Soil moisture distribution under trickle irrigation: a review

Arpna Bajpai and Arun Kaushal

ABSTRACT

The wetting pattern of soil under trickle (drip) irrigation is governed by soil texture, structure, initial water content, emitter spacing, discharge rate and irrigation frequency. For efficient management of trickle irrigation moisture distribution plays an important role. The degree of soil wetted volume in an irrigation system determines the amount of water required to wet the root zone. This article helps in understanding moisture distribution for different lateral spacing, emitter spacing, emitter discharge rates and drip line installation depth for trickle irrigation under various soil conditions all over the world. This review reveals that soil moisture distribution and uniformity within the soil profile were affected by the distance between emitters rather than the distance between drip lines. In drip irrigation systems, the less the dripper spacing, the greater the moisture distribution as well as water use efficiency and crop yield. The radial spread of moisture was greater at lower water application rates, whereas the vertical spread was greater at higher water application rates. The vertical movement of soil moisture was greater than the horizontal movement under surface as well as subsurface drip irrigation systems. Deeper drip tape installations had a potential risk of not providing moisture to shallow rooted crops.

Key words | discharge rate, drip line spacing, dripper spacing, soil moisture distribution pattern, trickle irrigation, wetting pattern

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INTRODUCTION

Water production enhancement has become a necessity in developing countries like India, where the ground water levels are decreasing at an alarming rate. The proportion of water used for agriculture in India is likely to diminish from the present level of 84% to 69% by 2025 with increasing demand from other sectors; but on the other hand the demand of water for agricultural purposes is estimated to increase to produce more food and fibre to fulfil the needs of the increasing population (Sivanappan 2016). The per capita availability of land has decreased from 0.34 ha in 1961 to 0.12 ha in 2015 (World Bank 2018). On the other hand, per capita water availability was assessed at more than 5,300 m^3 in 1951, had diminished to 1,588 m^3 in 2010, and is likely to be less than 1,500 m^3 by the year 2025 (Gautam 2016).The present day concern is the sustainable management and judicious use of water which can only be addressed by decreasing the cost of cultivation and maintenance through improving input use efficiency and by higher returns to the farmers. Trickle irrigation plays an important role in conserving water, fertilizer, labour, energy and electricity as well as increasing water and fertilizer use efficiency (Kumara & Palanisami 2010; Kaushal *et al.* 2012; Kumari *et al.* 2014; Sharma & Kaushal 2015; Rao *et al.* 2016; Rao *et al.* 2017; Rao *et al.* 2018). It had spread rapidly during the 1990s when it was used over 0.3 Mha, while present coverage in India is assessed at about 3.4 Mha (MIDH 2017). Trickle irrigation involves emitting water onto the soil at very low rates (2–20 litres/hour) from a system of small

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diameter pipes fitted with outlets called emitters. Water is applied close to plants so that only the part of the soil in which the roots grow is wetted. As applications are more frequent (usually every 1–3 days) than other irrigation methods, this results in a very favourable moisture level in the soil in which plants can flourish. With a subsurface drip irrigation system (SDI) the placement depth of laterals, emitter spacing, lateral spacing, discharge rate of emitters and system pressure all play an important role in the soil moisture distribution pattern and in delivering the required amount of water to the plant (Assouline *et al.* 2002; Lamm & Trooien 2005; Elmaloglou & Diamantopoulos 2008; Bozkurt & Mansuroglu 2011; Badr & Abuara 2013). Water is applied below the soil surface so water seeps from the emitters into the soil and spreads out towards the root zone. In a study by Njovu (2018), soil water stored in the root zone was determined by the volume of wetted soil. The water is delivered continuously in drops at the crop root zone and wets the root zone vertically by gravity and laterally by capillary action, thus helping to conserve water by reducing evaporative water losses in agricultural systems (Bainbridge 2001; Wei Wei *et al.* 2010).

Scientists, researchers, irrigation managers, farmers and environmentalists also prefer drip irrigation as its installation cost and maintenance requirements are lower than micro sprinklers. Also with drip irrigation the leaching of chemicals and the potential to contaminate groundwater can be minimized, whereas optimizing crop water uptake and application efficiency can be maximized. Soil texture has traditionally been the predictor of the wetted area and its shape in drip irrigation while soil structure has a pronounced effect. Thorburn *et al.* (2003) came to the conclusion that much variation in wetted dimensions can occur within a single textural class, depending on the soil structure. Camp *et al.* (1999) found that the efficacy of a subsurface drip irrigation system with the drip line placed below a compaction layer was poor, as water movement to the root zone was restricted. To achieve the best benefits and avoid leaching losses from drip irrigation, a precise design and an efficient irrigation schedule is important and that can be judged by the extent of the geometry of soil moisture distribution. One of the important parameters affecting water distribution to the plant in the field condition is the hydraulic characteristics of the drip irrigation system; therefore, it is essential to understand the hydraulic performance of drip irrigation systems in relation to soil moisture distribution. (Yaragattikar & Itnal 2003; Kaushal & Singh 2011; Bajpai & Saxena 2017; Reddy *et al.* 2018). It can be determined by the wetting pattern. An analytical solution known as 'wet up' can calculate the wetted perimeter for both surface and subsurface drip irrigation with the two assumptions that (a) hydraulic conductivity (K) is 1 $mmday^{-1}$; and (b) that the flow occurs from a point source (Cook *et al.* 2006). Wetted horizontal width indicates the optimum spacing and dripper spacing on a line. Wetted vertical depth allows the calculation of optimal time of application to minimize deep percolation loss of water, fertilizer loss and selection of the crop. It can also influence the root distribution pattern and the rate of plant water uptake (Junior *et al.* 2016). The wetted soil volume under an emitter as well as depth of rooting is also necessary to estimate the amount of soil water that can be available to a crop. (Liu *et al.* 2015; Ogaidi *et al.* 2016; Liua & Xu 2018). Galvez & Simmonds (2006) showed that wetted soil volume geometry under trickle irrigation takes an ellipsoidal-like shape when water is applied from a point source. Wetted soil shape under a point source is representative of most practical situations in trickle irrigation design. It was also measured theoretically by a number of authors (Matter 2002; El-Berry *et al.* 2003; Kandelous & Simunek 2010; Kandelous *et al.* 2011; Shan & Wang 2012; Singh *et al.* 2013).

The soil moisture distribution patterns showed that the vertical movement of soil moisture was greater than the horizontal movement under both surface and subsurface drip irrigation systems. (Lubana & Narda 2001; Ghobari & Marazky 2012). During infiltration, the soil water content changes both spatially and temporally, and redistribution of water in the soil strongly depends on the soil type, root distribution, rates of water application and irrigation methods (Daly & Porporato 2005).

The main objective of the present study is to understand the moisture distribution pattern for different lateral spacing, emitter spacing, emitter discharge rates and drip line installation depths for trickle irrigation under various soil conditions all over the world. This article also reviews the effect of the extent of the moisture wetting pattern (horizontal as well as vertical) on crop yield and water use efficiency for trickle irrigation.

FACTORS AFFECTING SOIL MOISTURE DISTRIBUTION UNDER SURFACE AND SUBSURFACE TRICKLE IRRIGATION

Effect of soil texture on soil moisture distribution

Cote *et al.* (2003) reported that for SDI with a drip line buried depth of 30 cm in sandy soil, the wetting pattern was elliptical in shape with the wetted depth larger than the wetted radius, resulting in 94% of the applied water below the emitter. For silty soil, the wetting pattern was roughly spherical.

Horizontal and vertical dimensions of the wetting front were observed by Rosa *et al.* (2004) as 28, 20 cm; 28, 25 cm and 28, 40 cm for 1, 1.8 and 3.4 lph discharge rates respectively in sandy loam soil for drip irrigated palm trees.

Soil wetting patterns under trickle irrigation studied by Aineeche *et al.* (2009) are presented in Table 1. It is seen from the table that as the volume of water applied increases, both the wetted width and the wetted depth increase. The maximum wetted width and depth was found in sandy soil followed by silt clay loam and loam soil for all volumes of irrigation water applied. The wetting front for sandy and clayey soils was studied by Salwa *et al.* (2010). The vertical wetting front was found to be greater in sandy soil as compared with clayey soil (36.07% more), while the horizontal wetting front was found to be greater in clayey soil as compared with sandy soil (13.08% more).

The shape and volume of wetted soil under trickle irrigation was reported by Nafchi *et al.* (2011). The average diameter of the wetted soil volume for clay, loam and sandy loam soil was observed as 49.12, 42.92, 22.29 cm; 62.58, 49.08, 40.22 cm; 66.50, 58.74, 48.11 cm and 71.75, 68.07, 50.12 cm for 2, 4, 8 and 12 lph water application rates respectively. The average diameter of the wetted soil volume was found to be greater in fine texture soils than in coarse texture soils.

Table 1 | Variation of soil moisture distribution pattern (wetted depth and wetted width) with soil texture for trickle irrigation

Soil texture	Irrigation volume applied (litre)	Wetted depth (cm)	Wetted width (cm)
Loam	2	10	5
	4	12	9
	6	15	12
Silt clay loam	2	10	14
	4	18	20
	6	20	25
Sand	2	37	15.5
	4	55	20
	6	60	25

The soil surface wetting pattern under trickle source irrigation in the arid lands of northeastern Badia was studied by Awwad *et al.* (2017). The soil surface wetted area in loam soil was 1.6–1.8 times that in sandy loam$_{77sand}$ soil; for silt loam soil it was 2.8–3.5 times that in sandy loam$_{77sand}$ soil; and it was 1.7–2.0 times that in the loam soil. Results revealed that the soil surface wetted area is directly proportional to the soil surface silt content, and increases approximately at the same ratio as the increase in silt content.

Effect of drip line spacing on soil moisture distribution

Galvez & Simmonds (2006) monitored three-dimensional water flow for lettuces under drip irrigation in sandy loam soil with laterals spaced at 65 cm and drippers spaced at 40 cm. The results showed that the impact of the compact soil layer was to reduce penetration of the wetting front to 25 cm depth, while there was homogeneous spread with the radial influence extending to 25 cm after irrigation and 30 cm after 24 hours.

In a study by Grabow *et al.* (2006), drip lines for SDI in sandy loam soil were buried at a depth of 0.25 m with laterals spaced at 0.91 and 1.82 m, and drippers spaced at 0.30 m. It was found that water moved laterally to the midpoint of both lateral spacings and vertically integrated to 0.53 m. Cotton yield and irrigation water use efficiency were 3.44 Mg ha^{-1}, 1.764 kg/m^3 and 3.22 Mg ha^{-1}, 0.980 kg/m^3 for 0.91 and 1.82 m lateral spacing respectively, which were statistically at par.

Soil moisture at different lateral spacing was measured by statistical indices for SDI in loam soil (Honari *et al.* 2017). The values of root mean square error and the normalized root mean square error for soil moisture were obtained as 0.0174 cm^3 cm^{-3}, 6.6% and 0.0178 cm^3 cm^{-3}, 6.3% for lateral spacings of 1.6 m and 1.2 m respectively for corn, while for wheat with a lateral spacing of 1.2 m it was 0.0190 cm^3 cm^{-3} and 7.5%.

Effect of drip line placement depth on soil moisture distribution

The moisture distribution pattern of SDI in sandy soil researched by Abedin (2006) indicated that a dripper line at 15 cm depth was better than 10 cm. At a depth of 15 cm the average moisture content was 10.6% up to a soil depth of 43 cm, whereas for a drip line at a depth of 10 cm the average moisture content was observed to be 9.4% up to a soil depth of 39 cm. The depth of wetting increased with the depth of placement of laterals as reported by Singh *et al.* (2006).

Soil water dynamics studied under subsurface drip irrigated onions in sandy loam soil by Patel & Rajput (2008) showed an elliptical shape wetting pattern when the drip laterals were placed deeper than 15 cm, and the wetted depth was observed to be larger than the surface wetting which caused high water content below the drippers. In a drip line at a depth of 10 cm and 100% irrigation level, the soil water content was observed to be 31% and 18% at 15 cm and 30 cm distance from the drip laterals, respectively, whereas at drip lateral depths of 15, 20 and 30 cm the soil surface remained relatively dry while a higher soil water content was observed at deeper soil depths viz. 24% and 26% at 45 cm and 60 cm depth respectively. The maximum onion yield (25.7 t ha^{-1}) was achieved with laterals at 15 cm depth, while the lowest yield (14.8 t ha^{-1}) was observed with laterals at 25 cm depth.

Douh *et al.* (2013) conducted research into the effect of SDI depth on soil water content distribution at different times after irrigation in sandy loam soil in Tunisia. The experiment consisted of three lateral placement depths at 5 cm (T1), 20 cm (T2) and 35 cm (T3). This study indicated that, after 6 hours of irrigation, for T1 the water content under the emitter reached 23%, for T2 the water content was 13% at 30 cm on either side of the dripper, whereas for T3 the water content was lowest, i.e. 15%, but increased to 21% at 40 cm on either side of the dripper. This experiment revealed that SDI at 35 cm depth could achieve higher efficiency rates with limited water to maximize maize yield, as the soil moisture content with laterals at 0.35 m (T3) depth was more uniform in comparison to that at 0.05 m and 0.20 m depth.

Soil moisture distribution under drip irrigated potatoes was investigated in Florida in sandy soil by Cabrera *et al.* (2016). The study consisted of two drip tape installation depths: surface at 0.05 m, and subsurface at 0.15 m. A lower yield and water use efficiency (19.9 Mg/ha, 7.4 kg/m^3) were found under 0.15 m irrigation depth as compared to 0.05 m (26.3 Mg/ha, 9.7 kg/m^3). As the surface drip irrigation had the drip line at a higher position in the soil profile compared to SDI, it resulted in an improved distribution of the soil moisture in the upper part of the soil profile, where 61–77% of the roots were located. The lower position of the drip line under the SDI reduced the soil moisture in the upper soil layer causing significant reduction of tuber marketable yield. This study showed that the shallow drip tape placement (0.05 m) was the most suitable position to irrigate the root zone to overcome poor capillarity.

Effect of discharge rate of dripper on soil moisture distribution

Skaggs *et al.* (2004) conducted a study on water infiltration and redistribution under drip irrigation on a sandy loam soil in California, USA. The research was conducted using 16 mm drip tubing with 30 cm emitter spacings, buried at a depth of 6 cm. Different rates of water application were applied i.e. 20, 40, and 60 L·m^{-1}. The root mean square error of redistribution of volumetric water content was observed as: 0.031 and 0.18 m^3 m^{-3} after 5.5 h and 28 h respectively for the water application rate of 20 L·m^{-1}; 0.027 and 0.013 m^3 m^{-3} after 10.75 and 31 h respectively for the water application rate of 20 L·m^{-1}; and 0.041 and 0.026 m^3 m^{-3} after 16 and 39 h respectively for the water application rate of 60 L·m^{-1}.

Ekhmaj *et al.* (2005) conducted research into the wetted surface radius under point-source trickle irrigation in sandy soil in Malaysia. The study revealed that the soil moisture decreased with the depth under the point of application, and also in the horizontal direction as the moisture was mostly stored within 0.2 m of the point source. The maximum wetted depth of 0.84 m was observed under the point source when irrigation was terminated for the 7 lph application rate, while the minimum wetted depth was 0.72 m for the 3.0 lph application rate. It was also reported that the wetted depth was greater than the maximum surface wetted radius for all application rates.

Thabet & Zayani (2008) conducted research into wetting patterns under trickle source irrigation in loamy sand soil in Tunisia, using two discharge rates of emitters i.e. 1.5 and 4 lph. The study observed that vertical movement of soil moisture was greater with the higher discharge rate i.e. 40 cm at 1.5 lph after 6 h water application whereas it was 52.5 cm at 4 lph after 6 h water application. However, after 3 h water application, the maximum wetted radius (30 cm) was observed with the lower discharge rate (1.5 lph), and the minimum (22 cm) at the higher discharge rate (4 lph).

Amer *et al.* (2010) conducted research to investigate the shape of the wetted soil volume for silt and clay soils, with different flow rates of 2, 4, 8, 16, and 24 lph and different operating times of trickle source irrigation for squash and grape crops in Egypt. The study revealed that the depth of wetted soil after soil-water redistribution was almost double the depth just after irrigation, but wetted soil width did not increase significantly. Higher emitter discharge rates increased wetted soil width but decreased wetted soil depth (Figure 1).

Kandelous *et al.* (2011) conducted research on soil water content distributions between two emitters of a SDI. The study revealed that the higher the emitter discharge the faster the horizontal wetting front advance while the vertical wetting front velocity was not so clear.

Molavi *et al.* (2012) reported that wetted bulb coordinates were the function of emitter discharge, water application time, average variation in volumetric water content and saturated hydraulic conductivity of soil. Shekhar *et al.* (2017) conducted an experiment in Samasthipur (Bihar, India) on soil moisture profile analysis under different discharge rates of drippers in sandy clay loam soil. The horizontal spread was observed to be about 25.4% and 47.8% greater when the emitter discharge rate increased from 2 to 4 lph and 2 to 6.0 lph respectively, whereas the vertical spread of water decreased with an increase in emitter discharge rate. The vertical spread decreased by 18% and 32% when the discharge rate was increased from 2 to 4.4 lph and 2 to 6.0 lph respectively. Saxena *et al.* (2018) reported that the maximum wetted radius at the soil surface as well as beneath the soil surface increased with an increase in emitter discharge rate, but the wetted depth showed a constant trend for vertisols. The variations in soil moisture distribution patterns (wetted width and wetted depth) with emitter discharge rate in different agro-ecological conditions are depicted in Table 2.

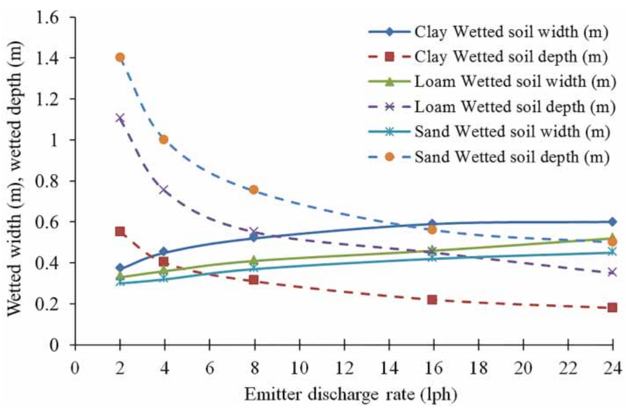

Figure 1 | Variation of wetted depth and wetted width with emitter discharge rate for trickle irrigation (*Source:* Amer *et al.* 2010).

Effect of emitter spacing on soil moisture distribution

Shan *et al.* (2011) studied wetting patterns for overlap zones under double point sources of drip irrigation. The study revealed that the wetting front increased with shorter emitter spacings. For 30 cm and 40 cm emitter spacings, the average volumetric water content was found to be 0.17, 0.15, 0.12 $cm^3\ cm^{-3}$ and 0.16, 0.13, 0.11 $cm^3\ cm^{-3}$ for 10 cm, 20 cm, and 30 cm distance from the drip line respectively. The wetting dimensions of the overlap zone for 10 l and 20 l irrigation volumes were observed as 60.5, 57 cm

Table 2 | Variation of soil moisture distribution pattern (wetted width and wetted depth) with emitter discharge rate for trickle irrigation

Emitter discharge rate (lph)	Soil texture	Wetted width (cm)	Wetted depth (cm)	Reference
2	Loam	185	–	Molavi *et al.* (2012)
	Sandy loam	210	–	
4	Loam	190	–	
	Sandy loam	220	–	
4	Loamy sand	76	44	Neshat & Nasiri (2012)
8		132	64	
24		246	135	
2	Clay loam	14.6	–	Subbaiah & Mashru (2013)
4		16.9	–	
8		18.4	–	
0.5	Vertisols	113	133	Saxena *et al.* (2018)
1		115	119	
2		132	119	
4		134	119	

and 60.4, 61 cm in horizontal and vertical directions respectively. The authors suggested selection of a shorter emitter spacing to increase the wetted area for improving water content and water use efficiency.

A study was carried out in Egypt on soil moisture distribution patterns under surface and subsurface drip irrigation systems in sandy soil by Badr & Abuara (2013). The experiment consisted of a combination of lateral and emitter spacings (100 cm, 50 cm), (100 cm, 30 cm), (75 cm, 50 cm) and (75 cm, 30 cm) at three lateral placement depths (0, 15 and 30 cm). Results showed that the change in the distance between lateral lines from 100 to 75 cm did not have any effect on soil moisture distribution. The study revealed that a SDI system at 30-cm soil depth is recommended as it represents the active root zone for most vegetable crops, and it also leads to better water saving in sandy soils. The soil moisture distribution under 30-cm dripper spacing was better than under 50 cm.

The effect of emitter spacing under drip irrigated sugarcane was studied by Huang *et al.* (2015). At emitter spacings of 30 cm, the wetted depth was 33.5 cm while at emitter spacings of 40 cm, the wetted depth was 31.5 cm. Studies recommend the emitter spacing of 30 cm for drip irrigation at the emitter discharge rate of 1.38 lph in latosols for sugarcane.

Effect of irrigation regime on soil moisture distribution

The soil moisture distribution pattern under drip irrigated Ber fruit in black soils was studied by Yaragattikar & Itnal (2003). The experiment consisted of different water application rates based on combinations of per cent wetted area (WA) and per cent pan evaporation (PE). The mean soil moisture content was 33.21% near the dripper and it decreased to 30.99, 27.48, 23.71 and 21.12% at 25, 50, 75 and 100 cm away from the emitter respectively. Irrespective of soil depth, the soil moisture percentage near the emitter for the lowest water application rate (20% WA and 25% PE) was 28.27%, and it was 37.32% for the highest water application rate (80% WA and 75% PE). The study revealed that the radial spread of moisture was greater at lower water application rates whereas the vertical spread was greater at higher water application rates.

Beniwal *et al.* (2006) conducted research into the effect of irrigation scheduling on moisture distribution under drip irrigated limes in Rajasthan for a loamy sandy soil. The experiment consisted of three irrigation levels, i.e. I_1 (ETc – Evapotranspiration coefficient), I_2 (0.7 ETc) and I_3 (0.4 ETc) and two lateral spacings of 20 cm and 40 cm with a dripper discharge of 4 lph. The soil moisture in the profile increased with increasing irrigation levels. The moisture content was higher at the 20 cm lateral spacing as compared with the 40 cm spacing. The vertical distribution of moisture content was observed to be lower at the surface and increased with increase in depth for all irrigation levels as depicted in Table 3. The results revealed that soil moisture decreased laterally, but increased vertically at each irrigation level. In addition, a higher increase in soil moisture was observed between 15 and 30 cm depth and thereafter it showed a uniform increase up to 60 cm.

Table 3 | Spatial distribution of volumetric soil moisture content (%) with different irrigation levels for trickle irrigation (ETc – evapotranspiration coefficient)

Irrigation levels/Soil depths (cm)	I_1 (ETc)		I_2 (0.7 ETc)		I_3 (0.4 ETc)	
	20 cm	40 cm	20 cm	40 cm	20 cm	40 cm
15	17	15	15	14	13	13
30	19	16	17	15.5	15	14
45	19	17	17.5	16.5	15	14.5
60	19	17	17.5	16.5	16	15

Shirahatti *et al.* (2007) conducted research into the impact of different methods of irrigation on yield levels of cotton in red soils in Karnataka, India. The experiment consisted of six drip treatments, i.e. T1 – 100% ETc and 100% Pw (percent area wetted), T2 - 100% ETc and 75% Pw, T3 - 75% ETc and 75% Pw, T4 - 100% ETc and 50% Pw, T5 - 75% ETc and 50% Pw, T6 - 50% ETc, and 50% Pw and control (surface irrigation). The highest yield was observed under T1 (1,235.0 kg/ha), the lowest yield under T6 (938.0 kg/ha) and under the control it was 962 kg/ha. The soil moisture distribution was highest under T1 (vertically it was 16.98–19.66% and laterally it was 19.66–15.36%) and under T6 it was 9.79–13.09% vertically and 13.85–12.50% laterally, and under the control it was just vertically 9.25–10.04%.

Ghobari & Marazky (2012) conducted research to evaluate the wetting patterns around drip and subsurface irrigation systems (DI and SDI) with three irrigation scheduling techniques (smart controllers, moisture sensors and manual control). The vertical movement of soil moisture was found to be higher than the horizontal movement under both DI and

SDI systems for 24 h after irrigation with all irrigation scheduling techniques. The trend of wetting for the manual control technique is shown in Figure 2. Soil moisture contour lines were found to be denser for the SDI system than the DI system in both lateral and perpendicular directions.

The effect of varying drip irrigation levels on soil water dynamics under drip irrigated broccoli in alfisol was studied by Jeelani *et al.* (2017). Soil moisture content was observed in five directions i.e. 22.5 cm downward and upward along the drip line, 22.5 cm right and left away from the drip line and at the dripper. The soil water content was observed as 0.37 and 0.39 $m^3\ m^{-3}$ for 0.4 and 0.8 CPE (cumulative pan evaporation) respectively for 22.5 cm downward along the drip line for 45–60 cm depth. A similar trend was observed for the other four directions. The soil water content showed an increasing trend from 0.4 CPE to 0.8 CPE. Highest yield and water use efficiency was observed at 0.8 CPE (6.59 Mg/ha, 19.82 $kg\ ha^{-1}\ mm^{-1}$) and the lowest at 0.4 CPE (5.46 Mg/ha, 18.24 kg -$ha^{-1}\ mm^{-1}$).

Effect of duration of water application on soil moisture distribution

The effects of emitter rate on drip irrigation water distribution patterns in sandy loam soil were studied by Skaggs *et al.* (2010). This study showed that low antecedent soil water content and low application rates increased the relative horizontal to vertical water spreading and this increase was attributed to the longer irrigation time instead of flow rates. Phull & Babar (2012) reported that wetted soil width and depth depends on the duration of water application and both of these increase with time. A greater wetted depth was observed compared to wetted width (Figure 3) for loamy sand mixed soil.

Zhang *et al.* (2012) conducted research into sandy loam soil wetting patterns of drip irrigation. The results showed that a higher application rate produces a larger surface wetted radius when the drip irrigation times are the same. At 8 h after irrigation the wetted radius was observed to be 50, 40, 40, 38, 30 and 20 cm for 3.9, 1.9, 1.7, 1.5, 1.2 and 0.5 lph emitter discharge respectively. The vertical wetted depth showed no difference from the beginning to 0.1 h, after which it increased with the increase of emitter flow. At 8 h after irrigation the wetted depth was observed to be 40, 30, 30, 25, 20 and 28 cm for 3.9, 1.9, 1.7, 1.5, 1.2 and 0.5 lph emitter discharge respectively. Kyada & Munjarappa (2013) reported that for clay loam soil the wetted width increases rapidly at the start of irrigation, but the increase was found to be very slow later on. A summary of the variation in soil moisture distribution patterns (wetted width and wetted depth) with irrigation duration in different agro-ecological conditions is given in Table 4.

Okasha *et al.* (2015) conducted research into the effect of different types of irrigation systems on soybean production

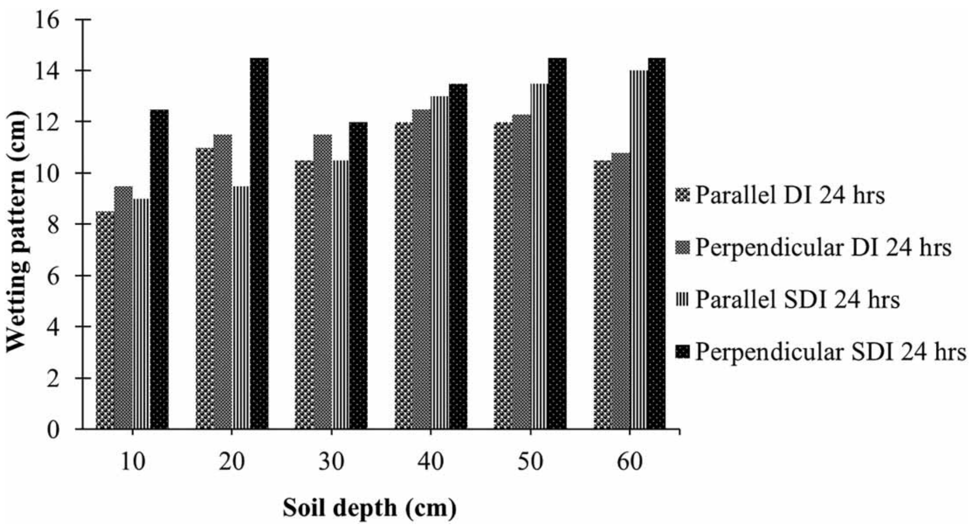

Figure 2 | Wetting patterns in parallel and perpendicular directions under drip and subsurface drip irrigation systems with manually controlled irrigation after 24 hours (*Source:* Ghobari & Marazky 2012).

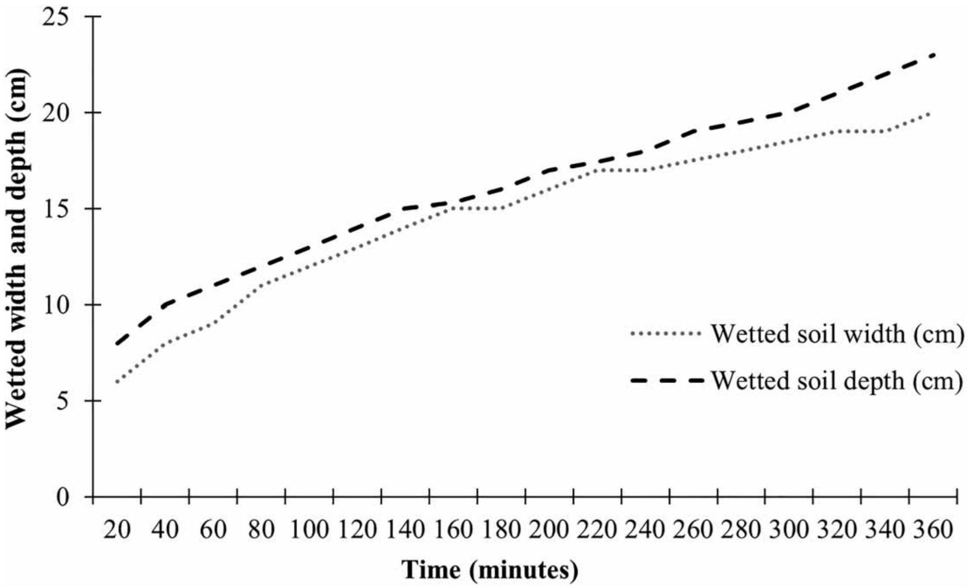

Figure 3 | Variation of wetted depth and wetted width with irrigation duration for trickle irrigation (*Source:* Phull & Babar 2012).

in clayey soil conditions in Egypt. The experiment consisted of continuous drip irrigation, pulse drip irrigation of 15 min on/15 min off, pulse drip irrigation of 20 min on/20 min off, and the four operating pressure head levels were 6, 5, 4, and 3 m. The wetted soil width increased with increasing operating pressure head, while the wetted soil depth decreased.

Table 4 | Variation of soil moisture distribution patterns (wetted depth and wetted width) with irrigation duration for trickle irrigation

Irrigation duration (h)	Discharge rate (lph)	Wetted width (cm)	Wetted depth (cm)	Location and soil type	Reference
3.2	4	16	17	Pakistan, loamy sand mixed	Phull & Babar (2012)
4.2		17	19		
6		20	23		
1	2	12	36	India, clay loam soil	Kyada & Munjarappa (2013)
2	2	23	41		
3	2	31	48		
4	2	36	52		
5	2	44	56		
1	4	26	44		
2	4	28	50		
3	4	38	52		
4	4	45	55		
5	4	55	60		
0.166	4	9.1	3.21	India, sandy loam soil	Reddy *et al.* (2018)
1.23		21.67	17.56		
1.5		24.78	22.67		
2		26.12	24.44		
2.33		28.22	27.5		

Pulsed drip irrigation achieved low values of wetted soil width when compared with continuous drip irrigation. The highest yield and water use efficiency were observed with pulse drip irrigation of 15 min on/15 min off at 6 m pressure head with a wetted width of 0.247 m (1,617.2 kg/fed, 0.54 kg/m^3). The lowest water use efficiency was observed (0.27 kg/m^3) under pulse drip irrigation of 20 min on/ 20 min off at 4 m pressure head with a wetted width of 0.207 m and the lowest yield with continuous drip irrigation at 4 m pressure head (650 kg/fed).

CONCLUSIONS

Soil moisture distribution under surface and subsurface trickle irrigation depends on soil texture, drip line spacing, drip line placement depth, discharge rate of emitter, emitter spacing, irrigation regime and duration of water application.

The wetting pattern shape is elliptical and spherical for sandy and silty soil respectively under subsurface drip irrigation. Under drip irrigation the vertical wetting front is greater in sandy soil as compared with clayey soil (36.07% greater), but the horizontal wetting front in clayey soil is greater as compared with sandy soil (13.08% greater). In a subsurface drip system in sandy loam soil for a lettuce crop, the water moved laterally to the midpoint of the drip line spacing and vertically integrated to a depth of 0.53 m. The depth of wetting increased with the depth of placement of laterals. For subsurface drip irrigation lateral placement depths of 15 cm, 35 cm and 5 cm are best for onion, maize and potato (a shallow rooted crop) respectively.

Under drip irrigation a higher emitter discharge rate favours both vertical and lateral movement of water in clayey and loam soils. In loamy soil, vertical movement of soil moisture was greater at a higher discharge rate while the wetted radius was greater at a lower discharge rate. For silt and clayey soil the depth of wetted soil after soil-water redistribution is almost double the depth just after irrigation, but wetted soil width does not increase significantly.

Under surface drip irrigation in silt loam soil the wetting front increased with shorter emitter spacing. Under surface and subsurface drip irrigation for sandy soil, moisture distribution with 30 cm dripper spacing is better than at 50 cm spacing. Emitter spacing of 30 cm for sugarcane is better when compared to 40 cm spacing in latosol soils with an emitter discharge rate of 1.38 lph.

A higher cotton yield was achieved under DI 100% ETc (1,235 kg/ha) with a moisture content of 15.36% at 30 cm distance from the emitter, and a lower yield was observed under DI 50% ETc with a moisture content of 12.50% in the same position. Soil water content also showed an increasing trend in alfisol from 0.4 CPE (0.37 $m^3\ m^{-3}$) to 0.8 CPE (0.39 $m^3\ m^{-3}$). The highest broccoli yield and water use efficiency were observed under 0.8 CPE (6.59 Mg/ha, 19.82 kg $ha^{-1}\ mm^{-1}$) and the lowest under 0.4 CPE (5.46 Mg/ha, 18.24 kg -$ha^{-1}\ mm^{-1}$).

Soil moisture contour lines were found to be denser for the sub surface drip irrigation system than the surface drip system in both lateral and perpendicular directions for all irrigation scheduling techniques. Under a drip irrigation system in clayey soil, initially the surface radius increases rapidly and later on increases very slowly. Wetted soil width and depth depend on duration of water application, and both of these increase with time. Wetted depth was observed to be greater than wetted width for loamy sand mixed soil. Wetted soil width increased with increasing operating pressure head, while wetted soil depth decreased. For a soybean crop under clayey soil conditions the highest yield and irrigation water use efficiency were observed at a pressure head of 6 m with pulse drip irrigation of 15 min on/15 min off as compared to lower heads with a continuous drip irrigation system. Soil moisture decreased laterally, but increased vertically at each irrigation level and a higher increase in soil moisture was observed between 15 and 30 cm depth and thereafter it showed a uniform increase up to 60 cm.

This study will help in understanding soil moisture distribution for different lateral spacing, emitter spacing, emitter discharge rates and drip line installation depths for trickle irrigation in various soil conditions to achieve better irrigation design, optimum use of water and for maximum water productivity with reduced cost. There is still a need to carry out further studies to see the effects of all the above-mentioned factors on soil moisture distribution under trickle irrigation for different agro-ecological regions of the world and for various crops as all these factors play a vital role.

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