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Peculiarities of Hydrodynamic and Electro-osmotic Flow of Water in Clay Soils

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ABSTRACT

Background: Global climate change, accompanied by recurrent droughts in arid and semi-arid regions, necessitates the development of more effective approaches for regulating soil water regimes. Conventional hydrodynamic methods often perform poorly in soils with thick clay horizons and low permeability, where electrokinetic processes may provide alternative pathways for enhancing water movement.

Methods: This study evaluated the parameters of hydrodynamic and electro-osmotic flow in irrigated meadow clay soils of Armenia. Laboratory experiments were conducted under controlled hydrostatic pressure gradients and applied electrical field gradients to characterize filtration behaviour and electro-osmotic response.

Result: A strong curvilinear relationship was observed between filtration rate and pressure gradient (R = 0.983), indicating plastic-viscous behaviour of the soil solution. A similar curvilinear dependence was identified between the electro-osmotic coefficient and electrical field gradient (R = 0.884). Electro-osmotic effects substantially increased the water permeability when the electrical field strength exceeded 2.57 V cm^{-1}. These findings demonstrated the potential of electro-osmotic phenomena to enhance water movement in heavy clay soils, offering promising applications for soil-water management under changing climatic conditions.

Key words: Electrical field gradient, Electro-osmotic coefficient, Heavy soils, Hydraulic pressure gradient, Water permeability.

INTRODUCTION

Efficient management of soil water regimes is critical for sustainable agriculture, irrigation planning and soil amelioration, particularly in heavy-textured, low-permeability soils (Kotorová and Mati, 2008; Lakshmi *et al.*, 2016; Kumari *et al.,* 2021; Tamiru *et al*., 2023). Conventional hydraulic methods, such as drainage and irrigation systems, often fail to ensure uniform water distribution in clay-rich horizons due to limited water movement (Frenkel *et al.,* 1978; Kotorová *et al.,* 2013; Machikowa *et al.*, 2020; Balaji and Pandiarajan, 2022). This constraint poses serious challenges for crop productivity, irrigation efficiency and reclamation of saline or waterlogged soils, especially in arid and semi-arid regions (McNeal and Coleman, 1966; Kumar *et al.,* 2015; Khoirunnisak *et al.*, 2024). These issues are directly relevant to farmers, irrigation managers and policymakers concerned with agricultural water security. Electrokinetic processes, particularly electro-osmosis, offer a promising alternative by facilitating water movement through soil pores under an external electric field. In contrast to hydraulic flow, electro-osmotic transport operates independently of pressure gradients, enabling water redistribution in clay soils and improving permeability (Lockhart, 1986; Smollen and Kaffar, 1994; Miller *et al.*, 1997; Zheng and Zhu, 2017; Butnan *et al.*, 2024). Although electro-osmotic phenomena are well studied theoretically, their practical use in heavy soils remains limited, underscoring the need for experimental evaluation of water movement under combined hydraulic and electrical influences (Gucal and Khyamyalyaynen, 2020).

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Traditionally, soil water movement is described by Darcy's law (Darcy, 1856), which assumes a linear relationship between flow rate and pressure gradient. However, numerous studies have shown that this linearity often breaks down under certain conditions, such as high Reynolds numbers, low flow rates, or when fluids display non-ideal rheological behavior (Kotov and Nerpin, 1958;

Nagy and Karadi, 1961; Nerpin and Chudnovsky, 1967). Experimental data indicated that flow frequently initiates only after a threshold pressure gradient is exceeded, underscoring the role of viscosity in flow initiation and behaviour (Gomboš, 2012). Depending on rheological properties, fluids are classified as Newtonian, non-Newtonian, or visco-plastic. These distinctions are particularly relevant for water transport in fine-textured soils, where capillary forces strongly influence hydraulic behaviour (Joshi, 2017; Qi *et al.,* 2018).

Electro-osmosis provides an additional mechanism of water movement in which ions in the diffuse layer migrate toward electrodes under an external electric field, carrying water molecules and generating directed pore flow. In clay soils, electro-osmotic transport is not simply proportional to electric field strength, requiring modified models that incorporate soil structure and pore characteristics (Bondarenko, 1973). Comparisons of hydraulic and electro-osmotic mechanisms show that although both depend on pore diameter, electro-osmotic flow declines more slowly with decreasing pore size. Thus, applying direct electric current to clay-rich soils can significantly enhance permeability, offering an effective tool for water management and engineering reclamation practices (Stefanidis, 2021).

This study extends existing theoretical research by experimentally investigating water movement in heavy-textured soils under the combined influence of hydrostatic pressure and external electric fields. The objective is to identify the key hydrodynamic parameters governing these processes, thereby providing insights essential for optimizing soil water regulation and improving the efficiency of reclamation and irrigation systems.

MATERIALS AND METHODS

Study area and soil sampling

The study focused on irrigated wet meadow-gray soils (classified as Anthrosols according to the WRB system) from the Masis region of Armenia. Soil samples were collected from 0-50 cm layer, air-dried, gently crushed and sieved through a 2 mm mesh.

Experiments were conducted during 2023-2024 at the Laboratory for Environmental Issues, Conservation of Water Resources and Their Efficient Use of the National University of Architecture and Construction of Armenia.

Physical, chemical and physicochemical properties of the soils were analyzed both with and without application of an electric current. Bulk density and total porosity in the soils of 0-50 cm layer were 1,300 kg m^{-3} and 53%, respectively (Table 1). Wilting point, field capacity and plant-available water were 14.2%, 29.3% and 15.1%, respectively.

The soil exhibited a light clay mechanical texture, with 48.6% physical clay, including 19.9% silt (Table 2). The top 0-50 cm soil contained 2.1% humus. Calcium carbonate content was high (21.5%), magnesium carbonate was 2.4% and exchangeable cations totaled 31.5 $cmol_c$ kg^{-1}. The exchangeable sodium percentage (ESP) was 4.8%.

The indicators of water-soluble salts in the 0-50 cm soil layer are presented in Table 3. The soil is characterized by a total salt content of 0.196%, an electrical conductivity (EC) of 1.78 dS m^{-1}, a pH of 7.5 and a water-soluble sodium concentration of 2.1 cmolc kg^{-1}. Carbonate (CO_3^{2}) was not detected.

Experimental setup

Laboratory experiments were carried out using a horizontally mounted soil column (1) with a length of 0.35 m (L) and diameter of 0.07 m (d), corresponding to a cross-sectional area of 0.00355 m^2 (A). Sand-gravel filters (2) were installed at both ends to prevent mechanical suffusion. A feeding tank (3) at the inlet maintained a constant water level (H_1), while filtrate was collected in a glass container (4) at the outlet (Fig 1).

The column was packed with dry meadow-brown soil compacted to the natural bulk density of 1,300 kg m^{-3}. Two titanium electrodes, anode (5) and cathode (6), were

Table 1: Physical and water-physical indicators of the (0-50 cm) soil.

Soil density (kg m^{-3})	Porosity (%)	Wilting moisture (%)	Field capacity (%)	Plant-available water (%)
1300	53.0	14.2	29.3	15.1

Table 2: Physical, chemical and physicochemical properties of the (0-50 cm) soil.

Humus	Silt	Clay	$CaCO_3$	$MgCO_3$	Exchangeable cations			ESP (%)
					Ca^{2+}	Mg^{2+}	Na^{+}	
		(%)			($cmol_c$ kg^{-1})			
2.1	19.9	48.6	21.5	2.4	20.0	10.0	1.5	4.8

Table 3: Chemical composition of soil water extract (0-50 cm layer).

Total salts (%)	EC (dS m^{-1})	pH	CO_3^{2-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^{+}
			(cmol kg^{-1})						
0.196	1.78	7.5	0	1.0	1.4	0.5	0.4	0.4	2.1

embedded in the soil and connected to a direct current source to induce electroosmotic flow.

Calculation of hydraulic and electro-osmotic flow parameters

During the experiments, various pressure gradients (*I*) were applied through the feeding tank (1, Fig 1) and the corresponding filtrate volumes (*W*) were measured. Each experimental run was conducted in triplicate to ensure reproducibility. The pressure gradient (*I*), filtration rate (V_I) and filtration coefficient (K_I) were calculated according to Equations (1)-(3).

$$I = \frac{H_1 - H_2}{L} \quad ...(1)$$

$$V_I = \frac{W}{At} \quad ...(2)$$

$$K_I = \frac{V}{I} \quad ...(3)$$

Where,

($H_1 - H_2$)= The hydraulic pressure across the soil column of length L.

t= The time at which the filtrate volume is collected.

A= The cross-sectional area of the column.

For electro-osmotic filtration, both hydraulic pressure gradients and electric field voltages were applied to the soil column. The electric field strength (*E*), the electro-osmotic velocity (V_E) and the electro-osmotic coefficient (K_E) were determined using the Equations (4) to (6):

$$E = \frac{U}{L} \quad ...(4)$$

$$V_E = \frac{Q_E}{A_t} \quad ...(5)$$

$$K_E = \frac{V_E}{E} \quad ...(6)$$

Where,

U= The voltage applied to the electrodes.

Q_E= The volume of filtrate from electro-osmotic flow, which was further calculated using Equation (7):

$$Q_E = Q_T - Q_I \quad ...(7)$$

Where,

Q_T= The combined hydraulic and electro-osmotic flow.

Q_I= Hydraulic flow alone.

In soils with heavy mechanical texture, the relationship between filtration rate and pressure gradient often deviates from Darcy's Law, exhibiting nonlinear behaviour. To account for this, both linear and nonlinear regression models were applied to the experimental data, expressed by Equations (8) and (9):

$$V = A + BI \quad ...(8)$$

$$V = aI^3 + bI^2 + cI + d \quad ...(9)$$

Where,

A, B and a, b, c, d= Regression parameters obtained from statistical fitting of the experimental results.

All experimental data were processed using Origin 6.1 software to calculate mean values, determine regression parameters and verify the consistency and reliability of the results.

RESULTS AND DISCUSSION

Hydrodynamic movement of water in soil

The experimental results of hydraulic filtration in clay soils are summarized in Table 4, with replicate data included for reliability. These results indicate that, although a general proportionality exists between pressure gradient (*I*) and filtration rate (V_I), the relationship is not strictly linear (Liu and Birkholzer, 2012). With increasing I, both V and the apparent filtration coefficient (K_I) rise, however, the variation in K_I demonstrates that Darcy's law cannot fully describe water movement in these soils.

Statistical evaluation of the relationship between *V* and *I*, using both linear and nonlinear regression models, is shown in Table 5 and illustrated in Fig 2. For linear regression, the correlation coefficient was *R*= 0.947, with a standard deviation (SD) of 1.16% and relative error (*E*) of 12.9%. In contrast, nonlinear regression produced a stronger correlation (*R*= 0.983), with lower SD (0.63%) and error (7.0%). These results clearly demonstrate that water flow in clay soils is better described by nonlinear rather than linear models, consistent with theoretical expectations for visco-plastic systems and similar to previously reported non-Darcian seepage behaviour in clay-rich porous media (Yin *et al.*, 2024).

The corresponding regression dependencies are presented in Equations (8) and (9), with parameter values summarized in Table 6. In particular, the rectilinear regression yielded a mean hydraulic conductivity (K_I) of 20.43 cm d^{-1}, while nonlinear regression produced a cubic parabolic form that accurately reflects the threshold behavior observed at low gradients. As shown in Equation (9), water movement begins only when I exceeds the limiting gradient I_0, after which the flow rate increases rapidly.

Thus, regression analysis confirms that the filtration process in clay soils deviates from Darcy's law, with water exhibiting visco-plastic properties. The cubic parabolic regression more accurately describes this nonlinear behavior and can therefore be applied in hydraulic and hydro-ameliorative calculations where precision is required.

Combined hydrodynamic and electroosmotic water movement

Analysis of the experimental data (Table 7) indicates that the combined action of hydraulic pressure and electric field markedly enhances the filtration rate. The increase is particularly pronounced at higher hydraulic gradients and

elevated electric field intensities, highlighting the synergistic effect of electroosmosis in facilitating water movement through clay soils. For example, at I = 0.46 and E = 0 V cm^{-1}, the filtration rate (V_I) was 7.48 cm d^{-1}, whereas under the same hydraulic conditions but with E = 2.57 V cm^{-1}, the rate increased to 9.58 cm d^{-1}. When the pressure gradient was raised to I= 0.80 and E= 3.43 V cm^{-1}, the filtration rate reached 31.8 cm d^{-1}.

The nonlinear dependence of total flow on electric field intensity is clearly illustrated in Fig 3. At lower electric field strengths (0-2.57 V cm^{-1}), the increase in filtration rate ranged from 2.1 to 3.3 cm d^{-1}, corresponding to hydraulic gradients of 0.46-0.80. At higher electric fields (2.57-3.43 V cm^{-1}), the rate of increase was much greater, ranging from 7.5 to 14.8 cm d^{-1}. These results show that electroosmosis exerts disproportionately strong effect once the electric field exceeds a threshold value, a phenomenon also reported in controlled laboratory studies on clayey soils (Jayasekera, 2004).

To clarify the contribution of electro-osmosis, the ratio of total flow under combined hydraulic and electroosmotic forces ($V_{I,E}$) to hydraulic flow alone (V_I) was analyzed. The resulting relative values are summarized in Table 8 and illustrated in Fig 4. The data clearly demonstrate that the application of an electric field substantially enhances water

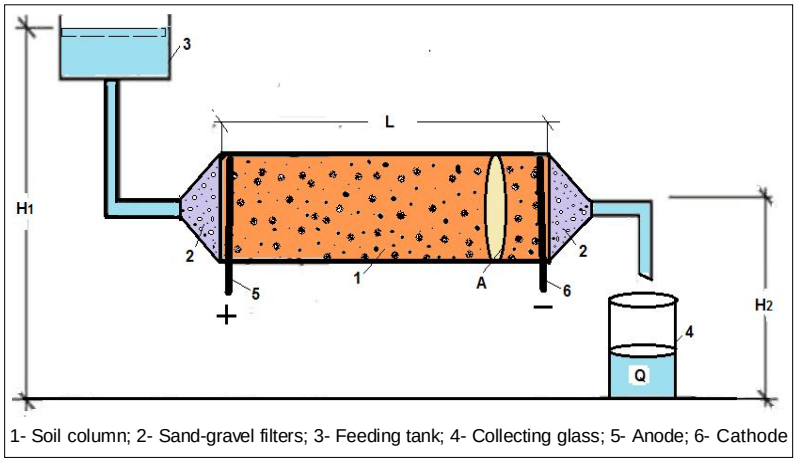


Fig 1: Experimental setup.

Table 4: Relationship between pressure gradient (I), filtration rate (V_I) and filtration coefficient (K_I).

№	I	V_I	K_I	№	I	V_I	K_I
		(cm day^{-1})				(cm day^{-1})	
1	0.03	0.45	15.00	15	0.48	6.18	12.92
2	0.03	0.42	14.00	16	0.48	6.78	14.13
3	0.12	1.54	12.83	17	0.48	6.78	14.13
4	0.12	1.27	10.58	18	0.58	8.90	15.34
5	0.12	1.27	10.58	19	0.58	9.33	16.09
6	0.21	3.54	16.85	20	0.58	9.33	16.09
7	0.21	3.39	16.14	21	0.67	12.11	19.53
8	0.21	3.39	16.14	22	0.67	12.72	19.00
9	0.30	5.94	19.80	23	0.67	13.57	20.25
10	0.30	5.08	16.93	24	0.67	13.56	20.24
11	0.30	5.09	16.97	25	0.67	13.57	20.25
12	0.39	5.42	13.89	26	0.76	15.29	20.12
13	0.39	5.94	15.23	27	0.76	16.11	21.20
14	0.39	5.94	15.23	28	0.76	16.11	21.20

Table 5: Statistical indicators of linear and nonlinear regression analysis describing the relationship between filtration rate (V_I) and pressure gradient (I).

Regression	R	SD	E (%)	N	P
Rectilinear	0.947	1.16	12.9	28	0.0001
Curvilinear	0.983	0.63	7.0	28	0.0001

movement through the soil, as reflected by the increasing V_I, E/V_I ratios with rising voltage intensity.

Statistical analysis confirmed the robustness of this relationship, revealing a strong positive correlation between the relative increase in flow and the applied electric field (R= 0.93, SD= 0.129, N= 25, P<0.0001). This dependency is quantitatively described as:

$$\frac{V_{I,E}}{V_I} = 1.00 + 0.079E - 0.171E^2 + 0.072E^3 \quad ...(10)$$

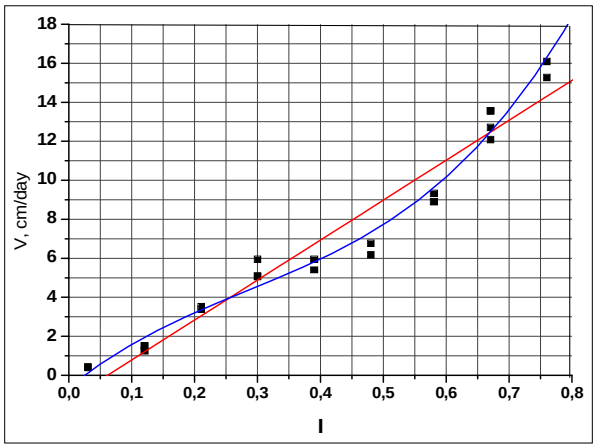


Fig 2: Linear and nonlinear regression analysis of the relationship between filtration rate *(V)* and pressure gradient *(I)*.

The fitted regression curve is presented in Fig 4, highlighting the consistent and predictable influence of electroosmosis on soil permeability.

These results confirm the theoretical prediction, that electroosmotic effects are particularly significant in clay soils. Because hydraulic flow in capillary decreases proportionally to R^4 with diameters, while electroosmotic flow decreases only to R^2, the electric field becomes increasingly effective as particles becomes finer (Mitchell and Soga, 2005).

Electroosmotic coefficient (K_E)

The dependence of K_E on electric field intensity is shown in Fig 5, with regression statistics provided in Table 9.

Linear regression yielded a correlation coefficient of R= 0.846 and SD= 0.251, whereas nonlinear regression provided a better fit with R= 0.884 and SD= 0.228. The regression equations describing this relationship are:

$$K_E = 10^{-5} E (1.374 - 0.590E + 0.096E^2) \quad ...(11)$$

$$K_E = 10^{-5} (0.173 + 0.419 E) \quad ...(12)$$

Parameter values are summarized in Table 10. Within the experimental range of E= 0.57-3.43 Vcm^{-1}, K_E varied between 0.525×10^{-5} and 1.525×10^{-5} $cm^2\ s^{-1}\ V^{-1}$.

These results agree well with published ranges (4.91×10^{-6} to 1.57×10^{-5} $cm^2\ s^{-1}\ V^{-1}$) reported by other researchers, confirming both the accuracy of the present

Table 6: Numerical values of the parameters of equations (8) and (9).

Curvilinear dependence	a	b	c	d
	52.545	-44.875	25.963	-0.612
Rectilinear dependence	A	B		
	-1.259	20.430		

Table 7: Filtration rates of clay soil under varying hydraulic pressure gra/dients and electric field intensities (cm d^{-1}).

$H_1 - H_2$ (cm)	I	Voltage of electric field (E) (V cm^{-1})				
		0	0.57	2.57	2.86	3.43
16	0.46	7.48	7.79	9.58	13.76	17.08
19	0.54	11.22	11.53	14.36	16.83	21.20
22	0.63	12.47	12.78	14.59	19.94	23.68
25	0.71	13.09	13.40	15.32	22.44	29.61
28	0.80	13.71	14.03	17.01	23.70	31.80

Table 8: Relative filtration rates (V_I, E/V_I) of clay soil under different hydraulic pressure gradients and electric field strengths.

I	E (V cm^{-1})				
	0	0.57	2.57	2.86	3.43
0.46	1.00	1.04	1.28	1.84	2.28
0.54	1.00	1.03	1.28	1.50	1.89
0.63	1.00	1.03	1.17	1.60	1.90
0.71	1.00	1.02	1.17	1.71	2.26
0.80	1.00	1.02	1.24	1.73	2.32

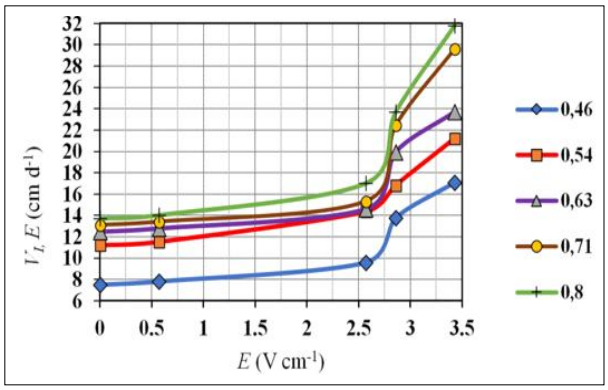


Fig 3: Dependence of total filtration rate on pressure gradient and electric field voltage in clay soils.

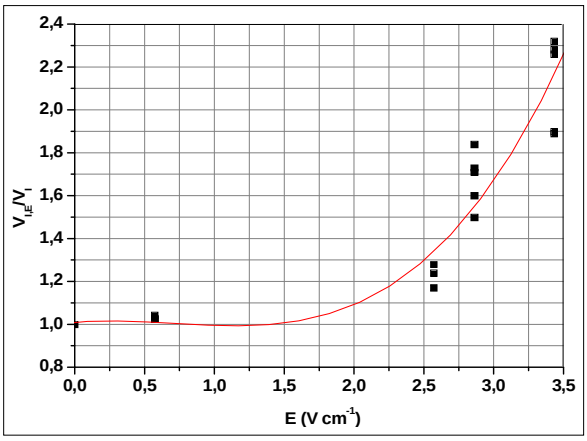


Fig 4: Dependence of the relative flow ratio ($V_{l,E}/V_l$) on electric field strength (E).

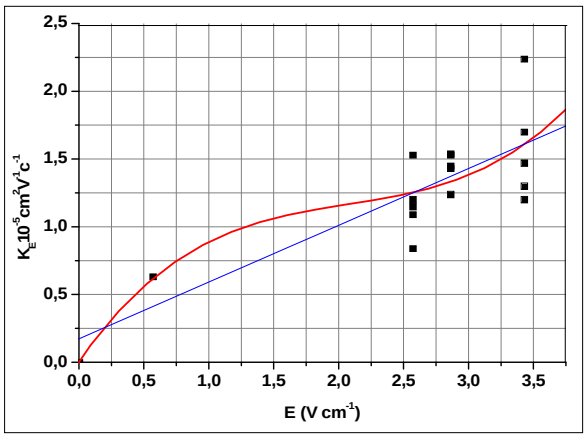


Fig 5: Rectilinear and curvilinear dependence of the electro-osmosis coefficient (K_E) on electric field strength (E).

Table 9: Statistical indicators of rectilinear and curvilinear regression analysis between the electro-osmosis coefficient and the gradient of the electric field.

Regression	R	SD	N	P
Rectilinear	0.84616	0.25091	25	<0.0001
Curvilinear	0.88395	0.22806	25	<0.0001

Table 10: Numerical values of the parameters of equations (11) and (12).

Curvilinear dependence	a	b	c	d
	0.008	1.374	-0.590	0.095
Rectilinear dependence	A	B		
	0.173	0.419		

experiments and the applicability of electroosmotic enhancement in heavy soils (Punia and Singh, 2018).

Implications for soil reclamation

The combined hydraulic and electroosmotic experiments demonstrate that the application of a direct electric current can significantly improve soil permeability in clay soils. This enhancement results from the fact that electroosmotic flow is less sensitive to pore size than hydraulic flow. Consequently, in clay soils where Darcy's law fails and hydraulic movement is severely restricted, electroosmosis provides a powerful mechanism for accelerating water movement.

For reclamation of saline-sodic soils in Armenia, these findings are highly relevant. By reducing the time and water required for leaching, electro reclamation methods can improve the efficiency and sustainability of irrigation practices. The experimental confirmation of nonlinear relationships, threshold gradients and strong electroosmotic responses provides a robust scientific basis for implementing these technologies in practice.

CONCLUSION

This study demonstrated that water movement in irrigated meadow-gray soils with clay mechanical composition does not fully confirm to Darcy's law. Filtration rates within a pressure gradient range of 0.024-0.76 exhibited both rectilinear (R= 0.947) and curvilinear (R= 0.983) dependencies on the applied gradient, with the presence of an initial threshold (I_0) confirming the plastic-viscous behaviour of the soil solution.

The combined influence of hydrostatic pressure and electric fields revealed that electro-osmotic effects are negligible below 2.57 V cm^{-1} but become significant at higher field strengths, substantially enhancing soil permeability. Regression-based models established strong correlations between relative flow velocities and applied fields, as well as between the electro-osmosis coefficient (Ke) and electric field intensity (R= 0.84-0.88), highlighting the nonlinear character of electro-osmotic transport.

These findings emphasize the potential of electro-reclamation as an effective method for improving water movement in clay soils. Beyond providing a theoretical and experimental basis for engineering applications, the results hold practical implications for multiple stakeholders. For researchers, they contribute to refining models of soil-water interactions under coupled hydraulic-electrical fields. For engineers and irrigation planners, they suggest new design strategies for drainage and amelioration systems in clay

soils. For policymakers and agricultural managers, they demonstrate the feasibility of incorporating electro-reclamation into water-saving and soil-rehabilitation programs, particularly in arid and semi-arid regions where efficient water use is a national priority.

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Disclaimers

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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