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Original article

Comparative Study of Salt Leaching Dynamics at Different Water Temperatures: Sand and Clay Soils

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Abstract
Many processes that dictate the movement of solutes through porous media are temperature-dependent. In porous media systems, water temperature can induce a qualitative change in solute transport behavior within layers. Nonetheless, the way they change soil salinity is still poorly quantified. This study aims to understand the impact of water temperature on hydraulic performance and salt leaching from sand and clay soils. The experiment was performed with eight columns containing sand and clay under four different water temperature conditions (25, 40, 60, and 80 °C). Results show that flow and leaching performance significantly increase with increasing water temperature. An increase in water temperature from 25 to 80 °C, sand flow rates increased from 4.62 (mL/min) to 6.87 (mL/min), and clay: from 2.70 (mL/min) to 6.18 mL/ min, respectively. In addition, soil salinity was remarkably reduced with rising temperature, where low EC values for sand (461 µS/cm) and clay (318 µS/cm) were reached at 80 °C. The enhanced mobilization of salts under increased thermal conditions was further supported by the trends observed in effluent conductivity. The results show that water temperature is a coupled driver of flow and solute release, with the efficacy being highly dependent on soil structure. Hence, an effective technique for salt leaching enhancement is thermal treatment, especially in low-permeable soils where conventional methods are hardly applicable.

Keywords. Water Temperature, Porous Media, Salt Transport, Soil Salinity, Hydraulic Conductivity**.**

Introduction

Soil salinization is an environmental hazard posed by soils that significantly reduce soil fertility, agricultural yield, and the quality of groundwater. It is estimated that over 20-33 % of irrigated land worldwide suffers from salinization, with this proportion only rising because of improper irrigation practices and climate change effects [1,2]. Soil salinity, causing osmotic stress in plants and degradation of soil structure, ultimately threatens crop yield and ecosystem function [3,4]. Leaching is a common remediation strategy used to scrub soluble salts from soils by applying water and washing ions through the soil profile [5]. Soil texture influences the effectiveness of leaching, as sandy soils with hydraulic conductivities ranging from 10^{-4} to 10^{-3} m/s tend to have more efficient drainage when compared to clay soils characterized by low permeabilities (10^{-9} - 10^{-6} m/s)[6-8] owing mainly to differences in pore size distribution and specific surface area. Physical and chemical differences between the two soil types produce unique behavior with respect to solute transport.

Electrical conductivity (EC) is commonly used as an indirect measure of soil salinity. Soils with EC over 4 dS/m, as salt-affected soils, are widely accepted [9], which can lower crop yield according to the soil type [10,11]. For this reason, in leaching processes, EC is regularly monitored in effluent water to evaluate salt removal efficiency and transport properties [12]. Water temperature is an important environmental variable that affects fluid properties and solute transport. The viscosity of water decreases about 40-50% when its temperature rises from 25°C to 60°C, which increases the flow rate and mass transfer in porous media [13]. Furthermore, as higher water temperature promotes the solubility and diffusion coefficients of ions, it may enhance salt release and transport from soil matrices.

Although many researchers have studied contaminant transport in porous media and soils, the majority of studies have mainly focused on the adsorption and desorption behaviour of organic pollutants and heavy metals [14,15]. Nonetheless, there has been scant focus on the influence of water temperature on governing salt leaching dynamics, particularly in terms of controlled column experiments that assess contrasting soil textures. Thus, the purpose of this study is to examine the impact of increased water temperature on salt leaching dynamics in porous media through laboratory-scale column experiments. Two types of soil, sand and clay, are chosen to exemplify very different hydraulic parameters.

Sodium chloride (NaCl) is an often-used model solute because of its high solubility capacity and relevance in salinization research. The cumulative leaching performance was based on effluent EC measurements over time. These findings are anticipated to deliver better comprehension of thermally assisted solute transport mechanisms in soils and thus assist in generating more effective leaching and soil remediation methods across heterogeneous environmental settings.

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Methods

Soil and Solution Characterization

Two soil types (sand and clay) were used in this study. Soil classification was based on particle size distribution using the USDA soil texture system [16]. Constant-head permeability was measured by tests based on Darcy's law (ASTM D2434). Soil porosity and bulk density were estimated from the standard phase relationships of porous media.

Soil chemical properties

Chemical properties of the soils, such as EC and pH, were analysed using a 1:5 soil-to-water extract. The suspension was formed according to the standard soil analysis procedures and filtered before measurement. The instrument was calibrated according to manufacturer instructions using standard buffer solutions (pH 4, 7, and 10 for pH; standard conductivity solutions for EC. These represent soil baseline management before salinization and leaching experiments. To ensure a uniform initial condition between all soils and avoid contamination across experiments, all soils were air-dried, homogenized, and sieved before use [8,14].

Effluent (leachate) characterization

EC was used as the primary indicator of dissolved salt solute concentration in the leachate (effluent) collected from the bottom of the soil columns during leaching experiments [18]. Immediately following the collection of each 80 mL effluent fraction, EC measurements were performed using a calibrated multiparameter probe (HANNA HI 9829) to prevent potential changes caused by evaporation or temperature fluctuations. Leachate pH was also measured to track changes in solution chemistry throughout the leaching experiment. All measurements were conducted under identical calibration conditions to ensure consistency [19].

Preparation of Saline Soils

NaCl was selected as a model salt due to its high solubility and strong connection with pore fluid salinization processes. 26 g/L stock NaCl solution was prepared by dissolving analytical grade NaCl [20] in distilled water. An appropriate mass of air-dried soil (1 kg per column) was added to a mixing container. The soil was well mixed with the liquid so that salt distribution in this soil matrix should be as homogeneous as possible. The prepared saline soils were equilibrated for 48 hours at room temperature to redistribute and stabilize the ions within the pore water phase. This was performed to ensure uniform conditions across all soil columns before the leaching experiments.

Column Experimental Design

Laboratory-scale vertical column systems were used to simulate transport of solutes through porous media in both one-dimensional and controlled conditions[8]. Transparent acrylic columns (internal diameter of 10 cm and height of 30 cm) were used. The bottom of each column had a perforated base lined by a fine mesh layer to contain the soil whilst permitting free drainage. The soil height was held constant at all columns (4 clay and 4 sand soils, set to 14 cm). Soils were packed with the goal of achieving uniform bulk density and limiting preferential flow and air entrapment. A fixed hydraulic head of 11 cm was applied above the soil surface to achieve saturated flow conditions and facilitate perpetual downward percolation.

Thermal Leaching Procedure

Leaching was carried out using distilled water to prevent background ions. The water was then heated at controlled temperatures of 25, 40, 60, and 80 °C with a thermostatically controlled water bath. A constant head of heated distilled water was maintained by adding it to the top of the column for each experimental run. Leaching was driven by gravity flow through the saturated soil column. Each leaching run was sampled in fractions of 80 mL effluent. Immediately post-collection, EC and PH of each fraction were quantified to assess changes in salt leaching dynamics.

The hydraulic response of each soil column was assessed by measuring the time taken for the first drop of leachate to form at the bottom. Time spent collecting each 80 mL effluent fraction was also noted in all the temperature conditions. Cumulative time was the sum of successive collection intervals in a trial across the experiment. The flow rate (mL/min) was then calculated by substituting the collected effluent volume for the respective time window in Equation (1):

$$Flow\ rate\left(\frac{\mathrm{mL}}{\mathrm{min}}\right)=\frac{\text{Volume(ml)}}{\text{Interval time(min)}} \qquad (1)$$

Leaching Efficiency and Transport Analysis

To evaluate the reduction in salt concentration during the leaching process, leaching efficiency was calculated to quantify the net removal of salts using equation (2): [21]:

$$(\text{Leaching efficiency\%})=\frac{EC_{initial}-EC_{final}}{EC_{initial}}\times 100 \qquad (2)$$

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Where: $EC_{initial}$ is the electrical conductivity of the soil after salinization (μS/cm), and EC_{final} is the electrical conductivity of the soil after completion of the leaching process (μS/cm).
A cumulative approach was used to estimate total transport of salts through the soil column using equation (3) [22]:

$$M = \sum(C_i \times V_i) \qquad (3)$$

Where: C_i is the EC or solute concentration of the effluent fraction; V_i is the corresponding effluent volume. This equation allows quantification of the total mass of salts leached from the soil profile during the experiment. Water movement through the soil column under constant head conditions was described using Darcy's law equation (4) [22]:

$$Q = K.A.\frac{\Delta H}{L} \qquad (4)$$

where: Q is the flow rate (cm^3/s); K is the hydraulic conductivity (cm/s); A is the cross-sectional area of the column (cm^2); Delta H is the hydraulic head (cm); L is the height of the soil column (cm). All experiments were performed in triplicate and reported as mean values for reproducibility and reliability.

Results

Physicochemical Properties of Soils

Initial physicochemical properties of sand and clay soils are summarised in (Table 1). The characteristics were characterized by two soils with significant differences in physical, hydraulic, and chemical properties. Sandy soil consisted of particles about 0.5-2.0 mm in diameter, and the relatively large hydraulic conductivity value of sand soil was equal to 2.47×10^{-3} cm/s, showing that it is highly permeable, which allows water to flow in freely. Its bulk density was 1.55 g/cm^3, and its porosity was 0.38. On the other hand, the clay soil with fine particles (<0.002 mm) had an extremely low hydraulic conductivity of 1.0×10^{-6} cm/s, suggesting limited flow conditions. Although less permeable due to the predominance of micropores, bulk density was 1.30 g/cm^3, and porosity was 0.50. EC values were low for both soils (sand: 95 μS/cm; clay: 100 μS/cm), indicating non-saline conditions at the start. pH values at the beginning of the experiment were 6.22 and 6.00 for sand and clay, respectively, which is mild acidity, typical of natural soils.

Table 1. Physicochemical properties of sand and clay soils before treatment

Soil type	Particle size	Hydraulic conductivity (cm/s)	Bulk density (g/cm^3)	Porosity	EC (μS/cm)	pH
Sand	0.5–2.0 mm	2.47×10^{-3}	1.55	0.38	95	6.22
Clay	<0.002 mm	1.0×10^{-6}	1.30	0.50	100	6.00

Effects of Leaching on Soil Characteristics

Physicochemical properties of the untreated soil types (sand and clay soils) based on their saline levels indicated EC values of 95 μS/cm and 100 μS/cm, respectively, as shown in (Table 2). Increased EC was high in both sands (3528 μS/cm) and clay soil types (4015 μS/cm) after salinization applications.

Table 2. Soil properties before and after treatment at different temperatures

Soil Type	Temperature (°C)	Condition	pH	EC (μS/cm)
Sand	25	Initial (Before salt)	6.22	95
Sand	25	After salinization	6.24	3528
Sand	25	After leaching	5.69	2785
Sand	40	Initial (Before salt)	6.22	95
Sand	40	After salinization	6.24	3528
Sand	40	After leaching	5.62	2376
Sand	60	Initial (Before salt)	6.22	95
Sand	60	After salinization	6.24	3528
Sand	60	After leaching	5.64	525
Sand	80	Initial (Before salt)	6.22	95
Sand	80	After salinization	6.24	3528
Sand	80	After leaching	5.67	461
Clay	25	Initial (Before salt)	6	100
Clay	25	After salinization	5.72	4015
Clay	25	After leaching	5.72	2408
Clay	40	Initial (Before salt)	6	100
Clay	40	After salinization	5.72	4015
Clay	40	After leaching	5.72	1040
Clay	60	Initial (Before salt)	6	100

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Clay	60	After salinization	5.72	4015
Clay	60	After leaching	5.70	560
Clay	80	Initial (Before salt)	6	100
Clay	80	After salinization	5.72	4015
Clay	80	After leaching	5.72	318

This represents a substantial increase and is indicative of the successful arraying of saline conditions necessary for assessing leaching. In the present study, all leaching experiments showed a significant decrease in EC across all water temperatures for both soils. Additionally, the degree of reduction was greatly water temperature dependent. As shown in (Figure 1).

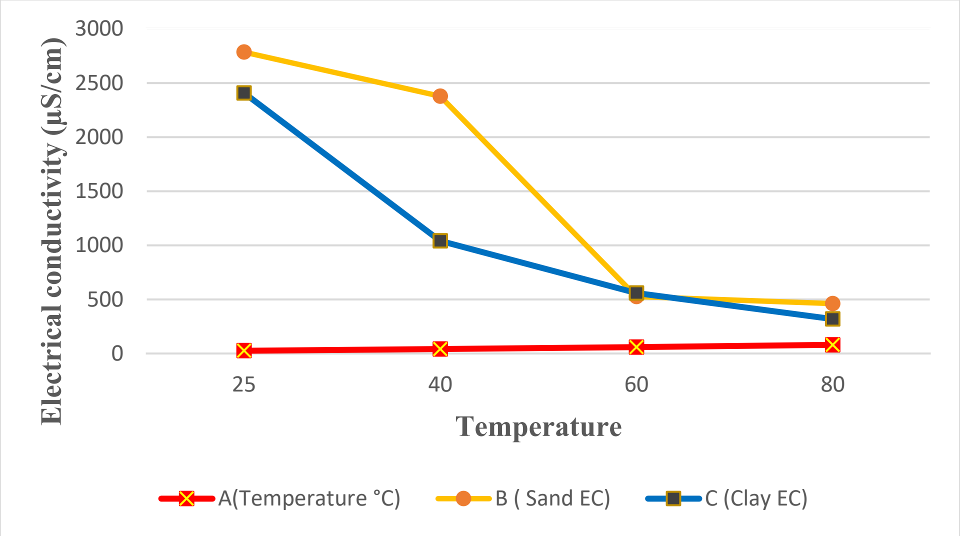

Figure 1. Effect of temperature on electrical conductivity (EC) after leaching for sand and clay soils.

As shown in (Figure 1), EC reduced with increasing water temperature in both sand and clay. In sand soil, EC decreased from 3528 µS/cm to 2785 µS/cm at 25 °C, while a much larger reduction was obtained at higher water temperatures (80 °C), reaching only 461 µS/cm. On the other hand, EC decreased from 4015 µS/cm to 2408 µS/cm at 25 °C and further dropped to 318 µS/cm at 80 °C in clay soil. These results align with previous publications that claimed increasing temperature fosters an efficient salt leaching ability by porous media due to a more effective mass transfer process[23,24]. Water temperature exerts its influence because of the inherent characteristics of several physicochemical mechanisms. Increased temperatures decrease water viscosity, thus facilitating flow through soil pores while also increasing the mobility of ions and diffusion coefficients to improve solute transport[25]. This, in turn, leads to the leaching of dissolved salts from the soil matrix. In contrast, Soil type comparison indicates sand (larger pores with lower adsorption) leaches salts more easily at low temperatures than clay, and this agrees with [26]. Clay performed significantly better in salt removal with increasing water temperature, possibly attributed to enhanced desorption/entropy and increased pore water flow [27].

In all conditions, pH was relatively stable (slight decreases after leaching for sand and remaining stable for clay). This is consistent with previous studies showing that salinity variations affect EC more than pH, which remains constant, unless strong chemical reactions occur [28,29]. In summary, these results underscore that temperature plays a key role in enhancing salt leach performance.

Effect of Water Temperature on Leaching Efficiency

The application of the Leaching efficiency for sand and clay soil was calculated using the reduction in EC between salinized and post-leaching conditions as expressed in Eq. (2). These results clearly show that water temperature has the most important effect on salt removal performance in both soil types. (Table 3) summarizes the calculated leaching efficiencies for sand and clay soils at selected water temperatures.

Table 3. Leaching efficiency (%) of sand and clay soils at different water temperatures

Temperature (°C)	Sand (%)	Clay (%)
25	21.06	40.00
40	32.66	74.13
60	85.11	86.05
80	86.94	92.08

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At 25 °C, the efficiency was shown to be relatively low (21.06%) on sand soil, suggesting that little salt was removed under such low thermal conditions. At 40 °C, a relatively low improvement of 32.66 % was recorded, before an abrupt increase at higher temperatures to record levels of leaching performance (85.11% and 86.94%) at 60 °C, then subsequently 80 °C, with thermally enhanced solute transport dominating the mechanism beyond the previously mentioned temperature threshold of approximately 60 °C. In clay soil, another, however, more recognizable response was noticed.

Leaching efficiency was even higher than sand, 40.00% at 25 °C means that some of the salts in clay are more readily dissolved during initial flushing, while the procedure for leaching with a high temperature may reach a point where this is more difficult to achieve. With the rise in temperature, the efficiency increased dramatically to 74.13 % at 40 °C and even reached more than 86.05 % at 60 °C, achieving its maximum of 92.08 % when the system temperature was raised to 80 °C through thermal improvement, as shown in (Figure 2). This result indicated that clay soil is more prone to temperature changes. This sensitivity increases salt removal efficiency in chronological conditions, which is consistent with [31,32].

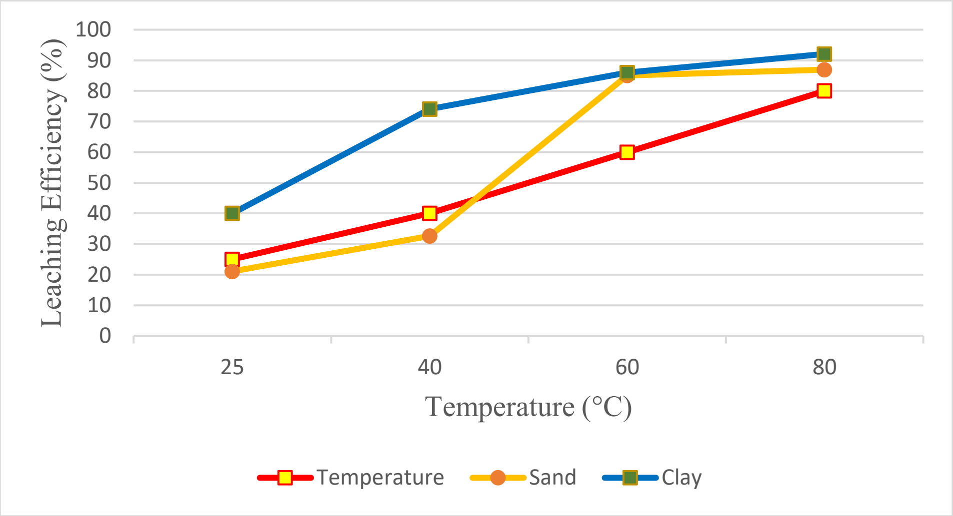

Figure 2. Leaching efficiency (%) of sand and clay soils under different water temperature conditions.

The contrasts between sand and clay are primarily seen in their physical configuration (Section 3.1). The larger pore spaces of sand provide opportunities for advective flow, but its ability to remove salt is limited at low temperatures because the interaction time is short. In contrast, clay has a microporous structure and a larger surface area that initially holds more ions but strongly responds when the temperature increases due to greater desorption and better pore water mobility. The increase in leaching efficiency with temperature is associated with a decrease in water viscosity and the consequent higher rates of ion mobility (diffusion) processes. Increased temperatures also improve hydraulic conductivity and promote rapid dispersal of pore water within the soil matrix, which accounts for more successful salt flushing.

Flow Behavior and Hydraulic Response

The hydraulic behaviour of sand and clay under varying temperature conditions was assessed using first drop time (FDT), interval time (IT), total cumulative dropping time, and flow rate, shown in (Table 4) and (Table 5). These parameters define the time evolution of water flux through porous media under constant head conditions and hydraulic response based on temperature. (Figure 3) shows the average flow rate as a function of temperature. For both soils, there was a clear increasing trend with temperature for the fraction of water moving through the soil matrix as a function of time, which means that thermal heating enhanced water mobility through the soil matrix.

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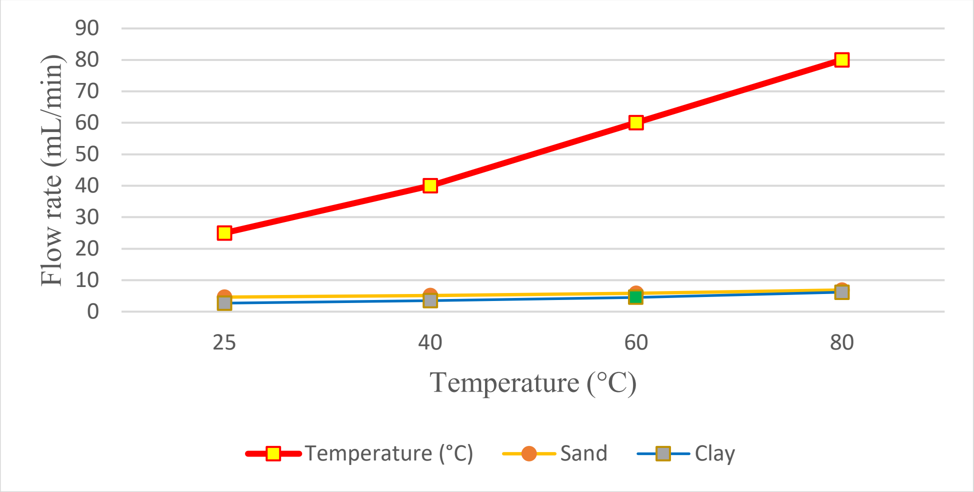

Figure 3. Variation of flow rate with temperature for sand and clay soils under constant head conditions.

For sand soil, the hydraulic response was improved from 27–37 °C. First drop time reduced from 41 min at 25 °C to 26 min at 80 °C (Table 4), suggesting enhanced initiation of flow with temperature. In a similar manner, the interval time to capture each 80 mL fraction was reduced, leading to the average flow rate increasing from 4.62 mL/min at 25 °C to 6.87 mL/min at 80 °C (Figure3). The continued reduction in cumulative collection time also provides evidence of enhanced hydraulic conductivity and increased percolation through the sand column.

Table 4. Sand effluent characteristics and flow behavior at different collection

Soil Type	**Temp (°C)**	**Sample No.**	FDT (min)	**Interval No.**	IT (min)	**Cumulative Time (min)**	**Volume (mL)**	**Flow Rate (mL/min)**	**EC (µS/cm)**	**PH**
Sand	25	1	41	1	18	66	80	4.44	26640	5.72
Sand	25	1	41	2	17	78	80	4.71	24532	5.72
Sand	25	1	41	3	17	91	80	4.71	22770	5.72
Sand	40	2	40	1	16	56	80	5	36830	5.74
Sand	40	2	40	2	16	72	80	5	30070	5.72
Sand	40	2	40	3	15	87	80	5.33	24500	5.71
Sand	60	3	35	1	13	48	80	6.15	27900	5.78
Sand	60	3	35	2	14	62	80	5.71	25300	5.75
Sand	60	3	35	3	14	76	80	5.71	21450	5.76
Sand	80	4	26	1	12	38	80	6.67	30150	5.65
Sand	80	4	26	2	12	50	80	6.67	28150	5.61
Sand	80	4	26	3	11	61	80	7.27	21640	5.62

In clay soil, a similar trend based on temperature was found, but the flow rates were lower than those in sand. The drop time for the first drop was reduced from 82 min at 25 °C to just 37 min when soil temperature reached 80 °C (Table 5), further suggesting thermal conditions facilitate infiltration of accumulating water in fine-textured soils. A clear water temperature sensitivity of the clay is shown with an increase from 2.70 mL/min at 25 °C to 6.18 mL/min at 80 °C (Figure 3). Notwithstanding this improvement, clay consistently performed less well in hydraulic terms than sand due to its micro-porous structure and lower intrinsic permeability.

The flow behavior of sand and clay reflects the physical properties described in section 3.1. The greater hydraulic conductivity and larger pore spaces of sand allow for rapid advective flow, combined with thermal equilibrium response timeframes, to occur more readily. Clay, on the other hand, has a significantly lower hydraulic conductivity and is dominated by micropores that impede the movement of water flow through the soil matrix, resulting in high retention capacity, therefore delaying flow initiation. The increase of flow rate with temperature is explained by Darcy's law (Eq. 4) and is sensitive to both fluid properties and hydraulic conductivity. Increased temperatures reduce water viscosity, making hydraulic conductivity easier and promoting faster flow of water through the soil. Temperature is one of the main factors that affects hydraulic behavior in both soils (Figure 3).

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Table 5. Clay effluent characteristics and flow behavior at different collection

Soil Type	**Temp (°C)**	**Sample No.**	FDT **(min)**	**Interval No.**	**IT (min)**	**Cumulative Time (min)**	**Volume (mL)**	**Flow Rate (mL/min)**	**EC (µS/cm)**	**PH**
Clay	25	1	82	1	30	112	80	2.67	20190	5.63
Clay	25	1	-	2	29	141	80	2.76	21970	5.61
Clay	25	1	-	3	30	171	80	2.67	11500	5.58
Clay	40	2	70	1	22	92	80	3.64	32740	5.86
Clay	40	2	-	2	23	115	80	3.48	30400	5.76
Clay	40	2	-	3	23	138	80	3.48	29900	5.74
Clay	60	3	56	1	18	74	80	4.44	45300	5.74
Clay	60	3	-	2	18	92	80	4.44	41930	5.79
Clay	60	3	-	3	17	109	80	4.71	17570	5.74
Clay	80	4	37	1	14	51	80	5.71	50210	6.25
Clay	80	4	-	2	13	64	80	6.15	31920	5.76
Clay	80	4	-	3	12	76	80	6.67	20480	5.72

Discussion

Results confirm that coupled hydraulic and solute transport in porous media is controlled largely by temperature. The dominant effect of higher temperature on flow behavior is mainly related to the reduction in water viscosity, which leads to improved hydraulic conductivity. This results in higher advective transport efficiency under constant hydraulic gradient, following porous media flow theory. These confirm that, properties of the fluid transmitted through Darcy-scale pore spaces directly influence transport. However, the thermal effect is highly dependent on soil structure. Given that sand has large interconnected pore spaces and high intrinsic permeability, the response to temperature changes is relatively modest since flow in this regime is already dominated by fast advection. On the other hand, clay soils have a fine pore network, whereby flow is restricted and largely controlled by fluid viscosity, making them much more sensitive to temperature. Thus, even slight permeability modifications at higher temperatures tend to drastically enhances the continuity and connectivity of flow in clay soils. This better leaching, which is less with the decrease in temperature, reflects higher advection and diffusion rates and lower retention of solute. This represents a transition from partial leaching at low temperatures into near-total salt removal in the range of 60–80 °C, which indicates that there is some thermal threshold where transport processes become more rapid. In particular, this effect is pronounced in clay soils, for which pore-scale transport becomes thermally activated at significantly elevated temperatures. Sand consistently exhibited higher flow rates than clay soil upon comparison. Leaching efficiency improved significantly in clay with increasing temperature. Sand allows water to pass quite freely, but does not seem very sensitive to heating. While clay is more sensitive to thermal effects because its relative influences of fluid viscosity and pore-scale resistance are higher. In general, leaching is better at higher temperatures, not only because of increased flow rates but also due to better ion mobility, lower retention, and smaller residence time of pore water. In this sense, temperature would be the master physical-chemical driver regulating water movement and solute release, while soil structure regulates the magnitude of response. Finally, thermal enhancement can be used to improve salt leaching in soils with low permeability, at least from a practical perspective. Under traditional leaching, such soils are typically non-productive. However, increasing water temperatures in the field should be designed with energy requirements and practical implementation in mind. There is a consideration of environment sustainability as well.

Conclusion

Controlled column of sand and clay soil experiments were conducted to determine the effects of temperature and salt leaching behaviour in sand and clay soils. The results confirmed that elevated water temperature positively improved flow conditions and salt extraction in both soils. Sandy soil was characterised by higher flow rates and leaching performance. In contrast, clay soil is characterised by slower flow rates and leaching performance due to its fine structure and increased water retention capacity. Moreover, clay soil was more sensitive to water temperature than sand. Finally, water temperature was the main factor responsible for increasing leaching efficiency. However, soil type was additionally key to determining the overall quantity of salt that could be flushed away as well. Overall, these results underline the feasibility of thermal enhancement for soil salinity management.

Conflict of interest. Nil

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