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IMPACT OF THE INSTALLATION DEPTH ON THE PERFORMANCE OF SUBSURFACE IRRIGATION SYSTEM AND ITS MODIFIED VERSION "KISSS" COMPARED TO THE SURFACE DRIP IRRIGATION SYSTEM

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ABSTRACT

Precision application of irrigation water, which is a key factor in improving water use efficiency as well as the quantity and quality of agricultural products, can be achieved through the application of modern irrigation technologies. Therefore, the objective of this research was to study the performance of subsurface irrigation system (SIS) and its modified version (the KISSS) installed at different soil depths against the conventional surface drip irrigation (SDI). The experimental work of this study was conducted on a field located in the Educational Farm of the College of Food and Agriculture Sciences of King Saud University, Riyadh, Saudi Arabia. Five irrigation systems were investigated in this study representing (i) the SDI, (ii) the SIS at 15 cm installation depth (SIS-15), (iii) the SIS at 25 cm installation depth (SIS-25), (iv) the KISSS at 15 cm installation depth (KISSS-15) and (v) the KISSS at 25 installation depth (KISSS-25). Experiments were conducted under two irrigation levels: (i) Level 1: 4 L h^{-1} × 2 hours, referred as 100% irrigation level, and (ii) Level 2: 4 L h^{-1} × 1 hour, referred as 50% irrigation level. The results indicated that the five tested irrigation systems responded significantly to the irrigation level and the elapsed time after the application of irrigation water. Also the results revealed that the distribution of soil moisture across the soil profile was significantly influenced by the installation depth of the laterals. When installed at the same soil depth, the modified KISSS showed the best results of soil moisture distribution compared to the SDI and SIS. The KISSS-15 and KISSS-25 distributed soil moisture in the horizontal direction more uniformly compared to the other systems as indicated by the high values of the coefficient of uniformity. On the other hand, the KISSS showed the highest moisture values in the upper part of the soil profile (soil depth ≤ 20 cm) and the lowest values of soil moisture values in deep locations (20 – 50 cm). These results imply that the KISSS improves the upwards movement of water and minimizes the deep percolation losses of irrigation water. Based on the best results of KISSS in terms of efficient distribution of soil moisture across the soil profile, especially in the horizontal direction; it is recommended to adopt the modified capillary irrigation subsurface system at depths commensurate with different crops.

Keywords: capillary irrigation, subsurface irrigation, installation depth, uniformity coefficient.

INTRODUCTION

The agricultural sector utilizes about 80% of total water resources on the global scale, and about 90% in Saudi Arabia (Multsch *et al.*, 2011). Severe arid conditions constrained agricultural production in the Arabian Peninsula. Except for the southwestern mountains, the average annual precipitation in the Kingdom of Saudi Arabia ranges from 80 mm to 140 mm; with maximum temperatures (in summer) often exceed 45 °C, very low relative humidity and clear skies most of the time (Alkolibi, 2002).

The use of modern technologies (e.g. sprinkler, drip and pot irrigation methods) in addition to the well planned irrigation systems (i.e. efficient irrigation systems) is a key factor in avoiding excessive irrigation which leads to wasting water as well as its negative impact on the performance of the cultivated crops. Connellan (2002) summarized the four major principles that need to be taken into consideration for efficient irrigation system as that: (i) the quantity of irrigation water must be optimum for both crop and soil, (ii) the irrigation schedule should match crop water requirements under various weather conditions, (iii) the irrigation water should be applied in a uniform and efficient manner, and (iv) the irrigation water must be precisely applied to the crop root zone; hence, water losses through runoff, deep percolation and poor coverage, will be minimized. Precise application of irrigation water improves water use efficiency and watering uniformity; hence, improves crop yield quantitatively and qualitatively (Singh and Rajput, 2007).

Drip (trickle) irrigation, refers to the application of water to the soil surface as drops or tiny streams through emitters (ASAE STANDARDS, 2003), is used to apply water and fertilizers on the soil surface (surface drip irrigation - SDI) or directly to the plant root zone (subsurface drip irrigation "or subsurface irrigation system" - SIS). The advantages of SIS over other irrigation systems have been reported by many scientists. Lamm (2002) summarized the major advantages of SIS related to irrigation water as that: (i) it increases water use efficiency by minimizing or eliminating evaporation, runoff and deep percolation, (ii) it minimizes water quality hazards by reducing runoff into streams and in addition to the less leaching of chemicals as a result of deep percolation, and (iii) it improves soil watering uniformity. Subsurface irrigation system (SIS) provides the highest water application efficiency (about 97%) compared to other irrigation systems, such as the Low Energy Precision Application (LEPA) center pivot (95%), the Low Elevation Spray Application (LESA) center pivot (88%), the Mid-Elevation Spray Application (MESA) center pivot (78%), and the furrow irrigation system (60%), Amosson *et al*. (2011). Yield response of various crops to different irrigation types was investigated by many scientists and researchers, and the results indicated that crop yield was the highest and water requirement was the lowest for SIS compared to other irrigation systems (Camp, 1998).

The subsurface irrigation system (SIS) has been further modified by adding impermeable membrane to improve the wetting pattern and to minimize the amount of water losses through deep percolation (i.e. inaccessible water to plants), and the modified SIS was first commercialized as a “Capillary Root Zone Irrigation (CRZI)” product; then after further development, the CRZI is currently available under a commercial name “Kapillary Irrigation Subsurface System (KISSS^{TM})”, Devasirvatham (2014). A well installed and managed KISSS, showed many advantages compared to conventional subsurface irrigation systems including the improvement in wetting pattern and uniformity in addition to savings of significant amounts of irrigation water and the reduced environmental risks through drainage (runoff) and deep percolation; while overwatering and soil saturation processes are associated with the improper implemented KISSS (Devasirvatham, 2009; Sarte, 2010).

A considerable research work to develop guidelines for using the KISSS under different soils and climates, have been done worldwide. Yiasoumi et al. (2008) reported that KISSS applied water directly to the root zone of plants with minimum water losses through runoff, evaporation and deep percolation compared to conventional drip irrigation systems. Guenter and Sullings (2010) reported that the KISSS which uses a unique geo-textile mat, increases water savings through the optimum distribution of sub-soil moisture (i.e. optimum water efficiency); hence, the KISSS is considered as most efficient compared to other irrigation systems, such as: sprinkler, furrow, conventional subsurface irrigation and drip irrigation.

The application uniformity of drip irrigation systems can be expressed by several uniformity parameters, such as the coefficient of uniformity, the distribution uniformity, the emitter flow variation, and the coefficient of variation of emitter flow (Safi *et al*., 2007). However, measurement of emitter discharge for a representative sample of emitters in a drip irrigation system is required for most of the uniformity coefficients (Camp *et al.*, 1997). The major parameters that can significantly affect the water use efficiency include the water application rate and design components of the irrigation system such as the size, depth, and spacing of pipes; as they have direct effects on water losses through deep percolation and soil saturation process (Al-Ghobari and El Marazky, 2012).

The key design parameters affecting the performance of the subsurface irrigation system (SIS) include the discharge capacity, the flow velocity, the drip-line spacing and the installation depth of the drip-line. These parameters significantly affect the uniformity of water spread, deep percolation and the potential to soil evaporation. Therefore, the major objective of this study was to evaluate the effect of the installation depth of subsurface and capillary subsurface irrigation systems on soil water distribution, across the parallel and vertical directions to the drip line, compared to the conventional surface drip irrigation system.

MATERIALS AND METHODS

Experimental site

A field study was conducted on an experimental area of “26 m × 11 m” located at the Educational Farm of the College of Food and Agriculture Sciences of King Saud University, Riyadh, Saudi Arabia with geographical coordinates of 24º:44′:11″ N and 46 º:37′: 04″ E. To describe the soil of the experimental field, composite soil samples at various soil depths were collected and subjected to laboratory analysis for soil texture; in addition to soil field capacity and wilting point, which were determined using gravimetric methods described by Johnson (1962). The soil of the study field was classified as sandy soil with other characteristics presented in Table 1.

Table-1. Soil characteristics of the experimental field.

Soil texture	Coarse sand: 76.4%, Fine sand: 12.3%, Silt: 7.5%, and Clay: 3.8%
Soil field capacity (Θ_{fc})	12.88%
Soil wilting point (Θ_{wp})	4.25%
Soil pH	7.81
Soil EC (dS m^{-1})	1.61

Laboratory evaluation of laterals

Three types of irrigation systems were adopted in this study, namely: a conventional surface drip irrigation (SDI) system, a subsurface irrigation system (SIS) and a Kapillary subsurface irrigation system (KISSS). The two lateral types used in this study (Fig. 1), namely: (i) the REHN lateral type used for the SDI and SIS systems, and (ii) the specialized KISSS lateral; were first evaluated in the laboratory at a constant discharge rate of about 4 L h^{-1}.

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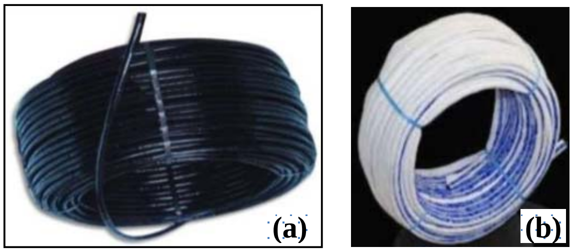

Figure-1. The utilized laterals: (a) REHN type lateral, and (b) KISSS type lateral.

Each lateral type was tested in a system of three lateral segments of 3 m length, a pump, a water tank, a valve and a pressure gauge, as shown in Figure-2. Each lateral type has six emitters with 50 cm spacing between them. The two lateral systems were tested at two pressures (0.5 and 1.0 bar) for an operating time of 5 minutes, and replicated three times for each pressure. The volume of water in all catch cans was recorded and the discharge rate of each of the tested emitters for both lateral types was calculated accordingly, using Equation (1).

$$Q = \frac{V}{t} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

Where:

Q = discharge rate (L h^{-1}); V = volume of water in cans (L); and t = application time (h).

Figure-2. Laboratory evaluation of the laterals used for the tested irrigation systems.

Experimental layout

Three drip irrigation systems were tested in this study, namely: (a) the conventional surface drip irrigation (SDI), (b) the subsurface irrigation system (SIS), and (c) the Kapillary irrigation subsurface system (KISSS). The laterals for the SIS and KISSS systems were installed at two depths under the soil surface; these depths were 15 and 25 cm. Hence, five irrigation systems were investigated in this study representing: (1) the SDI, (2) the SIS at 15 cm installation depth (SIS-15), the SIS at 25 cm installation depth (SIS-25), the KISSS at 15 cm installation depth (KISSS-15) and the KISSS at 25 installation depth (KISSS-25). Experiments were conducted under two irrigation levels: (i) Level 1: 4 L h^{-1} × 2 hours, referred as 100% irrigation level, and (ii) Level 2: 4 L h^{-1} ×1 hour, referred as 50% irrigation level. As shown in Figure-3, each system was designed and installed in one of the five field plots of the three replicates (R_1, R_2 and R_3). Each plot comprised three laterals (each of three meters length). The laterals were connected to PVC sub main laterals, which were connected to a galvanized steel main line. The main line, sub main line and lateral lines were placed above or below the ground surface according to the irrigation system used in the study.

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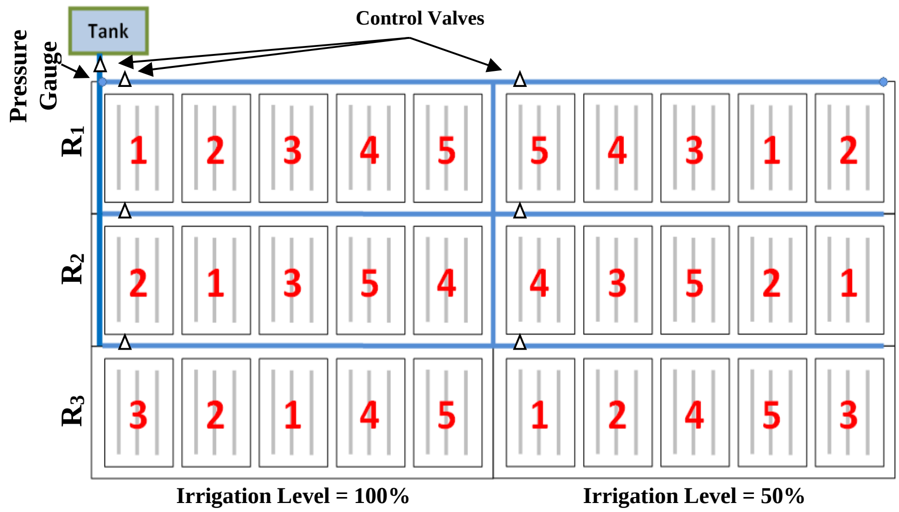

Figure-3. Experimental layout.

Soil moisture measurements

Soil water contents at specific depths were measured for the assessment of soil moisture spatial patterns exhibited by the five tested drip irrigation systems as described by Guber *et al*. (2008). Soil moisture observations through the soil profile were collected, using the volumetric soil moisture sensor (Model: WaterScout SM100), at different locations in the direction of the lateral lines (parallel) at distances of 0, 10, 15 and 25 cm from the Emitters, and in the direction perpendicular to the Emitters at depths of 7.5, 20, 30 and 50 cm, as shown in Figures 4, 5 and 6. Measurements were taken for two elapsed times of 24 and 48 hours after the application of irrigation water.

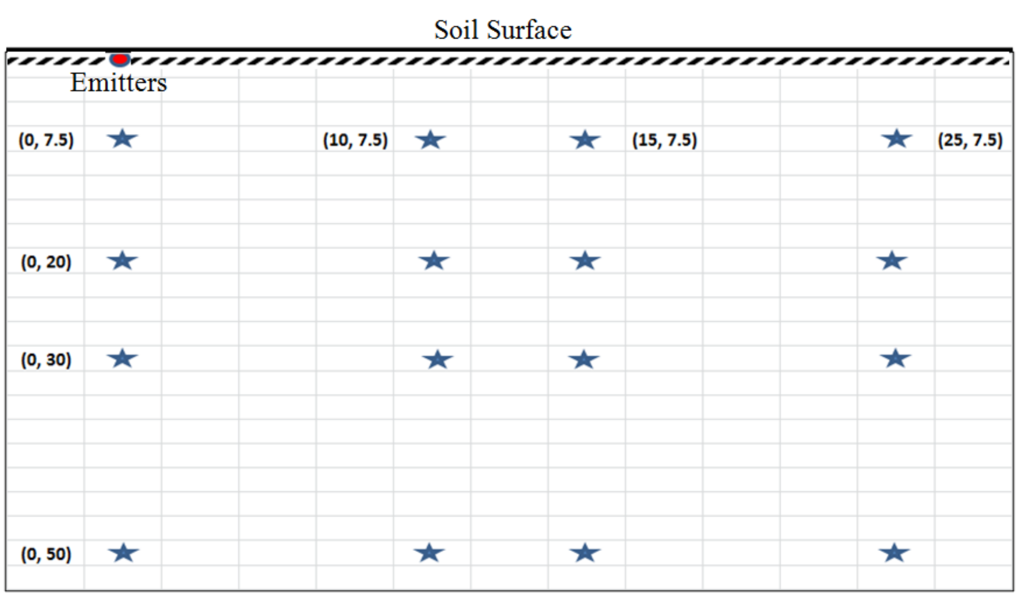

Figure-4. Sampling locations with respect to the Emitters for soil moisture measurements for the SDI system.

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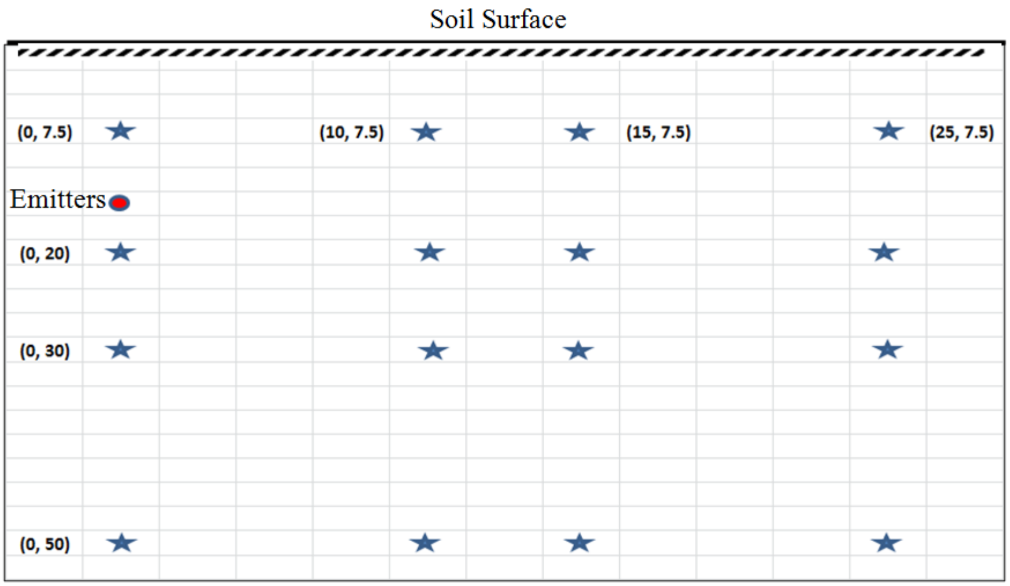

Figure-5. Sampling locations with respect to the Emitters for soil moisture measurements for both the SIS-15 and the KISSS-15.

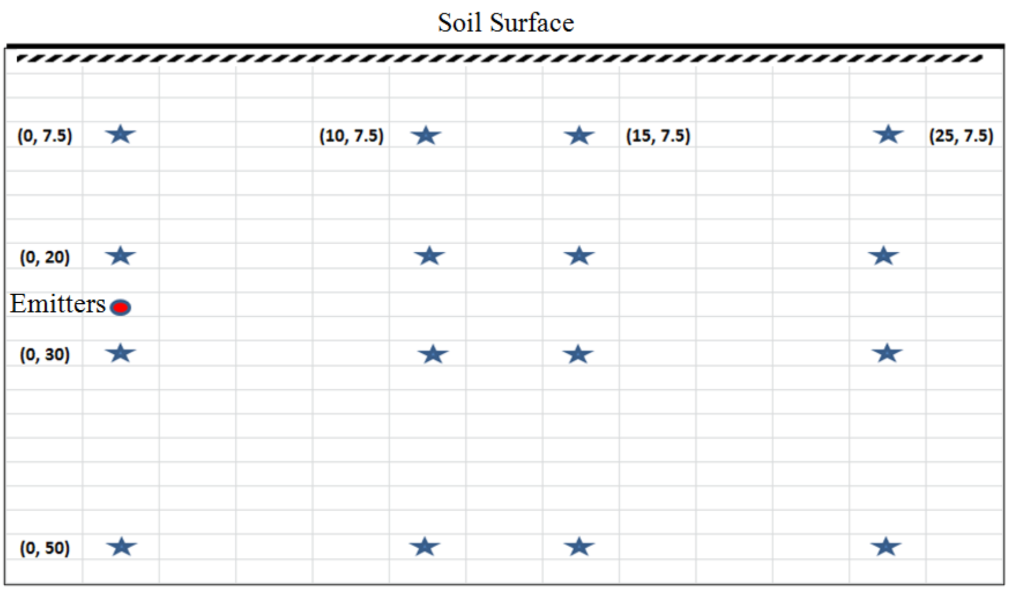

Figure-6. Sampling locations with respect to the Emitters for soil moisture measurements for both the SIS-25 and the KISSS-25.

Field evaluation of water application uniformity

The collected observations of soil moisture from different locations in the parallel and perpendicular directions with respect to the Emitters were used to determine water application uniformity of each of the five investigated drip irrigation systems. Coefficient of uniformity (C_u) as shown was determined, using Equation (2), by utilizing the average data of soil moisture measurements collected at 4 depths in a direction perpendicular to the laterals (7.5, 20, 30 and 50 cm) and at four distances in a direction parallel to the laterals (0, 10, 15 and 25 cm). These average values were calculated for each of the two irrigation levels (50% and 100%), and for the two elapsed times (24 and 48 h).

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$$CU = \left\{1 - \frac{\sum_{i=1}^{n}|X_i - \bar{X}|}{n\bar{X}}\right\} \times 100 \quad (2)$$

Where

CU = Coefficient of uniformity (%).
X_i = Soil moisture reading.
$\bar{X}$ = Average moisture reading in vertical and horizontal direction.

RESULTS AND DISCUSSIONS

Laboratory evaluation of emitters

Two lateral types used in this study, namely: the KISSS lateral and the REHN lateral type were subjected to intensive performance evaluation in the Laboratory. The average results of the discharge rate (L h^{-1}), coefficient of uniformity - CU (%), and coefficient of variations - CV (%) for the two utilized lateral systems (REHN and KISSS) under two operating pressures are presented in Figure-7. It was observed that the discharge rate, for both systems, increased significantly with the increase in the operating pressure. Under the lowest operating pressure (0.5 bar), the KISSS system resulted in higher discharge rate (2.421 L h^{-1}) compared to the REHN system (2.304 L h^{-1}) but with low CU and high CV values. While, under the highest operating pressure (1.0 bar), the KISSS system resulted in a discharge rate (4.043 L h^{-1}) which was approximately equal to that of the REHN system (4.085 L h^{-1}), with high CU and low CV values. Therefore, the results of this study showed that the REHN lateral exhibited the best results under low operating pressure, while the KISSS system showed the best results under high operating pressure.

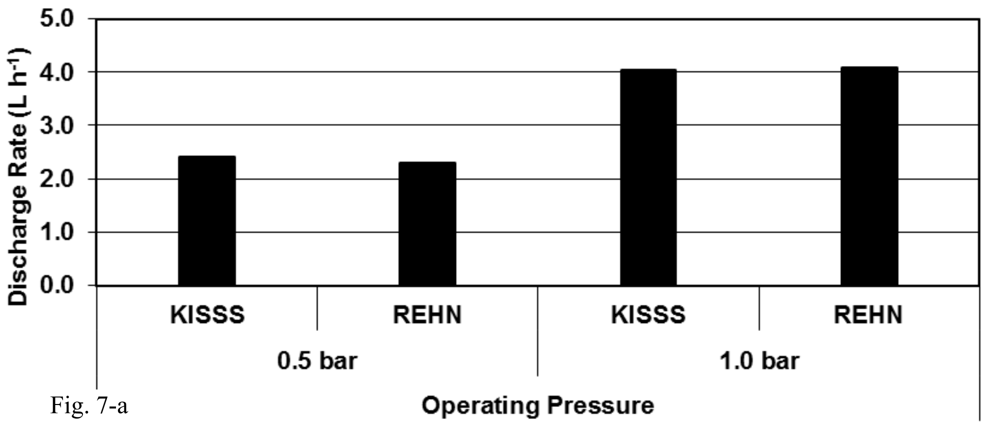

Fig. 7-a

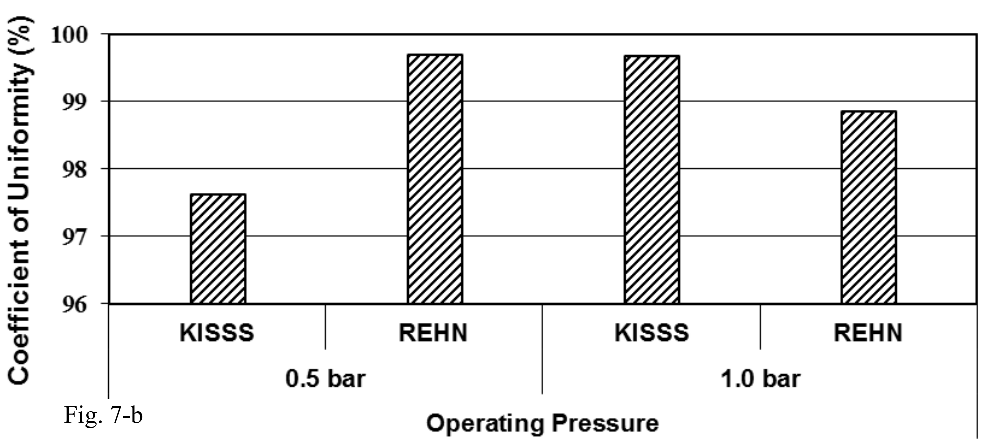

Fig. 7-b

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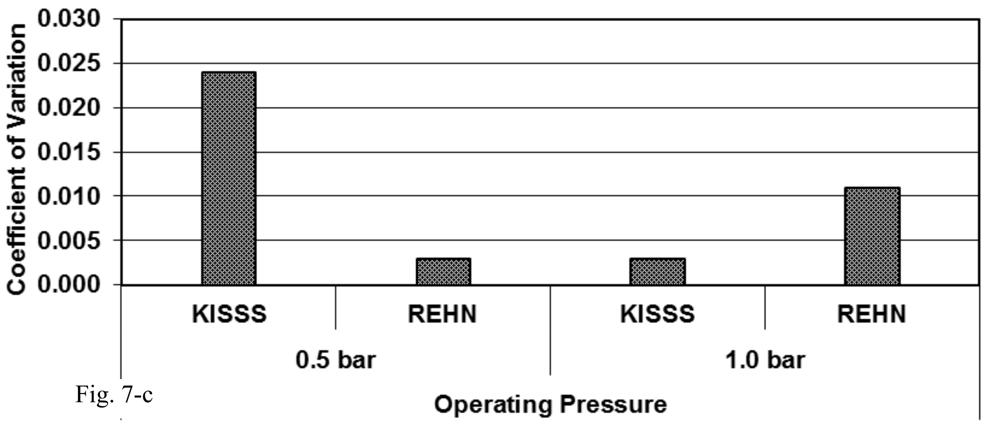

Fig. 7-c

Figure-7. (a) Average discharge rate, (b) Coefficient of uniformity, and (c) Coefficient of variation, for the KISSS and REHN laterals.

Field evaluation of the tested drip irrigation systems

The performance of the SIS, SDI and KISSS was evaluated in the field on the basis of soil moisture distribution across the subsoil in both directions parallel and perpendicular to the laterals. Also the studied drip irrigation systems were subjected to further assessment under two water application levels (i.e. at 50% and 100% irrigation levels) as well as under two elapsed times (24 and 48 hours).

(i) Soil moisture distribution as a function of locations relative to the Emitters

As illustrated by Figures 4-6, soil moisture was recorded from sampling points located at four depths under soil surface (7.5, 20, 30 and 50 cm) and at 4 distances from the Emitters in a direction parallel to the laterals (0, 10, 15, 25 cm). To describe the trend of soil moisture content across the subsurface profile, soil moisture measurements were taken at 24 and 48 hours after the application of irrigation water for both irrigation levels. The mean values of soil moisture distribution, representing the five tested drip irrigation systems, are given in Figures 8-11.

These results indicated that for the upper 7.5 cm of the soil profile, the KISSS-15 exhibited the highest soil moisture for all sample distances away from the Emitter (49.58-51.24%) followed by the KISSS-25 (47.26-48.66%); while, the lowest soil moisture at a soil depth of 7.5 cm was recorded for SIS-25 (18.20 - 21.14%). However at 20 cm depth, the KISSS-25 showed the highest soil moisture values (52.47 - 55.13%) with high significant differences from the other four systems; while, the SDI showed the lowest moisture values, especially at far horizontal distances from the Emitter (15 and 25 cm). Moving deeper in the soil up to 30 cm, the results indicated that the SIS-25 was associated with the highest moisture values (32.04 - 43.50%) across the four selected sampling points away from the Emitter (0, 10, 15 and 25 cm) in the direction parallel to the Laterals; while the KISSS-15 exhibited the lowest moisture values (21.01-24.45%). Similar to the moisture pattern at 30 cm depth, the highest soil moisture values, at 50 cm depth, were recorded for the SIS-25 (34.02 - 44.51%) and the lowest values were for the KISSS-15 (16.09 - 17.50%). With the highest moisture values recorded for the KISSS in the upper part of the soil profile (≤ 20 cm depth) as well as the fact that the KISSS showed the lowest values of soil moisture values in deep locations (20 - 50 cm), these results supported the hypothesis that the KISSS improves the upwards movement of water depending on the capillary properties of the soil; while minimizes deep percolation of irrigation water. This hypothesis is based on the assumption that the impermeable layer facility of the KISSS generates a short-term water-table from which the upward movement of water, through capillary action, increases (Devasirvatham, 2009).

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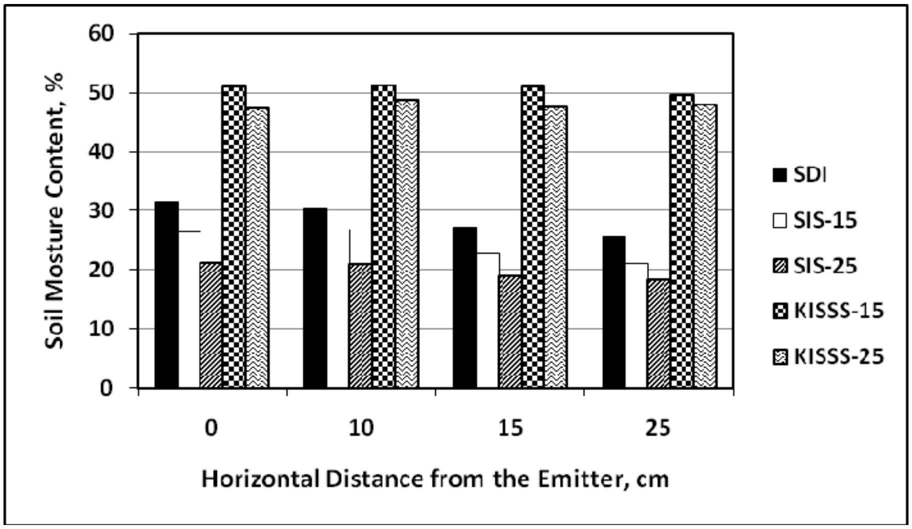

Figure-8. Mean values of soil moisture content at a depth of 7.5 cm.

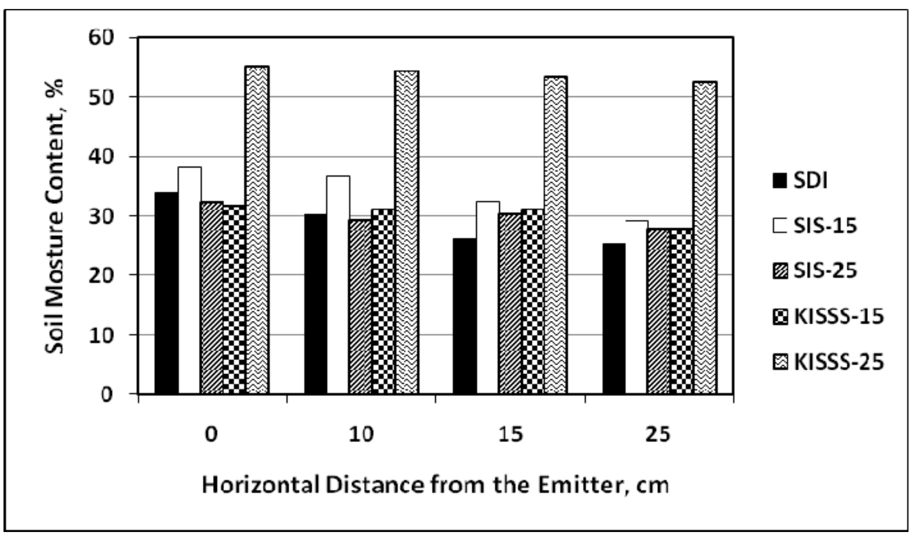

Figure-9. Mean values of soil moisture content at a depth of 20.0 cm.

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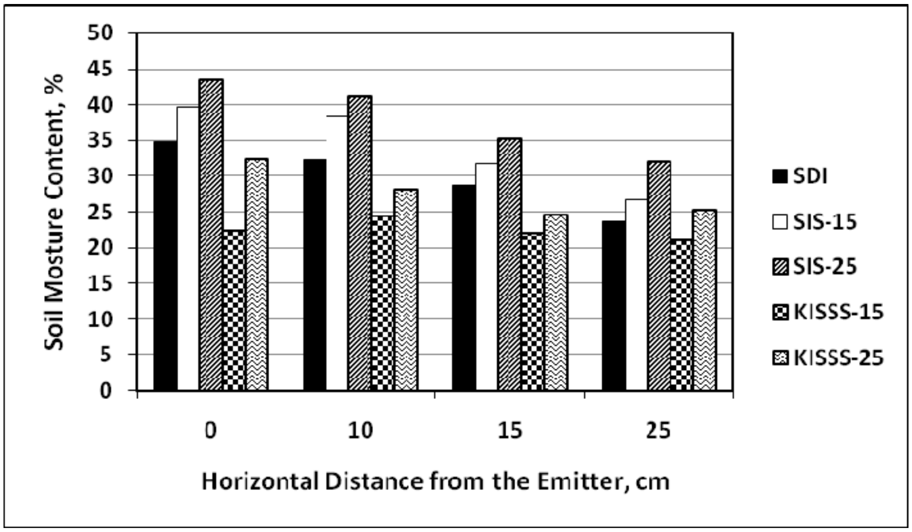

Figure-10. Mean values of soil moisture content at a depth of 30.0 cm.

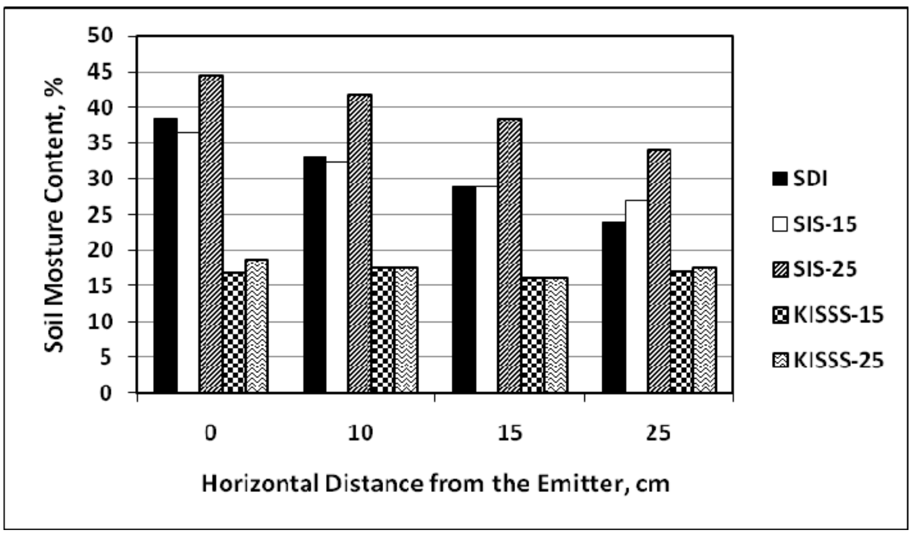

Figure-11. Mean values of soil moisture content at a depth of 50.0 cm.

(ii) Coefficient of uniformity (CU) of soil moisture across the soil profile

(a) Uniformity of moisture distribution in the horizontal direction

To study the distribution uniformity of soil moisture coefficient along the soil profile in the horizontal direction (i.e. direction parallel to the laterals) of the five tested drip irrigation systems, the CU values were calculated and statistically analyzed. The mean values of CU for the five drip irrigation systems under two irrigation levels (50% and 100%) and two elapsed times (24 and 48 hours) are presented in Fig. 12. On the average, the results showed that the coefficient of uniformity for all the five irrigation systems was high under 100% irrigation level compared to 50% level; and that after an elapsed time of 48 hours, the five tested drip irrigation systems distributed water more uniform compared to measurement at 24 hours. From Fig. 12, it can be noticed that each irrigation system performed in a different manner as indicated by CU values. The results showed that both KISSS-15 and KISSS-25 distributed soil moisture in the horizontal direction more uniformly compared to the other systems. On the other hand, the subsurface irrigation system (SIS) exhibited more uniform distribution of soil water in the horizontal direction compared to the surface drip irrigation (SDI) for both installation depths (SIS-15 and SIS-25) for measurements recorded after 24 hours from the

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application of irrigation water and for an installation depth of 25 cm (SIS-25) for measurements after 48 hours. These results were in agreement with reported by Al-Ghobari and El-Marazky (2012) that the mean values of CU in the horizontal direction for the subsurface irrigation system were higher than with surface drip irrigation at any depth of the soil profile and time of measurements (24 and 48 h) after irrigation.

(b) Uniformity of moisture distribution in the vertical direction

To study the impact of each of the five tested drip irrigation systems on the uniformity of distribution of soil moisture in the vertical direction across the soil profile, the values of CU were determined vertically below the soil surface at various vertical depths (7.5, 20, 30 and 50 cm) and various horizontal distances (0, 10, 15 and 25 cm) from the emitters (Figures 4-6). The mean values of CU for the five tested irrigation systems under two irrigation levels and two elapsed times are presented in Figure-13. This figure indicated that the uniformity coefficient increased with the increase in the amount of irrigation water, i.e. high CU values were observed with 100% irrigation level compared to 50%. While, less values of CU were observed with the increase in the elapsed time i.e. CU values were higher for the elapsed time of 24 hours than of 48 hours. The results also indicated that along the vertical direction, soil water was distributed more uniform with the surface drip irrigation under all experimental levels compared to the other tested drip irrigation systems. The KISSS, however, exhibited the lowest values of CU among the tested systems. The increase of mean CU values associated with both the SDI and SIS, could be attributed to the increase in the downward movement of soil water under the emitters compared to the modified KISSS system, which implies that the KISSS improved the upward movement of soil water as a result of the impermeable layer facility of the KISSS system that prevents water from moving downward below the drip line.

The results of this study revealed that the KISSS exhibited high uniformity of soil moisture distribution in horizontal direction, especially at the top 20 cm depth of the soil profile where the KISSS-25 induced the highest values of CU with significance differences (P<0.05) compared to the other irrigation systems. The superiority of the KISSS was also reported by Schiavon et al. (2011) that the plastic tape facility of the KISSS pasted on the geo-textile above the emitters deflects the discharged water and prevents tunneling process into the neighboring soil. Also, Rogers and Giggins (2006) reported that savings in water use of up to 50% were achieved using the capillary root zone irrigation "CRZI" system compared to the conventional subsurface drip irrigation system. In addition, the installation depth off KISSS exhibited high importance in the efficient use of irrigation water with drip irrigation system. Even for the conventional subsurface irrigation system, Zin El-Abedin (2006) reported that the moisture content distribution for the vertical plane indicated that the dripper line at 15 cm depth was better than at the 10 cm depth. The same was reported by Dabral et al. (2012) that the wetting pattern was significant in deciding the depth of lateral placements below the soil surface. The higher values of soil moisture associated with both the SDI and SIS at deeper soil depths (i.e. at 50 cm depth) indicated high loss of irrigation water through deep percolation compared to the modified capillary irrigation system (KISSS).

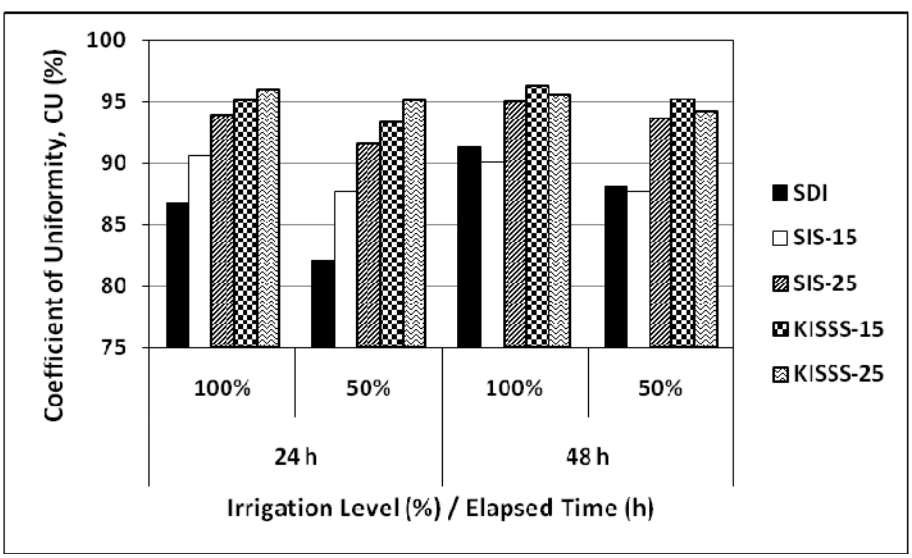

Figure-12. Mean values of the coefficient of uniformity in a direction parallel to laterals.

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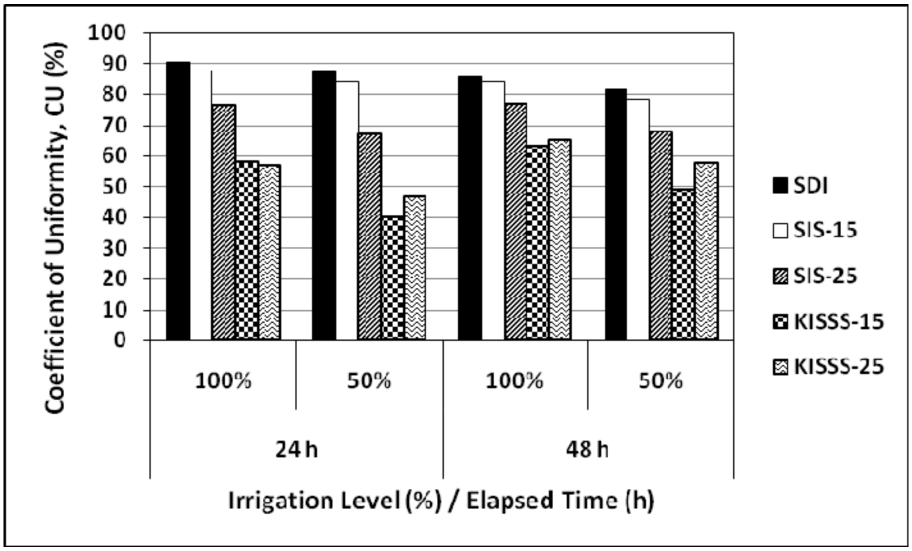

Figure-13. Mean values of the coefficient of uniformity in the vertical direction.

CONCLUSIONS

The following conclusions could be drawn from this study:

- The five tested drip irrigation systems response significantly to the irrigation level and the elapsed time after the application of irrigation water.
- The installation depth was significantly affected the distribution of soil moisture in the soil profile.
- When installed at the same soil depth, the modified KISSS showed the best results of soil moisture distribution compared to the SDI and SIS.
- The KISSS distributed soil moisture in the horizontal direction more uniformly compared to other systems as indicated by its high values of the coefficient of uniformity.
- The KISSS showed the highest moisture values in the upper part of the soil profile (soil depth ≤ 20 cm) and the lowest values of soil moisture values in deep locations (20-50 cm). These results imply that the KISSS improves the upwards movement of water and minimizes the deep percolation losses of irrigation water.
- Based on the best results of KISSS in terms of efficient distribution of soil moisture across the soil profile, especially in the horizontal direction; it is recommended to adopt the modified capillary irrigation subsurface system at depths commensurate with different crops.

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