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ORIGINAL ARTICLE

Impact of Conventional and Modified Subsurface Drip Irrigation Systems on Water Distribution through the Soil Profile

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ABSTRACT
Water in Saudi Arabia, despite its environmental and climatic arid conditions, is the key factor in the development processes. Therefore the main objective of this research is to study the feasibility of saving water through the use of capillary irrigation with special emphasis on studying the distribution pattern of soil moisture content in the soil under subsurface irrigation systems. Experiments were conducted in the educational farm of the College of Food and Agriculture Sciences, King Saud University. Experiments were designed for two levels of irrigation based on the application time: (i) 4 l/h for two hours (Level1), and (ii) 4 l/h for one hour (Level2). Three drip irrigation systems were investigated in this study: (i) surface drip irrigation (SDI), (ii) conventional subsurface irrigation system (SIS), and (iii) modified Kapillary irrigation subsurface system (KISSS). Both SIS and KISSS laterals were installed at a soil depth of 25 cm. Soil moisture measurements were carried out in a grid form: vertically at four soil depths from the laterals and horizontally at four distances from the emitters. Soil moisture values were used for the generation of wetting patterns through the soil profile. The results indicated that the SIS maintained same amount of water in the top soil layer as the SDI, but it was associated with the highest amount of water losses through deep percolation. The KISSS showed significant improvement in the performance of subsurface irrigation in terms of high water content in the top soil layer and less water losses through deep percolation.
Keywords; *Drip irrigation, Subsurface irrigation, Capillary irrigation, Wetting patterns*

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INTRODUCTION

Global use of water in the agricultural sector is estimated at about 80% of the total available quantity, while in Saudi Arabia it was estimated at about 90% [1]. Climate changes constitute additional factors leading to the worsening of the situation in terms of future sharp decline of water and increase in temperatures, which then lead to increase in drought and consequently to the increase in crop water requirement and the result will be high deficit between supply and demand of water [2, 3]. The Kingdom of Saudi Arabia suffers from the harsh climatic conditions that significantly reduce the efficiency of agricultural production. Climatic conditions in the Kingdom of Saudi Arabia are characterized by a very low amount of annual rainfall ranging between 80 and 140 mm, extreme temperatures (especially in summer) often exceeded 45 °C and a very low relative humidity [4].

The efficient use of amounts of water available to the agricultural sector can be attained through the implementation of a well planned irrigation systems and the use of modern irrigation techniques such as sprinkler and drip irrigation technologies. Drip irrigation, also known as trickle irrigation or microirrigation, is the application of water to the soil surface (surface drip irrigation - SDI) or directly to the plant root zone (subsurface drip irrigation "or subsurface irrigation system" - SIS) as drops or tiny streams; through a network of valves, laterals, tubes and emitters [5, 6].

Drip irrigation is characterized as the most efficient irrigation technique, compared to other irrigation systems, because of its high water application efficiency and distribution uniformity; and it is highly recommended for arid and semi-arid climatic conditions [7, 3]. Compared to conventional drip irrigation systems, subsurface drip irrigation improves soil moisture conditions as it delivers water and fertilizer directly to the roots of plants, and hence it was found to result in yield gains of up to 100% and water savings of up to 40–80% as well as the associated savings in fertilizer, pesticide, and labor [8]. Another advantage of surface drip irrigation, compared surface and sprinkler irrigation systems, is its low evaporative losses as a result of the smaller surface area [9, 10]. Also Thompson et al. [11] reported some advantages of subsurface drip irrigation including: (i) it allows the efficient elimination of crop water stress, (ii) the ability to apply water and nutrients to the most active part of the root zone, (iii) protection of drip lines from damage due to cultivation and tillage, and (iv) the ability to use wastewater for irrigation while preventing direct human contact. In general, subsurface drip irrigation is characterized as one of the most efficient water delivery systems; hence, subsurface drip irrigation can contribute greatly in improving crop water use efficiency and conserving water, taking into consideration SDI critical management parameters such as choice of tube, emitter spacing and installation depth [12]. Subsurface irrigation system has a higher capability of decreasing water loss by evaporation, runoff, and deep percolation in comparison to other irrigation systems that supply water to the soil surface. In addition, the high cost of traditional drip irrigation systems, due to annual replacement of system components, is substantially reduced when subsurface components are permanently installed below the soil tillage zone [13, 14].

The major design characteristics of subsurface irrigation system (SIS), such as drip-line spacing, crop/drip-line orientation, emitter spacing, installation depth, and drip-line flow rate are considered as site-specific as they are functions of soil type, climate and crop conditions [15]. Also Rogers and Lamm [16] reported that SIS systems result in high-yielding crops and water-conserving production practices when the systems are properly designed, installed, operated and maintained. The same was reported by [17] that the success of SIS depends mainly on the design, installation, operation, management and maintenance.

A new modified version of the subsurface irrigation, by adding impermeable membrane to improve the wetting pattern and to minimize the amount of water losses through deep percolation, is now available under a commercial name “Kapillary Irrigation Subsurface System (KISSSTM)”, [18]. 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 and deep percolation; while overwatering and soil saturation processes are associated with the improper implemented KISSS [19, 20]. Also, Jan and Kristen [21] reported that the KISSS applied water directly to the root zone of plants with minimum water losses through runoff, evaporation and deep drainage. In this system, water is applied below the ground surface directly to the plant root area, resulting in a significant improvement in water application over the traditional drip irrigation system.

Design and planning information on depths and widths of the wetted zone of soil under subsurface application of water plays important roles in the management of subsurface irrigation System (SIS) to ensure delivering the required amount of water and chemicals to the plant [22]. Therefore, the main objective of this research was to study the performance of subsurface irrigation system (SIS) and its modified version (KISSS) and to compare both of them with the conventional surface drip irrigation system.

MATERIAL 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 24°:44′:11″ N and 46 °:37′: 04″ E. The soil of the experimental field is classified as sandy soil (76.4%: coarse sand, 12.3%: fine sand, 7.5%: silt and 3.8%: clay); with soil field capacity of 12.88%, soil wilting point of 4.25%, soil pH of 7.81 and soil EC of 1.61 dS m^{-1}.

Experiment Layout

Three drip irrigation systems tested in this study include: (i) the conventional surface drip irrigation (SDI), (ii) the subsurface irrigation system (SIS), and (iii) the Kapillary irrigation subsurface system (KISSS). The laterals for the SIS and KISSS systems were installed at a depth of 25 cm from the soil surface, while the SDI laterals were laid on the ground surface. 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 1. Each one of the three systems (SIS, SDI and KISSS) was installed in one of the three field plots of the three replicates (R1, R2 and R3). Each plot comprised three laterals (each of three meters length).

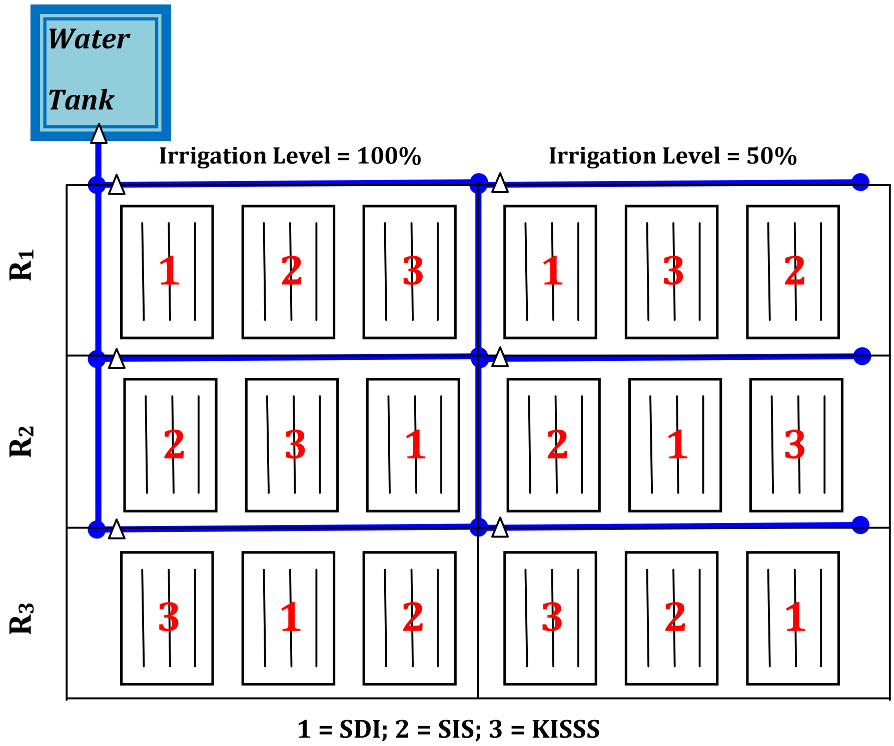

Figure 1. Field experiments layout.

Soil moisture content measurements

Soil moisture content was measured at specific depths by using soil moisture sensor Waterscout SM 100* soil moisture sensor. This sensor measured soil moisture content with little or no disturbance to the root zone. The thin shape and pointed tip allows for easy insertion into the soil or growing medium. Soil moisture measurements were carried out at different distances parallel to the lateral line (0, 10, 15 and 25 cm) and various depths perpendicular to the emitter line (7.5, 20, 30 and 50 cm), as shown in Figures 2 and 3. The soil moisture measurements were repeated at two times (24 and 48 h) after irrigation. The collected soil moisture data was used to determine soil moisture wetting patterns using SURFER10 computer software. The CoStat computer software system, (version 6.311) was used for statistical analysis of the collected soil moisture results.

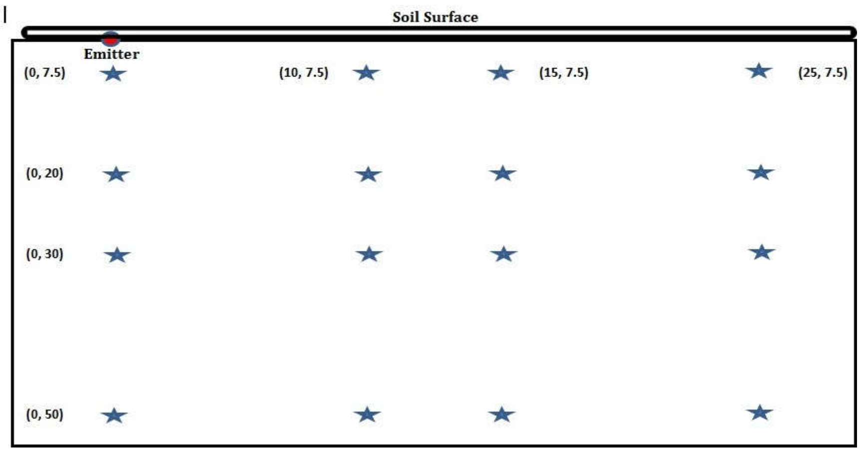

Figure 2. Sampling locations with respect to the Emitters for soil moisture measurements under the SDI system.

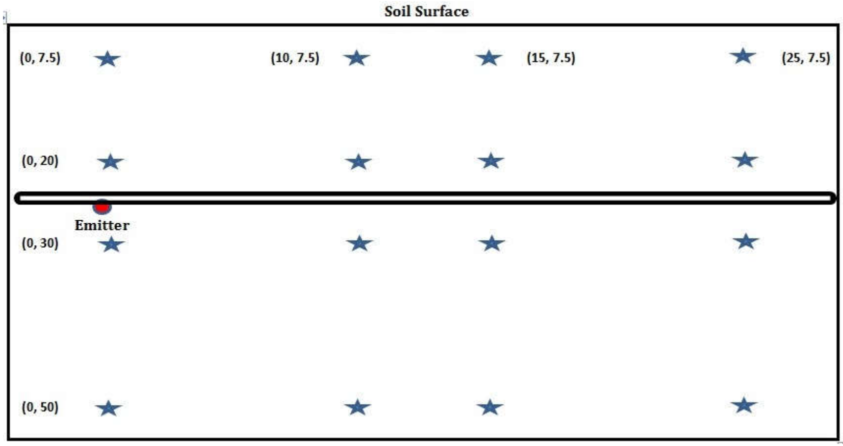

Figure 3. Sampling locations with respect to the Emitters for soil moisture measurements under both SIS and KISSS installed at 25 cm depth.

RESULTS AND DISCUSSION

To study the distribution of soil moisture through the soil for the three tested drip irrigation systems (SDI, SIS and KISSS), the collected soil moisture measurements taken at different soil depths and distances from the emitters were analyzed and processed using SURFER 10 software to generate soil moisture wetting patterns under different irrigation levels and elapsed times.

Soil moisture distribution and wetting patterns under 50% irrigation level

The results indicated that, for the surface drip irrigation (SDI), soil moisture measurements taken at 24 h after irrigation the soil moisture content in the top 15 cm soil layer was higher and homogenous compared to measurements taken at deeper soil depths as shown in Figure 4-a. While for measurements taken after 48 h, it was observed that soil moisture was moved downward and increased gradually in a vertical direction Figure 4-b. The decreased soil moisture at shallower depths after 48 h from irrigation may be due to water lost by evaporation and deep percolation processes. These results were in agreement with Elmaloglou and Diamantopoulos [23].

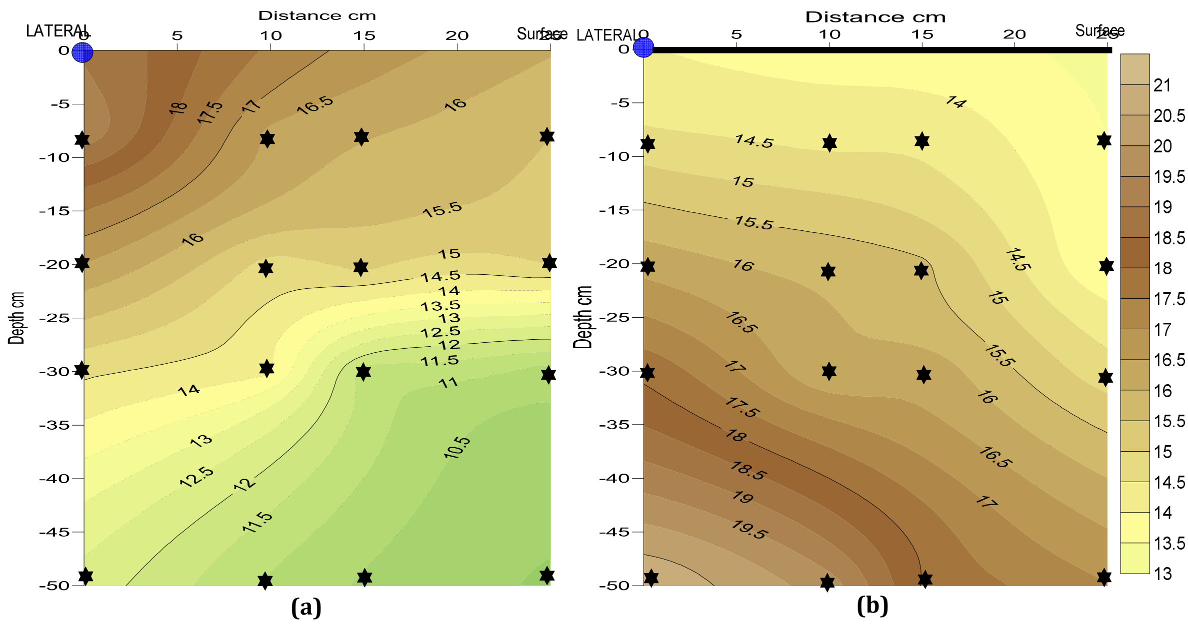

Figure 4. Soil moisture wetting patterns for SDI at 50% irrigation Level: (a) at 24 h, and (b) at 48 h after irrigation.

For the SIS, soil moisture content in the top soil above the installation depth of the lateral was lower than below the lateral depth for both measurements taken at 24 and 48 h (Figures 5-a and 5-b). While, the results for KISSS showed high soil moisture values above the lateral depth (25 cm) for both measurements taken at 24 and 48 h after irrigation, Figure 6.

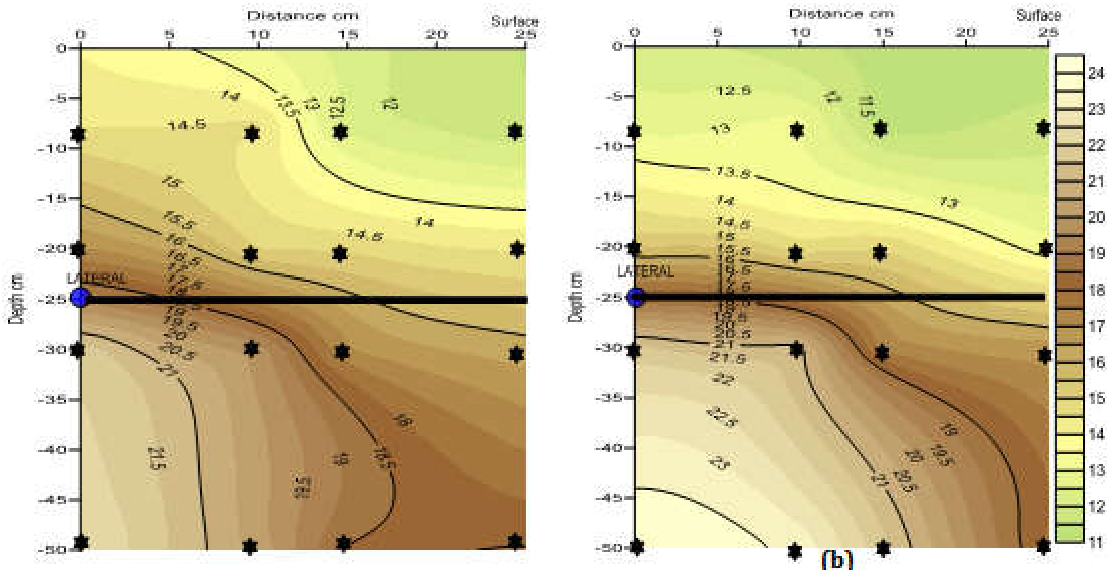

Figure 5. Soil moisture wetting patterns for SIS at 50% Irrigation Level: (a) at 24 h, and (b) at 48 h after irrigation.

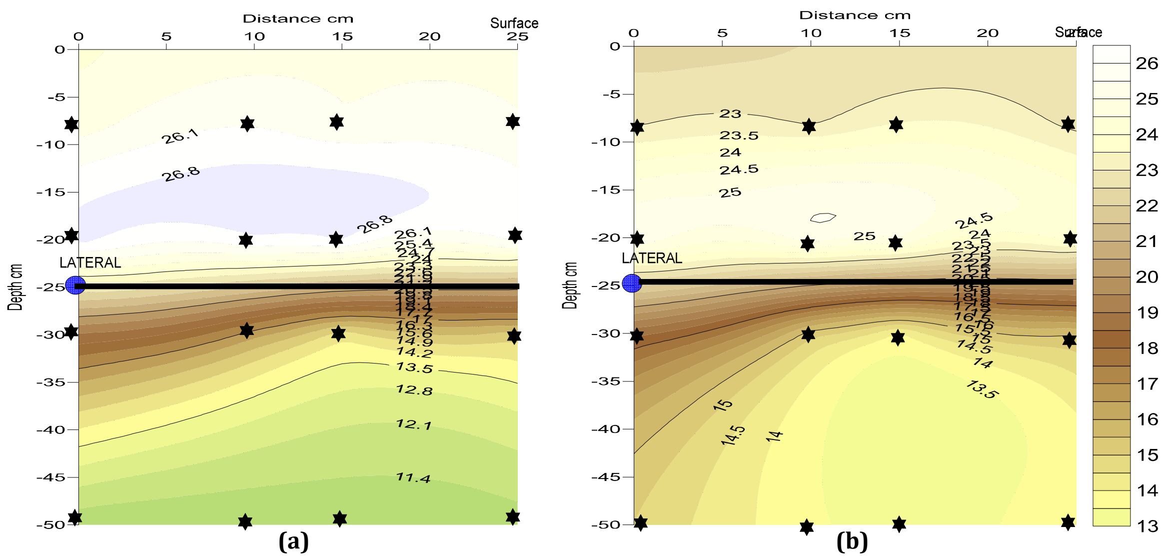

Figure 6. Soil moisture wetting patterns for KISSS at 50% Irrigation Level: (a) 24 h and (b) 48 h after irrigation.

The above results indicated that KISSS resulted in more uniform distribution of soil moisture with high values above the lateral depth (25 cm) compared to the SDI and SIS. A study conducted by Devasirvatham [24] indicated that the soil water content was consistently higher in horizontal direction for KISSS compared with the conventional SIS.

Soil moisture distribution and wetting patterns under 100% irrigation level

The soil moisture results taken under 100% irrigation level in an obvious increase in soil moisture with low values in soil depths above the laterals for both SDI and SIS; while, the KISSS showed high soil moisture values above the laterals as illustrated by Figures 7-9. Increasing the amount of the applied water in the drip irrigation system to 100% irrigation levels was associated with an increase in soil moisture, for both measurements taken at 24 and 48 h after irrigation. Singh et al. [22] observed an enhancement in the wetted soil pattern in both vertical and horizontal directions with the increase in discharge rate.

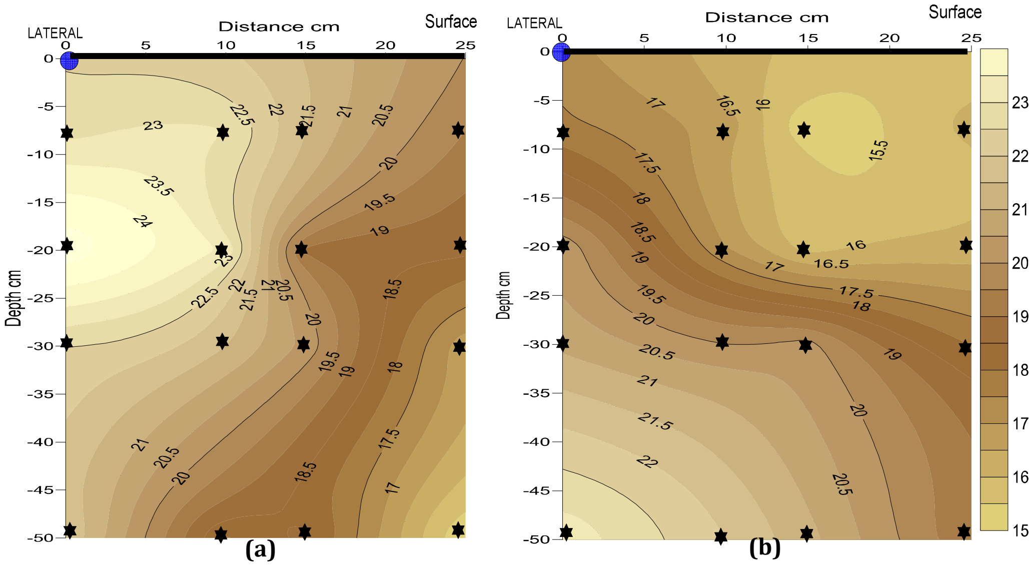

Figure 7. Soil moisture wetting patterns for SDI at 100% irrigation Level: (a) at 24 h, and (b) at 48 h after irrigation.

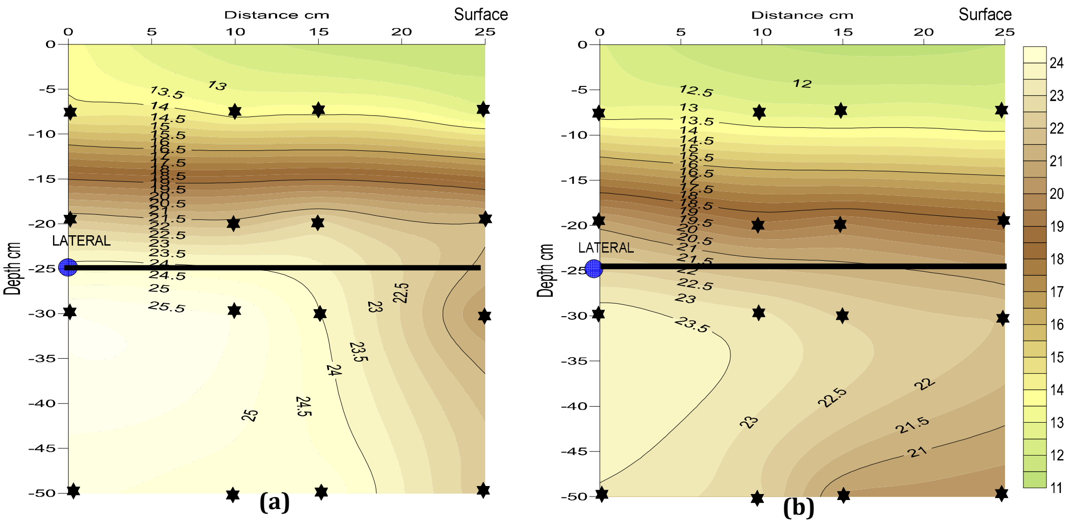

Figure 8. Soil moisture wetting patterns for the SIS at 100% Irrigation Level: (a) at 24 h, and (b) at 48 h after irrigation.

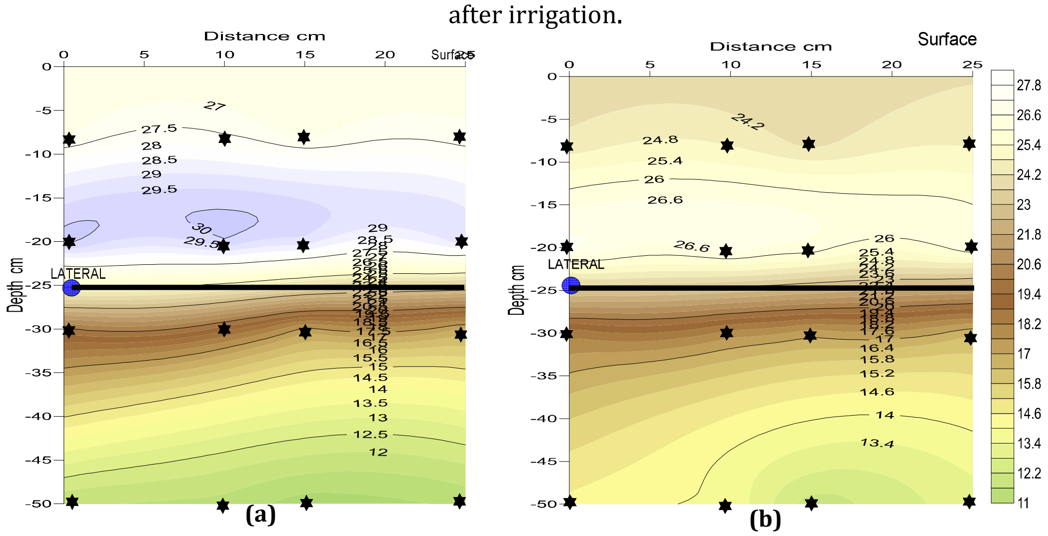

Figure 9. Soil moisture wetting patterns for KISSS at 100% Irrigation Level: (a) 24 h and (b) 48 h after irrigation.

Impact of the tested irrigation systems on soil moisture distribution

The results of study indicated that, at the top soil layer above the installation depth (25 cm) of the laterals of subsurface irrigation systems, KISSS showed higher soil moisture content compared to the conventional subsurface irrigation system (SIS). To investigate the performance of the three tested drip irrigation systems in terms of water retention in the top soil layers as well as waste of water through deep percolation, statistical analysis were performed on soil moisture values taken at 20 and 50 cm soil depth representing top soil layers and deep soil layers, respectively. Tables 1-2 show the average results taken at 20 and 50 cm soil depths, respectively.

Table 1. Average soil moisture at a soil depth of 20 cm and different horizontal distances from the emitters parallel to the laterals

Irrigation System	Soil moisture content (%)			
	D_0*	D_{10}	D_{15}	D_{25}
KISSS	29.71 a**	29.38 a	29.01 a	28.68 a
SDI	20.95 b	19.80 b	19.73 b	18.28 b
SIS	20.26 b	19.38 b	19.40 b	18.26 b

Table 2. Average soil moisture at a soil depth of 50 cm and different horizontal distances from the emitters parallel to the laterals

Irrigation System	Soil moisture content (%)			
	D_0*	D_{10}	D_{15}	D_{25}
SIS	25.10 a**	24.07 a	21.57 a	20.19 a
SDI	21.39 b	20.27 b	18.70 bc	17.07 c
KISSS	20.28 b	18.39 bc	16.70 c	16.25 c

*D0 - D25: Distances of 0, 10, 15 and 25 cm from emitter parallel to the laterals.
**Means followed by the same letter were not significantly different at P≤ 0.05.

The results indicated that KISSS showed the highest soil moisture values in the top soil layer represented by measurements at 20 cm depth of the soil profile compared to the SDI and SIS systems, for all distances along the laterals from the emitters. These results were in agreement with Yiasoumi et al. [25] that the KISSS can enhance soil water retention in the top soil layers for longer time than conventional surface and subsurface drip irrigation systems. The results also indicated the conventional subsurface irrigation system (SIS) exhibited the highest soil moisture values at 50 cm depth for all distances along the laterals from the emitters followed by the SDI system, and KISSS showed the least values. These results imply that the KISSS was superior to other conventional drip irrigation systems both in terms of high water retention in the top soil layer and less water losses through deep percolation.

CONCLUSIONS

The following conclusions could be drawn from this study:

- Although, the conventional subsurface irrigation system (SIS) maintained same amount of water in the top soil layer as the surface drip irrigation (SDI), it showed the highest amount of water losses through deep percolation.
- The modified Kapillary irrigation subsurface system (KISSS) showed significant improvement in the performance of subsurface irrigation both in terms of high water content in the top soil layer and less water losses through deep percolation.
- Replacing the conventional subsurface irrigation system (SIS) with the modified Kapillary irrigation subsurface system (KISSS) will result in high amount of water savings through the decrease of water losses through both evaporation and deep percolation.

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