Received: 9 June 2022 | Revised: 7 November 2022 | Accepted: 10 November 2022
DOI: 10.1002/hyp.14763

RESEARCH ARTICLE

WILEY

Impact of soil texture and salt type on salt precipitation and evaporation under different hydraulic conditions

Xinhu Li[1,2,3] | Min Guo[1,2,3] | Hongchao Wang[1,2,3]

[1]State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, China

[2]Akesu National Station of Observation and Research for Oasis Agro-ecosystem, Akesu, Xinjiang, China

[3]University of Chinese Academy of Sciences, Beijing, China

Correspondence
Xinhu Li, State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China.
Email: lixinhu@ms.xjb.ac.cn

Funding information
National Natural Science Foundation of China, Grant/Award Number: 41977013; West Light Foundation of Chinese Academy of Sciences, Grant/Award Number: 2020-XBQNXZ-012

Abstract

Salt precipitation and evaporation in porous media is an important research topic. However, several aspects remain controversial; notably, whether efflorescence inhibits evaporation in wet soil, the influence of soil texture on salt crust formation and the effect of sulphate precipitation on evaporation under changing hydraulic conditions. Therefore, this study investigates the influence of salt type (NaCl and Na_2SO_4) and soil texture (sandy soil, sandy loam and silt loam) on salt precipitation and evaporation under different hydraulic conditions (with and without fixed groundwater). Our results demonstrated that a NaCl salt crust strongly inhibited evaporation, even from wet soil (with groundwater), owing to its denser salt structure, which inhibited fluid flow. Moreover, the salt crust pattern differed based on soil texture. Relatively thin, flat and uniform salt crusts were developed in finer soils (silt loam), with greater evaporation resistance, whereas thick and rough salt crusts were developed in coarser soil (sandy soil), with less evaporation resistance. Na_2SO_4 was precipitated as subflorescence in drying soil, whereas wet soils exhibited a mixed salt precipitation pattern including both efflorescence and subflorescence. Notably, evaporation was primarily inhibited by efflorescence, rather than subflorescence. Our research provides novel insights into the dynamics of salt precipitation and evaporation in natural soils.

KEYWORDS
crystal, efflorescence, salt crust, soil salinization, subflorescence, water loss

1 | INTRODUCTION

Salt accumulation in the topsoil of arid regions causes salt precipitation (Norouzi Rad et al., 2013; Shokri-Kuehni, Vetter, et al., 2017), which, in porous media, can affect evaporation (Li & Shi, 2021a; Nachshon, Shahraeeni, et al., 2011; Norouzi Rad et al., 2015), soil temperature (Li & Shi, 2021a; Shokri-Kuehni, Vetter, et al., 2017), wind erosion (Nickling & Ecclestone, 1981; Nield et al., 2016) and rock decay (Benavente et al., 2010; Rodriguez-Navarro & Doehne, 1999; Ruiz-Agudo et al., 2007). Salt can be precipitated as efflorescence on the soil surface in 'crusty' or 'patchy' patterns (Eloukabi et al., 2013) based on the matrix texture, or as subflorescence within soil pores (Rodriguez-Navarro & Doehne, 1999) based on the salt type. However, the association between salt precipitation and evaporation remains nebulous.

The effect of efflorescence on evaporation remains a hot research topic. Indeed, multiple studies have reported that sodium chloride (NaCl) precipitation as efflorescence significantly reduces soil evaporation, with water loss occurring via vapour diffusion rather than fluid movement through the salt crust, even when the soil is wet (Fujimaki et al., 2006; Gran et al., 2011; Nachshon, Shahraeeni, et al., 2011; Nachshon & Weisbrod, 2015; Nachshon, Weisbrod, et al., 2011). A thicker crust (Nachshon & Weisbrod, 2015; Nachshon, Weisbrod, et al., 2011) or greater mass of precipitated salt (Fujimaki et al., 2006) can develop a stronger vapour diffusion resistance. However, other studies (Sghaier & Prat, 2009; Shokri-Kuehni et al., 2020; Shokri-

Kuehni et al., 2021; Shokri-Kuehni, Norouzi Rad, et al., 2017) have suggested that the salt crust is a porous structure, thereby allowing for fluid flow through the precipitated salt, hence evaporation is not inhibited if the soils remain wet (i.e. if the hydraulic connection between the saline solution and soil surface is maintained).

This is because the smaller pore size of the salt crust compared with the underlying matrix (Nachshon et al., 2018) cases variations in matric suction that drives the saline solution into the salt crust. A similar phenomenon has been reported when finer soil overlies coarser soils, as the coarse-textured soil has a lower matric suction than the fine-textured soil at the same soil water content (Li et al., 2014). Furthermore, previous studies (Desarnaud et al., 2015; Veran-Tissoires & Prat, 2014) have also indicated that evaporation occurs through the salt crust, yet suggested that water loss is inhibited since the salt crust has smaller pores, or small number of open pores. Therefore, to determine whether water loss is inhibited via efflorescence when the soil remains wet, we investigated the influence of NaCl precipitation on evaporation in wet soils (i.e. non-drying soils, where the hydraulic connection between the solution and soil surface is maintained via fixed groundwater).

The effect of soil texture on the salt precipitation pattern (efflorescence) and evaporation behaviour is also unclear. The texture of porous media strongly influences the dynamics of salt precipitation and water flux, with salt precipitation patterns varying substantially among different media textures (Eloukabi et al., 2013; Nachshon, Shahraeeni, et al., 2011; Nachshon, Weisbrod, et al., 2011; Norouzi Rad et al., 2015; Veran-Tissoires et al., 2012). For example, salt precipitation in the form of discrete 'patchy' efflorescence has been reported in coarse porous media (glass beads or sand with a diameter of >0.2 mm) (Eloukabi et al., 2013; Veran-Tissoires et al., 2012), which did not inhibit evaporation. Conversely, the 'crusty' salt precipitation (i.e. salt crust) observed on the surface of finer porous media (glass beads or sand with a diameter of 5–160 μm or < 50 μm, respectively) strongly inhibited evaporation (Eloukabi et al., 2013; Veran-Tissoires & Prat, 2014).

These findings are attributed to the relatively larger pore size of the coarse porous media, thereby causing a greater upward growth of salt precipitation and thicker efflorescence (Eloukabi et al., 2013; Norouzi Rad et al., 2015). Conversely, salt precipitation was dominated by lateral growth and salt crust formation in finer porous media.

However, most previous studies have used synthetic glass beads or quartz sand; thus, research on the effect of texture on salt precipitation patterns is limited in natural soils. Compared with coarse sand or beads, natural soils typically have smaller particle and pore sizes, which may hinder the formation of 'patchy' efflorescence. Moreover, the thickness or morphology of salt crusts may differ based on soil texture due to variations in particle and pore sizes among natural soils. Such differences may then influence water loss from the soil, hence we investigated the differences in salt precipitation and evaporation behaviour according to natural soil texture.

The effects of subflorescence on evaporation under different hydraulic conditions remain debatable. Previous studies have reported that sodium or magnesium sulphate is predominantly precipitated as subflorescence within soil pores (Nachshon & Weisbrod, 2015; Piotrowski et al., 2020; Rodriguez-Navarro & Doehne, 1999). However, most studies on subflorescence have focused on its destructive effect on stone structures (Rodriguez-Navarro & Doehne, 1999), with few analysing its effect on evaporation from natural soils. Nachshon and Weisbrod (2015) have shown that subflorescence by $MgSO_4$ does not inhibit evaporation from drying soils, however subflorescence reduces evaporation (Piotrowski et al., 2020). Theoretically, salt precipitated in the pores of porous media reduces the porosity or pore size, thereby inhibiting fluid movement and water loss (Ruiz-Agudo et al., 2007); however, the influence of subflorescence by Na_2SO_4 on evaporation remains unclear. In addition, research on subflorescence has involved drying porous media, with little consideration for the dynamics of Na_2SO_4 precipitation in wet soil. We hypothesize that sulphate may precipitate on the surface of wet soils as efflorescence since the saline solution may pass through the soil surface or previously formed subflorescence and vaporize on the surface during evaporation.

Therefore, to address knowledge gaps in literature, this study investigates the impacts of natural soil texture and salt type on salt precipitation patterns and evaporation behaviour under different hydraulic conditions (drying and wet). Three specific hypotheses are tested: (1) NaCl salt crusts significantly inhibit evaporation even in wet soil owing to their denser structure resulting from smaller pores or fewer open pores; (2) the thickness and morphology of salt crusts vary based on soil texture, thereby causing variations in evaporation resistance among natural soils; (3) Na_2SO_4 precipitates on the soil surface as subflorescence in dry soil, thereby inhibiting evaporation, but may precipitate as efflorescence if the soil remains wet, which more strongly inhibits evaporation.

2 | MATERIALS AND METHODS

Three soil textures were used in this study: Sandy soil contained 98.76% sand, 0% clay and 1.24% silt; sandy loam contained 65.77%

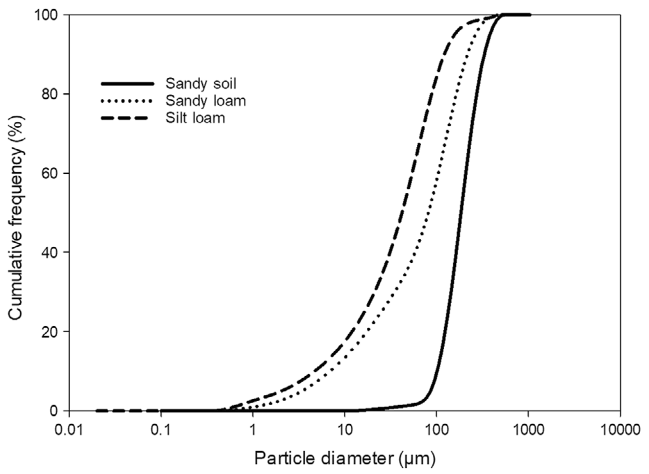


FIGURE 1 The soil particle size distribution for sandy soil, sandy loam and silt loam

TABLE 1 Experimental treatments

	Treatment N$_O$	Soil texture	Initial soil solutions	Drying/wet
1	N1	Sandy soil	Distilled water	Drying
2	N2	sandy loam	Distilled water	Drying
3	N3	Silt loam	Distilled water	Drying
4	C1	Sandy soil	NaCl (25%)	Drying
5	C2	Sandy loam	NaCl (25%)	Drying
6	C3	Silt loam	NaCl (25%)	Drying
7	H1	Sandy soil	Na_2SO_4 (19%)	Drying
8	CG1	Sandy soil	NaCl (25%)	Wet
9	HG1	Sandy soil	Na_2SO_4 (19%)	Wet

Note: Drying soils: the soil was initially saturated with the saline solution or distilled water with no groundwater supply. Wet soils (non-drying): the soil column was connected via a Mariotte tube to a fixed groundwater table at a depth of 5 cm, which ensured that the soils remained wet by maintaining the hydraulic connection between the saline solution and soil surface.

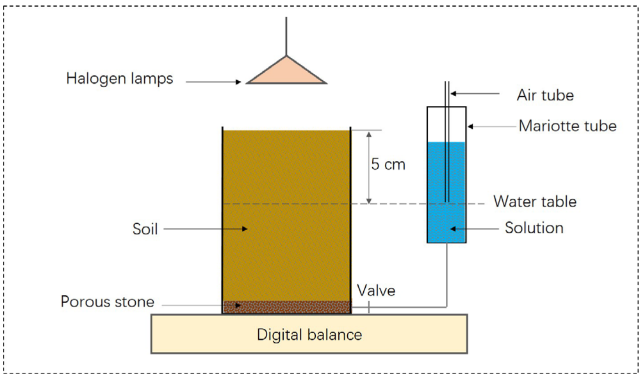


FIGURE 2 An illustration of the experimental soil column

sand, 2.27% clay and 31.96% silt; silt loam contained 41.53% sand, 4.85% clay and 53.62% silt. The silt loam and sandy loam had similar clay mineral compositions, which primarily consisted of illite, followed by chloride and a small amount of kaolinite. The particle size distribution for the three soils is shown in Figure 1. The disturbed soil was packed in a column, with a bulk density of 1.54, 1.49 and 1.46 g cm^{-3} for sandy soil, sandy loam and silt loam, respectively. The soil column inner diameter and height were 13 and 11 cm, respectively, with a porous stone (1 cm thick) laid at the bottom. Two salt solutions (25% NaCl and 19% Na_2SO_4 by weight) and distilled water were used to saturate the soils. The 25% NaCl solution was selected since it was close to the NaCl saturation concentration (26% by weight), to avoid potential osmotic effects on evaporation and ensure that all changes in evaporation were due to salt precipitation (Nachshon, Shahraeeni, et al., 2011). The 19% Na_2SO_4 solution was used as the stable mineral phase, as higher concentrations would cause a transition to the anhydrous phase. The six saline soil treatments (C1, C2, C3, H1, CG1 and HG1) and three salt-free soil treatments (control treatments, N1, N2 and N3) with three replicates are described in Table 1.

To generate drying soils, the soil was only initially saturated by the saline solution or distilled water with no groundwater supply. Distilled or solution water was slowly introduced into the soil from bottom to top, while avoiding air trapping. Water was allowed to drain from the bottom after the soil was saturated. To generate wet soils (non-drying), the soil column was connected via a Mariotte tube to a fixed groundwater table at a depth of 5 cm after saturating the soil (Figure 2). The column was then placed on a balance for 24 h to achieve equilibrium, ensuring that the soils remained wet by maintaining the hydraulic connection between the saline solution and soil surface. A plastic film was placed on top of each soil column to prevent evaporation until the experiment began. Halogen lamps were used to drive evaporation, and the relative humidity and room temperature were maintained at 45 ± 2% and 25 ± 1.4°C, respectively, throughout the experiment.

The soil column was weighed using a digital balance (WP20, SINTON, China) to measure evaporative water loss. The experiment lasted 30 days; a digital camera was used to photograph the surface of the soil columns, and Image J (Ferreira & Rasband, 2012) software was used to determine the percentage of salt cover (efflorescence).

Salt crust samples were taken using a steel ring and dried in an oven for water content determination, and to verify whether the salt crust remained wet for treatment CG1 until the experiment ended (Figure 3). The salt crust samples were also used to determine the porosity of the salt crust. To confirm that the salt crust pattern was strongly influenced by the soil texture, we packed different soils into the same column (heterogeneous configuration) in either a 'double ring' and 'half–half' configuration. The heterogeneous soil had a different evaporation demand (10 mm day^{-1}) and solution concentration (15%). A thin plastic plate or tube spacers were used to separate the two sizes of sand segments during packing, while after packing, the spacers were pulled out, and the columns were lightly shaken to ensure tight packing. The procedure was performed using the same methods used for the homogenous soil columns (Treatments C1, C2 and C3).

The dynamic precipitated salt mass (NaCl) was estimated for close-to-saturation saline solutions as follows:

FIGURE 3 Representative image of a salt crust sample used for oven drying

$$m_s(t) = \sigma m_w(t) \quad (1)$$

where $m_s(t)$ is the mass of precipitated salt (g), and $m_w(t)$ is the mass of evaporative water (g). The σ is the proportionality factor (0.36), which is a relationship between the amount of NaCl that precipitates and the amount of evaporated water (Desarnaud et al., 2015), based on the assumption that the salt precipitated at concentrations that exceeded the saturation limit.

The mean particle size, d_g (μm), and pore diameter, R_m (μm), of the soil were calculated as follows (Chang et al., 2019; Shirazi & Boersma, 1984):

$$d_g = \exp \sum_{i=1}^{n} (f_i \ln M_i) \quad (2)$$

$$R_m = 0.3 d_g \quad (3)$$

where f_i is the percentage of the soil with pore diameters equal to M.

The pore number was the total number of pores exposed in the cross-sectional area, and can be calculated as follows (Arya et al., 1999):

$$N_{pore} = \frac{A\varphi}{A_{pore}} \quad (4)$$

where N_{pore} is the pore number, A is the soil surface area (m^2), φ is the soil porosity, and A_{pore} is the soil pore area (m^2).

The volume specific surface area of salt grains (cubic) was calculated as follows:

$$A_{sv} = \frac{a_s}{\rho_s V_s} \quad (5)$$

where a_s is the surface area (m^2), ρ_s is the crystal density ($kg\,m^{-3}$), and V_s is the volume (m^3).

We assumed that the reduction in evaporation was only attributed to the salt crust formed under stable evaporation conditions. The fluid flow mainly depended on the hydraulic conductivity of the salt crust, thus, evaporation via fluid flow through the salt crust was expressed using Darcy's law (Eloukabi et al., 2013):

$$Q = -A\rho_e \frac{K_e}{\mu}\left(\frac{\Delta p_e}{L_S} + \rho_e g\right) \quad (6)$$

where Q is the mass flow rate ($kg\,s^{-1}$), ρ_e is the solution density ($kg\,m^{-3}$), K_e is the permeability of the salt crust (m^{-2}), g is gravitational acceleration ($m\,s^{-2}$), A is the area (m^2), μ is the solution viscosity (Pa s), and Δp_e is the pressure difference between the bottom and top of the salt crust (Pa).

$$K_e = b^2 \frac{\varphi_e^3 d^2}{(1-\varphi_e)^2} \quad (7)$$

$$\Delta p_e = \frac{c}{b}\frac{6(1-\varphi_e)\sigma}{\varphi_e d} - \frac{6(1-\varphi)\sigma}{\varphi d} \quad (8)$$

Here, φ_e is the porosity of the salt crust, φ is the porosity of the soil, d is the particle size (m), b and c are numerical factors equal to 1×10^{-2} and 6×10^{-2}, respectively, and σ is the surface tension ($N\,m^{-1}$). L_s is the thickness of the salt crust (m), which was calculated as follows (Desarnaud et al., 2015):

$$L_s = \frac{m_s}{\rho_s A(1-\varphi_e)} \quad (9)$$

Evaporation via diffusion through the salt crust was expressed using Fick's law (Gupta et al., 2014; Shokri-Kuehni, Norouzi Rad, et al., 2017):

$$Q = AD\frac{M}{RT}\left(\frac{\Delta P_v}{\delta}\right) \quad (10)$$

$$\Delta P_v = p_s(1-\mathrm{RH}) \quad (11)$$

where D is the diffusion coefficient in free air ($m^2\,s^{-1}$), p_s is the saturated vapour pressure (kPa), and RH is the relative humidity in air (%).

Finally, the evaporation rate from individual pores was calculated as follows (Veran-Tissoires & Prat, 2014):

$$Q_{pore} = 2R_e D\frac{M}{RT}\Delta P_v \quad (12)$$

$$Q_e = n_p J_{pore} \quad (13)$$

where R_e is the pore size of the salt crust, and n_p is the number of pores.

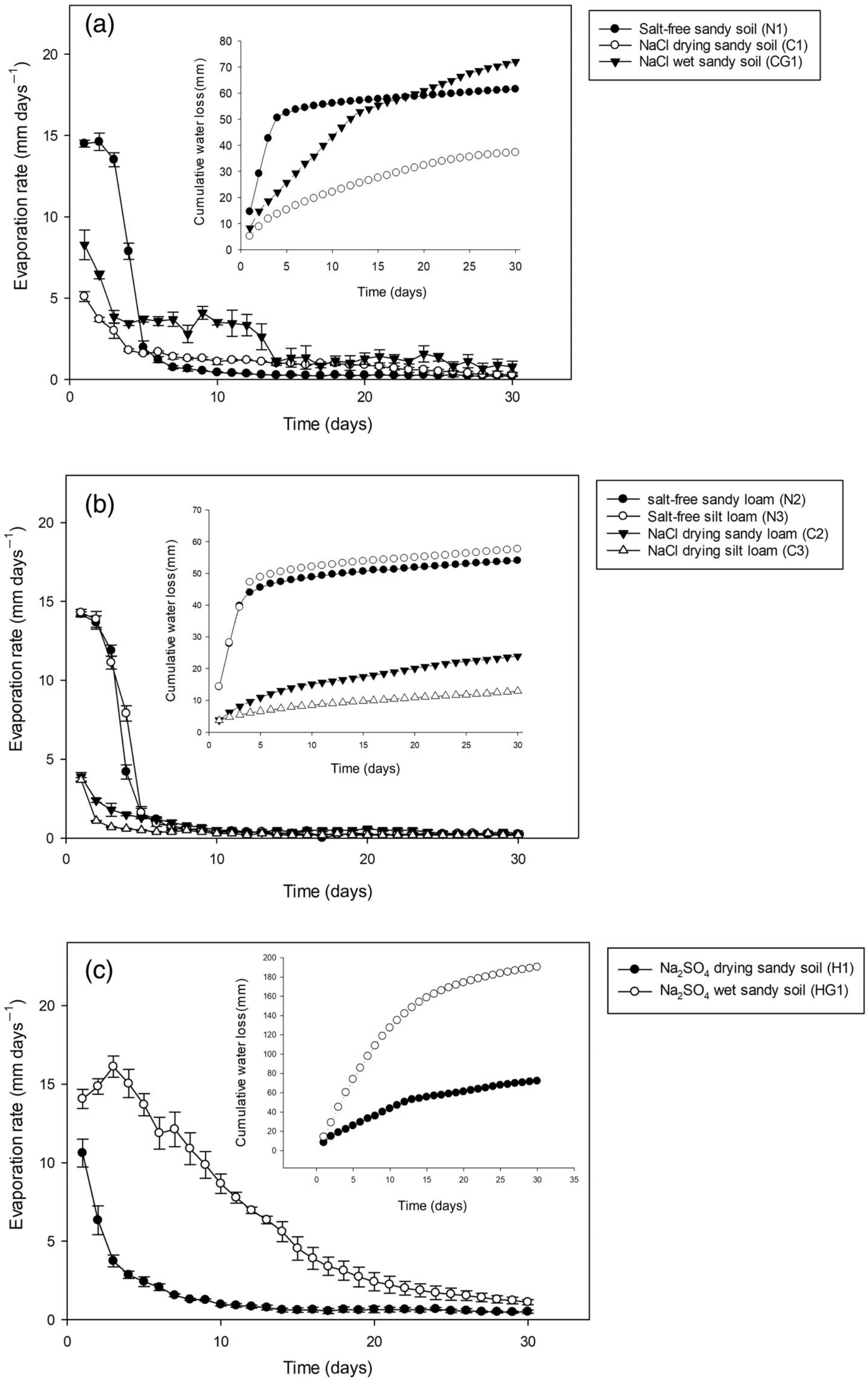


FIGURE 4 The evaporation rate and cumulative water loss with time under (a) salt free, NaCl dried and wet sandy soil, (b) salt free, NaCl dried silt loam and sandy loam, and (c) $NaSO_4$ dried and wet sandy soil conditions

3 | RESULTS AND DISCUSSION

3.1 | Wet soil experiments with NaCl solution (efflorescence)

3.1.1 | Dynamics of water loss

The experimental results for wet sandy soil with NaCl solution (Treatment CG1), which produced efflorescence, showed a total water loss of 68.9 mm (Figure 4a), suggesting that water loss was significantly inhibited by the salt crust development. The evaporation rate decreased significantly from 8.3 to 3.9 mm day^{-1} in the first 3 days, and less than 1.0 mm day^{-1} in the last 3 days (Figure 4a). Nachshon, Shahraeeni, et al. (2011) and Fujimaki et al. (2006) have also reported a sharp decline in evaporation in wet soil, although the authors these findings to a reduction in vapour diffusion rather than fluid flow through the salt crust, with the salt crust increasing the vapour diffusion resistance. Vapour diffusion through the salt crust also occurs

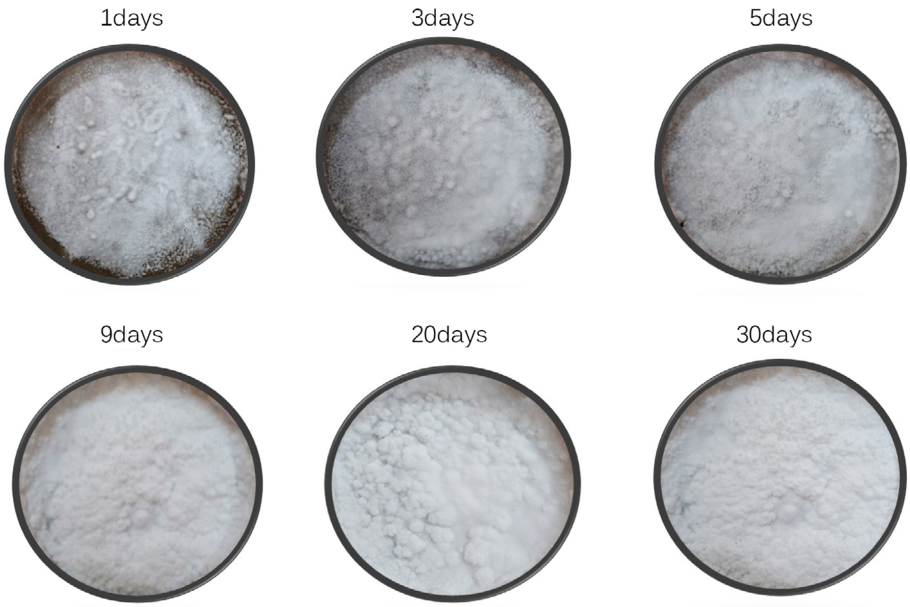


FIGURE 5 Evolution of salt crust by sodium chloride for wet soil (the hydraulic connection was maintained between the solution and salt crust)

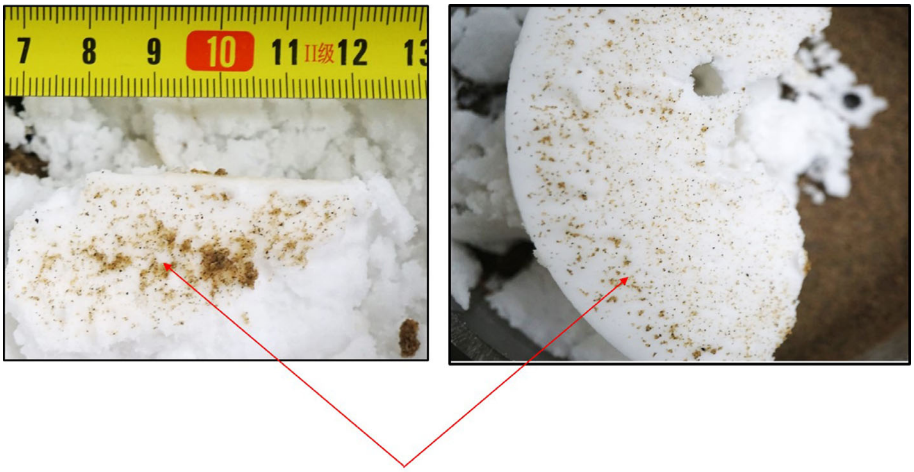


FIGURE 6 The salt crust was detached for wet soils with sodium chloride after experiment

through a gap between the salt crust and soil surface (Nachshon et al., 2018; Nachshon, Shahraeeni, et al., 2011), with the detachment of the crust from the soil surface forming a salt dome on the surface of the salt crust.

3.1.2 | Morphology of salt crust

The surface of the salt crust showed some doming (Figure 5), although the bottom of the salt crust was flat (Figure 6) and not significantly separated from the soil surface, with no gap between the salt crust and soil surface, while the soil was attached to the bottom of the salt crust. Upon destroying the salt crust, we observed a large and strong blocky structure with a strength value of 2.7 ± 0.4 kg cm^2 (measured using a hand penetrometer) (Figure 6). Additionally, the salt crust had a water content of 14% based on mass (drying of the salt crust samples), suggesting that the salt crust remained wet during the experiment, thus, water loss had occurred via fluid flow through the salt crust, while evaporation was inhibited.

This contrasts with previous findings of no inhibition of evaporation under conditions of fluid flow through the salt crust (Shokri-Kuehni et al., 2020). Therefore, decreased evaporation may be linked to the crust structure.

3.1.3 | Relationship between evaporation and salt structure

For wet soils containing NaCl, the salt crust consistently showed a rough surface, suggesting that variations in the evaporation area had a small effect on water loss over time. Based on Darcy's law (Equation 6), we adjusted the parameter φ_e to simulate the variations of evaporation; the calculated and measured results are shown in Figure 7. The φ_e value was 0.032 for the simulated results, indicating

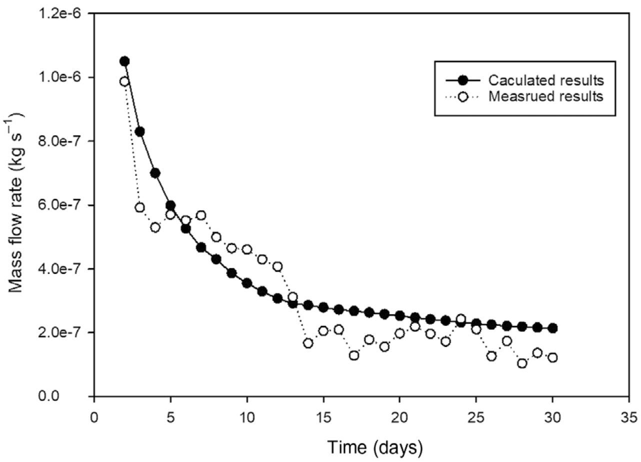


FIGURE 7 Model calculated and measured results for evaporative water loss with salt crust for wet sandy soils

a 12.8-time reduction in porosity compared with the underlying sandy soil. Eloukabi et al. (2013) reported that φ_e was 0.04 and φ was 0.36 for underlying packing beads, which corresponded to a 100 times reduction in the mean pore size. Our research results were similar to those of Eloukabi et al. (2013), which indicated that a denser salt crust structure caused a sharp reduction in water loss. A salt crust porosity of 0.24 was also measured by drying salt crust samples in an oven, which was lower than that of the underlying soil but higher than the calculated value. A possible reason for this discrepancy is that traditional drying methods cannot acquire accurate porosity values as it is difficult to achieve a perfect cylinder (Figure 3), and the salt crust structure was destroyed during steel ring sampling. Thus, the actual porosity should be smaller. The salt crust porosity should be measured using high-resolution X-ray scanning. In addition, future studies should also validate the model by Eloukabi et al. (2013) to express the permeability of salt crusts based on a standard Kozeny–Carman relationship.

Evaporation is not inhibited by salt crust formation according to Fick's law (Equation 10), and only influenced by the vapour pressure difference between the surface of the salt crust and the air, independently of the mass or thickness of precipitated salt in cases where the soil is wet (Shokri-Kuehni et al., 2020; Shokri-Kuehni, Norouzi Rad, et al., 2017). In this scenario, evaporation would only decrease after a reduction in the vapour pressure gradient caused by the solution concentration, and is compensated by the increase in evaporation area caused by salt precipitation (Sghaier & Prat, 2009; Shokri-Kuehni et al., 2020). Thus, the evaporation rate should be similar to that of salt-free soil. In contrast, we observed a sharp reduction in evaporation in wet soils, as previously reported (Fujimaki et al., 2006; Nachshon, Shahraeeni, et al., 2011) and confirmed for salt crust with very low porosity using the Darcy's law. Thus, Fick's law may be limited to simulating evaporation from a wet salt crust; however, Veran-Tissoires and Prat (2014) have suggested that the number of open pores may be reduced following salt crust formation. If we assume such a reduction, the pore size would be the same during the evolution of the salt crust. Based on Equations (12) and (13), the evaporation rate depends on the number of open pores, n_p, due to the consistent ambient conditions during the experiment. Therefore, we deduced that the pore number was continually reduced as evaporation decreased. For example, when the salt crust had covered the entire soil surface by day 2, the number of open pores was reduced by 90% on the final day of the experiment, corresponding to a decrease in approximately one order of magnitude. The number of open pores continually decreased during evolution of the salt crust, possibly since the salt grains coalesced and new salt grains were precipitated in the pores of the original salt structure. Thus, evaporation was inhibited by salt crust formation.

Evaporation was inhibited by a porosity according to Darcy's law, whereas the number of open pores was reduced according to Fick's law. Both assumptions account for the sharp reduction in the effective evaporation area, with both a reduction of porosity and pore number likely occurring during evolution of the salt crust. The pore structure of salt crusts warrants further investigations.

3.2 | Drying soil experiments with NaCl solution (efflorescence)

3.2.1 | Dynamics of water loss

Results from the drying soil with NaCl solution experiments showed the greatest water loss in sandy soil (37.2 mm), followed by sandy loam (24.2 mm), then silt loam (13.1 mm) (Figure 4a,b). Compared with salt-free soils, the accumulative water loss was reduced by 40%, 56%, and 78%, for sandy soil (Treatment C1), sandy loam (Treatment C2), and silt loam (Treatment C3), respectively. The three saline soils developed a salt crust and showed significant inhibition of water loss, to various degrees.

For silt loam (C3), the evaporation rate showed a sharp reduction in the first 2 days, from 3.7 to 1.1 mm day^{-1}, then remained low (<0.4 mm day^{-1}) and relatively stable after 10 days (Figure 4b). For sandy loam (C2), the evaporation rate showed a sharp reduction in the first 3 days, from 3.9 to 1.8 mm day^{-1}, then remained low (<0.6 mm day^{-1}) and relatively stable after 15 days (Figure 4b). For sandy soil (C1), the evaporation rate showed a sharp reduction in the first 4 days, from 5.1 to 1.8 mm day^{-1}, then remained low (<0.6 mm day^{-1}) and relatively stable after 25 days (Figure 4a). These results indicate that silt loam with a salt crust showed the greatest evaporation resistance, followed by sandy loam and sandy soil.

3.2.2 | Salt crust pattern differences

Previous studies have attributed the evaporation difference in saline soil to the salt precipitation pattern (i.e. 'patchy' or 'crusty') (Eloukabi et al., 2013; Norouzi Rad et al., 2015; Veran-Tissoires & Prat, 2014), ambient conditions (Gupta et al., 2014; Nachshon, Shahraeeni, et al., 2011; Shokri-Kuehni, Norouzi Rad, et al., 2017), precipitated salt

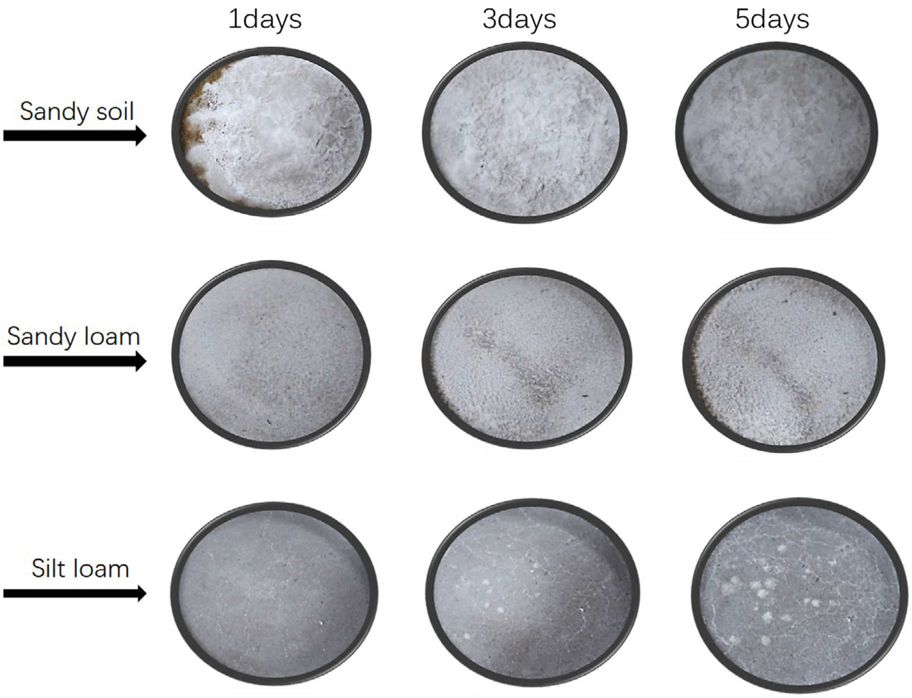


FIGURE 8 Evolution of salt crust for three textural soils.

mass (Fujimaki et al., 2006), or salt crust thickness (Nachshon, Shahraeeni, et al., 2011). In this study, all three soils exhibited a 'crusty' salt precipitation pattern and the same ambient conditions (Figure 8); however, the amount of precipitated salt differed between soil types, with the least precipitated salt in silt loam (61.5 g), followed by sandy loam (114.2 g) and sandy soil (177.9 g). Previous studies have also reported a positive association between the mass of precipitated salt and the evaporation resistance of salt crusts (Fujimaki et al., 2006; Nachshon, Weisbrod, et al., 2011), with higher precipitated salt mass showing stronger evaporation resistance. In contrast, our results showed that the lowest precipitated salt mass generated the strongest evaporation resistance in silt loam, with a positive association between the mass of precipitated salt and evaporation resistance only within the same soil texture. This phenomenon was attributed to differences in the salt precipitation pattern among the three soil textures.

Figure 8 shows the evolution of the salt crust from days 1–5 (the period with the greatest changes). Although the salt precipitated as a salt crust for all soils, the crust appeared thinner, flatter, and more uniform in silt loam, while thicker and rougher in sandy soil; this has not been reported by previous studies that only distinguished between "crusty" or 'patchy' precipitation patterns according to the texture of the porous media (glass beads or sand). The difference in evaporative water loss was also attributed to this difference in salt crust patterns.

3.2.3 | Association between the salt crust pattern and soil texture

Differences in the salt precipitation pattern ('crusty' or 'patchy') according to the texture of porous media has been previously reported (Eloukabi et al., 2013; Norouzi Rad et al., 2015; Veran-Tissoires & Prat, 2014). However, in this study, all natural soils were covered by 'crusty' salt precipitation, suggesting that the development of a 'crusty' or 'patchy' texture is not influenced by the texture of natural soil, rather attributed to the fine particle size of natural soils, whereby the coarsest soil type (sandy soil) had a mean particle diameter of 190 μm, which is less than the previously reported threshold required to form patchy efflorescence (200 μm) (Eloukabi et al., 2013; Norouzi Rad et al., 2015; Veran-Tissoires & Prat, 2014). Hence, we observed no patchy salt precipitation.

Nevertheless, the mass of precipitant and the morphology of the salt crust differed between the three soil textures, which is attributed to three possible reasons: first, a greater number of pores provides more evaporation sites (Norouzi Rad et al., 2015). In this study, the number of pores was 2.1×10^6, 8.2×10^6, and 2.4×10^7 for sandy soil, sandy loam, and silt loam, respectively. Therefore, during the initial 12 h of salt crust evolution, the precipitated salt was distributed more uniformly in the finer soil with more pores and discretely in coarser soil with fewer pores (Figure 9). Second, a smaller pore size could limit the vertical growth of precipitated salt (Eloukabi et al., 2013; Veran-Tissoires & Prat, 2014). In this study, the mean pore diameter was 57, 30, and 18 μm for sandy soil, sandy loam, and silt loam, respectively. This difference in pore size might have influenced the growth direction of precipitated salt, with the smallest pore size (silt loam) being more prone to lateral growth.

Third, we assume that the initial salt precipitation occurred in the soil pores, followed by coalescence of the salt grains to form a larger salt structure. The distance between two salt grains, d_e, which equals the particle size d_g, was 190, 99, and 59 μm for sandy soil, sandy loam, and silt loam, respectively. With the size of the salt grain being less than or equal to the pore size of the soil, the volume specific surface

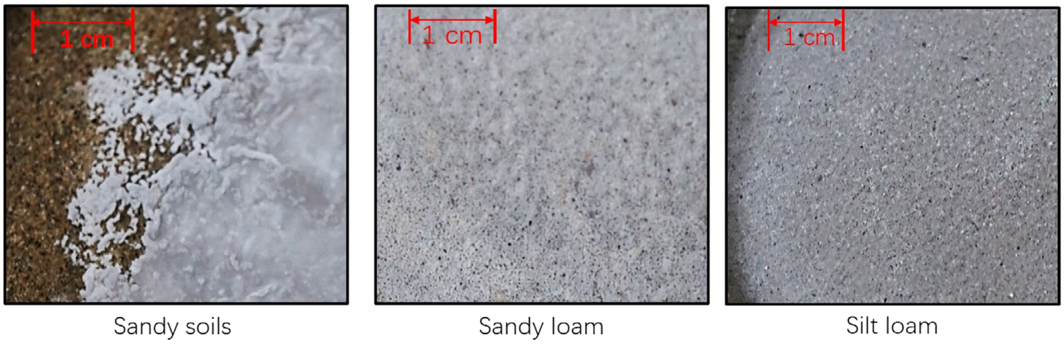
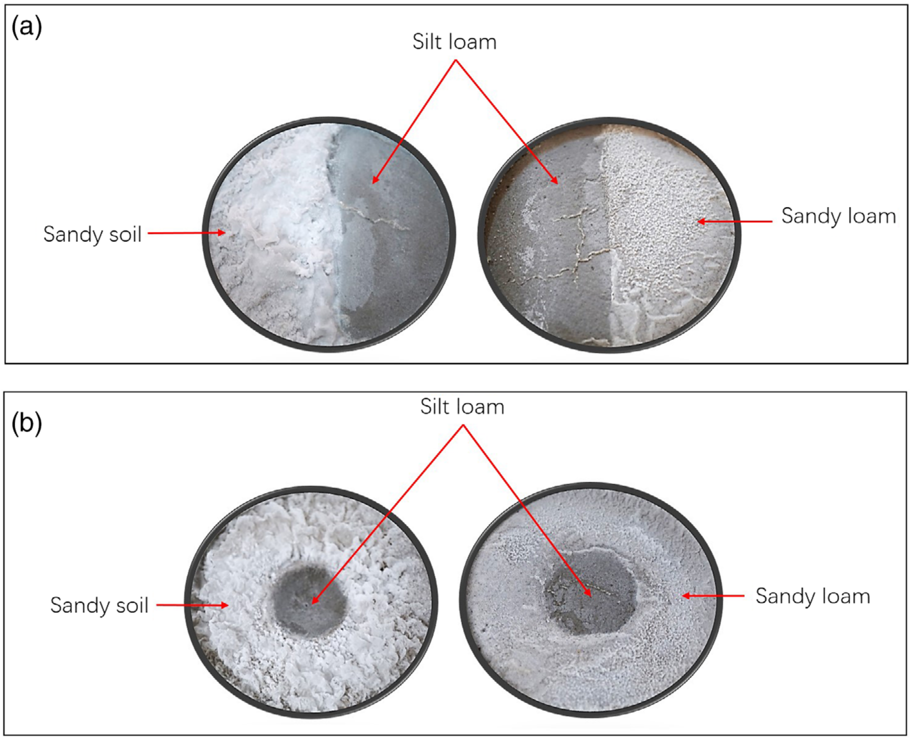


FIGURE 9 Precipitated salt distribution on the soil sulphate for three soils in first 12 h.

FIGURE 10 Salt crust on heterogeneous configuration soil column (a) double ring, (b) half-half



area was 16, 31, and 52.2 $cm^2\ cm^{-3}$ for sandy soil, sandy loam, and silt loam, respectively. A larger salt particle surface area and smaller distance between them can facilitate particle coalescence to form a salt crust, leading to earlier crust formation with the same amount of precipitated salt. A larger and more discrete salt structure was observed in sandy soil, whereas very small and uniform precipitated salt was observed in silt loam (Figure 9).

Differences in the salt crust pattern between different soil textures were observed in the same column, confirming that the salt crust pattern depends on the soil texture rather than the evaporation conditions or solution concentration (Figure 10). Notably, we did not quantify the thresholds to distinguish between the salt crust patterns of the three soils as the lateral growth rate of salt precipitation is unclear. That is, evidence for horizontal coalescence between two salt grains or salt structures on the surface of porous media is limited; therefore, lateral coalescence of salt precipitation on the surface of porous media should be considered in future research.

3.2.4 | Association between the salt crust pattern and evaporation

We investigated the effect of different salt crust patterns on evaporation. The results showed that less salt was precipitated in silt loam, although the salt crust showed stronger evaporation resistance and greater inhibition of water loss, despite all soil textures developing a salt crust. The aforementioned calculation based on Darcy's law indicated that a thicker salt crust exhibited more evaporation resistance; however, the opposite result was observed for drying soil. Under the same evaporation conditions and solution concentration but different

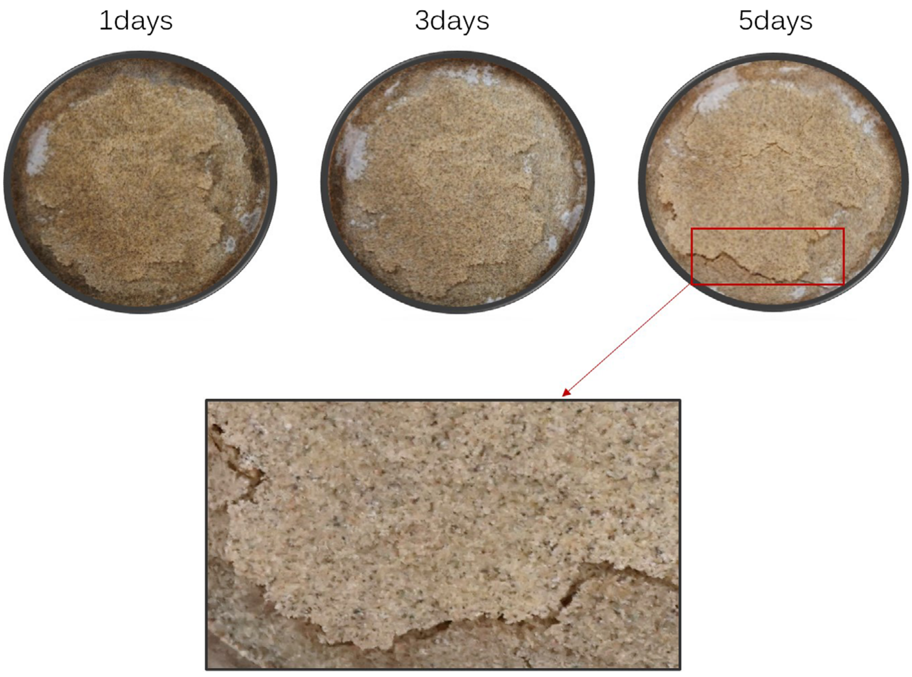


FIGURE 11 Evolution of salt precipitation by sodium sulphate for drying sandy soils

soil texture, and equal μ, ρ_e, K_e, and Δp_e during the first 3 days when the soil surface was wet, when the salt crust reached the same thickness, the ratio of salt crust evaporation between sandy soil and silt loam was as follows:

$$Q_s/Q_{sil} = A_s/A_{sil} \quad (14)$$

where Q_s and Q_{sil} are the mass flow rate for the salt crust in sandy soil and silt loam, and A_s and A_{sil} are the area of salt crust in sandy soil and silt loam.

If the salt crust formed a unit area (a circle with a radius of 'r'), salt precipitation would be more prone to vertical growth in sandy soil (assuming a hemisphere, $A_s = 2\pi r^2$), whereas salt precipitation would be more prone to lateral growth in silt loam (assuming a flat surface, $A_{sil} = \pi r^2$). The salt crust evaporation area of sandy soil was two times that of silt loam under; this difference may be larger since several folds were observed in the salt crust on sandy soil. Therefore, assuming the same hydraulic properties for all three salt crusts, the evaporation difference depends on the evaporation area, as observed on day 1 (Figure 8) and is mainly influenced by the morphology of the salt crust.

Previous studies have reported that salt crust resistance varies with evaporation conditions (Li & Shi, 2021b; Nachshon, Shahraeeni, et al., 2011), that is, higher evaporation forms a denser salt crust structure with stronger evaporation resistance (Nachshon, Shahraeeni, et al., 2011). In this study, the evaporation area differed based on the different salt crust patterns formed on different soil textures, which further influenced evaporation.

In this study, it was difficult to acquire the area of the salt crust. The morphology and area of the salt crust should be considered when estimating evaporation; accordingly, methods for quantifying the area of the salt crust should be investigated in future studies, along with the physical properties of salt crusts, in particular the pore structure (size and number of open pores), to quantify solution transport through salt crusts.

3.3 | Drying soil experiments with Na_2SO_4 solution (subflorescence)

3.3.1 | Dynamics of water loss

Na_2SO_4 was precipitated as subflorescence in drying sandy soils (H1), that is predominantly within the soil pores, with only a small amount of salt found as efflorescent on the soil surface (Figure 11). These findings agree with those of previous studies (Piotrowski et al., 2020; Rodriguez-Navarro & Doehne, 1999). The total water loss was 45.9 mm (Figure 2c), 25% less than salt-free soil. The evaporation rate decreased from 10.6 to 2.9 mm day^{-1} during the initial 4 days, then further decreased, becoming low and stable at approximately 0.6 mm day^{-1} (Figure 2c). Previous studies have debated whether evaporation is inhibited by subflorescence (Nachshon & Weisbrod, 2015; Nachshon, Weisbrod, et al., 2011; Piotrowski et al., 2020). Our experiment results suggest that evaporation was inhibited by Na_2SO_4 subflorescence, which was attributed to a reduction in soil pore size by precipitated salt. However, as the reduction of evaporation was significantly greater in drying soils with NaCl solution (C1, C2 and C3), our results also suggest that subflorescence has less inhibitory effect on evaporation compared with efflorescence.

Previous studies have also reported that subflorescence by $MgSO_4$ (Nachshon & Weisbrod, 2015) and NaI (Nachshon, Weisbrod, et al., 2011) exhibited similar cumulative evaporation to a salt-free

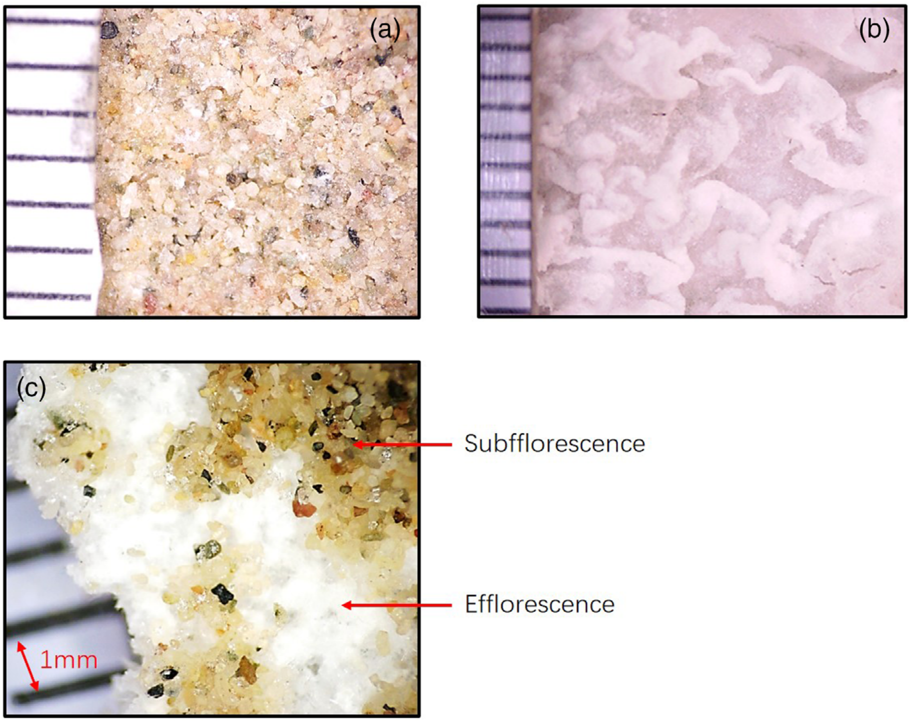


FIGURE 12 Representative pictures of salt precipitation (35× magnification). (a) Salt precipitation as subefflorescence by sulphate in drying sandy soil, (b) salt crust in drying sandy loam, and (c) mix precipitation pattern

sand column, indicating that salt precipitated within the porous media had a minor influence on evaporation. However, more recent studies have reported that evaporation is inhibited with subflorescence by $NaSO_4$ (Piotrowski et al., 2020). In this study, Na_2SO_4 precipitation reduced water loss by 25%; however, this reduction was not completely attributed to subflorescence as the vapour pressure gradient was reduced by the saline solution. For example, the saturated vapour pressure, p_s, was reduced by 15% (25°C), which contributed to water loss resistance. Smaller water loss resistance with subflorescence formation may be attributed to the formation of Na_2SO_4 crystals within larger pores of porous media (Ruiz-Agudo et al., 2007). In contrast, NaCl efflorescence formed a denser salt structure; thus, the evaporation resistance was smaller with subflorescence formation than efflorescence formation (Figure 12a,b).

3.3.2 | Impact of subflorescence on soil structure

Ruiz-Agudo et al. (2007) have reported the detachment of successive layers in stone caused by Na_2SO_4 weathering. In this study, we observed detachment of a thin soil layer, indicating that Na_2SO_4 also damaged the soil structure (Figure 11). This phenomenon was attributed to the tendency of Na_2SO_4 to accumulate in a narrow zone beneath the soil surface (at a few millimetres depth), which causes damage to the surface layer (Ioannou et al., 2005; Ruiz-Agudo et al., 2007). Na_2SO_4 formed subflorescence rather than efflorescence, which was attributed to the solution physical properties, that is a slower capillary flow rate and lower surface tension than NaCl (Rodriguez-Navarro & Doehne, 1999).

3.4 | Wet soil experiments with Na_2SO_4 solution (mixed subflorescence and efflorescence)

3.4.1 | Dynamics of water loss

For wet soils with Na_2SO_4 solution (HG1), the evaporation rate significantly decreased over time (Figure 2c). Compared with wet soil containing NaCl, the evaporation rate did not exhibit a sharp decrease; evaporation was significantly decreased after day 5, then decreased almost linearly from days 8 to 18, from 12.1 to 3.9 mm day^{-1}, and remained stable at 1.2 mm day^{-1} in the last 2 days. The evaporation rate was significantly higher than that for wet soil with NaCl, which was attributed to the difference in salt precipitation patterns. That is, although substantial efflorescence was observed, the amount was much less than that for wet soil with NaCl (Figure 13). Moreover, a significant difference was observed between wet and drying soil containing Na_2SO_4 solution, with only a little efflorescence in the drying soil.

3.4.2 | Mixed salt precipitation pattern

Along with efflorescence, subflorescence was also observed, and the soil was cemented by precipitated salt, indicating that efflorescence and subflorescence occurred simultaneously in wet soils containing Na_2SO_4. This suggests that the hydraulic conditions influence the Na_2SO_4 precipitation pattern by causing a transition from subflorescence to efflorescence; these results have not been previously reported. If the hydraulic connection was maintained between the soil

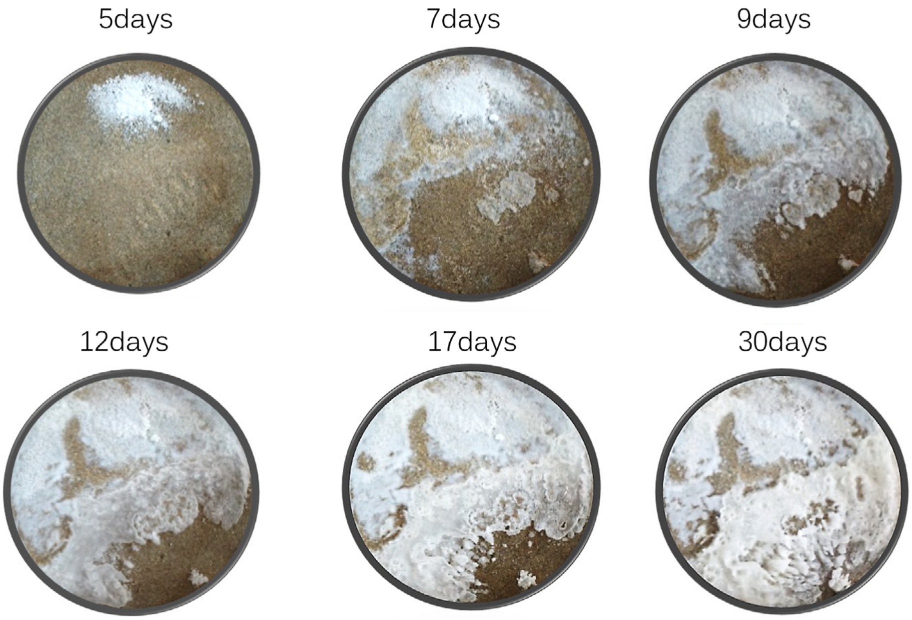


FIGURE 13 Evolution of salt precipitation by sodium sulphate for wet sandy soils

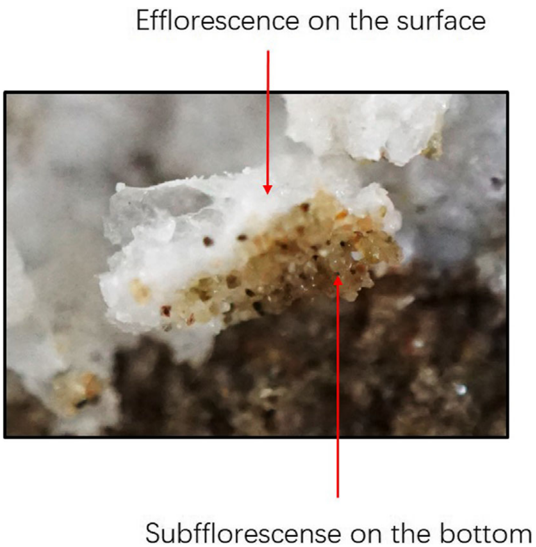


FIGURE 14 The mix salt precipitation pattern (efflorescence and subefflorescence in same site different depth) by sodium sulphate for wet soils

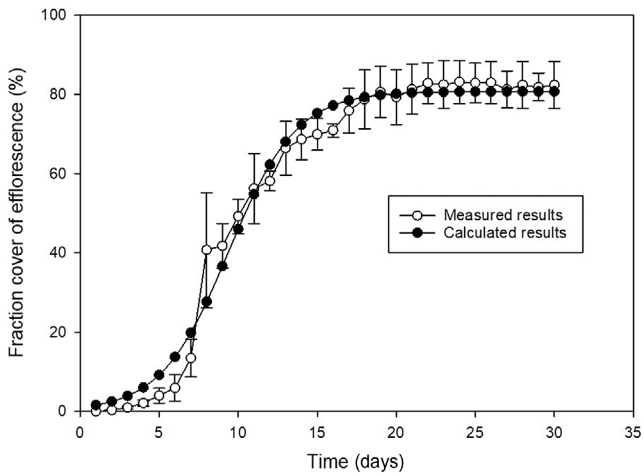


FIGURE 15 Variation of efflorescence cover fraction with time and a fit curve by logistic growth model

surface and solution, the solution would have passed through the soil surface and formed efflorescence via continual evaporation. It was also possible that the solution passed through previously formed subflorescence, thereby forming efflorescence on top of the subflorescence. This suggests a three-layer structure consisting of soil, subflorescence, and efflorescence (Figure 14). Figures 13 and 14 illustrate the differences in the efflorescence formed by Na_2SO_4 and NaCl, as well as the existence of a mixed Na_2SO_4 precipitation pattern, which has not been previously reported. This complicated multiple layer structure or mixed precipitation pattern could not be distinguished using a digital camera, hence should be investigated using X-ray tomography techniques in future studies.

3.4.3 | Association between mixed salt precipitation and evaporation

For wet soils, abundant Na_2SO_4 efflorescence was observed on the soil surface, in contrast to drying soil containing Na_2SO_4, as well as a mixed salt precipitation pattern of simultaneous subflorescence and efflorescence at different soil depths (Figures 12c and 14). The variation in evaporation based on the areal ratio of efflorescence, subflorescence, and mixed salt precipitation can be expressed as follows:

$$\frac{dQ_{toal}}{dt} = A_{free}J_{free} + A_{ef}J_{ef} + A_{sub}J_{sub} + A_{mix}J_{mix}. \tag{15}$$

where A_{free}, A_{sub}, A_{ef} and A_{mix} are the areas of salt-free soil, subflorescence, efflorescence and mixed salt precipitation, respectively, and

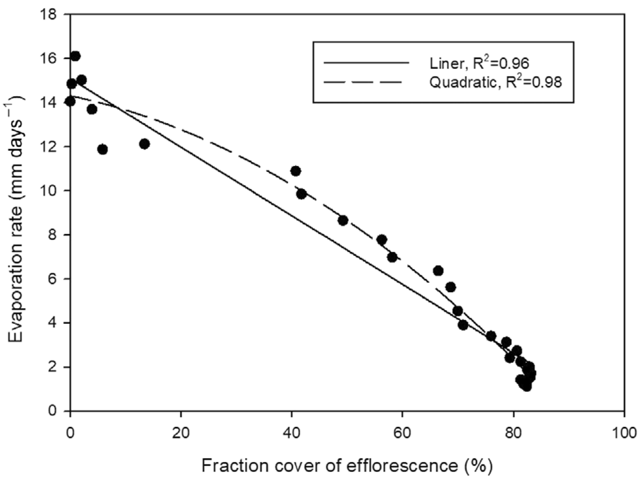


FIGURE 16 Association between fraction cover of efflorescence by sodium sulphate and evaporation rate for wet soil

J_{free}, J_{sub}, J_{ef} and J_{mix} are the evaporation rates of salt-free soil, subflorescence, efflorescence and mixed salt precipitation, respectively.

Although it was difficult to distinguish between different salt precipitation areas using only a digital camera, wet soil containing Na_2SO_4 showed a slower decrease in the evaporation rate over time and the efflorescence cover rate (Figure 2c and 13), hence we established a relationship between the evaporation rate and percentage of efflorescence cover. The fraction of efflorescence (%) showed an 'S' curve, which was fitted with a logistic growth model (Figure 15):

$$f_s(t) = 80.744/\left(1+e^{-0.467(t-9.399)}\right), R^2 = 0.98 \quad (16)$$

A statistical relationship between salt cover and the evaporation rate was then determined (Figure 16):

$$J = -0.0012f_s^2 - 0.0574f_s + 14.234, R^2 = 0.98 \quad (17)$$

$$J = -0.1584f_s + 15.078, R^2 = 0.96 \quad (18)$$

where J is the evaporation rate (mm day^{-1}), f_s is the percentage of efflorescence cover (%), and t is time (day).

According to this relationship (Equation 18), the evaporation rate was reduced by 0.16 mm day^{-1} when the salt cover fraction increased by 1% under the experimental conditions. Thus, we deduce that evaporation reduction predominantly depends on the efflorescent cover, with subflorescence having a minor influence on evaporation in wet soils. This may be explained by the substantial difference in solution flow resistance between the efflorescence and subflorescence, with evaporation strongly inhibited by efflorescence.

Figure 12b,c shows that efflorescence had a denser salt structure than subflorescence; a denser porous media structure and smaller porosity are associated with more resistance for fluid flow and therefore stronger evaporation resistance. We suggest that the pore structure of salt precipitation is a key parameter that determines the hydraulic properties of salt layers. Moreover, the significant Na_2SO_4 efflorescence cover in wet soils and greater Na_2SO_4 subflorescence in drying soil imply that the hydraulic conditions influence the transition from subflorescence to efflorescence. Additionally, the formation of Na_2SO_4 subflorescence is caused by its higher viscosity and lower surface tension than NaCl, however, magnesium sulphate has higher viscosity, approximately four times that of Na_2SO_4 (Ruiz-Agudo et al., 2007). This causes a lower capillary flow and potentially less efflorescence on the soil surface and more subflorescence within the soil pores, even if the soil remains wet. Therefore, differences in salt precipitation patterns should be considered for more salt types.

4 | CONCLUSIONS

In this study, we empirically investigated salt precipitation and evaporation behaviour in natural soils according to salt type (NaCl and Na_2SO_4) and soil texture (sandy soil, sandy loam and silt loam) under different hydraulic conditions (drying and wet soil). Darcy's and Fick's laws were employed to explain of effect of salt precipitation on evaporation. Three hypotheses were verified, and the main conclusions are as follows:

(1) NaCl precipitation as efflorescence strongly inhibited evaporation in wet soil. This was attribute to the denser NaCl salt crust characterized by very low porosity or fewer open pores, which inhibited fluid flow through the salt crust.

(2) Salt crust patterns varied with soil texture. Thinner, flatter, and more uniform salt crusts developed in finer soil (silt loam), which exhibited greater evaporation resistance, whereas thicker and rougher salt crusts developed in coarse soil (sandy soil), which exhibited less evaporation resistance. This evaporation difference was attributed to the difference in the evaporation area between salt crust patterns.

(3) Na_2SO_4 was precipitated as subflorescence in drying soil, which had less inhibitory effects on evaporation compared with the efflorescence formed by NaCl precipitation. However, abundant Na_2SO_4 efflorescence was formed, as well as subflorescence, in wet soils, revealing a mixed salt precipitation pattern. Thus, our results indicated that soil hydraulic conditions influence the transition from subflorescence to efflorescence. When both Na_2SO_4 efflorescence and subflorescence occurred, evaporation was predominantly inhibited by efflorescence.

Our study provides novel insights into the influence of natural soil texture on salt crust precipitation and the effect of hydraulic conditions on the transition from subflorescence to efflorescence, thereby expanding our understanding of the dynamics of salt precipitation and evaporation. However, further investigations are warranted to quantify the pore size, pore number, and porosity of different salt precipitation patterns, as well as salt grain coalescence and lateral growth of salt precipitation, to accurately describe the different salt crust patterns. Additionally, saline solution with a higher viscosity (e.g. magnesium sulphate) should also be analysed as it may reduce the influence of hydraulic conditions on the transition from subflorescence to efflorescence.

ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (grant no. 41977013) and West Light Foundation of Chinese Academy of Sciences (grant no. 2020-XBQNXZ-012).

DATA AVAILABILITY STATEMENT

The data that support this study will be shared upon reasonable request to the corresponding author.

ORCID

Xinhu Li https://orcid.org/0000-0003-2238-3543

REFERENCES

Arya, L. M., Leij, F. J., Shouse, P. J., & van Genuchten, M. T. (1999). Relationship between the hydraulic conductivity function and the particle-size distribution. *Soil Science Society of America Journal*, *63*, 1063–1070. https://doi.org/10.2136/sssaj1999.6351063x

Benavente, D., Sanchez-Moral, S., Fernandez-Cortes, A., Cañaveras, J. C., Elez, J., & Saiz-Jimenez, C. (2010). Salt damage and microclimate in the Postumius tomb, Roman necropolis of Carmona, Spain. *Environmental Earth Sciences*, *63*(7–8), 1529–1543. https://doi.org/10.1007/s12665-010-0815-9

Chang, C.-C., Cheng, D.-H., & Qiao, X.-Y. (2019). Improving estimation of pore size distribution to predict the soil water retention curve from its particle size distribution. *Geoderma*, *340*, 206–212. https://doi.org/10.1016/j.geoderma.2019.01.011

Desarnaud, J., Derluyn, H., Molari, L., de Miranda, S., Cnudde, V., & Shahidzadeh, N. (2015). Drying of salt contaminated porous media: Effect of primary and secondary nucleation. *Journal of Applied Physics*, *118*(11), 114901. https://doi.org/10.1063/1.4930292

Eloukabi, H., Sghaier, N., Ben Nasrallah, S., & Prat, M. (2013). Experimental study of the effect of sodium chloride on drying of porous media: The crusty–patchy efflorescence transition. *International Journal of Heat and Mass Transfer*, *56*(1–2), 80–93. https://doi.org/10.1016/j.ijheatmasstransfer.2012.09.045

Ferreira, T., & Rasband, W. (2012). ImageJ User Guide Version IJ 1.46. https://imagej.nih.gov/ij/docs/guide/user-guide.pdf

Fujimaki, H., Shimano, T., Inoue, M., & Nakane, K. (2006). Effect of a salt crust on evaporation from a bare saline soil. *Vadose Zone Journal*, *5*(4), 1246–1256. https://doi.org/10.2136/vzj2005.0144

Gran, M., Carrera, J., Olivella, S., & Saaltink, M. W. (2011). Modeling evaporation processes in a saline soil from saturation to oven dry conditions. *Hydrology and Earth System Sciences*, *15*(7), 2077–2089. https://doi.org/10.5194/hess-15-2077-2011

Gupta, S., Huinink, H. P., Pel, L., & Kopinga, K. (2014). How ferrocyanide influences NaCl crystallization under different humidity conditions. *Crystal Growth & Design*, *14*(4), 1591–1599. https://doi.org/10.1021/cg4015459

Ioannou, I., Hall, C., Hoff, W. D., Pugsley, V. A., & Jacques, S. D. (2005). Synchrotron radiation energy-dispersive X-ray diffraction analysis of salt distribution in Lepine limestone. *Analyst*, *130*(7), 1006–1008. https://doi.org/10.1039/b504274g

Li, X., Chang, S. X., & Salifu, K. F. (2014). Soil texture and layering effects on water and salt dynamics in the presence of a water table: A review. *Environmental Reviews*, *22*(1), 41–50. https://doi.org/10.1139/er-2013-0035

Li, X., & Shi, F. (2021a). Effects of evolving salt precipitation on the evaporation and temperature of sandy soil with a fixed groundwater table. *Vadose Zone Journal*, *20*(3), e20122. https://doi.org/10.1002/vzj2.20122

Li, X. H., & Shi, F. Z. (2021b). Salt precipitation and evaporative flux on sandy soil with saline groundwater under different evaporation demand conditions. *Soil Research.*, *60*, 187–196. https://doi.org/10.1071/Sr21111

Nachshon, U., Shahraeeni, E., Or, D., Dragila, M., & Weisbrod, N. (2011). Infrared thermography of evaporative fluxes and dynamics of salt deposition on heterogeneous porous surfaces. *Water Resources Research*, *47*(12), W12519. https://doi.org/10.1029/2011wr010776

Nachshon, U., & Weisbrod, N. (2015). Beyond the salt crust: On combined evaporation and subflorescent salt precipitation in porous media. *Transport in Porous Media*, *110*(2), 295–310. https://doi.org/10.1007/s11242-015-0514-9

Nachshon, U., Weisbrod, N., Dragila, M. I., & Grader, A. (2011). Combined evaporation and salt precipitation in homogeneous and heterogeneous porous media. *Water Resources Research*, *47*(3), W03513. https://doi.org/10.1029/2010wr009677

Nachshon, U., Weisbrod, N., Katzir, R., & Nasser, A. (2018). NaCl crust architecture and its impact on evaporation: Three-dimensional insights. *Geophysical Research Letters*, *45*, 6100–6108. https://doi.org/10.1029/2018gl078363

Nickling, W. G., & Ecclestone, M. (1981). The effects of soluble salts on the threshold shear velocity of fine sand. *Sedimentology*, *28*(4), 505–510. https://doi.org/10.1111/j.1365-3091.1981.tb01698.x

Nield, J. M., McKenna Neuman, C., O'Brien, P., Bryant, R. G., & Wiggs, G. F. S. (2016). Evaporative sodium salt crust development and its wind tunnel derived transport dynamics under variable climatic conditions. *Aeolian Research*, *23*, 51–62. https://doi.org/10.1016/j.aeolia.2016.09.003

Norouzi Rad, M., Shokri, N., Keshmiri, A., & Withers, P. J. (2015). Effects of grain and pore size on salt precipitation duringevaporation from porous media. *Transport in Porous Media*, *110*(2), 281–294. https://doi.org/10.1007/s11242-015-0515-8

Norouzi Rad, M., Shokri, N., & Sahimi, M. (2013). Pore-scale dynamics of salt precipitation in drying porous media. *Physical Review. E, Statistical, Nonlinear, and Soft Matter Physics*, *88*(3), 032404. https://doi.org/10.1103/PhysRevE.88.032404

Piotrowski, J., Huisman, J. A., Nachshon, U., Pohlmeier, A., & Vereecken, H. (2020). Gas permeability of salt crusts formed by evaporation from porous media. *Geosciences*, *10*(11), 423. https://doi.org/10.3390/geosciences10110423

Rodriguez-Navarro, C., & Doehne, E. (1999). Salt weathering: Influence of evaporation rate, supersaturation and crystallization pattern. *Earth Surface Processes and Landforms*, *24*(3), 191–209. https://doi.org/10.1002/(sici)1096-9837(199903)24:3<191::Aid-esp942>3.0.Co;2-g

Ruiz-Agudo, E., Mees, F., Jacobs, P., & Rodriguez-Navarro, C. (2007). The role of saline solution properties on porous limestone salt weathering by magnesium and sodium sulfates. *Environmental Geology*, *52*(2), 269–281. https://doi.org/10.1007/s00254-006-0476-x

Sghaier, N., & Prat, M. (2009). Effect of efflorescence formation on drying kinetics of porous media. *Transport in Porous Media*, *80*(3), 441–454. https://doi.org/10.1007/s11242-009-9373-6

Shirazi, M. A., & Boersma, L. (1984). A unifying quantitative analysis of soil texture. *Soil Science Society of America Journal*, *48*(1), 142–147. https://doi.org/10.2136/sssaj1984.03615995004800010026x

Shokri-Kuehni, S. M. S., Norouzi Rad, M., Webb, C., & Shokri, N. (2017). Impact of type of salt and ambient conditions on saline water evaporation from porous media. *Advances in Water Resources*, *105*, 154–161. https://doi.org/10.1016/j.advwatres.2017.05.004

Shokri-Kuehni, S. M. S., Sahimi, M., & Shokri, N. (2021). A personal perspective on prediction of saline water evaporation from porous media. *Drying Technology*, *1-6*, 691–696. https://doi.org/10.1080/07373937.2021.1999256

Shokri-Kuehni, S. M. S., Vetter, T., Webb, C., & Shokri, N. (2017). New insights into saline water evaporation from porous media: Complex interaction between evaporation rates, precipitation, and surface temperature. *Geophysical Research Letters*, *44*(11), 5504–5510. https://doi.org/10.1002/2017gl073337

Shokri-Kuehni, S. M. S., Raaijmakers, B., Kurz, T., Or, D., Helmig, R., & Shokri, N. (2020). Water table depth and soil salinization: From pore-scale processes to field-scale responses. *Water Resources Research*, *56*(2), e2019WR026707. https://doi.org/10.1029/2019wr026707

Veran-Tissoires, S., Marcoux, M., & Prat, M. (2012). Discrete salt crystallization at the surface of a porous medium. *Physical Review Letters*, *108*(5), 054502. https://doi.org/10.1103/PhysRevLett.108.054502

Veran-Tissoires, S., & Prat, M. (2014). Evaporation of a sodium chloride solution from a saturated porous medium with efflorescence formation. *Journal of Fluid Mechanics*, *749*, 701–749. https://doi.org/10.1017/jfm.2014.247

How to cite this article: Li, X., Guo, M., & Wang, H. (2022). Impact of soil texture and salt type on salt precipitation and evaporation under different hydraulic conditions. *Hydrological Processes*, *36*(11), e14763. https://doi.org/10.1002/hyp.14763