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Investigation of the Wetting Front Distribution in Vertically Layered Arid Soils under Drip Irrigation

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Abstract

Soil wetting front depends on various factors, including soil texture, emitter flow rate, land slope, and volume of irrigation water. Accurate estimation of the curved shape of the wetting front distribution helps to know how much advanced water and liquid fertilizers have transported in porous media. A cube-shaped physical model was built, and the experiments were performed at emitter flow rates of 2, 4, and 8 L/h and slopes of 0, 10, and 20% on 4 soil samples. Samples 1 and 2 were homogeneous soils, and samples 3 and 4 were vertically layered soils. The homogeneous soil samples had light, loamy sand (L) and heavy, clay (H) textures. The vertically layered soil samples included three layers. The results showed that the change in soil texture from L to LHL increased the average maximum wetting front radius downstream of the emitter (R_0^-) At the mentioned flow rates by 18, 24 and 35%, respectively. The change in soil texture from L to LHL decreased the mean depth of the wetting front (D) by 16%, 28%, and 40%, respectively. With changing from H to HLH, the mean R_0^- The mentioned flow rates decreased by 27, 32, and 41%, respectively, and the mean D increased by 22, 35, and 53%, respectively. Based on statistical analysis, results indicated that there were significant differences ($p<0.05$) between the layered and homogenous soils. Changing the soil texture around the emitter from L to H, especially on sloping lands, increases the wetting front radius and decreases its depth. Whereas changing the texture from H to L decreases the wetting front radius and increases its depth, thus reducing water loss.

1. Introduction

Nowadays, related to food security and economic issues, the use of drip irrigation methods has become very common (Singh Brar et al. 2016; Seifi & Mirlatifi 2020). Wetting front dimensions in drip irrigation considerably affect irrigation system design, its management, and also crop quality and quantity (Schwartzman & Zur 1986; Qiu et al. 2017). Wetting front advance, along with its distribution in soils, is one of the important parameters in drip irrigation (Azizi et al. 2023). The wetting front depends on various factors, including soil texture and structure, emitter flow rate, irrigation time, land slope,

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and volume of irrigation water (Neshat & Nasiri 2012). When water begins to flow through the soil, the capillary force determines the wetting pattern, and, with the increase in wetted depth, the effect of the gravitational force increases. Water movement through the soil is mainly influenced by capillary force in fine-textured soils and by gravitational force in coarse-textured soils. Consequently, lateral movement of water is greater in fine-textured soils, whereas water penetrates more deeply in coarse-textured soils (Patel & Rajput 2009). An increase in emitter flow rate at a constant volume of irrigation water increases the percentage of wetted area but decreases its wetted depth (Thabet & Zayani 2008). Soil wetted depth is greater when larger volumes of irrigation water are applied (Khan et al. 1996). The soil profiles containing heavy soil in top layers, that the wetting pattern was decreased vertically and increased horizontally compared to the soil profiles that have relatively light texture at the middle layer (Mohammed & Abed, 2020).

Land slope affects moisture distribution (Patel & Rajput 2008). Topographic variations potentially alter both the magnitude and directions of unsaturated flow (Chu et al. 2018). Land slope is one of the main factors for the expansion of the wetting front downstream of the dripper and a factor inhibiting its expansion upstream of the dripper (Ramzanian et al. 2021). Most agricultural lands in the foothills have slopes greater than 5% (Bodhinayake & Xioa 2004). Water infiltration rate into soil declines with an increase in land slope (Haggard et al. 2005; Huat et al. 2006). In addition, during irrigation, the horizontal flow component is dominant, and the vertical flow component decreases at greater slopes (Hoover 1985). When the wetting front begins to expand, the horizontal component advances at a high velocity, but as time passes by, its velocity decreases and, after a long time, it becomes very negligible (Clothier et al. 1985).

In some cases, digging a hole to plant seedlings alters the vertical layer of soil, which changes the texture of the soil compared to the surrounding soil (Ramzanian et al. 2023). Layered soils are a simple type of heterogeneous soils found in nature. In light soils, the wetting front is narrow and elongated and sometimes causes water loss at soil depth. In heavy soils, the wetting front is wide, which may cause water to leave the root zone and thus decrease irrigation efficiency. Consequently, sometimes farmers change soil texture at the local scale at planting time to better match wetting front dimensions with root zone depth and width to prevent water loss. Therefore, this research intended to study the dimensions of the wetting front in vertically layered soils at various discharge rates and slopes and compare them with those of the wetting front in homogeneous soils. In arid and semi-arid regions where rainfall is sporadic and temporally and spatially undesirable, the optimal use of water and soil resources increases water use efficiency and improves irrigation system performance. Accordingly, information on water spread and penetration in soil is especially important in arid land management. Consequently, water use efficiency and distribution can be suitably enhanced by changing the arrangement of the layers in the soils of arid regions.

Many studies have been conducted on factors influencing wetting front dimensions using empirical, semi-empirical, and numerical models (Al-Omran et al., 2008; Kandelous & Simunek, 2010; Tripathi, 2017; Selim et al., 2018; Shiri et al., 2020; Kumar et al., 2021). However, few studies have been conducted and/or reported on vertically layered soils. Although the laboratory results obtained on wetting front distribution differ from those observed in field conditions, these laboratory results can be useful for a preliminary prediction of the wetting front conditions.

Consequently, the present research studied the wetting front dimensions in vertically layered soils with various slopes and at different emitter flow rates and compared them with homogeneous soils.

2. Materials and Methods

2.1. The physical model

A cube-shaped physical model with dimensions of 60 cm (width) × 160 cm (length) × 120 cm (height) was constructed to study the advance of the wetting front in soil under drip irrigation. A gate was installed at one side of the model to facilitate soil removal. The model was made of metal except for its front part, which was covered with 10 mm thick clear tempered glass to observe the wetting front. The glass surface was covered with sand particles to prevent the formation of unusual flows on it (Figure 1). The irrigation system consisted of a water storage tank, an electric pump, a gate valve, a pressure gauge, a transfer pipe, and a pressure-compensating emitter (Figure 2).

Figure 1. The physical model used for the soil experiments.

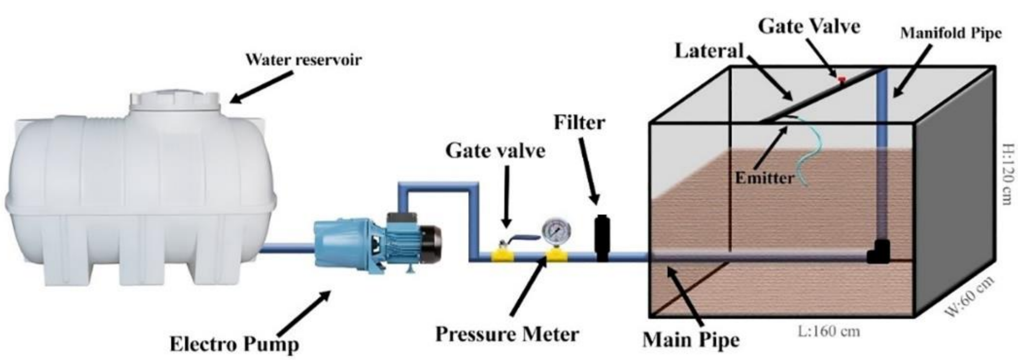

Figure 2. A schematic design of the physical model used in the present research.

2.2. Experimental setup

Two types of soil, one light-textured and one heavy-textured, were used in the research (Table 1). Each 10-cm thick soil layer was poured into the model and compacted to match the density of the original soil. After each experiment, the soil was spread in thin layers and air-dried. The soil was then reweighed, and its weight was compared to the initial value to control moisture content, ensuring experiments were conducted under identical conditions. The hydraulic conductivity of the studied soils was measured in the laboratory using the constant head method.

The longitudinal slopes of the soils were 0%, 10%, and 20%, and the cross slope was 0%. The experiments were performed at flow rates of 2, 4, and 8 L/h on 4 soil samples. All experiments were conducted in triplicate. Samples 1 and 2 were homogeneous soils, while samples 3 and 4 consisted of vertically layered soils. The homogeneous soil samples had light, loamy sand (L) and heavy clay (H) textures. The vertically layered soil samples included three layers, with the middle one being 33 cm thick. In soil sample 3, layers 1 and 3 had a light texture, and layer 2 had a heavy texture (LHL). In soil sample 4, layers 1 and 3 had a heavy texture, and layer 2 had a light texture (HLH). The emitter was installed at the center of layer 2 (Fig. 3).

Table 1. Physical characteristics of the soils used in the research.

Soil Type	Soil Texture	Code	Sand (%)	Silt (%)	Clay (%)	Bulk density *(gr/cm³)*	Saturated Hydraulic conductivity *(cm/h)*
Light	Loamy sand	L	84	5	11	1.55	3.96
Heavy	Clay	H	29	24	47	1.35	0.8

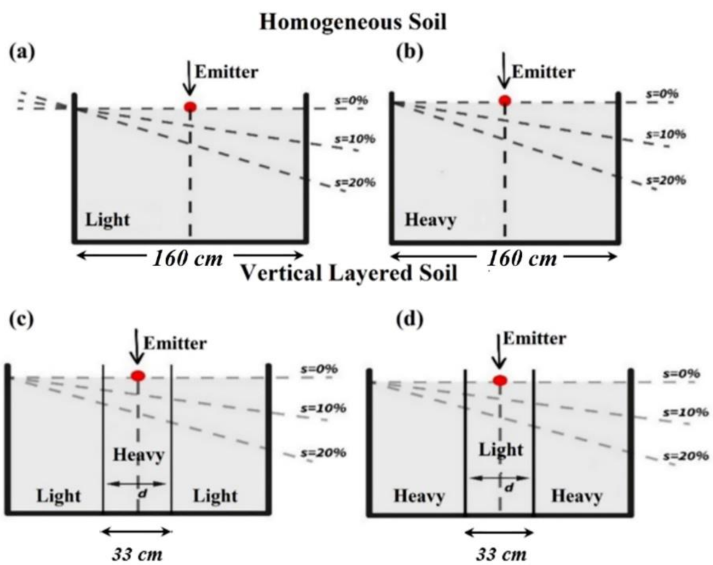

Figure 3. Schematic diagram of the experiments in the present research.

The wetting front was monitored for different periods depending on the emitter flow rate: 8 periods (5, 25, 45, 90, 180, 360, 540, and 720 min) for the 2 L/h emitter; 7 periods (5, 25, 45, 90, 180, 270, and 360 min) for the 4 L/h emitter; and 6 periods (5, 25, 45, 90, 135, and 180 min) for the 8 L/h emitter. A constant irrigation water volume of 24 L was used for all experiments. In each experiment, the contour lines at the mentioned periods were drawn on the tempered glass using a whiteboard marker. The t-test was used for statistical analysis and determination of the significance (or non-significance) of the difference between the homogeneous soil and the vertically layered soil in maximum wetted radius. Wetting pattern dimensions, the percentage of wetted area, and the complete shape of the wetting fronts were calculated and visualized using wetting pattern images and Grapher software (Version 7.0.1870) (Fig. 4). (R0: wetting radius of emitter for flat land, R_0^-: downstream wetting radius of emitter for slope land; R_0^+: Upstream wetting radius of emitter for slope land; R: wetting diameter; D: wetting depth; A: wetting area; A+: upstream wetting area of emitter for slope land, A-: downstream wetting area of emitter for slope land; β: the angle of inclination of the soil surface from the horizontal).

3. Results and Discussions

Figures 5 and 6 show the complete shapes of the wetting fronts in the studied soils. In all soil samples, changing the soil texture affected the wetting front. Changing the soil texture from L to LHL increased the width of the wetting front in all soil samples. Increases in soil slope and/or emitter flow rate enhanced the effect of changing the soil texture. In the LHL soil sample, with a decrease in soil infiltration rate, and also with an increase in soil slope and/or emitter flow rate, the wetting fronts had a greater opportunity to generate runoff, and the horizontal force of the flow component increased and further widened the wetting front. In addition, changing the soil texture from H to HLH caused increase in the infiltration rates of the In the LHL soil sample, with decrease in soil infiltration rate, and also with increase in soil slope and/or emitter flow rate, the wetting fronts had a greater opportunity to generate runoff and the horizontal force of the flow component increased and further widened the wetting front.

3.1. Maximum wetting front radius

Figure 7 shows the effects of changing the soil texture at various emitter flow rates on the maximum wetting front radius. Changing the soil texture from L to LHL at all emitter flow rates and all three studied slopes increased. R_0^-. Consequently, R_0^- at higher emitter flow rates. In addition, the horizontal flow component increased with increases in soil slope leading to larger R_0^- values. Besides the slope, the horizontal flow component was influenced by soil suction. Therefore, the increasing trend in R_0^- 10 to 20% slopes was affected by soil suction and its rising trend decreased.

R_0^- decreased when soil texture was changed from H to HLH. The average reductions in R_0^- at the studied slopes for emitter flow rates of 2, 4 and 8 L/h were 27, 32 and 41%, respectively. The saturated hydraulic conductivity of the soil with L texture was about 5 times higher than that of the soil with H texture. Consequently, c the hanging soil texture from L to H decreased R_0^-. The effect of changing soil texture became more pronounced with increases in emitter flow rates and the declining trend in R_0^- intensified.

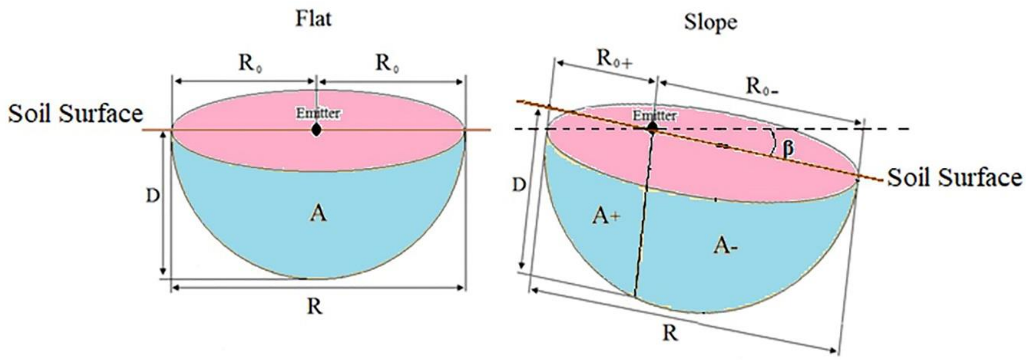

Figure 4. Schematic description of the moisture pattern distribution in flat and slope land.

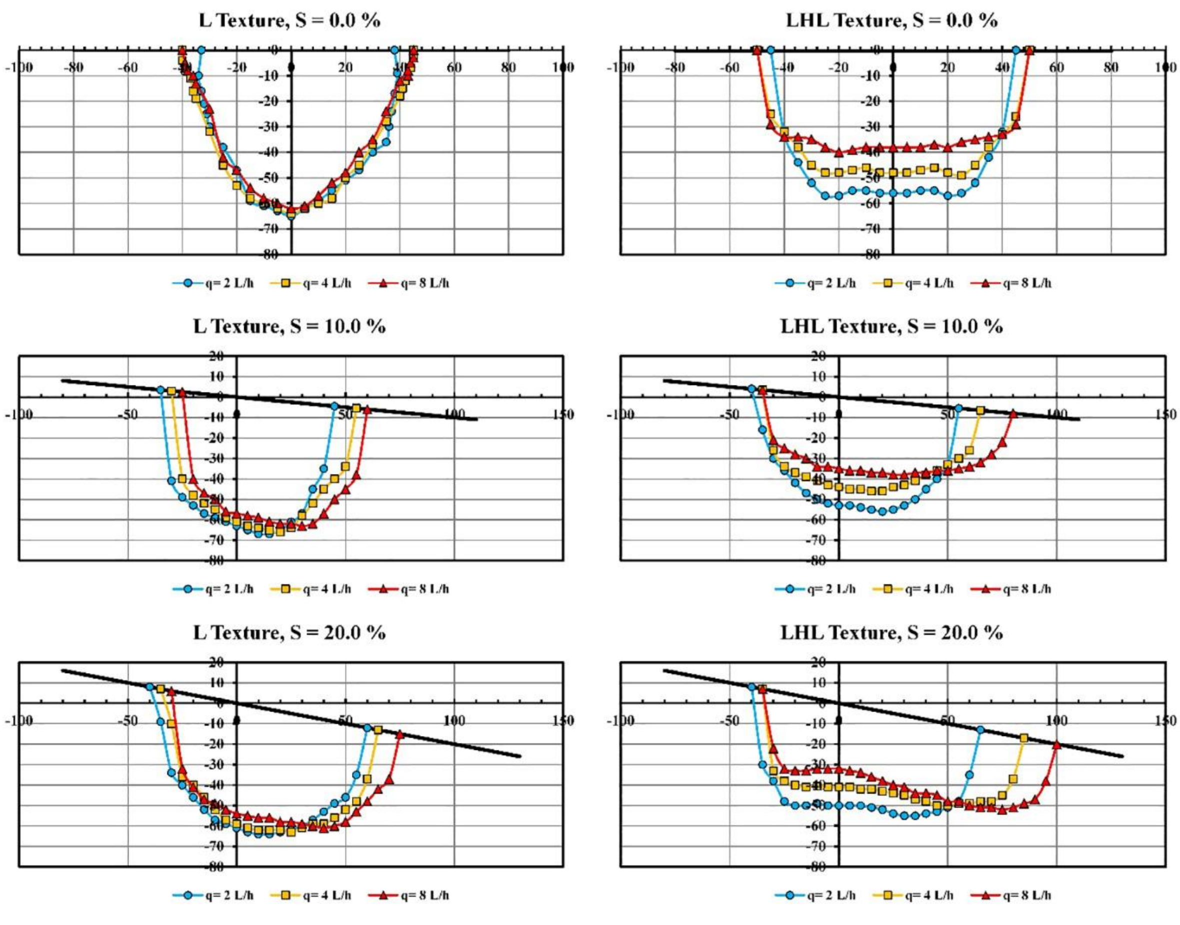

Figure 5. The shapes of wetting fronts in L and LHL soils at emitter flow rates of 2, 4 and 8 L/h and 0, 10 and 20% slopes.

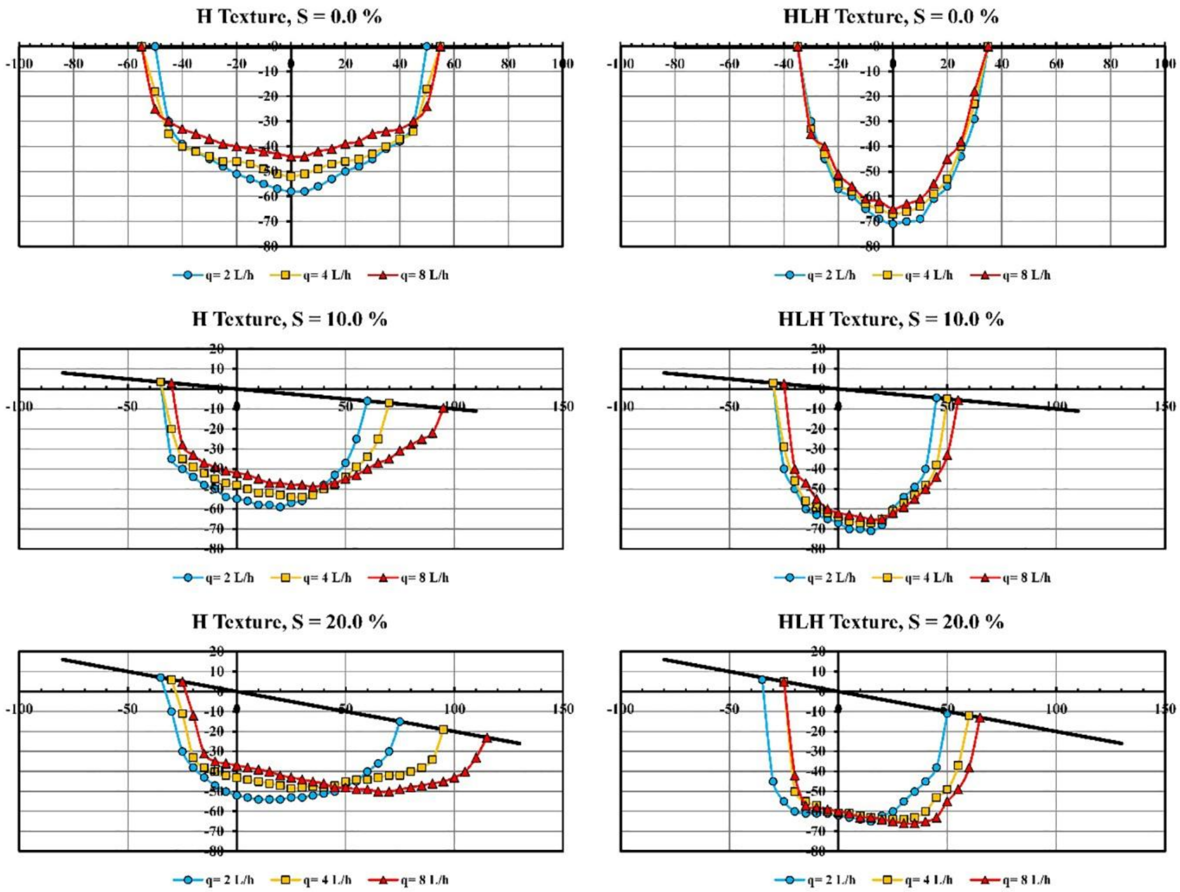

Figure 6. The shapes of wetting fronts in H and HLH soils at emitter flow rates of 2, 4 and 8 L/h and 0, 10 and 20% slopes.

3.2. Depth of the wetting front under the emitter

Figure 8 presents the effect of changing the soil texture on the depth of the wetting front (D) at the studied emitter flow rates and slopes. Changing the soil texture from L to LHL reduced D. The average reduction in D at emitter rates of 2, 4, and 8 L/h were 16%, 28 and 40%, respectively. Higher emitter flow rates increased the reduction in D.

A rising trend in changes in D was observed when the soil texture was changed from H to HLH. The increases in D at emitter flow rates of 2, 4, and 8 L/h were 22%, 35%, and 53%, respectively. D exhibited larger increases at higher emitter flow rates. As in the soil with L texture, in the soil with H texture, no considerable changes were observed in D at any of the emitter flow rates with an increase in slope, although the change in D showed an increasing trend.

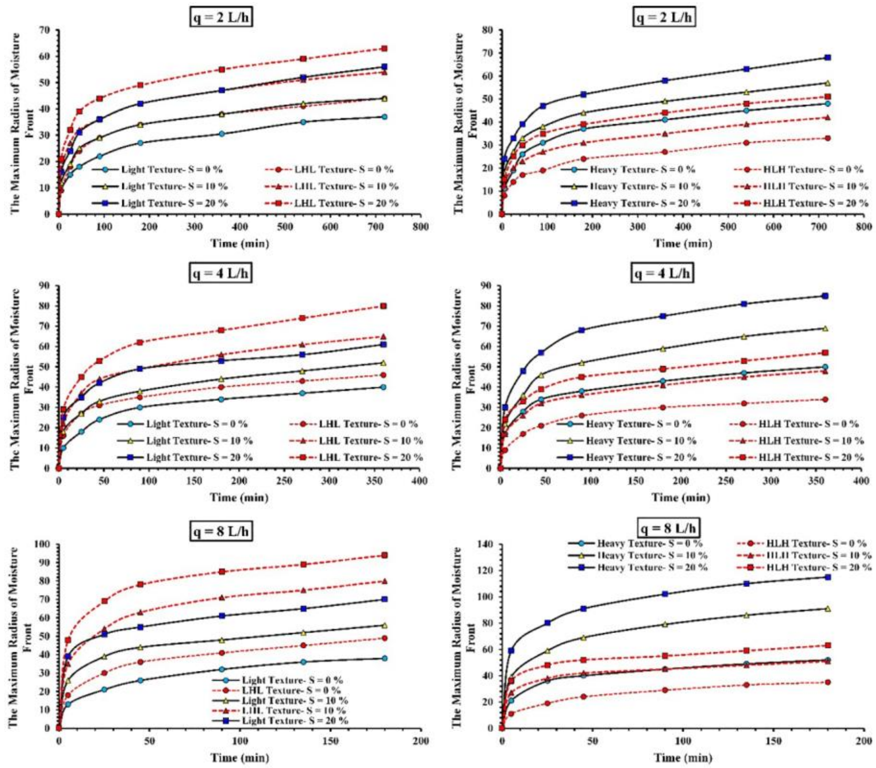

Figure 8. The effect of change in soil texture on the maximum wetting front radius ($\boldsymbol{R_0^-}$) at different emitter flow rates and soil slopes.

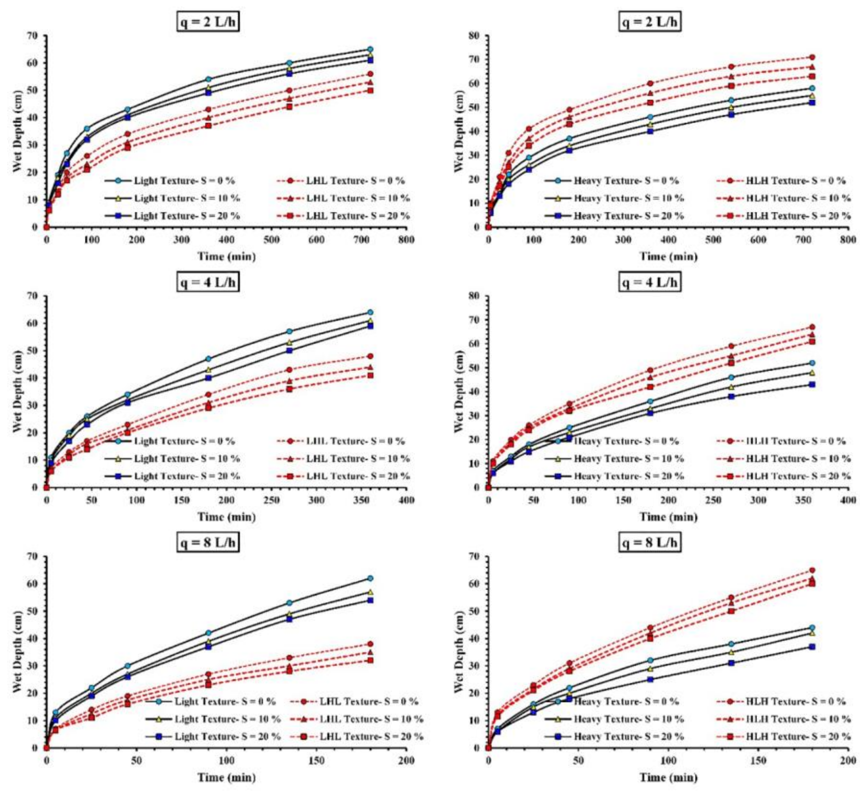

Figure 8. The effect of change in soil texture on wetting front depth (D) at different emitter flow rates and soil slopes.

3.3. Depth of the Maximum wetting front radius

The results of measuring the depth of the maximum wetting front radius in the studied soils are listed in Table 2. Changing the soil texture from L to LHL decreased the wetting front depth. A rising trend was observed in the reductions in wetting front depths at higher emitter flow rates or soil slopes, and the effect of changing the local soil texture became more pronounced. In addition, changing the soil texture from H to HLH increased the depth of the wetting front radius. This increase was enhanced at higher emitter flow rates and soil slopes.

Table 2. Effects of changing the soil texture on the depth of the maximum wetting front radius (cm) for different slope and emitter discharge.

Discharge (L/h) / Soil texture	S = 0 %			S = 10 %			S = 20 %		
	2	**4**	**8**	**2**	**4**	**8**	**2**	**4**	**8**
L	19.0	16.0	15.0	14.0	13.0	11.0	11.0	10.0	8.5
LHL	15.0	13.0	11.5	9.5	8.0	6.5	8.0	6.5	5.0
Changes (%)	**21**	**19**	**23**	**32**	**38**	**41**	**27**	**35**	**41**
H	14.0	12.0	11.0	9.0	8.0	6.0	7.5	6.0	4.5
HLH	16.0	14.5	12.0	13.0	12.0	10.0	11.5	10.0	9.0
Changes (%)	**-14**	**-21**	**-9**	**-44**	**-50**	**-67**	**-53**	**-67**	**-100**

3.4. The percentage of the wetted area

Table 3 shows the effects of changing the soil texture on the percentage of wetted area at different emitter flow rates and soil slopes. This percentage did not change considerably when the soil texture was changed from L to LHL. The difference was negligible, considering human errors in measurements and the impossibility of providing identical conditions for the two soil types. In addition, the percentage of the wetted area declined by less than 14% when the soil texture was changed from H to HLH, but there was no uniform trend in these changes.

Table 3. The effects of changing the soil texture on the wetted area (A) (cm2).

Discharge (L/h) / Soil samples	S = 0 %			S = 10 %			S = 20 %		
	2	**4**	**8**	**2**	**4**	**8**	**2**	**4**	**8**
L	3500	3600	3200	3900	3700	3600	4500	4200	3850
LHL	3400	3300	3200	4000	3800	3500	4300	4100	3900
Changes (%)	**2.9**	**8.3**	**0.00**	**-2.6**	**-2.70**	**2.8**	**4.4**	**2.4**	**-1.30**
H	4400	4200	3600	4600	4400	4100	4700	4550	4300
HLH	4050	3650	3350	4150	3850	3600	4350	4050	3850
Changes (%)	**7.95**	**13.10**	**6.94**	**9.8**	**12.5**	**12.2**	**7.5**	**11.0**	**10.5**

3.5. The percentage area on the two sides of the emitter

In both the L and the H soil samples, the percentage of the wetted area downstream of the emitter (A-) increased at higher emitter flow rates and soil slopes (Table 4). These results conform to those found by Thabet and Zayani 2008. The change in soil texture from L to LHL increased the percentage of the wetted area downstream of the emitter, but the percentage of wetted area downstream the emitter decreased when the soil texture was changed from H to HLH.

Table 4. Percentages of the wetted area on the two sides of the emitter in the studied soils.

Soil Texture	Emitter Discharge (L/h)	S = 0 %		S = 10 %		S = 20 %	
		A^-	A^+	A^-	A^+	A^-	A^+
L	**2**	51	49	60	40	63	37
	4	52	48	62	38	68	32
	8	49	51	66	34	72	28
LHL	**2**	49	51	62	38	68	32
	4	51	49	67	33	73	27
	8	48	52	73	27	78	22
H	**2**	52	48	66	34	70	30
	4	51	49	69	31	74	26
	8	48	52	73	27	81	19
HLH	**2**	50	50	57	43	64	36
	4	49	51	65	35	72	28
	8	48	52	70	30	78	22

In the HLH soil sample, the opportunity for the water to infiltrate into the soil improved with an increase in the infiltration rates. In these soil samples, an increase in soil slope led to the formation of wider wetting fronts, indicating the effect of the horizontal force of the slope on the wetting front, which was also reported by other researchers (Haggard et al. 2005; Huat et al. 2006; Patel and Rajput 2009). Moreover, in all of the studied soil samples, increases in emitter flow rate, especially on sloping surfaces, enhanced runoff potential and contributed to the further widening of the wetting front (Li et al. 2004; Thabet and Zayani 2008).

The average increases in R_0^- at the studied slopes at emitter flow rates of 2, 4 and 8 L/h were 18, 24 and 35%, respectively. The increasing trend in R_0^- up to the 10% slope but this increasing trend exhibited a small decline at 10 to 20% slopes. Changing the soil texture from L to H decreased water infiltration rate into the soil and increased runoff potential. Furthermore, increasing the emitter flow rate from 2 L/h to 8 L/h led to higher runoff potential.

The role played by changing the soil texture became more obvious with an increase in emitter flow rate, and soil infiltration was further limited due to the low water infiltration rate in the middle soil layer. At none of the emitter flow rates did the soil slope play a tangible role in the reduction in D, although D exhibited an increasing trend.

On flat land, the wetting front is circular. However, it is elliptical in sloping land, and the wetted area downstream of the emitter (A-) is larger than that upstream of the emitter (A+). The results of the present research agreed with those reported by Moncef and Khemaies (2016).

3.6.Statistical analysis of the t-test

The t-test was used for statistical analysis and determination of the significance (or non-significance) of the difference between the homogeneous soil and the vertically layered soil in maximum wetted radius. Table 5 presents the results of the t-test at a 95% confidence interval for four different soils. According to the results listed in this table, the homogeneous and vertically layered soils differed significantly in maximum wetted radius under the emitter in all four soils at the 5% level (P<0.05).

The t-test was used to determine whether the wetted depths under the emitter were significantly different for the homogeneous and vertically layered soils. Table 6 lists the results of the t-test at a 95% confidence interval for the four different soils. According to these results, there were significant differences between the studied soils in the maximum wetted depth under the emitter at the 5% level (P<0.05) in all the compared cases.

Table 5. Analysis of the t-test related to the comparison between homogeneous and vertically layered soils in maximum wetted radius.

Paired Samples Test	Variables	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig.(2-tailed)
					Lower	Upper			
Pair 1	L – HLH	4.44	1.50	0.50	3.28	5.60	8.83	8	0.000
Pair 2	H – HLH	24.55	13.16	4.38	14.43	34.67	5.59	8	0.001
Pair 3	L – LHL	-13.44	7.16	2.38	-18.94	-7.94	-5.63	8	0.000
Pair 4	H – LHL	6.66	5.89	1.96	2.13	11.19	3.39	8	0.009

Table 6. Analysis of the t-test concerning the comparison between the homogeneous and vertically layered soils in wetted depth under the emitter.

Paired Samples Test	Variables	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig.(2-tailed)
					Lower	Upper			
Pair 1	L - HLH	-3.77	1.56	0.52	-4.97	-2.57	-7.24	8	0.000
Pair 2	H - HLH	-16.55	4.21	1.40	-19.79	-13.31	-11.77	8	0.000
Pair 3	L – LHL	16.55	5.57	1.85	12.27	20.83	8.91	8	0.000
Pair 4	H - LHL	3.77	1.92	0.64	2.30	5.25	5.89	8	0.000

4. Conclusions

The results showed that changing the soil texture from L to LHL broadened the wet bulb, and changing it from H to HLH gave the wet bulb. The change in soil texture from L to LHL slightly changed the percentage of the wetted area but the average increase in the maximum radius of the wetting front downstream of the emitter (R_0^-) at emitter flow rates of 2, 4 and 8 L/h decreased by 18, 24 and 35% and the mean reductions in the wetting front depth (D) were 16, 28 and 40%, respectively. Moreover, changing the soil texture from H to HLH also slightly reduced the percentage of the wetted area but the average reductions in R_0^- for the mentioned emitter flow rates were 27, 32 and 41%, respectively, and the mean increase in D were 22, 35 and 53%, respectively. Moreover, the change in soil texture from L to LHL increased the percentage of the wetted area downstream of the emitter, whereas the change from H to HLH decreased it. On sloping lands, farmers change the soil texture around trees to match wetting front dimensions to root width and depth to reduce water loss. Consequently, changing the soil texture around the emitter from L to H, especially on sloping lands, increases the wetting front radius and decreases its depth, whereas changing the texture from H to L decreases the wetting front radius and increases its depth, thus reducing water loss.

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Conflicts of Interest

The author declares no conflict of interest.

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