Formation Process of Soil Salt Crust under Different Initial Salt Concentrations and Its Influence Mechanism on Evaporation: Postprint

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Abstract

Soil salt crusts exert significant influences on soil hydrological processes. Variations in initial salt concentration (ISC) can differentially affect the formation process of salt crusts, consequently leading to disparities in soil evaporation. However, the underlying mechanism through which salt crust formation under different ISC conditions influences soil evaporation remains inadequately understood. Therefore, this study employed a combination of experimental simulation and theoretical analysis to dynamically monitor and analyze the processes of salt crust formation, evaporation, and soil surface temperature dynamics in sandy soil under varying ISC conditions, aiming to elucidate the mechanism of salt crust formation and its impact on soil evaporation under different ISC scenarios. The results demonstrated that higher ISC values resulted in earlier emergence of salt crusts on the soil surface, greater coverage, and, under identical light intensity and duration conditions, smaller increases in soil surface temperature and reduced evaporation rates. A logarithmic function provided a satisfactory fit for the relationship between different ISC levels and cumulative evaporation (R2>0.90). As ISC increased, the inhibition efficiency of salt crusts on soil evaporation escalated from 24.14% (10 g · L-1) to 71.99% (250 g · L-1). ISC significantly influences the salt crust formation process and, by affecting soil surface temperature variations, induces substantial differences in soil evaporation.

Full Text

Formation Process of Soil Salt Crust and Its Influence Mechanism on Evaporation Under Different Initial Salt Concentrations

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Abstract

Soil salt crusts exert important effects on soil hydrological processes. Differences in initial salt concentration (ISC) substantially influence the formation process of salt crusts, thereby leading to variations in soil evaporation. However, the influence mechanism of salt crust formation on soil evaporation under different initial salt concentrations remains unclear. Therefore, this study combined experimental simulation with theoretical analysis to dynamically monitor and analyze the formation of salt crusts, evaporation dynamics, and variations in soil surface temperature in sandy soils under different ISC treatments, aiming to elucidate the formation process of salt crusts and their influence mechanism on soil evaporation. The results demonstrate that higher initial salt concentrations lead to earlier appearance of salt crusts on the soil surface, greater coverage, smaller increases in soil surface temperature under the same light intensity and exposure duration, and consequently lower evaporation rates. A logarithmic function effectively describes the relationship between initial salt concentrations and cumulative evaporation ($R^2 > 0.90$). As ISC increases, the inhibition efficiency of salt crusts on soil evaporation rises from 24.14% ($10\ g\cdot L^{-1}$) to 71.99% ($250\ g\cdot L^{-1}$). The initial salt concentration significantly affects the salt crust formation process and, by influencing changes in soil surface temperature, causes substantial differences in soil evaporation.

Keywords: initial salt concentration; salt crust; formation and development; soil surface temperature; soil evaporation

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1. Materials and Methods

1.1 Experimental Design

The test soil was collected from the northern margin of the Tarim Basin in Xinjiang (40°39 N, 80°49 E). According to the USDA soil classification system, the test soil is classified as sand, with silt, sand, and clay fractions of 8.43%, 91.33%, and 0.24%, respectively. The median particle diameter (D_{50}) is 100.63 m, bulk density is $1.56\ g\cdot cm^{-3}$, saturated water content is 39.67%, and saturated hydraulic conductivity is $440.37\ cm\cdot d^{-1}$.

The soil was first washed from bottom to top with tap water. When the electrical conductivity reached approximately $600\ S\cdot cm^{-1}$ (the conductivity of tap water), distilled water was used to slowly wash the soil from bottom to top until the electrical conductivity was less than $50\ S\cdot cm^{-1}$. The washed soil was then air-dried, passed through a 2 mm sieve, and uniformly packed into acrylic tubes (height 35 cm, diameter 10 cm). Filter stones were placed at the bottom of each tube.

Five initial salt concentration treatments were established: 10 $\mathrm{g \cdot L^{-1}}$, 40 $\mathrm{g \cdot L^{-1}}$, 80 $\mathrm{g \cdot L^{-1}}$, 150 $\mathrm{g \cdot L^{-1}}$, and 250 $\mathrm{g \cdot L^{-1}}$, plus a control (0 $\mathrm{g \cdot L^{-1}}$ distilled water). Each treatment had three replicates (18 soil columns total). Solutions with different concentrations were slowly introduced from the bottom to saturate the soil columns. When the solution overflowed the soil surface, water inflow was stopped, the soil surface was sealed to minimize evaporation, and the upper valve was opened to ensure complete air removal. After saturation, the lower valve was opened to allow the solution to drain slowly, completing the initial saturation process.

All soil columns were wrapped with an insulating film to reduce external temperature effects. A halogen lamp was positioned 38 cm above the soil surface to provide heat for driving evaporation. Evaporation was monitored using an automatic weighing platform (Beijing Shiyu Tong Technology Co., Ltd.) connected to a data logger (Beijing Shiyu Tong Technology Co., Ltd.) with a 5-minute recording interval. The total experimental period was 25 days.

During the experiment, a digital camera (Sony ILCE-6000) and infrared thermal imager (FLIR Tools) were used to photograph the soil surface at 10:00, 14:00, and 22:00 daily to monitor dynamic changes in salt crust coverage and soil surface temperature. ImageJ software was used to calculate salt crust coverage, and infrared images were processed to obtain soil surface temperatures. After the experiment, salt crusts were separated from the soil surface, dissolved, filtered, and weighed to determine final salt crust salt content.

Evaporation inhibition efficiency quantifies the ability of certain indicators to suppress soil water evaporation during the evaporation process. This study introduced inhibition efficiency to evaluate the suppressive effect of salt crusts on soil water evaporation under different treatments. Daily evaporation, cumulative evaporation, and evaporation inhibition efficiency were calculated as follows:

$$ED_t = \frac{M_t}{\pi r^2 \rho_w} \times 10 \quad (\mathrm{mm \cdot d^{-1}})$$

$$EC_t = \sum ED_t \quad (\mathrm{mm})$$

$$I = \frac{EC_0 - EC_t}{EC_0} \times 100\% \quad (\%)$$

where ED_t is daily evaporation on day t ($\mathrm{mm \cdot d^{-1}}$); M_t is daily evaporation mass (difference between soil column mass on day t and day $t+1$) (g); r is the radius of the acrylic tube (cm); ρ_w is water density (1 $\mathrm{g \cdot cm^{-3}}$); EC_t is cumulative evaporation on day t (mm); I is evaporation inhibition efficiency of salt crust (%); and EC_0 is cumulative evaporation of the control treatment (mm).

1.2 Data Processing

Data were statistically analyzed using Excel 2016, SPSS 26, and Origin 2018 software. Independent samples t-tests were used for significance testing between treatments at the $\alpha = 0.05$ level.

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2. Results

2.1 Formation and Development of Salt Crusts Under Different Initial Salt Concentrations

[Figure 2: see original paper] shows the variation process of soil salt crust coverage under different initial salt concentrations. The evolution process can be divided into three stages: (1) initial stage, where small amounts of salt crystals appear on the soil surface; (2) rapid growth stage, where salt crust coverage increases rapidly; and (3) stable stage, where salt crust coverage remains relatively stable.

In the control treatment, no salt crystals appeared throughout the experiment. With increasing ISC, salt crystals appeared on the soil surface earlier: 2.5 d (10 $\mathrm{g \cdot L^{-1}}$), 0.5 d (40 $\mathrm{g \cdot L^{-1}}$), 0.45 d (80 $\mathrm{g \cdot L^{-1}}$), 0.2 d (150 $\mathrm{g \cdot L^{-1}}$), and 0.2 d (250 $\mathrm{g \cdot L^{-1}}$). During the rapid growth stage, higher ISC led to faster attainment of relatively stable coverage (when the growth rate becomes very low) and greater final coverage. The stable-stage coverage values were 4.04% (10 $\mathrm{g \cdot L^{-1}}$), 48.99% (40 $\mathrm{g \cdot L^{-1}}$), 89.72% (80 $\mathrm{g \cdot L^{-1}}$), 90.12% (150 $\mathrm{g \cdot L^{-1}}$), and 98.39% (250 $\mathrm{g \cdot L^{-1}}$), reached at 25 d, 17 d, 14 d, 10 d, and 8 d, respectively.

During the stable stage, salt crust coverage remained relatively constant under most treatments, though the 250 $\mathrm{g \cdot L^{-1}}$ treatment showed slight cracking and decreased coverage after 20 days of evaporation. The salt content in the crusts was 1.13 g (10 $\mathrm{g \cdot L^{-1}}$), 5.57 g (40 $\mathrm{g \cdot L^{-1}}$), 14.00 g (80 $\mathrm{g \cdot L^{-1}}$), 16.23 g (150 $\mathrm{g \cdot L^{-1}}$), and 21.97 g (250 $\mathrm{g \cdot L^{-1}}$). [Figure 3: see original paper] shows the measured and predicted days of salt crust appearance under different initial salt concentrations, confirming that higher ISC leads to earlier salt crust formation.

2.2 Soil Evaporation Process

2.2.1 Daily Evaporation Process [Figure 4: see original paper] illustrates the variation in daily evaporation under different initial salt concentrations. Except for the 10 $\mathrm{g \cdot L^{-1}}$ treatment, all other treatments showed significant differences ($P < 0.05$). Daily evaporation in both control and salt treatments showed a declining trend, which could be divided into three stages, though the timing of these stages differed substantially.

In the control treatment, the evaporation process consisted of: (S1) 1-8 d, with constant high daily evaporation (7.43 mm $\cdot$ d^{-1}) as soil water supply fully met evaporation demand and the surface remained wet; (S2) 9-17 d, where daily evaporation rapidly decreased from 7.43 to 1.10 mm$\cdot$d^{-1} as water supply became insufficient and most shallow capillary water disconnected; and (S3) 18-25 d, where daily evaporation gradually stabilized at 0.46-1.00 mm $\cdot$ d^{-1} as capillary pores completely disconnected and evaporation became dominated by vapor diffusion.

Salt treatments also exhibited three stages (SS1-SS3) as described by Nachshon et al. [9]. shows the duration of each evaporation stage. Compared with the control, stage SS1 was shorter and decreased with increasing ISC, from 2.5 d (10 g $\cdot$ L^{-1}) to 0.2 d (250 g $\cdot$ L^{-1}). Due to reduced solute potential (except at 10 g $\cdot$ L^{-1}), evaporation rates decreased slowly. Stage SS2 showed rapid decreases in daily evaporation: 4.22, 2.15, 1.49, 1.68, and 1.97 mm $\cdot$ d^{-1} for 40, 80, 150, and 250 g $\cdot$ L^{-1} treatments, respectively. Stage SS3 showed stable low evaporation rates (1.02-1.64 mm $\cdot$ d^{-1}) as water vapor diffused through the salt crust.

2.2.2 Cumulative Evaporation [Figure 5: see original paper] shows that cumulative evaporation increased over time but at a decreasing rate. Higher ISC resulted in lower cumulative evaporation. Cumulative evaporation was 93.86 mm (0 g $\cdot$ L^{-1}), 77.55 mm (10 g $\cdot$ L^{-1}), 54.63 mm (40 g $\cdot$ L^{-1}), 39.23 mm (80 g$\cdot$L^{-1}), 33.92 mm (150 g$\cdot$L^{-1}), and 24.33 mm (250 g$\cdot$L^{-1}). Compared with the control, cumulative evaporation decreased by 17.37% (10 g $\cdot$ L^{-1}), 41.79% (40 g $\cdot$ L^{-1}), 58.20% (63.86% from 0 to 250 g $\cdot$ L^{-1}), 63.86% (80 g $\cdot$ L^{-1}), and 74.03% (150 g $\cdot$ L^{-1}).

A logarithmic function effectively described the relationship between evaporation days (t) and cumulative evaporation (EC_t):

$$EC_t = a \times \ln(t)$$

where a is a fitting parameter. shows that fitting was excellent for all treatments (R^2 > 0.93). Parameter a decreased with increasing ISC, indicating lower cumulative evaporation. The relationship between a and ISC followed:

$$a = \frac{3156}{110.3 + ISC}, \quad R^2 = 0.9698$$

Substituting this into the previous equation yields a predictive function for cumulative evaporation:

$$EC_t = \frac{3156 \times \ln(t)}{110.3 + ISC}$$

Additionally, the relationship between cumulative evaporation on day 1 (EC_1) and ISC showed an exponential relationship:

$$EC_1 = 8.264 \times \mathrm{EXP}(-0.0024 \times ISC), \quad R^2 = 0.9208$$

Thus, the complete function for cumulative evaporation as a function of evaporation days (t) and initial salt concentration (ISC) is:

$$\begin{cases} EC_1 = 8.264 \times \mathrm{EXP}(-0.0024 \times ISC), & t = 1 \\ EC_t = \frac{3156 \times \ln(t)}{110.3 + ISC}, & t > 1 \end{cases}$$

2.2.3 Evaporation Inhibition Efficiency [Figure 6: see original paper] shows that evaporation inhibition efficiency increased with both ISC and evaporation time. For all salt treatments, inhibition efficiency first increased then decreased slightly. Maximum inhibition efficiencies were 24.14% (10 $\mathrm{g} \cdot \mathrm{L}^{-1}$), 47.76% (40 $\mathrm{g} \cdot \mathrm{L}^{-1}$), 62.29% (80 $\mathrm{g} \cdot \mathrm{L}^{-1}$), 71.99% (150 $\mathrm{g} \cdot \mathrm{L}^{-1}$), and 71.99% (250 $\mathrm{g} \cdot \mathrm{L}^{-1}$). Overall, salt crusts inhibited soil evaporation, with higher ISC producing stronger inhibition.

2.3 Soil Surface Temperature Variation Under Different Initial Salt Concentrations

[Figure 7: see original paper] shows that continuous lighting increased soil surface temperature in all treatments, but the magnitude of increase varied with ISC. The temperature change process also exhibited three stages. In the control treatment: (S1) temperature increased slowly ($0.38°\mathrm{C} \cdot \mathrm{d}^{-1}$) with constant high evaporation; (S2) temperature increase accelerated ($0.72°\mathrm{C} \cdot \mathrm{d}^{-1}$) as evaporation decreased rapidly; (S3) temperature increase slowed ($0.25°\mathrm{C} \cdot \mathrm{d}^{-1}$) with stable low evaporation.

In salt treatments, stage SS1 showed slow temperature increases that diminished with higher ISC: $0.29°\mathrm{C} \cdot \mathrm{d}^{-1}$ (10 $\mathrm{g} \cdot \mathrm{L}^{-1}$), $0.21°\mathrm{C} \cdot \mathrm{d}^{-1}$ (40 $\mathrm{g} \cdot \mathrm{L}^{-1}$), $0.12°\mathrm{C} \cdot \mathrm{d}^{-1}$ (80 $\mathrm{g} \cdot \mathrm{L}^{-1}$), $0.06°\mathrm{C} \cdot \mathrm{d}^{-1}$ (150 $\mathrm{g} \cdot \mathrm{L}^{-1}$), and $0.08°\mathrm{C} \cdot \mathrm{d}^{-1}$ (250 $\mathrm{g} \cdot \mathrm{L}^{-1}$). Stage SS2 showed further temperature increases but at lower rates than stage SS1. Stage SS3 exhibited minimal temperature increases as evaporation stabilized.

A strong positive correlation existed between evaporation days and soil surface temperature for all treatments ($\mathrm{R}^2 > 0.70$). The slope decreased with increasing ISC, indicating that higher ISC resulted in smaller temperature increases, which contributed to reduced evaporation.

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3. Discussion

The evaporation process in the control treatment can be described by the classic three-stage model, which is widely accepted for distilled water treatments [9,22-23]. The salt treatment evaporation stages (SS1–SS3) correspond to those defined by Nachshon et al. [9]: SS1 involves slow evaporation rate decline due to reduced solute potential; SS2 features rapid evaporation rate decline due to salt crust formation; SS3 involves stable low evaporation as water vapor diffuses through the salt crust.

Previous studies have shown considerable variation in describing evaporation from salt-affected soils. Shokri-Kuehni et al. [11] proposed four stages for saline soil evaporation, while Kuehni et al. [17] suggested three stages with different characteristics. Our results align with Nachshon et al. [9] because both studies used initial saturation without continuous water supply, allowing soil drying. In contrast, some other studies [11,27] used continuous water supply, maintaining wet conditions throughout.

Our study demonstrates that higher ISC leads to lower evaporation rates, consistent with previous research [12-14]. However, unlike earlier studies that did not analyze dynamic salt crust evolution, our work shows that ISC significantly affects salt crust formation dynamics and soil surface temperature, thereby causing substantial differences in evaporation. As ISC increases, salt crust coverage grows more rapidly and reaches greater maximum coverage, increasing crust thickness and resistance. This enhanced resistance further reduces evaporation rates, similar to the effects of mulch or gravel cover [15,34-36].

The relationship between ISC and cumulative evaporation is nonlinear (logarithmic, $R^2 > 0.90$), indicating that salt crust formation processes significantly impact evaporation and temperature patterns. This suggests that initial salt concentration and resulting salt crust characteristics must be considered in quantitative analyses of water and heat transport in highly saline soils.

Evaporation inhibition efficiency decreased slightly in later evaporation stages in our study, unlike results from continuous-supply experiments [14]. This difference likely arises because our experiment allowed soil drying. Non-saline soils accumulated greater evaporation in early stages, developing thicker dry surface layers that increased vapor diffusion resistance. Although saline soils had additional salt crust resistance, their thinner dry layers resulted in higher late-stage evaporation rates than non-saline soils, reducing inhibition efficiency over time.

Soil temperature affects evaporation, and salt crusts influence surface temperature [15,17]. Our results show that higher ISC leads to smaller temperature increases, consistent with Fujimaki et al. [15] who reported that salt crusts increase soil albedo, reducing energy input and surface temperature. The albedo increases with surface salt accumulation [16]. However, Nachshon et al. [18] found that salt crusts increased surface temperature, possibly because their experiment lacked radiation. In our radiative conditions, the energy released during salt crystallization was negligible compared to the albedo effect, resulting in reduced temperature increases.

4. Conclusions

This study analyzed the effects of different initial salt concentrations on salt crust formation and its influence on soil evaporation through laboratory simulation. The main conclusions are:

1. Higher initial salt concentrations cause earlier salt crust formation, more rapid coverage growth, and greater final coverage. Salt crust evolution includes initial appearance, rapid growth, and stable stages.
2. Soil evaporation under salt treatments can be divided into three stages: slow decline due to solute potential reduction, rapid decline due to salt crust formation, and stable low evaporation via vapor diffusion through the crust. Higher ISC shortens the first stage and accelerates evaporation rate decline.
3. The relationship between ISC and cumulative evaporation is logarithmic ($R^2 > 0.90$). Cumulative evaporation decreases nonlinearly with increasing ISC, from 93.86 mm ($0\ g \cdot L^{-1}$) to 24.33 mm ($250\ g \cdot L^{-1}$).
4. Evaporation inhibition efficiency increases with ISC, ranging from 24.14% to 71.99%. Salt crusts provide additional resistance to water vapor diffusion, significantly suppressing evaporation.
5. Higher ISC results in smaller soil surface temperature increases due to increased albedo. The reduced temperature rise contributes to decreased evaporation.

These findings enhance understanding of evaporation processes in salinized soils and provide theoretical foundations for quantitatively describing soil evolution and water cycling in arid regions.

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