Postprint: Quantitative Simulation of Evaporation Resistance of Salt Crust Under Different Influencing Factors

Authors: Li Jialin, Li Xinhu, Wang Hongchao, Cui Mengmeng, Guo Yubo, JIN Haodong, Ren Xiaoxiao

Date: 2026-01-19T13:54:39+00:00

Abstract

Salt crusts are typical surface structures in arid regions and significantly affect water transport processes at the soil-atmosphere interface. The evaporation resistance of salt crusts is a key controlling parameter in soil water evaporation processes; however, quantitative analyses of salt crust evaporation resistance under different influencing factors remain unclear. Therefore, through simulation experiments combined with theoretical analyses, we dynamically monitored and analyzed the formation of salt crusts and the evolution of their evaporation resistance under varying soil particle sizes (fine sand: 0.10–0.25 mm; coarse sand: 0.50–0.85 mm), radiation (200 W · m-2, 500 W · m-2, and 800 W · m-2), salt concentrations (5.0% and 17.5% NaCl), wind speeds (3.5 m · s-1 and 8.0 m · s-1), hydraulic connection conditions (progressive drying and water supply), and evolution times. Based on the Shapley additive explanations (SHAP) method, the contributions of each factor were quantified and their importance was ranked. The results show that: (1) the evaporation resistance of salt crusts exhibits a continuously increasing trend with evolution time. By the end of the experiments, the evaporation resistance of salt crusts was highest under the DL3 treatment (5.0% NaCl, progressive drying, 800 W · m-2 radiation, fine sand), reaching 9.39$×$104 s · m-1; in contrast, it was lowest under the WH2 treatment (5.0% NaCl, water supply, 8.0 m · s-1 wind speed, fine sand), at 293.08 s · m-1. (2) The ranking of the contributions of the influencing factors to the evaporation resistance of salt crusts was: hydraulic connection > radiation > evolution time > soil particle size > salt concentration > wind speed. Among these, radiation exerted a positive effect on salt crust evaporation resistance, whereas soil particle size had a negative effect. The findings provide theoretical support for the quantitative description of evaporation resistance in salt crusts.

Quantitative Modeling of Evaporation Resistance in Salt Crusts Under Varying Influencing Factors

LI Jialin[1,2,3], LI Xinhu[1,2,3], WANG Hongchao[1,2,3], CUI Mengmeng[2], GUO Yubo[1,2,3], JIN Haodong[1,3], REN Xiaoxiao[1,3]

[1]State Key Laboratory of Desert and Oasis Ecology, Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, Xinjiang 830011, China
[2]National Field Scientific Observation and Research Station of Aksu Oasis Farmland Ecosystem, Aksu, Xinjiang 843017, China
[3]University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

Salt crusts are a typical surface structure in arid regions that significantly affect soil-atmosphere water transfer processes. Evaporation resistance of salt crusts represents a key controlling parameter in soil water evaporation dynamics, yet quantitative analysis of this resistance under different influencing factors remains unclear. This study employed simulation experiments and theoretical analysis to dynamically monitor and analyze salt crust formation and evaporation resistance evolution under the influences of soil particle size (fine sand: 0.10-0.25 mm; coarse sand: 0.50-0.85 mm), radiation intensity (200 $\mathrm{W \cdot m^{-2}}$, 500 $\mathrm{W \cdot m^{-2}}$, and 800 $\mathrm{W \cdot m^{-2}}$), salt concentration (5.0% and 17.5% NaCl), wind speed (3.5 $\mathrm{m \cdot s^{-1}}$ and 8.0 $\mathrm{m \cdot s^{-1}}$), hydraulic connectivity (gradual drying vs. water supply), and evolution time. Using the Shapley additive explanation (SHAP) method, we quantified the contributions of each factor and ranked their importance. Results showed: (1) Salt crust evaporation resistance exhibited a continuous increasing trend over time. At experiment termination, the maximum resistance (9.39×10^4 $\mathrm{s \cdot m^{-1}}$) occurred under the DL3 treatment (5.0% NaCl, gradual drying, 800 $\mathrm{W \cdot m^{-2}}$ radiation, fine sand), while the minimum resistance (293.08 $\mathrm{s \cdot m^{-1}}$) was observed under the WH2 treatment (5.0% NaCl, water supply, 8.0 $\mathrm{m \cdot s^{-1}}$ wind speed, fine sand). (2) The contribution ranking of influencing factors was: hydraulic connectivity > radiation > evolution time > soil particle size > salt concentration > wind speed. Radiation exerted a positive effect on salt crust evaporation resistance, whereas soil particle size showed a negative effect. These findings provide theoretical support for quantitative characterization of salt crust evaporation resistance.

Keywords: salt crust; evaporation resistance; influencing factors; SHAP method

1. Introduction

Salt crusts are widely distributed in arid and semi-arid regions. Under intense evaporation and shallow saline groundwater, soil salts migrate upward with water and accumulate at the surface. When salt concentration reaches its solubility limit, crystallization begins and aggregates continuously. With persistent evaporation, salt crystals grow progressively, eventually forming a continuous salt crust layer at the soil surface. Research indicates that salt crusts significantly inhibit evaporation and affect ecohydrological processes. Evaporation resistance of salt crusts is a key parameter for quantitatively describing soil water evaporation and significantly influences regional hydrological cycles.

Studies show that salt crust evaporation resistance is affected by multiple factors, including radiation, soil particle size, wind speed, salt concentration, evolution time, and hydraulic connectivity. However, existing research has only explored the effect of soil particle size on evaporation resistance, while other factors' mechanisms remain unclear. Therefore, quantitative analysis of different factors' effects on salt crust evaporation resistance is urgently needed.

Current calculation methods for salt crust evaporation resistance have limitations. First, due to its nonlinear characteristics, conventional statistical methods cannot effectively identify resistance patterns. Second, although numerical models can simulate evaporation resistance, they require numerous parameters (e.g., salt crystallization density, capillary number, porosity) that are difficult to obtain, making calculations complex and hard to generalize. Additionally, few models incorporate multiple influencing factors. To establish a more accurate and effective factor-based model, factor importance must first be clarified. To overcome these limitations, this study introduces the Shapley additive explanation (SHAP) method, which assigns contributions to each feature through Shapley values from game theory, enabling precise quantification of each factor' s impact on model predictions.

This study analyzed salt crust evaporation resistance variation characteristics under the combined effects of soil particle size, radiation intensity, wind speed gradients, salt concentration, hydraulic connectivity, and evolution time. Using the SHAP method, we quantified each factor' s contribution magnitude and directional effect (positive/negative) to provide theoretical support for quantitative description of salt crust evaporation resistance.

---

2. Materials and Methods

2.1 Experimental Design The experiment was conducted in 2024 at the Aksu Oasis Farmland Ecosystem National Field Scientific Observation and Research Station in Xinjiang. Polyvinyl chloride (PVC) tubes and caps were used to construct experimental soil columns (internal diameter 12.5 cm, height 12.5 cm). A standard flow calibration column (RX-300, Shanghai Rongxing Pump

Industry) was modified into a Mariotte bottle with a silicone-sealed filling port and an acrylic air guide tube. Both soil columns and Mariotte bottles underwent hydrostatic pressure testing to ensure no leakage before use.

2.1.1 Soil Particle Size Experimental soil was collected from sand dunes in the upper Tarim River region (40°39\$ ‘20’ ‘N, 80°54’ 44’’ \$E). The standardized sand pretreatment procedure involved: (1) flushing sand grains upward with tap water until electrical conductivity stabilized at ~600 $\mu\mathrm{S}\cdot\mathrm{cm}^{-1}$ (equivalent to tap water conductivity); (2) rinsing with distilled water until conductivity dropped below 20 $\mu\mathrm{S}\cdot\mathrm{cm}^{-1}$ to effectively remove salts; (3) air-drying and sieving to obtain fine sand (0.10–0.25 mm) and coarse sand (0.50–0.85 mm) fractions; (4) packing sand into custom columns in layers at standard bulk densities (fine sand: $1.65 \pm 0.02\ \mathrm{g}\cdot\mathrm{cm}^{-3}$; coarse sand: $1.63 \pm 0.02\ \mathrm{g}\cdot\mathrm{cm}^{-3}$).

2.1.2 Salt Concentration Given that NaCl is the main component of salt crusts in the upper Tarim River region, this study used NaCl as the representative salt. To systematically reveal salt concentration effects, we set two gradients: 5.0% (low) and 17.5% (high) salt concentration.

2.1.3 Evaporation Driving Conditions (Radiation and Wind Speed) To investigate differences in salt crust characteristics and evaporation resistance under isothermal (wind-driven) versus non-isothermal (radiation-driven) conditions, we designed radiation and wind speed gradients. The experiment included three radiation levels: 200 $\mathrm{W}\cdot\mathrm{m}^{-2}$, 500 $\mathrm{W}\cdot\mathrm{m}^{-2}$, and 800 $\mathrm{W}\cdot\mathrm{m}^{-2}$, with corresponding wind speed gradients to match potential evaporation rates across radiation treatments, ensuring equivalent evaporative driving forces but different thermal conditions. An extreme radiation treatment (800 $\mathrm{W}\cdot\mathrm{m}^{-2}$) was added to simulate harsh environments. The average ambient temperature during the experiment was 22.53 ± 0.74°C with relative humidity of $67.84\% \pm 5.35\%$.

For radiation treatments, soil columns were wrapped with insulation to reduce external heat disturbance. A halogen lamp was placed directly above the column, with height adjusted to control surface radiation at $200 \pm 10\ \mathrm{W}\cdot\mathrm{m}^{-2}$, $500 \pm 20\ \mathrm{W}\cdot\mathrm{m}^{-2}$, or $800 \pm 30\ \mathrm{W}\cdot\mathrm{m}^{-2}$. For wind speed treatments, a fan (Delta AFB1212HJ) was placed 10 cm horizontally from the column, with speed controlled at $3.5 \pm 0.2\ \mathrm{m}\cdot\mathrm{s}^{-1}$ or $8.0 \pm 0.6\ \mathrm{m}\cdot\mathrm{s}^{-1}$.

2.1.4 Hydraulic Connectivity Hydraulic connectivity refers to the continuity of liquid water pathways in the soil pore network. We established two contrasting conditions: (1) Water supply condition (maintained hydraulic connectivity) using a Mariotte bottle system [Figure 1: see original paper] that continuously supplied water from the bottom at a constant level 5 cm below the soil surface; (2) Gradual drying condition (disconnected hydraulic connectivity) with no groundwater supply. Both treatments maintained 24-hour saturation time (solution infiltration to the surface followed by immediate sealing) to ensure uniform salt distribution. The gradual drying treatment required additional drainage until no gravitational water remained.

2.1.5 Measurements of Water Loss, Temperature, and Salt Crystallization An infrared thermal imager (FLIR, resolution 0.1°C, Sony China) and digital camera (Sony ILCE-6000) monitored soil surface temperature and salt crust evolution. For gradual drying treatments, water loss was measured daily at 22:00 using an electronic balance; for water supply treatments, evaporation was recorded via Mariotte bottle readings at the same time. All observations (temperature, images, mass) were synchronized at consistent intervals. After the experiment, salt crust thickness was measured with vernier calipers and mass determined using an electronic balance. Infrared images were processed with FLIR Tools software, salt crust coverage quantified using ImageJ, and data analyzed with Excel 2019 and Origin 2021. Kruskal-Wallis non-parametric tests ($\alpha = 0.05$) assessed statistical differences between treatments.

2.1.6 Experimental Treatments A strictly controlled experimental design investigated effects of soil particle size, radiation, salt concentration, wind speed, and hydraulic connectivity on salt crust evaporation resistance. The experiment comprised 24 salt treatments with 3 replicates each. Specific treatments are detailed in .

2.2 Theoretical Framework

2.2.1 Salt Crust Evaporation Resistance Soil evaporation rate is jointly affected by environmental conditions and soil properties. In saline soils, salt crust evaporation resistance characterizes the additional hindrance to evaporation caused by salt crystallization. Based on water vapor transport theory, this resistance is determined by the water vapor concentration gradient between surface soil and atmosphere, aerodynamic resistance, and soil dry-layer resistance:

$$r_{sc} = \frac{C_{sat}^{soil} \cdot RH_{soil} - C_{sat}^{air} \cdot RH_{air}}{E} - r_{air} - r_{soil}$$

where r_{sc} is salt crust evaporation resistance ($\mathrm{s \cdot m^{-1}}$); E is mass evaporation rate ($\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$); C_{sat}^{soil} and C_{sat}^{air} are saturated vapor concentrations at soil and atmospheric temperatures ($\mathrm{kg \cdot m^{-3}}$); RH_{soil} and RH_{air} are relative humidities of soil and air; r_{air} is aerodynamic resistance; and r_{soil} is soil dry-layer resistance (present only in gradual drying treatments).

For comparative analysis, we used volumetric evaporation rate (E_{vol}, $\mathrm{mm \cdot d^{-1}}$) as the unit, related to mass evaporation rate through:

$$E_{vol} = \frac{E}{\rho_w} \times 86400$$

where h is water depth (mm), m is evaporated mass (kg), A is soil surface area (m^2), ρ_w is water density ($1000\ \mathrm{kg}\cdot\mathrm{m}^{-3}$), and t is time (d). Based on the physical relationship where $1\ \mathrm{kg}\cdot\mathrm{m}^{-2}$ corresponds to 1 mm water depth and time unit conversion ($1\ \mathrm{d} = 86400\ \mathrm{s}$), we derive $1\ \mathrm{kg}\cdot\mathrm{m}^{-2} = 86400\ \mathrm{mm}\cdot\mathrm{d}^{-1}$.

Saturated vapor concentration is calculated via the ideal gas law:

$$C_{sat} = \frac{e_{sat}\cdot M_w}{R^*\cdot T}$$

where C_{sat} is saturated vapor concentration ($\mathrm{kg}\cdot\mathrm{m}^{-3}$), T is temperature (K), e_{sat} is saturation vapor pressure (Pa), M_w is molar mass of water ($0.018\ \mathrm{kg}\cdot\mathrm{mol}^{-1}$), and R^* is the universal gas constant ($8.31\ \mathrm{J}\cdot\mathrm{mol}^{-1}\cdot\mathrm{K}^{-1}$).

Soil relative humidity is calculated from heat balance between liquid water and vapor:

$$RH_{soil} = \exp\left(\frac{\psi\cdot M_w}{R^*\cdot T}\right)$$

where ψ is soil matric potential (MPa).

For water supply treatments where soil remains saturated, soil dry-layer resistance exists only in gradual drying treatments, calculated as:

$$r_{soil} = 10e^{0.3563(\theta_{top}-0.05)}$$

where θ_{top} is water content at the soil surface.

Aerodynamic resistance is calculated as:

$$r_{air} = \frac{\ln\left(\frac{z_{ref}-d}{z_{0h}}\right)\ln\left(\frac{z_{ref}-d}{z_{0m}}\right)}{\kappa^2\cdot U^*}$$

where U^* is friction velocity ($\mathrm{m}\cdot\mathrm{s}^{-1}$), κ is von Karman constant, z_{ref} is reference height for temperature measurement (m), d is zero-plane displacement, and z_{0h} and z_{0m} are surface roughness lengths for heat and momentum fluxes, with atmospheric stability correction factors.

2.2.2 Salt Crust Physical Characteristics Average salt crystallization rate is calculated as:

$$\bar{R}_{cry} = \frac{m_{cry}}{t_{evap}}$$

where $\bar{R}_{cry}$ is average crystallization rate ($\mathrm{kg} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$), m_{cry} is salt crystal mass (kg), and t_{evap} is total evaporation duration (d).

The relationship between salt crust porosity and permeability follows the Kozeny-Carman equation:

$$k_{sc} = \frac{b \cdot \phi_{sc}^3 \cdot d^2}{180(1-\phi_{sc})^2}$$

where k_{sc} is salt crust permeability (m^2), ϕ_{sc} is salt crust porosity, d is particle diameter (m), and b is a numerical factor (0.5-1.0).

2.2.3 Shapley Additive Explanation (SHAP) Method To eliminate dimensional differences, all feature data were normalized via min-max scaling to the [0,1] interval. Using preprocessed data, a Random Forest Regressor model (n_{estimators}=100, random_{state}=0) was trained, and SHAP values were computed to quantify feature importance. The SHAP value for feature i is calculated as:

$$\phi_i = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(|N|-|S|-1)!}{|N|!} \left[f(S \cup \{i\}) - f(S) \right]$$

where ϕ_i is the SHAP value for feature i; S is a subset of features excluding i; N is the complete feature set; and $f(S)$ is the model prediction using subset S.

Feature importance was calculated as mean absolute SHAP values:

$$|\phi_i| = \frac{1}{|\Omega|} \sum_{j \in \Omega} |\phi_i^{(j)}|$$

where $|\phi_i|$ is the average absolute SHAP value for feature i, $\phi_i^{(j)}$ is the SHAP value for feature i in sample j, and Ω is the total sample set.

2.2.4 Gaussian Process Regression (GPR) Model This study employed GPR to analyze nonlinear relationships between salt crust evaporation resistance and influencing factors (radiation, wind speed, soil particle size, salt concentration, salt crust coverage, and hydraulic connectivity). The model configured radial basis kernel functions for each treatment group, with kernel scaling factors and length scales automatically optimized via maximum likelihood estimation. To avoid local optima, random restart optimization was used with 10 training repetitions.

The kernel function is:

$$k(x, x') = \sigma_f^2 \times \exp\left(-\frac{(x - x')^2}{2L^2}\right)$$

where x is a test sample, x' is a reference sample, $k(x, x')$ is the kernel output measuring similarity, σ_f^2 is the scaling factor, and L is the length scale.

The predictive mean for new input data is:

$$\bar{y}_* = k(x_*, X)(K + \sigma_n^2 I)^{-1} y$$

where K is the kernel matrix of training samples, σ_n^2 is observation noise, I is the identity matrix, y is training target values, and $\bar{y}_*$ is the predicted value for test point x_*.

2.2.5 Model Evaluation Metrics Model validation used coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE). Higher R^2 indicates better simulation accuracy, while lower RMSE and MAE indicate better capture of measured value trends.

3. Results

3.1 Soil Evaporation and Salt Crust Evolution This study systematically investigated how salt concentration, soil particle size, wind speed, radiation, and hydraulic connectivity affect daily soil evaporation. Results showed significant differences in evaporation rates between treatments ($P < 0.05$). Based on evaporation rate characteristics, all treatments exhibited three distinct stages [FIGURE:2-5].

For gradual drying treatments, Stage 1 (Days 1-4) showed slowly decreasing evaporation rates due to minor salt crystallization at the surface. Stage 2 (Days 5-7) featured rapid evaporation decline as extensive salt crystallization occurred and crust coverage increased sharply [Figure 6: see original paper]. Stage 3 (Days 8-21) reached stable low evaporation as vapor diffusion through the salt crust dominated. The formation of internal crystallization [5,29-32] clogged soil pores and increased evaporation resistance. At experiment end, the DL3 treatment showed maximum resistance (9.39×10^4 $\mathrm{s \cdot m^{-1}}$), while the WH2 treatment showed minimum resistance (293.08 $\mathrm{s \cdot m^{-1}}$).

For water supply treatments, hydraulic connectivity maintenance sustained high evaporation rates during Stage 1 for extended periods [Figure 3: see original paper]. As salt crystallization progressed and crusts formed, resistance increased, causing rapid evaporation decline in Stage 2. Stage 3 stabilized at low rates due to limited water migration through the crust.

3.2 Salt Crust Evaporation Resistance Dynamics Salt crust evaporation resistance increased continuously throughout the experiment, but growth rates varied significantly by treatment. In low-salt gradual drying radiation treatments, resistance grew slowly during Days 1-4 when crust morphology remained unstable. As crystallization continued and effective evaporation area decreased, resistance increased rapidly. Final resistances reached 1998.18 $\mathrm{s \cdot m^{-1}}$ and 5573.11 $\mathrm{s \cdot m^{-1}}$ for fine and coarse sand, respectively.

In low-salt water supply radiation treatments, fine sand showed slower initial resistance growth (Days 1-10) because limited crystallization prevented continuous crust formation. As crystallization progressed, evaporation area decreased and water transport became restricted, causing rapid resistance increase. Final resistances reached 401.14 $\mathrm{s \cdot m^{-1}}$ and 374.78 $\mathrm{s \cdot m^{-1}}$ for fine and coarse sand, respectively.

In high-salt water supply radiation treatments, coarse sand exhibited significantly higher resistance than fine sand. For example, under 800 $\mathrm{W \cdot m^{-2}}$ radiation, coarse sand peaked at 1.36×10^5 $\mathrm{s \cdot m^{-1}}$, while fine sand only reached 1.85×10^4 $\mathrm{s \cdot m^{-1}}$. This difference likely relates to pore structure: large pores in coarse sand promoted vertical salt crystal growth and created micro-air gaps between crust and soil surface, further hindering water transfer.

In high-salt water supply wind speed treatments, fine sand resistance increased from 56.30 $\mathrm{s \cdot m^{-1}}$ to 396.21 $\mathrm{s \cdot m^{-1}}$ during Days 1-10, then stabilized. Final resistances were 946.63 $\mathrm{s \cdot m^{-1}}$ and 795.79 $\mathrm{s \cdot m^{-1}}$ for fine sand under 3.5 $\mathrm{m \cdot s^{-1}}$ and 8.0 $\mathrm{m \cdot s^{-1}}$ wind speeds, respectively—significantly higher than corresponding radiation treatments.

3.3 Factor Contribution Quantification and Simulation SHAP analysis revealed that hydraulic connectivity most significantly affected salt crust evaporation resistance. Under identical conditions, gradual drying treatments showed higher resistance than water supply treatments ($P < 0.05$). For extreme hydraulic states, we assigned values of 0 (theoretical minimum: nearly closed water pathways) and 1 (theoretical maximum: fully connected pathways), consistent with physical boundaries. Since salt crust coverage follows a typical S-curve over time [5,29-32], we used it as an evolution time indicator.

Results showed the contribution ranking: hydraulic connectivity > salt crust coverage (evolution time) > radiation > soil particle size > salt concentration > wind speed. Radiation positively affected resistance: increasing from 200 $\mathrm{W \cdot m^{-2}}$ to 800 $\mathrm{W \cdot m^{-2}}$ raised average crystallization rates from 2.05 $\mathrm{g \cdot d^{-1}}$ to 7.87 $\mathrm{g \cdot d^{-1}}$, decreased porosity from 0.30 to 0.18, and increased resistance from 293.08 $\mathrm{s \cdot m^{-1}}$ to 401.14 $\mathrm{s \cdot m^{-1}}$.

Soil particle size negatively affected resistance: smaller particles yielded higher resistance. Fine sand treatments showed resistances approximately 3.83$×10ˆ{4}$ times higher than coarse sand treatments under equivalent conditions.

Higher salt concentration increased solution osmotic pressure, accelerating crystallization. High-salt treatments had average crystallization rates (6.02–33.85 $g \cdot d^{-1}$) about 5.57$×10^{3}$ times higher than low-salt treatments, with correspondingly lower porosity and higher resistance.

Wind speed effects were relatively minor. Under similar potential evaporation, wind speed' s impact remained weaker than radiation' s. GPR modeling [Figure 9: see original paper] achieved high fitting accuracy ($R^2 > 0.81$), effectively capturing complex nonlinear relationships between evaporation resistance and influencing factors. However, simulation accuracy varied significantly between treatments. Larger length scales in the kernel function caused the model to focus on overall trends rather than local fluctuations, potentially explaining smaller errors in some treatments.

4. Discussion

This study found that higher radiation increased average salt crystallization rates, produced smaller crystals with tighter bonding, reduced salt crust porosity, lowered permeability, and increased evaporation resistance. This aligns with previous research [20,22] showing that higher radiation leads to more rapid evaporation rate decline and that high crystallization rates produce uniformly distributed powdery microcrystals that reduce porosity and increase resistance.

Gradual drying treatments showed significantly higher resistance than water supply treatments, likely because the former produced both surface and internal crystallization that clogged pores, while the latter only formed surface crusts. High salt concentration enhanced this effect by increasing crystallization rates and reducing crystal size, forming dense crust structures with lower permeability. This mechanism, where salt concentration affects crust structure through crystallization rate, represents a novel finding.

Soil particle size effects can be explained through Kozeny-Carman theory and Darcy' s law: smaller particles produce smaller crystals, reducing permeability and significantly increasing resistance. This aligns with Rad et al. [23] showing that fine-grained soils form salt crusts with smaller crystal sizes.

Salt crust formation is time-dependent. As evaporation continues, increasing crust coverage reduces evaporation area while thickness and mass increase, significantly raising resistance. This supports Fujimaki et al. [34] who found positive correlations between crust mass/thickness and water transfer resistance.

Under similar potential evaporation demand, wind speed' s effect was significantly weaker than radiation' s. This difference arises because radiation alters temperature, affecting crystallization kinetics and crust physical characteristics, whereas wind speed treatments under isothermal conditions produce fundamentally different crystallization dynamics. Temperature thus emerges as a key factor, though its specific effects on crystallization kinetics require further investigation using infrared thermography.

The SHAP method effectively addressed nonlinear modeling challenges, providing a flexible, high-accuracy prediction tool ($R^2 > 0.81$) for salt crust evaporation resistance without relying on predefined functional forms.

---

5. Conclusions

1. Salt crust evaporation resistance increased continuously over time. At experiment end, maximum resistance (9.39×10^4 s · m^{-1}) occurred under the DL3 treatment (5.0% NaCl, gradual drying, 800 W · m^{-2} radiation, fine sand), while minimum resistance (293.08 s · m^{-1}) occurred under the WH2 treatment (5.0% NaCl, water supply, 8.0 m · s^{-1} wind speed, fine sand).
2. SHAP analysis ranked factor contributions as: hydraulic connectivity > evolution time > radiation > soil particle size > salt concentration > wind speed. Hydraulic connectivity showed the most significant effect, with gradual drying treatments (combining surface and internal crystallization) producing much higher resistance than water supply treatments (surface crystallization only).
3. Radiation and salt concentration positively affected resistance: higher radiation (800 vs. 200 W · m^{-2}) increased crystallization rates (7.87 vs. 2.05 g · d^{-1}), reduced porosity (0.18 vs. 0.30), and raised resistance (401.14 vs. 293.08 s · m^{-1}). High salt concentration amplified this effect.
4. Soil particle size negatively affected resistance: smaller particles reduced crystal diameter, decreased permeability, and significantly increased resistance. Fine sand treatment resistance (3.83×10^4 s · m^{-1}) was substantially higher than coarse sand (2.04×10^4 s · m^{-1}).
5. Under similar potential evaporation, radiation treatments showed significantly higher resistance than wind speed treatments due to temperature effects on crystallization kinetics.
6. The SHAP method provided an effective, flexible, high-accuracy ($R^2 > 0.81$) tool for modeling salt crust evaporation resistance, offering a new quantitative approach for saline soil water transfer research.

References

[1] Shokri N. Pore scale dynamics of salt transport and distribution in drying porous media[J]. Physics of Fluids, 2014, 26(1): 191-209.

[2] Sghaier N, Prat M. Effect of efflorescence formation on drying kinetics of porous media[J]. Transport in Porous Media, 2009, 80(3): 461-474.

[3] Shokri Kuehni S M S, Sahimi M, Shokri N. A personal perspective on prediction of saline water evaporation from porous media[J]. Drying Technology, 2022, 40(4): 691-696.

[4] Nachshon U, Weisbrod N. Beyond the salt crust: On combined evaporation and subflorescent salt precipitation in porous media[J]. Transport in Porous Media, 2015, 110(2): 295-310.

[5] Gran M, Carrera J, Massana J, et al. Dynamics of water vapor flux and water separation processes during evaporation from a salty dry soil[J]. Journal of Hydrology, 2011, 396(3-4): 215-220.

[6] Gupta S, Huinink H P, Pel L, et al. How ferrocyanide influences NaCl crystallization under different humidity conditions[J]. Crystal Growth & Design, 2014, 14(4): 1591-1599.

[7] Desarnaud J, Derluyn H, Molari L, et al. Drying of salt contaminated porous media: Effect of primary and secondary nucleation[J]. Journal of Applied Physics, 2015, 118(11): 1541-1551.

[8] Wang H C, Li X H, Guo M, et al. Effect of salt types on salt precipitation and water transport in saline sandy soil[J]. Hydrological Processes, 2024, 38(3): e15123, doi: 10.1002/hyp.15123.

[9] Nachshon U, Weisbrod N, Dragila M I, et al. Combined evaporation and salt precipitation in homogeneous and heterogeneous porous media[J]. Water Resources Research, 2011, 47(3): W03513, doi: 10.1029/2010WR009677.

[10] Nachshon U, Shahraeeni E, Or D, et al. Infrared thermography of evaporative fluxes and dynamics of salt deposition on heterogeneous porous surfaces[J]. Water Resources Research, 2011, 47(12): W12519, doi: 10.1029/2011WR010776.

[11] Eloukabi H, Sghaier N, Prat M, et al. Drying experiments in a hydrophobic model porous medium in the presence of a dissolved salt[J]. Chemical Engineering & Technology, 2011, 34(7): 1085-1094.

[12] Wen W, Lai Y, You Z. Numerical modeling of water vapor salt transport in unsaturated soil under evaporation[J]. International Journal of Heat and Mass Transfer, 2020, 159: 120114, doi: 10.1016/j.ijheatmasstransfer.2020.120114.

[13] Li X H, Guo M. Experimental study of evaporation flux, salt precipitation, and surface temperature on homogeneous and heterogeneous porous media[J]. Advances in Civil Engineering, 2022, 2022: 7434471, doi: 10.1155/2022/7434471.

[14] Shokri N, Hassani A, Sahimi M. Multi-scale soil salinization dynamics from global to pore scale: A review[J]. Reviews of Geophysics, 2024, 62(4): e2023RG000804, doi: 10.1029/2023RG000804.

[15] Shokri Kuehni S M S, Raaijmakers B, Kurz T, et al. Water table depth and soil salinization: From pore scale processes to field scale responses[J]. Water Resources Research, 2020, 56(2): e2019WR026707, doi: 10.1029/2019WR026707.

[16] Li X H, Shi F Z. The effect of flooding on evaporation and the groundwater table for a salt crusted soil[J]. Water, 2019, 11(5): 1003, doi: 10.3390/w11051003.

[17] Wang Xiaojing, Xu Xinwen, Lei Jiaqiang, et al. Spatiotemporal distribution of salt crust in a shelter forest belt under drip irrigation with salt water[J]. Arid Zone Research, 2006, 23(3): 399-404.

[18] Zhang Jianguo, Xu Xinwen, Lei Jiaqiang, et al. Chemical properties of the salt crust layer in shelterbelts under drip irrigation with saline water in a mobile desert[J]. Arid Zone Research, 2009, 26(2): 255-260.

[19] Duan Zhao, Li Ruiyi, Song Kun, et al. Damage characteristics and mechanisms of soil structures under salt weathering[J]. Arid Land Geography, 2024, 47(12): 2041-2050.

[20] Li X H, Shi F Z. Salt precipitation and evaporative flux on sandy soil with saline groundwater under different evaporation demand conditions[J]. Soil Research, 2021, 60(2): 187-196.

[21] Li X H, Shi F Z. Effects of evolving salt precipitation on the evaporation and temperature of sandy soil with a fixed groundwater table[J]. Vadose Zone Journal, 2022, 20(3): e20122, doi: 10.1002/vzj2.20122.

[22] Li X H, Guo M, Wang H C. Impact of soil texture and salt type on salt precipitation and evaporation under different hydraulic conditions[J]. Hydrological Processes, 2022, 36(11): e14763, doi: 10.1002/hyp.14763.

[23] Rad M N, Shokri N, Keshmiri A, et al. Effects of grain and pore size on salt precipitation during evaporation from porous media[J]. Transport in Porous Media, 2015, 110(2): 281-294.

[24] Eloukabi H, Sghaier N, Ben Nasrallah S, et al. Experimental study of the effect of sodium chloride on drying of porous media: The crusty-patchy efflorescence transition[J]. International Journal of Heat and Mass Transfer, 2013, 56(1-2): 80-93.

[25] Rad M N, Shokri N, Sahimi M. Pore scale dynamics of salt precipitation in drying porous media[J]. Physical Review E, 2013, 88(3): 032404, doi: 10.1103/PhysRevE.88.032404.

[26] Argaman E, Singer A, Tsoar H. Erodibility of some crust-forming soils/sediments from the southern Aral Sea basin as determined in a wind tunnel[J]. Earth Surface Processes and Landforms, 2006, 31(1): 47-63.

[27] Dai S, Shin H, Santamarina J C. Formation and development of salt crusts on soil surfaces[J]. Acta Geotechnica, 2016, 11(5): 1103-1115.

[28] Tang Yang, Li Xinhu, Guo Min, et al. Formation process of soil salt crust and its influence mechanism on evaporation under different initial salt concentrations[J]. Arid Land Geography, 2022, 45(4): 1137-1145.

[29] Nachshon U, Weisbrod N, Katzir R, et al. NaCl crust architecture and its impact on evaporation: Three-dimensional insights[J]. Geophysical Research Letters, 2018, 45(12): 6100-6108.

[30] Shokri Kuehni S M S, Vetter T, Webb C, et al. New insights into saline water evaporation from porous media: Complex interaction between evaporation rates, precipitation, and surface temperature[J]. Geophysical Research Letters, 2017, 44(11): 5504-5510.

[31] Rose D A, Konukcu F, Gowing J W. Effect of watertable depth on evaporation and salt accumulation from saline groundwater[J]. Australian Journal of Soil Research, 2005, 43(5): 565-573.

[32] Fujimaki H, Shimano T, Inoue M, et al. Effect of a salt crust on evaporation from a bare saline soil[J]. Vadose Zone Journal, 2006, 5(4): 1246-1256.

[33] Wang Hongchao. The difference of physical properties for soil salt crust and its influence on water-heat transport resistance[D]. Beijing: University of Chinese Academy of Sciences, 2024.

[34] Bittelli M, Ventura F, Campbell G S, et al. Coupling of heat, water vapor, and liquid water fluxes to compute evaporation in bare soils[J]. Journal of Hydrology, 2008, 362(3-4): 191-205.

[35] van de G A A, Owe M. Bare soil surface resistance to evaporation by vapor diffusion under semiarid conditions[J]. Water Resources Research, 1994, 30(2): 181-188.

[36] Roussel C. Visualization of explainable artificial intelligence for GeoAI[J]. Frontiers in Computer Science, 2024, 6: 1414923, doi: 10.3389/fcomp.2024.1414923.

[37] Wang H J, Fan Z P, Chen J Y, et al. Discovering key sub-trajectories to explain traffic prediction[J]. Sensors, 2023, 23(130): s23010130, doi: 10.3390/s23010130.

[38] Ding X J, Liu J, Yang F, et al. Random radial basis function kernel-based support vector machine[J]. Journal of the Franklin Institute, 2021, 358(18): 10121-10140.

[39] Zhao Z, Fitzsimons J K, Fitzsimons J F. Quantum-assisted Gaussian process regression[J]. Physical Review A, 2019, 99(5): 052331, doi: 10.1103/PhysRevA.99.052331.

[40] Gran M, Carrera J, Olivella S, et al. Modeling evaporation processes in a saline soil from saturation to oven dry conditions[J]. Hydrology and Earth System Sciences, 2011, 15(7): 2077-2089.

[41] Wang Hongchao, Li Xinhu, Guo Min, et al. Dynamic variation of energy balance under the influence of salt-crusted soil formation and development[J]. Arid Land Geography, 2024, 47(3): 424-432.

[42] Valeriani C, Sanz E, Frenkel D. Rate of homogeneous crystal nucleation in molten NaCl[J]. Journal of Chemical Physics, 2005, 122(19): 194501, doi: 10.1063/1.1896348.

Note: Figure translations are in progress. See original paper for figures.