Experimental study on macropore flow effects in unsaturated soil on subsurface drainage and soil desalination**

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Abstract
Discharging of moisture and salt from unsaturated soil has always been a difficult problem. Therefore, a laboratory experiment in unsaturated soil, under drip irrigation, on subsurface drainage and soil desalination through subsurface drainage pipes (SDP) was conducted for using soil flume, where artificial macropore flow tubes (MFT) were deployed and connected to SDP. We conducted seven different deployment treatments of the artificial MFT, including four deployment tube densities (0, 3, 4, and 5) and two deployment arrangements (curved and straight). The results showed that no flow was observed in the SDP under the base treatment without MFT, increasing flow rates to 9.71 L, 10.7 L, and 12.3 L under the three straight line treatments and 7.81 L, 9.81 L, and 11.2 L under the three curved line treatments. Water content in both the upper and lower soil layers was almost uniform in the treatments with MFT, and an overall desalination trend was observed; the average desalination rate of curved MFT treatments was lower than that of the straight MFT treatments under the same MFT density. The findings serve as the foundation for future studies on drainage and desalination in unsaturated soil and facilitate the design of tile drainage under drip irrigation.

KEYWORDS
drip irrigation, preferential flow, salt leaching, subsurface drainage, unsaturated soil

RÉSUMÉ
L’évacuation de l’humidité et du sel des sols non saturés a toujours été un problème difficile. Par conséquent, des expériences de laboratoire dans un sol insaturé, sous irrigation goutte à goutte, sur le drainage souterrain et le desalination du sol à travers un tuyau de drainage souterrain (SDP) ont été menées pour utiliser un canal de drainage du sol, où des tubes d’écoulement...
de macropores artificiels (MFT) ont été déployés et connectés au SDP. Sept traitements de déploiement différents du MFT artificiel, y compris 4 densités de tube de déploiement (0, 3, 4 et 5) et deux dispositions de déploiement (courbe et droite) ont été réalisés. Les résultats ont montré qu’aucun débit n’a été observé dans le SDP sous le traitement de base sans MFT, augmentant les débits de 9,71 L, 10,7 L et 12,3 L sous les trois traitements en ligne droite et 7,81 L, 9,81 L et 11,2 L sous les trois traitements de lignes courbes. La teneur en eau dans les couches supérieure et inférieure du sol était presque uniforme dans les traitements avec MFT et une tendance générale au dessalement a été observée; le taux de dessalement moyen des traitements MFT courbes était inférieur à celui des traitements MFT droits sous la même densité MFT. Les résultats servent de base à de futures études sur le drainage et le dessalement dans les sols non saturés et facilitent la conception du drainage en poterie sous irrigation goutte à goutte.

MOTS CLÉS
irrigation goutte à goutte, flux préférentiel, drainage souterrain, sol non saturé, lixiviation du sel

1 | INTRODUCTION

The movement of soil water and salt in saline-alkali farmland under film-covered drip irrigation is significantly different from that under surface irrigation (Tan et al., 2009). Drip irrigation under film cover supplies water only to the shallow (upper) soil layer and thus is characterized by unsaturated soil, making salt remain in the soil and thus causing salt accumulation in farmland (Li, Liu, & Zheng, 2012). Some scholars reported that drip irrigation confined salt in the soil layer near the wetting front, producing a salinization zone below the plough layer. When the groundwater level is high and strong evaporation occurs, salt may return to the soil surface. While the conventional drainage ditch-based salt leaching under surface irrigation may be effective in terms of salt leaching, the conventional approach requires the arable land for the drainage ditch and a large amount of irrigation water, resulting in a loss of the advantages of drip irrigation (Li et al., 2016). Tile drainage and salt leaching through subsurface drainage pipes (SDP) could be a feasible alternative to drip irrigation for saline-alkali farmland. However, the matric suction in unsaturated soil and the air pressure in SDP often prevent soil water from entering the SDP. These issues need to be addressed before the tile drainage and salt leaching through SDP can be effectively implemented in drip irrigation.

While macropores with a diameter larger than that of capillary pores are present in farmland soil, the feeble matric suction makes water flow faster in the macropores than that in the capillary pores in the matrix flow zone. As a result, water and solute generally bypass the matrix flow zone and migrate into the deep soil, producing a preferential flow that is also known as a macropore flow (MF) (Childs, 1969; Zhang, Lin, & Wang, 2003; Wu et al., 2006; Jarvis, Koestel, & Larsbo, 2016). MF is a non-equilibrium gravity flow of relatively high flow velocity and obvious funnel suction, causing a suction effect on nearby matrix flow and thereby producing a suction flow towards the MF (Wang et al., 2003; Germer & Braun, 2015). Previous studies on macropores and MF in soil mainly focused on the characteristics of MF in undisturbed soil or simulations by using artificial macropores (Jarvis, Koestel, & Larsbo, 2016). Ghodrati, Chadorain, & Chang (1999) investigated the migration mechanism of MF using semi-cylindrical macropores and demonstrated that the ratio of macropores and soil matrix on MF had a more significant effect than the macropore size. Nachabe (1995) determined the hydraulic conductivity (K) of soil containing macropores (diameter ≥1 mm) using a tension osmometer and stated that the hydraulic conductivity of the macropores was 3.6 times higher than that of the soil matrix. Wasten & Luxmoore (1986) found that macropores, which occupy 0.32% of the soil volume, were responsible for 96% of overall water flux. Iqbal & Krothe (1996) demonstrated that the flow rate in soil containing macropores was six times higher than that in soil without macropores. Wu, Zhang, & Gao (2009) simulated soil with different effective surface porosities and macropores at different depths by filling soil with gravels to study the macroporous flow
and preferential solute transport in unsaturated soil. The results indicated that macropores had significant effects on preferential flow of soil water, especially on the wet zone of internal sections of soil that contained macropores. By coupling the matrix flow zone in soil with the preferential flow zone in a crack network, it was demonstrated that soil water prefers to migrate downwards along channels in the network and exchange water with the matrix flow zone, leading soil water to the soil layer bottom in a short time (Zhu, Chen, & Liu, 2016). As for the effects of macropores on solute migration, it was suggested that the speed of non-equilibrium solute migration induced by macropore convection was significantly higher than that of dispersion-induced solute migration (Akhtar et al., 2003). Sun et al. (2012) investigated the effects of soil macropores on preferential flow and demonstrated that macropores in deep soil had a more significant effect on the migration of water or solute than macropores in surface soil.

Despite the progress made in understanding MF, previous studies focused only on the characteristics or mechanisms of MF and few studies discussed practical applications of MF theory. To investigate tile drainage and salt leaching in unsaturated soil, artificial macropore flow tubes (MFT), and SDP. Fruit-free nutrition bags were used as the water supply system, and their needles acted as drip irrigation emitters with a spacing of 25 cm. The emitters were fixed at 12.5, 37.5, 62.5, and 87.5 cm away from a side of the glass soil tank, as shown in Figure 1. The transparent soil tank had the dimensions of $100 \times 20 \times 80$ cm$^3$, and its bottom was covered with a 20-cm gravel layer. A 10-mm porous PVC plate with pores at a spacing of $50 \times 50$ mm was placed on the top of the gravel layer and the bottom of the soil layer to form a free permeable layer and an exhaust gas layer at the bottom of the soil to support the soil in the soil tank. Porous, soft stripes made of a fibre net with a length of 53 cm and an average diameter of 5 mm were used as the tubes that can generate MF in soil, called macropore flow tubes (MFT) in this paper. Perforated PVC pipes with a diameter of 5 cm containing pores with a diameter of 0.5 cm spaced 2 cm apart (porosity = 3.1%) were used as SDP and were wrapped with permeable non-woven fabrics. MFT and SDP were connected at a right angle and were buried at the centre of the soil tank. The SDP had a slope of 1/500 (Irrigation Experiment Standard, 2005), and its outer wall was 7.5 cm from the inner wall of the soil tank, as shown in the testing setup in Figure 1.

## 2 | MATERIALS AND METHODS

### 2.1 | Soil

Laboratory experiments were conducted in a soil flume at the Centre of Hydraulic and Civil Engineering, Shihezi University (86°03′27″ E, 44°18′25″ N, altitude = 451 m), in the period of April 2017 to October 2017. The testing soil was obtained from Beiquan Town, Shihezi City, Xinjiang, China. A hydrometer was used to measure the clay content of the testing soil, while the pressure-membrane apparatus was employed to determine soil moisture characteristics. Field moisture capacity was measured using the drainage method. Table 1 summarizes the fundamental physical characteristics of the soil.

### 2.2 | Instruments

The testing soil flume system comprised a water supply system, a soil tank, artificial macropore flow tubes (MFT), and SDP. Fruit-free nutrition bags were used as the water supply system, and their needles acted as drip irrigation emitters with a spacing of 25 cm. The emitters were fixed at 12.5, 37.5, 62.5, and 87.5 cm away from a side of the glass soil tank, as shown in Figure 1. The transparent soil tank had the dimensions of $100 \times 20 \times 80$ cm$^3$, and its bottom was covered with a 20-cm gravel layer. A 10-mm porous PVC plate with pores at a spacing of $50 \times 50$ mm was placed on the top of the gravel layer and the bottom of the soil layer to form a free permeable layer and an exhaust gas layer at the bottom of the soil to support the soil in the soil tank. Porous, soft stripes made of a fibre net with a length of 53 cm and an average diameter of 5 mm were used as the tubes that can generate MF in soil, called macropore flow tubes (MFT) in this paper. Perforated PVC pipes with a diameter of 5 cm containing pores with a diameter of 0.5 cm spaced 2 cm apart (porosity = 3.1%) were used as SDP and were wrapped with permeable non-woven fabrics. MFT and SDP were connected at a right angle and were buried at the centre of the soil tank. The SDP had a slope of 1/500 (Irrigation Experiment Standard, 2005), and its outer wall was 7.5 cm from the inner wall of the soil tank, as shown in the testing setup in Figure 1.

### 2.3 | Methods

The density of the MFT was 3, 4, or 5, and they were either straight or curved (Figure 2). Six samples were collected, and each sample was tested twice. Drainage through SDP without MFT was used as the base treatment and repeated three times. In order to prevent the salt in irrigation water from entering soil and affecting the analysis of soil salt leached by irrigation water by different drainage methods, purified water with a salinity of 0.15 g/L was used for drip irrigation, the emitter flow rate

| **Soil type** | **Clay content (<0.01 mm, %)** | **Volumetric weight (g/cm$^3$)** | **Porosity (%)** | **Field moisture capacity (% in mass)** | **Saturated water content (% in mass)** |
|---------------|-------------------------------|---------------------------|-----------------|-----------------------------------|--------------------------------------|
| Sandy loam    | 15.1                          | 1.63                      | 42.7            | 17.2                              | 26.2                                 |
was maintained at 1 L/h, and the irrigation water volume was maintained at 62.8 L for each treatment (Table 2).

The testing soil was air-dried, grinded, and sieved using a Φ = 2 mm sieve to remove any impurities, and homogeneously mixed soil was loaded into the soil tank layer by layer according to the designed volumetric weight. Following each load, the soil was compacted to a 10-cm layer, and the total height of the soil layer was 60 cm. The SDP was buried at a depth of 55 cm, and then the soil was left undisturbed for 1 day. The initial water
content ($\theta$, in mass) and salt content ($C_0$) were measured by sampling from the soil tank (Table 3).

### 2.4 Parameters

When considering the effects of the pattern and density of the MFT on the movement and distribution of water in soil, the movement of the wetting front was monitored in real-time during the irrigation process and was labelled on the transparent soil tank glass. Following each test, the locations containing different wetting front curves were extracted to measure wetting front trends for different samples as a function of time using the software Origin 85 (OriginLab Corporation, Northampton, USA).

The water and salt contents of the soil were determined using the earth auger method. Samples were taken at the locations 6.25 cm, 18.75 cm, 31.25 cm, and 43.75 cm from the soil tank edge along the axial direction, and two rows of sampling sites were set at the top and lateral (5 cm from the centre) parts of the SDP (Figure 3). The other half of the soil tank was used as repeated sampling zone.

Sites 1, 2, 3, and 4 were at the top of the SDP (every 10 cm from the surface to the SDP), and sites 5, 6, 7, and 8 were in the lateral part of the SDP (every 10 cm from the surface down to the depth of 60 cm). The tile drainage water was collected using a 1-L bucket at the outlet of the SDP. Soil water content was measured using the drying method. Soil salt content was determined by measuring the electric conductivity of the soil extraction solution and the salt mass ratio was calibrated using the drying residue method described in Equation 1:

$$y = 3.44x + 0.248; \; (R^2 = 0.983; n = 104),$$

where $y$ refers to the soil salt content (g/kg), $x$ refers to the electric conductivity of the soil extraction solution (ms/cm), and $n$ refers to the sample numbers.

The numerical average of the repeated tests was used as the value. The soil salt content change rate was calculated using Equation 2:

$$\eta = \frac{\omega_1 - \omega_0}{\omega_0} \times 100\%,$$

where $\omega_1$ refers to the soil salt content at the end of a test (in g), $\omega_0$ refers to the initial soil salt content (in g), and $\eta$ refers to the change rate of the soil salt content (%). The symbol “+” denotes soil salification, and “−” denotes soil desalination.

The relationship between soil water content and soil matric suction was measured using a pressure-membrane apparatus (1500F1; Soil Soisture Equipment Corp., USA) and described with the following logarithmic function:

$$S = \frac{1}{78.3 + 65.2 \ln \theta}; \; (R^2 = 0.996),$$

where $S$ refers to the soil water suction (MPa), $\theta$ refers to the volumetric soil water content (%), and $R$ is the correlation coefficient.

### Table 2 Experimental treatments

| Pattern of MFT | Density of MFT | Irrigation (L) | Treatment label | Repeated times |
|---------------|---------------|---------------|----------------|---------------|
| Straight      | 3             | 62.8          | V3             | 2             |
|               | 4             | 62.8          | V4             | 2             |
|               | 5             | 62.8          | V5             | 2             |
| Curved        | 3             | 62.8          | Z3             | 2             |
|               | 4             | 62.8          | Z4             | 2             |
|               | 5             | 62.8          | Z5             | 2             |
| No MFT        | 0             | 62.8          | CK             | 3             |

Abbreviation: MFT, macropore flow tube.

### Table 3 Background values of different soil samples

|       | V3 | V4 | V5 | Z3 | Z4 | Z5 | CK |
|-------|----|----|----|----|----|----|----|
| $\theta$ (%, in mass) | 1.6 | 0.8 | 0.9 | 1.8 | 1.4 | 0.9 | 1.5 |
| $C_0$ (g/kg) | 20.7 | 17.5 | 17.5 | 13.1 | 22.3 | 16.8 | 20.6 |
3 | RESULTS AND ANALYSIS

3.1 | Effects of MFT on tile drainage

The tile drainage and salt leaching through SDP, enhanced with MFT, were experimentally investigated under six different treatments plus a base or reference treatment without MFT. Experimental results indicated that while no flow was observed under the CK (Contrast check) or base/reference treatment, flow was always observed under the V3, V4, and V5 treatments with straight MFT. Particularly, the tile drainage amount increased with the increasing density of the MFT from 9.71 L, 10.7 L, to 12.3 L for V3, V4, and V5, respectively. The tile drainage amount under the Z3, Z4, and Z5 treatments was 7.81 L, 9.81 L, and 11.2 L, respectively, and all the treatments containing curved MFT had a lower drainage amount than those containing straight MFT. The seepage water in gravel was observed at the end of the experiments, and the salinity of seepage water was 297 g/L, 220 g/L, 207 g/L, 199 g/L, 259 g/L, and 190 g/L for V3, V4, V5, Z3, Z4, and Z5, respectively.

While no flow was observed, the base CK treatment had an average water content of 24%, which is higher than with all other treatments involving MFT. Flow was observed in the six treatments with different densities and patterns of MFT, where the water content varied between 20%–23%, which was lower than the saturated soil water content of 26.2% and that of the CK treatment, and higher than the field moisture capacity (17.2%). The treatments containing curved MFT had a lower drainage amount than those containing straight MFT. The seepage water in gravel was observed at the end of the experiments, and the salinity of seepage water was 297 g/L, 220 g/L, 207 g/L, 199 g/L, 259 g/L, and 190 g/L for V3, V4, V5, Z3, Z4, and Z5, respectively.

3.2 | Funnel suction effects of MFT on tile drainage

When the MF rate exceeded the matrix flow rate, a preferential flow was formed, producing a funnel suction effect on water in the nearby soil, thereby reducing the water holding capacity (Wang, Lu, & Wu, 2002; Germer & Braun, 2015). Water in the matrix flow zone surrounding the MFT tended to flow horizontally into the macropores under the funnel suction effect (Warrick et al., 2008), resulting in an expanding impact zone of the MF, as shown in Figure 4. During the experiments, it was observed that the migration velocity of the wetting front increased with the density of the MFT.

Figure 4A represents the relationships between wetting front depth and required time for different treatments. From the figure, the time required for the wetting front to reach the specified depth for the treatment with MFT was shorter than that for the CK treatment. For instance, the time for the wetting front to reach a depth of 50 cm was 31.4 h, 28 h, 24 h, 24 h, and 18 h for the treatments CK, V4, V5, Z4, and Z5, respectively. The treatments Z4 and Z5 had larger impact zones than those of the treatments V4 and V5 involving the curved MFT. Additionally, tile drainage volumes in the treatments V4 and V5 were higher than those in the treatments Z4 and Z5.

Table 4 summarizes the matric suction effects of the top and lateral parts of SDP under different treatments as calculated using Equation 3.

The average matric suction in CK treatment was 3.53 kPa, while the average matric suctions at the top and lateral parts of the SDP differed by 0.016 kPa. For treatments V3–V5 and Z3–Z5, the average matric suction at different layers was approximately 6.82 kPa, which was nearly double the values of CK treatment. The average matric suction in treatment V3 was 6.82 kPa, which was 90.8%–94.5% higher than that of the CK treatment, and the average matric suctions in the top and lateral parts of the SDP were highly consistent. This suggested that the water migration at the lateral parts of the SDP in the treatments with MFT was different than that of the lateral parts of the SDP in the CK treatment. According to the fundamental theories and the force balance theories of water migration in unsaturated soil, water prefers to migrate from locations with high water potential to those with low water potential. The treatments with MFT had higher matric suction than that of the CK treatment. However, flow was observed in the treatments...
with MFT but not in the CK treatment, demonstrating that the water in MFT was significantly affected by gravity and pressure potential. Furthermore, the water in unsaturated soil was suctioned into the SDP by the funnel suction effect. As a result, the water migration in the lateral part of the SDP in the treatments containing MFT was dominated by MF, causing drainage flow in the SDP; for the CK treatment, water migration in the lateral part of the SDP was dominated by matrix flow.

Figure 4 illustrates the water content of different treatments and shows that the water content in the CK treatment was high in the upper layer and low in the lower layer, demonstrating the infiltration of matrix flow (Allaire, Roulier, & Cessna, 2009). MF was most significant in the treatments V4 and Z4. Specifically, the water content near the MFT increased, indicating that water was concentrated here. Treatments V5 and Z5 had a higher density of MFT, which increased the MF impact zone and reduced the water content in all layers, producing insignificant non-uniform flow.

### 3.3 Effects of MFT density on salt removal through SDP

Soil water content determines the soil salt solubility, while the water infiltration rate affects salt elution...
In the treatment without MFT, desalination was observed in the upper layer, and salification was observed in the lower layer. In contrast, in the treatments with MFT, desalination was observed in both the upper and lower layers, and the desalination rate and desalination depth increased with the density of MFT, as shown in Figure 5.

Instead of removing salt, the irrigation water leaches salt from the upper layer to the lower layer in the CK treatment (Figure 5A), which lead to desalination in the top 0–30-cm layer and salinization in the bottom 30–60-cm layer. The average desalination rates in the top part (0–30 cm, sites 1–4) and the lateral part (0–30 cm, sites 5–8) of the SDP were $-44.0\%$ and $-38.2\%$, respectively. Additionally, salt distributions at different sites of the CK treatment were more dispersed compared with those at sample sites with MFT. This observation is consistent with the water distribution found in the CK treatment.

Overall, the soil layers in the treatments with MFT were in a state of desalination even though the upper layer with different MFT densities had a higher desalination rate than the lower layer. The lower layer desalination rate increased with the increasing MFT densities (Figures 5B, 5C, and 5D), demonstrating that funnel suction induced by MFT was conducive to the convective migration of salt, and salt was discharged into the SDP along the MFT.

In treatment V3, desalination rates in the top and lateral parts of the SDP were similar in the 10–30-cm layer and significantly different in the 30–60-cm layer. When the density of MFT was low, the matrix flow zone

**FIGURE 4** (Continued)
| Soil depth/cm | 0   | 10  | 20  | 30  | 40  | 50  | 60  |
|--------------|-----|-----|-----|-----|-----|-----|-----|
| CK           |     |     |     |     |     |     |     |
| SDP top part | 3.51| 3.53| 3.52| 3.53| 3.55| 3.57| –   |
| SDP lateral part | 3.52| 3.51| 3.51| 3.51| 3.53| 3.54| 3.52|
| V3           |     |     |     |     |     |     |     |
| SDP top part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| –   |
| SDP lateral part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| 6.82|
| V4           |     |     |     |     |     |     |     |
| SDP top part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| –   |
| SDP lateral part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| 6.82|
| V5           |     |     |     |     |     |     |     |
| SDP top part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| –   |
| SDP lateral part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| 6.82|
| Z3           |     |     |     |     |     |     |     |
| SDP top part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| –   |
| SDP lateral part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| 6.82|
| Z4           |     |     |     |     |     |     |     |
| SDP top part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| –   |
| SDP lateral part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| 6.82|
| Z5           |     |     |     |     |     |     |     |
| SDP top part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| –   |
| SDP lateral part | 6.82| 6.82| 6.82| 6.82| 6.82| 6.82| 6.82|

Abbreviation: SDP, subsurface drainage pipe.

**FIGURE 5** Effects of macropore flow tube density on salt discharge by subsurface drainage pipes. CK (Contrast check)
between MFT tended to be large, and salt migration in this area was dominated by dispersion in the matrix flow zone and convection–dispersion near the MFT. The desalination rates in the lower layers were significantly different because there were significant differences between the migration velocities of salt in the matrix flow zone and near the MFT.

The MF impact zone and the induced funnel suction increased with the increasing MFT densities, enhancing the salt removal from the top and lateral parts of the SDP in treatments V4 and V5. In treatment V4, the average desalination rate measured at sites 1–8 was $-73.6\%$, $-76.4\%$, $-75.8\%$, $-72.5\%$, $65.0\%$, $-69.6\%$, $-67.3\%$, and $-65.1\%$, respectively. In treatment V5, the average desalination rate measured at sites 1–8 was $-78.3\%$, $-76.5\%$, $-75.0\%$, $-74.6\%$, $-74.9\%$, $-74.2\%$, $-75.1\%$, and $-74.8\%$, respectively, which was higher than the corresponding values from treatment V4. The above data indicated that increasing the density of MFT could facilitate the desalination rate and the uniformity in the top and lateral portions of the SDP.

3.4 Effects of MFT pattern on salt removal through SDP

Irregularly curved macropores, instead of straight macropores, are most commonly observed in farmland (Shaw et al., 2000). The curved pores increase the flow length and thereby reduce the flow velocity of soil water. The variation trends in desalination rates under different treatments with curved MFT are illustrated in Figure 6.

Salt distributions in different treatments with curved MFT were similar to those with straight MFT, and the desalination rate decreased with increasing the soil depth. It could be seen from Figure 6 that, compared with

![Figure 6](image-url)
treatments involving straight MFT, the desalination rate profiles tended to merge together especially in the lower soil layer in treatments with curved MFT. The profiles indicated that a curved MFT created an expanded desalination impact zone of high desalination rates especially in the top soil layer.

In the top (0–20 cm) soil layer, the desalination rates at the top sites 1–4 in treatments Z3, Z4, and Z5 were higher than those at the lateral sites 5–8. However, in the soil layer deeper than 20 cm, the desalination rates of the top and lateral parts were similar because the MFT were absent in the top parts of treatments with curved MFT. In addition, the top 0–10 cm layer was a matrix flow zone following irrigation because of the same tube length in the treatments with both the straight and the curved MFT. Nevertheless, water flow occurred in MFT in the layer below 10 cm, resulting in a funnel suction effect on the soil water in the upper layer. For this reason, the quantity of soil water flowing into the macropores from the 0–10 cm layer of the top part of the SDP exceeded that from the lateral part. This produced a higher desalination rate in the 0–20 cm layer (the transition zone of the matrix and MF) of the top part of the SDP in treatments with curved MFT than in that of the lateral part. The drainage conditions in the layers below 20 cm were controlled by curved MFT, and the curved MFT reduced both the hydraulic gradient at the ends and the flow rates in the tubes. As a result, the flow patterns were uniform and salt distributions were homogeneous, making the desalination rates of the top and lateral parts of the SDP below 20 cm similar.

The average desalination rates of treatments Z3 and Z4 were similar, while treatment Z5 had an average desalination rate that was 8.96% and 11.6% higher than the corresponding ones of treatments Z3 and Z4, respectively. Since the curved MFT reduced the water flow rate, these treatments had lower desalination rates compared with the treatments with straight MFT. Therefore, the treatments with curved MFT had a lower average desalination rate than the treatments with straight MFT under the same MFT density. The average desalination rates of the treatments with curved MFT and straight MFT differed by 15.2%, 10.6%, and 3.26% under MFT densities of 3, 4, and 5, respectively.

4 | DISCUSSION

Since there was low matric suction in the macropores, the MF was primarily driven by gravity force and thus is gravity flow with a high flow rate (Logsdon, 1995), and consequently salt migration in MF was dominated by convection. The funnel suction effect by MF on water in the nearby matrix flow zone was equivalent to an additional transverse suction in the matrix flow zone. This induced transverse migration of nearby water (Germer & Braun, 2015), causing the migration of salt in this zone through the convection–dispersion process.

Water movement was dominated by matrix flow in the CK treatment, whose matrix suction was 3.5 + kPa. As a result, the water content in the upper soil layer was significantly higher than that in the lower soil layer, while desalination was observed in the upper layer and salinization was observed in the lower layer. Funnel suction enhanced the infiltration of water near the MFT in treatments with MFT (Wang et al., 2003) whose matrix suction was 6.8 + kPa, causing a preferential movement of water and solute along the MFT (Beven & Germann, 1982) and rapid movement into the SDP, which indicates that the MFT can guide the water in unsaturated soil into the SDP for drainage and improve the drainage efficiency. In addition, since solute exchange occurs between the preferential flow zone and the matrix flow zone (Liu, Bodvarsson, & Finsterle, 2002), treatments with MFT exhibited homogeneous distributions of water and salt in soil, and the homogeneity increased with the density of MFT (Figure 4). For treatments V3, V4, and V5, the overall desalination rates in the top part of the SDP were different from those in the lateral part by 31.6%, 110%, and 21.4%, respectively. Under identical conditions, the desalination rates of treatments Z3, Z4, and Z5 were 45.8%, 29.1%, and 30.9%, respectively. Additionally, the desalination rates of treatments Z3 and Z5 were higher than those of treatments V3 and V5, respectively, suggesting that an increased funnel suction can effectively promote solute exchange between the two flow zones.

According to the Hagen–Poiseuille equation of curved capillary tubes containing circular sections (Sutera & Skalak, 1993), the hydraulic gradient of a macroporous tube can be described using Equation 4:

$$\frac{\Delta P}{L_t} = \frac{128 \mu q}{\pi d^4},$$

where $\Delta P$ refers to the pressure difference between the two ends of the capillary tube (or MFT), $L_t$ refers to the practical length of the capillary tube (or MFT), $q$ refers to the water flux in the capillary tube (or MFT), $d$ refers to the diameter of the capillary tube (or MFT), and $\mu$ refers to the dynamic viscosity of fluid. In this study, $d$ and $L_t$ were the same for all treatments and were kept constant during all testing processes. The measured tile drainage in treatments with curved MFT was lower than in treatments with straight MFT, indicating that there was a lower pressure difference between the two ends of the
curved MFT. When the distance between the top parts of curved MFT and the soil surface increased, a matrix flow zone was developed at the top of the tube, which reduced $\Delta P$ and decelerated water migration. This caused a reduction in the funnel suction and a hindrance in the desalination in treatments with curved MFT. Therefore, stronger desalination effects were observed in treatments with straight MFT compared with treatments with curved MFT.

5 | CONCLUSIONS

Based on the results from this study, the following conclusions can be drawn:

- There was no flow in SDP under the base treatment without the artificial MFT. The soil water content profile is characterized by a high water content in the upper layer and a low content in the lower layer. Flow was observed in SDP in all treatments containing MFT. The vertical water content profile was relatively uniform in both the upper and lower soil layers. Furthermore, the flow rate in SDP increased from 9.71 L to 12.3 L when the density of vertical MFT increased from 3 to 5, while the flow rate in SDP increased from 7.81 L to 11.2 L when the density of curved MFT increased from 3 to 5.

- Matrix flow was observed under the base treatment without MFT, while the preferential flow was observed in treatments containing MFT. Compared with the base treatment without MFT, the preferential flow under the treatment with MFT produced a funnel suction effect on nearby water movement towards the MFT and thereby decreased the soil water content. Additionally, the migration velocity of the wetting front near MFT increased with the MFT density.

- In terms of soil salinity, the upper soil layers experienced desalination with an average desalination rate of 41.1%, while the lower soil layer experienced salinization under the same irrigation water volume and the base treatment without the artificial MFT. Under the treatments with MFT an overall desalination trend was observed in both the upper and the lower soil layers, and the desalination rate and desalination depth increased with the density of MFT. Increasing MFT density had a positive effect on promoting the desalination rate and uniformity around the SDP. The average desalination rate of different samples fell within the range of −67% to 81%.

- The curved MFT treatment reduced the flow rate and thereby the average desalination rate. Specifically, the differences between the average desalination rates of samples for the curved and the straight MFT treatments were 15.2%, 10.6%, and 3.26% under a MFT density of 3, 4, and 5, respectively.

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