased dominance of Na^+ ions. These findings align

with previous reports (Brady and Weil, 2002) and extend our understanding of soil restoration in Egypt's saline-sodic soils.

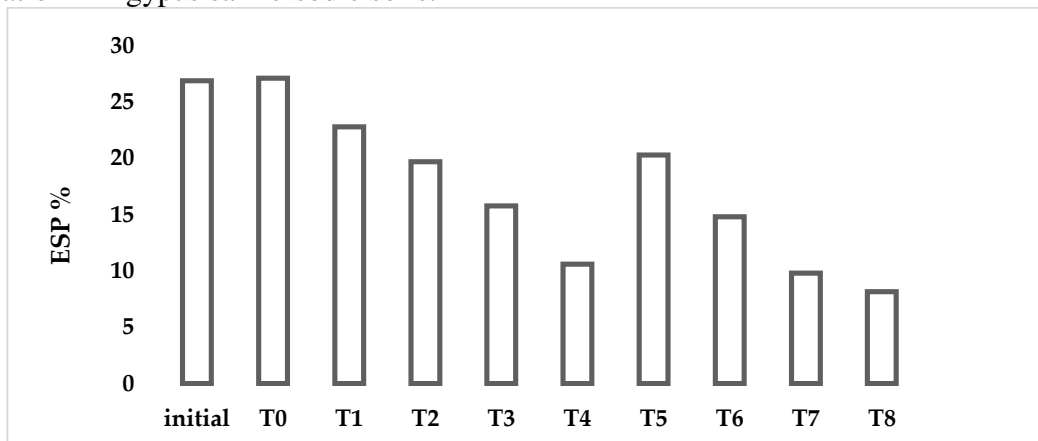


Figure3. Distribution of ESP % values for the different treatments

Additionally, the introduction of filter cake amplified the reduction in sodium levels. This effect is attributed to the organic matter content in the soil, promoting granulation and elevating the cation exchange capacity (CEC). Organic amendments, responsible for 90% of the soil's absorption power, generate cations such as Ca^{2+} , Mg^{2+} , and K^+ during decomposition. Consequently, these amendments enhance Mg^{2+} and exchangeable calcium while concurrently diminishing soil sodium levels (Swarup, 1992).

Water Movement

The introduction of gypsum, either independently or in conjunction with filter cake followed by leaching, leads to a substantial enhancement in hydraulic conductivity (HC), as illustrated in Figure 4. Additionally, the particle softness of gypsum exerts an influence on hydraulic conductivity. Various soil treatments resulted in significant increases in Ks, with values of 171.6, 209, 231.3, 261.2, 201.5, 268.7, 335.8, and 395.5 in comparison to the initial soil efficiency for T0, T1, T2, T3, T4, T5, T6, T7, and T8, respectively. Notably, the treatment groups exhibited the following order: $\text{T8} > \text{T7} > \text{T6} > \text{T4} > \text{T3} > \text{T2} > \text{T5} > \text{T1}$. This pattern highlights that gypsum, particularly its minute particles, amplifies the dissolution and accumulation of calcium ions in soil exchange sites, owing to an increased presence of soil particles containing higher concentrations of Ca_2^+ ions. Contrastingly, as observed in the control group (T0), the absence of gypsum modification results in a higher discharge of slurry, leading to a reduction in HC.

Consistent with earlier research (Wahby, 1986; Nadler *et al.*, 1986), the addition of gypsum was found to enhance soil hydraulic conductivity. The elevation in hydraulic conductivity values can be attributed to two primary factors: a greater proportion of large water-stable aggregates and a lower exchangeable sodium percentage (ESP), consequently reducing the dispersion observed in such sodic soils.

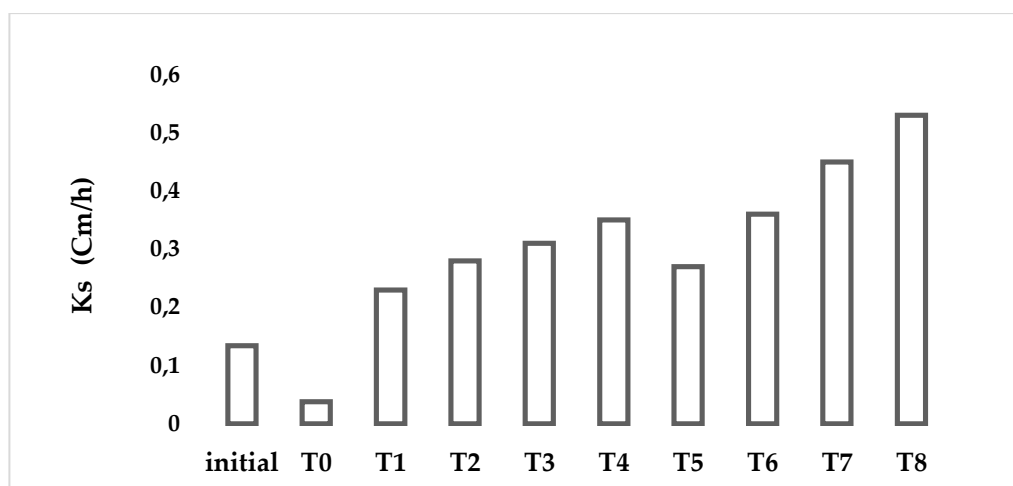


Figure 4. Distribution of Ks cm/hr values for the different treatments

Statistical Analysis

Statistical examination of the interplay between three variables—pH, EC, and ESP—with Ks is presented in Table 7, accompanied by visual representations in Figures 5-7. The findings indicate a consistent association across all treatments: higher Ks values correspond to lower levels of pH, EC, and ESP compared to the control. This pattern may arise due to the formation of thawed aggregates and the subsequent decline in ESP values during successive washings under various treatments, ultimately enhancing water movement and the hydraulic conductivity of the soil. Figure 7 specifically illustrates the substantial and statistically significant impact of sodicity (ESP) on Ks.

Table 7. Statistical analysis of Ks, EC_e, ESP, and pH values from different treatments

Statistics	Ks	EC _e	ESP	pH
Mean	0.30	11.79	17.60	8.12
Standard Error	0.05	2.30	2.18	0.10
Median	0.30	10.74	17.74	8.15
Standard Deviation	0.14	7.27	6.88	0.33
Minimum	0.04	3.10	8.16	7.69
Maximum	0.53	28.14	27.13	8.72
Count	10.00	10.00	10.00	10.00
Correlation matrix				
Correlation	Ks	EC _e	ESP	pH
Ks	1.00			
EC _e	-0.85	1.00		
ESP	-0.95	0.87	1.00	
pH	-0.91	0.80	0.82	1.00

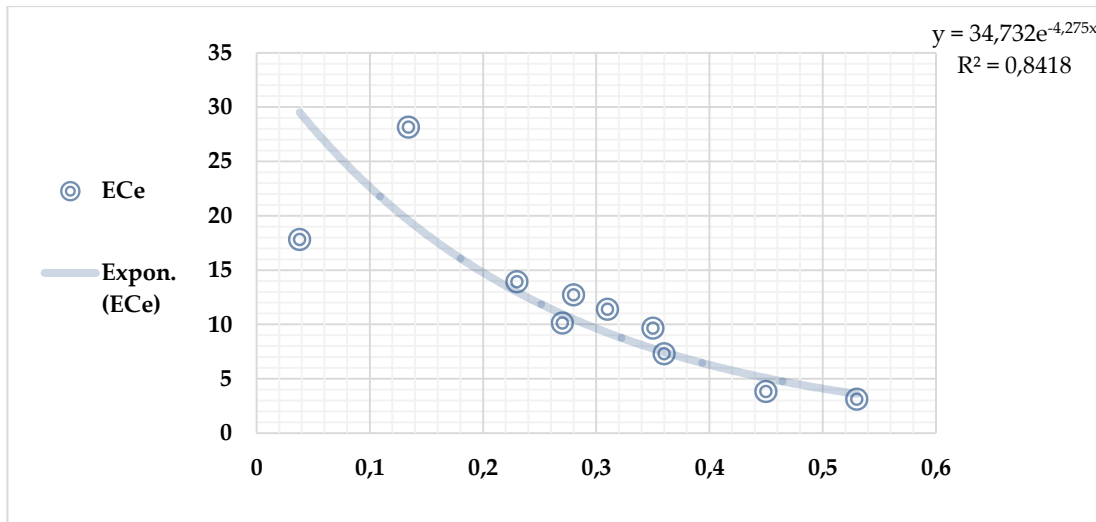


Figure5. Relationship between Ks cm/hr and EC_e dS/m values for the different treatments

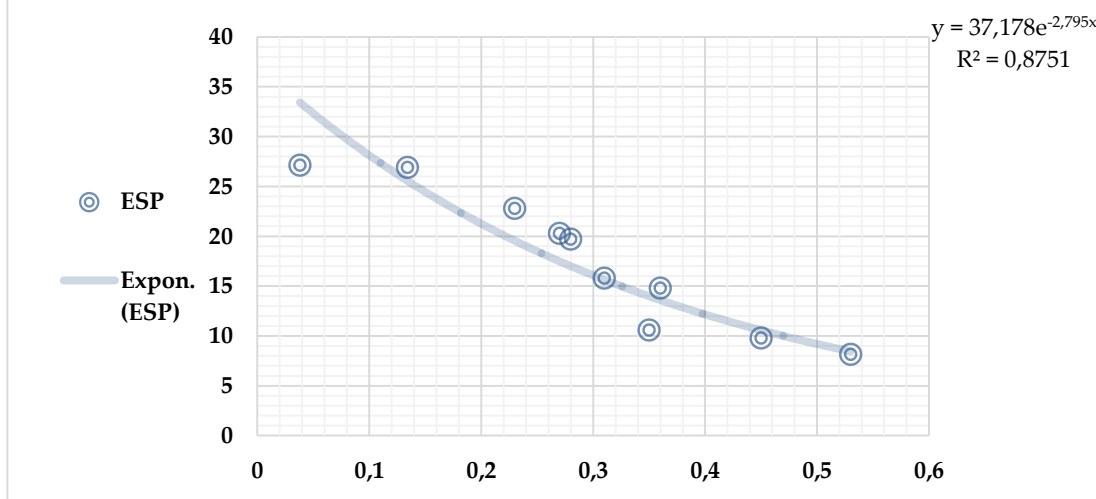


Figure6. Relationship between Ks cm/hr and ESP% values for the different treatments

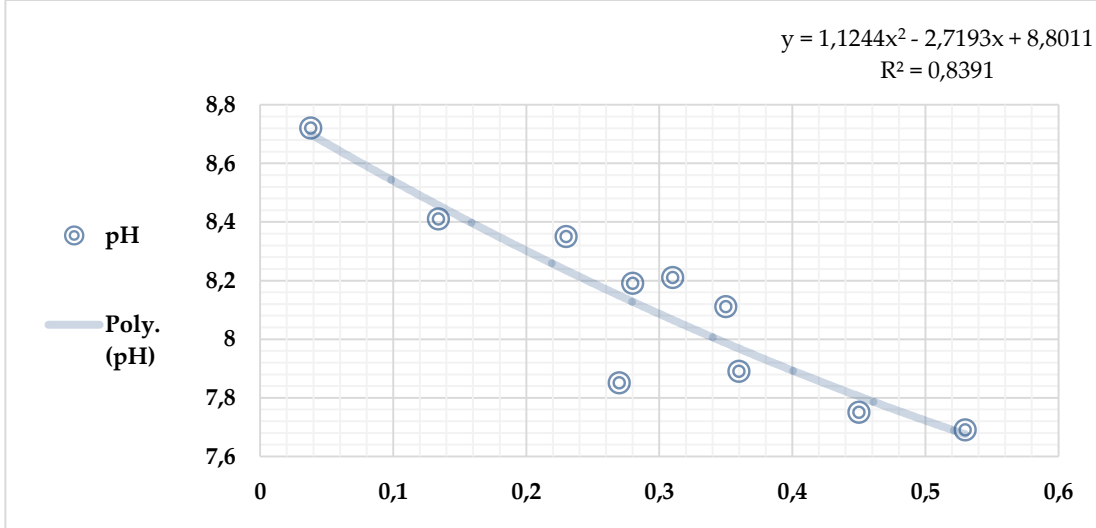


Figure7. Relationship between Ks cm/hr and pH values for the different treatments

Table 7 depicts an inverse correlation between the Electrical Conductivity of the soil (EC_e) values and the Saturated Hydraulic Conductivity (Ks), as evidenced by a negative correlation coefficient of -0.85. Conversely, the relationship between Ks and EC_e appears to be exponential, as illustrated in Figure 5. Notably, EC_e tends to increase rapidly as Ks decreases

and stabilizes when K_s approaches lower values. This trend signifies an inverse relationship, with lower K_s values corresponding to higher EC_e values.

To further explore this exponential relationship, regression analysis can be employed to fit an exponential curve to the data points.

The resulting equation, such as $EC_e = a * \exp(-b * K_s)$, where 'a' and 'b' are constants derived from regression analysis, encapsulates the relationship between K_s and EC_e . Determining the specific values of 'a' and 'b' depends on the regression analysis method used. An example formula derived from regression analysis is;

$$EC_e \left(\frac{dS}{m} \right) = 34.732 * e^{(-4.275 * K_s \left(\frac{cm}{ha} \right))}$$

with a coefficient of determination $R^2 = 0.6025$

In summary, an increase in the value of K_s (cm/hr) leads to a decrease in soil salinity (EC_e dS/m) due to efficient leaching and downward movement of soluble salts with leaching water.

Figures 8-10 present statistical analyses of the relationships between Electrical Conductivity (EC) and Exchangeable Sodium Percentage (ESP) factors (Figure 9), EC and pH (Figure 10), and ESP and pH (Figure 11). The analyses reveal no significant relationship among these variables, as observed decreases in each factor are not correlated with decreases in the others.

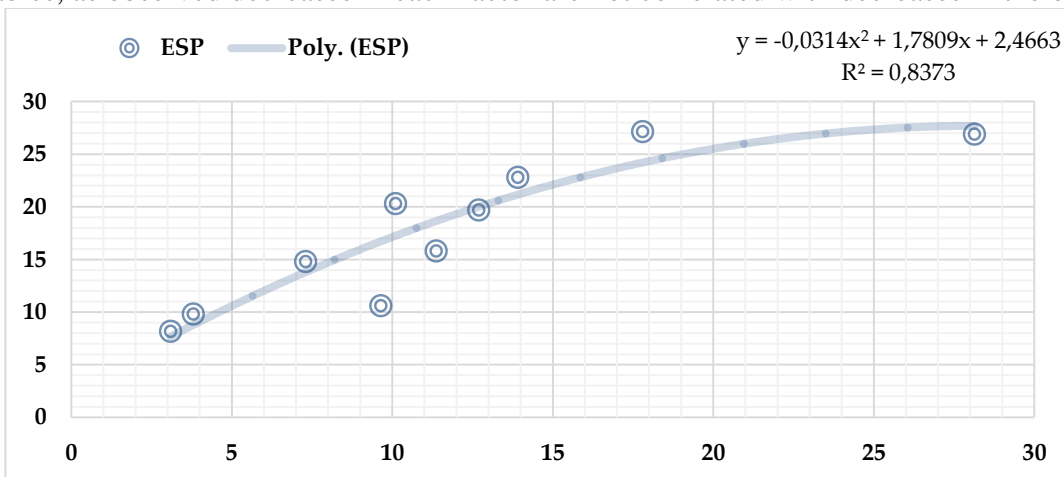


Figure8. Relationship between EC_e dS/m and ESP% values for the different treatments

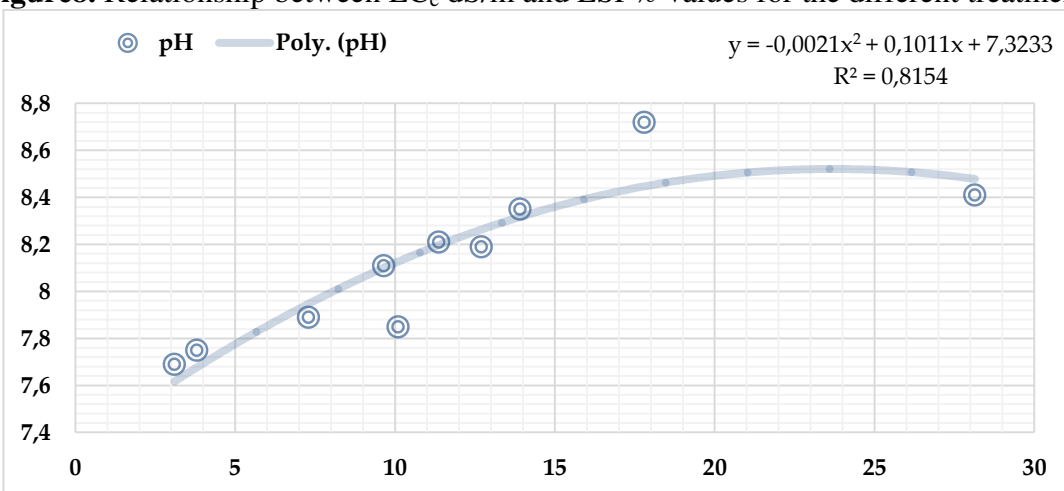


Figure9. Relationship between EC_e dS/m and pH values for the different treatments

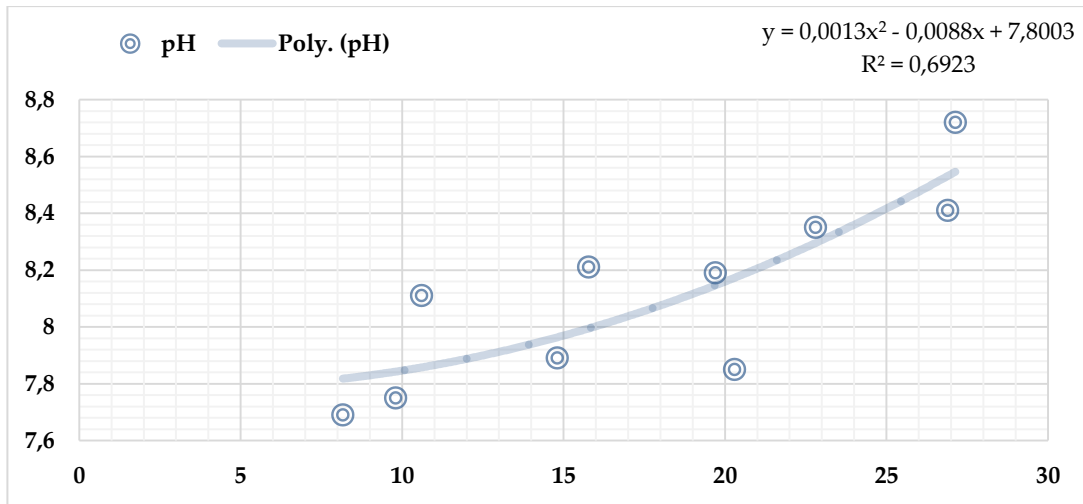


Figure10. Relationship between ESP% and pH values for the different treatments

Conclusions

In the course of this investigation, column technology was employed to conduct a rigorous leaching experiment, with the primary objective of evaluating the effectiveness of conventional gypsum and the particle size of gypsum—either independently or in conjunction with filter cake—on the reclamation of saline-sodic soil.

The soil specimens were sourced from the EL Abbasa district in the Egyptian province of El Sharkia, offering a representative setting for our study. The comparative analysis yielded compelling evidence that relative to the control group, the applied treatments consistently yielded elevated Saturated Hydraulic Conductivity (Ks) while concurrently diminishing soil electrical conductivity, pH, and Exchangeable Sodium Percentage (ESP). Particularly noteworthy was the synergistic effect observed when combining gypsum with filter cake, resulting in marked reductions in sodium and salinity levels.

Furthermore, the adoption of finer gypsum particles during the reclamation process demonstrated a pronounced impact on reducing soil salinity and sodicity. Notably, the inclusion of filter cake exhibited a more robust influence in mitigating electrical conductivity, pH, EC, and ESP when compared to the application of gypsum alone.

The hierarchical ranking of treatment effectiveness, as derived from the observed outcomes, is delineated as follows: T8 > T7 > T5 > T6 > T4 > T3 > T2 > T1. These findings underscore the paramount importance of integrating gypsum and filter cake for optimal soil property improvement and the successful reclamation of saline-sodic soil.

Recommendations for Future Research

1. **Particle Size Optimization:** Further research is warranted to fine-tune the selection of gypsum particle sizes for optimal reclamation efficacy, considering the nuanced impacts on soil salinity and sodicity.
2. **Long-Term Monitoring:** Extended monitoring studies are recommended to assess the sustainability of the reclamation effects over time and investigate any potential long-term variations in soil properties.
3. **Field-Scale Application:** Expanding our insights to field-scale applications would provide a more comprehensive understanding of the practical implications and scalability of the proposed reclamation methods.
4. **Economic Viability:** An economic analysis should be conducted to evaluate the cost-effectiveness of the proposed treatments, considering factors such as material availability and application feasibility.

In conclusion, the findings from this study not only contribute valuable insights into the reclamation of saline-sodic soil but also lay the foundation for future research endeavors aimed at refining and implementing these strategies in real-world agricultural contexts.

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Disclosure statement

The authors declare that there are no conflicts of interest related to this article.

Availability of data and materials

All data generated in the study have been included in the manuscript.

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