Agricultural Water Management 209 (2018) 55–61

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Integrating deficit irrigation into surface and subsurface drip irrigation as a strategy to save water in arid regions

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ARTICLE INFO

Keywords:
Subsurface drip irrigation
Deficit irrigation
Irrigation water use efficiency
Tomato
Water saving

ABSTRACT

Development of sustainable and efficient irrigation strategies is a priority for producers faced with water shortages. A promising management strategy for improving irrigation water use efficiency (IWUE) is deficit irrigation, which attempts to optimize yield and IWUE. Soil water use, crop yield and IWUE of tomato were evaluated for two consecutive years under two types of irrigation methods (subsurface and surface drip irrigation) and three irrigation strategies: 1.0 of full irrigation supply (T1), 0.8 of full irrigation supply (T2) and 0.6 of full irrigation supply (T3). The results showed that the highest yields were found in the plots irrigated by subsurface drip irrigation at T1 (94.1 ton/ha) and T2 (81.4 ton/ha). Conversely, the fully stressed treatment (T3) reduced the amount of irrigation water by 40%, but significantly decreased mean tomato yield by 25.6% and 26.1% under subsurface and surface drip irrigation, respectively, as compared to T1. The maximum IWUE tended to be higher for subsurface drip than for surface drip irrigation system. The greatest IWUEs were obtained from subsurface drip and surface drip at T3 (19.7 kg/m^3 and 18.3 kg/m^3), whereas the lowest IWUEs were those estimated in T1 (15.9 kg/m^3 and 14.8 kg/m^3, respectively). The primary conclusion is that deficit irrigation strategies present certain advantages to crop water management with minimal effects on production and quality, thus contributing to crop sustainability.

1. Introduction

Saudi Arabia, one of the driest and hottest countries in the world, is roughly located between north latitudes 17 and 31 and east longitudes 37 and 56. Temperatures can reach more than 50 °C (122 °F) in some areas, producing overwhelmingly hot and dry conditions. Long-term average rainfall across the country is 114 mm per year (DeNicola et al., 2015). High temperatures and low precipitation together with high variability of both factors increase evapotranspiration, reduce soil moisture, and damage the soil by mechanical weathering (Alkolibi, 2002). These conditions have a negative impact on agriculture and water availability which made Saudi Arabia a very poor country in terms of agricultural potential and water resources.

The country has scanty rains and no lakes, rivers, or streams. Total municipal water use in Saudi Arabia is about 9%. Agriculture accounts for 88% and industry consumes only 3% of the available water (Al-Zahrani and Baig, 2011). Mismanagement of water use in the agricultural sector and an increasingly Westernized and consumerism-based shift in lifestyle are mostly to blame for Saudi Arabia's water-starved status, as precious groundwater sources have been injudiciously used over many years to the point of depletion. Achieving greater irrigation water use efficiency (IWUE) is a primary challenge and it includes the employment of techniques and practices that deliver irrigation water to the crops more accurately. In this context, a combination of deficit irrigation (DI), surface drip irrigation (SDI) and subsurface drip irrigation (SSDI) may play an important role in increasing IWUE. DI is a water conservation technique that exposes crops to a particular level of water stress during a certain developmental phase or throughout the entire growing season without a significant reduction in yield (Pereira et al., 2012).

The risk of DI is low because the response curve of crop yield to water supply often has a wide plateau, and a considerable amount of water can be saved without a significant yield reduction compared with full irrigation (Zhang, 2003). Kumar et al. (2007) studied the effect of DI on water saving and onion yield. They demonstrated that applying 80% and 60% of crop water requirements bring about yield reductions of 14% and 38%, and saved 18% and 33% of irrigation water compared to full irrigation within 2 years, respectively. Patanè et al. (2011) indicted that applying a 50% reduction in crop water for the entire or even partial growing season helps reduce fruit losses and maintain a high fruit quality. According to Nahar and Gretzmacher (2002), glucose, fructose, sucrose, malic acid, ascorbic acid and citric acid content

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https://doi.org/10.1016/j.agwat.2018.07.010
Received 25 January 2018; Received in revised form 26 June 2018; Accepted 12 July 2018
0378-3774/ Published by Elsevier B.V.

increased significantly with water stress. Besides, DI reduces production costs, conserves water and minimizes leaching of nutrients and pesticides in to ground water (Nuruddin et al., 2003).

The use of pressurized irrigation system applying water through an emitter on soil surface (SDI) or below the soil surface (SSDI) at a small operational pressure and minimizing soil evaporation has been popular for saving water and improving IWUE (Camp, 1998; Lamm et al., 1995; Ayars et al., 2015). Cui et al. (2008) pointed out SDI and SSDI can improve IWUE by 26.7–46.4% and fruit quality of table grape without detrimental effect on the fruit yield in arid region. Hassanli et al. (2009) conducted a comparison between three irrigation methods: SDI, SSDI and furrow irrigation. The results demonstrated that the minimum amount of water along with highest use efficiency, is delivered through SSDI and SDI, respectively. del Amor and del Amor (2007) performed a comparison between SDI and SSDI systems. They found that higher tomato crop yields were achieved by SSDI as compared to SDI in sandy soil. Similarly, Al-Omran et al. (2010) concluded that SSDI increased the IWUE and yield of their tomato crop by producing a good moisture distribution in the root zone, leading to a conservation of irrigation water.

Information on deficit irrigation scheduling is limited for many crops especially tomato, which is a vital horticultural crop within arid regions (Maas and Hoffman, 1977). Accordingly, in light of water limitations, there is a necessity to establish different irrigation strategies that may facilitate the conservation of water under both high evaporative demand and chronic shortages without incurring considerably influencing yields. For this reason, different deficit irrigation approaches have been applied to tomato plants under SDI and SSDI systems. Considering the issues analyzed above, the objectives of the present study are i) to evaluate the response of tomato yield and quality to various combinations of DI, SDI and SSDI, and ii) to determine the minimum irrigation treatment in tomatoes where the production and crop quality are least affected.

2. Materials and methods

2.1. Site description

Field experiments were conducted at the experimental site of King Saud University, Riyadh, Saudi Arabia. The geographical coordinates of the location are a latitude of 24.43 °N, longitude of 46.43°4 E, and altitude of 635 m. The climate in this region is definitely semi-arid with an average yearly precipitation of 100 mm. During the experimental period, the maximum and minimum mean monthly temperatures were 29.74 and 19.94 °C in May and February, respectively. The highest mean relative humidity was 30.29% during April, whereas the lowest one was 24% in February. Other climatic parameters are shown in Fig. 1. The soil has been classified as SC, clayey sand (Baylot et al., 2013) comprising of 72.6% sand, 12.75% silt and 14.65% clay. Soil bulk density was 1.64, 1.61 and 1.59 g cm − 3 for soil depths at 0.2, 0.4 and 0.6 m, respectively. More information on the soil texture, field capacity (FC), wilting point (WP) and bulk density (ρ_d) (Table 1).

2.2. Irrigation scheduling

The experimental area was prepared, leveled and partitioned into two main fields isolated with buffer zones of 6 m. Each field was subdivided into nine plots with surface-area dimensions of 7 m in width x 10 m in length (Fig. 2). The plots in the first field were irrigated by SDI system, whereas SSDI was used to irrigate the plots in the second field. The plots in the both fields were irrigated daily with various amounts of water according to the daily reference crop evapotranspiration calculated by the FAO Penman-Monteith equation (Eq. 1) (Fig. 3). The irrigation treatments were composed of three approaches: T1 = 100% of crop evapotranspiration, T2 = 80% of crop evapotranspiration and T3 = 60% of crop evapotranspiration. The amounts of water were recorded at every irrigation event through multi-jet dry dial water meters settled along the sub-main lines.

$$ET_o = \frac{0.408\Delta(R_n\text{-}G) + \gamma\left[\frac{(900U_2)}{T+237}\right](e_s - e_a)}{\Delta + \gamma(1+0.34U_2)} \quad (1)$$

where ET_o is the daily reference crop evapotranspiration rate (mm/d), R_n is the net radiation at the canopy surface (MJ/m^2/day), G is the soil heat flux at the soil surface (MJ/m^2/day), T is the mean daily air temperature (°C), γ is the psychometric constant (kPa/°C), U_2 is the mean daily wind speed at a 2.0 m height (m/s), e_s is the mean saturation vapor-pressure (kPa), e_a is the mean actual vapor-pressure (kPa), (e_s-e_a) is the saturated vapor pressure deficit (kPa) and Δ is the slope of the saturated vapor pressures temperature curve (kPa/°C).

2.3. Measurement of soil water content

Once the experiment initiated, the volumetric soil water content was measured daily to a depth of 0.6 m at 0.2 m intervals in each of the irrigation treatments using multi-sensor capacitance probes (EnviroSCAN). The EnviroSCAN device (Sentek Pty Ltd, Stepney, Australia) is a multi-sensor capacitance probe measuring water content in different depths of a soil profile. A support rod was fitted with several sensors and inserted into a polyvinyl chloride access tube installed in the soil. Each sensor consists of two conductive rings acting as capacitor with the surrounding medium (solid soil, air and water) as dielectric.

Sensor readings were normalized to a so-called scaled frequency SF = (Fa – Fs) / (Fa – Fw), where Fa is the sensor specific reading in air, Fw is the reading in water and Fs is the frequency reading in moist soil. Fa and Fw were determined for each sensor in the laboratory. Soil water content (θ_{ES}) was calculated from SF by means of a standard default calibration relationship (Eq. 2), which generally delivers adequate results for common soil types (Paltineanu and Starr, 1997; Evett et al., 2002). Data were measured, processed and stored in a standard RT6-logger from Sentek Company, from which the actual database was downloaded.

$$SF = 0.1957 \times \theta_{ES}^{0.4040} + 0.0285 \quad (2)$$

2.4. Crop data

Tomato plants (*Lycopersicon esculentum* Mill, GS-12) were transplanted into the field on February 12, 2015 and February 12, 2016. The seedlings were cultivated in a single row with a line spacing of 0.8 m and an interplant spacing of 0.4 m. The tomato plants were grown for about 97 days, which as divided into four stages namely initial (20 days), development (30 days), middle (32 days) and late season (15 days). The crop coefficients during the crop season were 0.70, 1.15, 0.90 and 0.75 during the initial, developmental, middle, and late season stages, respectively (Allen et al., 1998).

All plots received a basic application of 300 kg N/ha and 100 kg K2SO4/ha. Herbicides and insecticides were applied to each plot when necessary. The plant height, number of branches, fresh leaf weight, fresh stem weight and fresh plant weight were determined. Leaf samples were collected, washed in distilled water and dried at 70 °C in forced air-oven until the weight became constant (48–72 h) to calculate the dry matter contents. The early and total yields were recorded in each treatment for all replications, and the data were presented as tons per hectare. Five tomato samples were collected, juiced and filtered for measuring tomato content of total soluble solids (TSS, %), ascorbic acid (mg/100 g FW) and titratable acidity (TA, %) (Carrapiso and García, 2000).

2.5. Yield reductions and water saving

Reductions in the total fruit yield and decrease in water use were