https://doi.org/10.17221/94/2020-SWR

Polymer and deficit irrigation influence on water use efficiency and yield of muskmelon under surface and subsurface drip irrigation

Faisal I. Zeineldin[1]*, *Yousef Al-Molhim*[2]

[1]*Water Studies Center, King Faisal University, Al-Ahsa, Saudi Arabia*
[2]*Department of Environmental and Natural Resources, College of Agriculture and Food Sciences, Al-Ahsa, Saudi Arabia*

**Corresponding author: faisalzeineldin@yahoo.ca*

Citation: Zeineldin F.I., Al-Molhim Y. (2021): Polymer and deficit irrigation influence on water use efficiency and yield of muskmelon under surface and subsurface drip irrigation. Soil & Water Res., 16: 191–203.

Abstract: Water scarcity is a major constraint facing vegetable production sustainability in open field farming of arid regions like the Kingdom of Saudi Arabia. This study was carried out in an open field of the Research and Training Station of King Faisal University in the eastern region of the Kingdom. The objective was to assess the influences of the polymer addition (PA), deficit irrigation regime (DIR), and their combination on the production and water use efficiency (WUE) of muskmelons. PA treatments of 0.0, 0.2 and 0.4% and the irrigation treatments of 100, 75 and 50% of reference evapotranspiration (ET_o), were imposed throughout the growth stages of muskmelons under surface drip irrigation (DI) and subsurface drip irrigation (SDI). The polymer addition of 0.4% enhanced the field water holding capacity of the medium sandy soil within the locality of the emitters by 43.6%. The soil water content of the surface layer within the vicinity of the polymer amended soil layer increased in a range of 72.4 to 99.4% to the combined influences of the 0.4% PA with the DI and SDI, but were marked more under the SDI. The combination of the 100% ET_o DIR with polymer additions significantly ($P < 0.05$) enhanced the muskmelon fruit yield (MFY) under the SDI compared to DI. The PA of 0.4% improved WUE and MFY by 67.7, 70.4% under the SDI, and 58.6, 24.2% under the DI, respectively. Without the polymer addition (0.0% PA), the MFY significantly ($P < 0.05$) decreased with the increase of the DIRs under both DI and SDI.

Keywords: deficit irrigation regime; drip irrigation methods; K-highly crossed-linked polyacrylamide; melon water productivity; open field farming

Most open field cultivations in the Kingdom of Saudi Arabia (KSA) take place on coarse-textured sandy soils accompanied by a highly atmospheric evaporative demand. This may lead to high water losses by deep percolation and evaporation. There are several high economic value non-protected vegetables such as muskmelons, watermelons and okra grown across the agricultural regions of KSA and amounts to a total area of 77 409 ha (MEWA 2018). Irrigation of these vegetables depends on fresh non-renewable groundwater. Therefore, due to the extensive freshwater extraction, the groundwater levels at the Al-Ahsa oasis, in the eastern region of KSA, decrease annually by 1 to 2 m (SIO 2019).

Optimising the irrigation management and improving the physical properties of the sandy soils is highly in demand to minimise irrigation water losses on open cultivation fields. Deficit irrigation is considered as a sustainable practice capable of improving water use efficiency (WUE) and reduc-

Supported by the Deanship of Scientific Research (DSR) at King Faisal University, Al-Ahsa under the Research Project No. 150218.

https://doi.org/10.17221/94/2020-SWR

ing the deep percolation of irrigation water. On the other hand, polymer addition has the potential of increasing the water-holding capacity of sandy soils; but it has an adverse effect by increasing the saturated hydraulic conductivity (Dorraji et al. 2010; Alkhasha et al. 2018). To achieve sustainability of open field agricultural practices and save the limited valuable water resources in KSA, the Ministry of Environment, Water, and Agriculture (MEWA) proposed new crop structures excluding crops like alfalfa. Accordingly, open field vegetable areas in the eastern region are expected to expand at the expense of forage areas. Vegetable open field areas are going to increase about three folds from 1 154 to 3 705.09 ha (MEWA 2018).

In the eastern region of KSA, at the Al-Ahsa oasis, muskmelons are one of the highly valuable economic vegetable crops grown on the sandy soils of the open fields and irrigated mainly from fresh groundwater (1.3 dS/m). The sandy soils are characterised by a low water holding capacity and a high-saturated hydraulic conductivity of about half a meter per day. Although farmers adopted the use of modern irrigation systems such as drip irrigation systems, still they overirrigate by increasing the frequency of the water application. This practice leads to huge water losses and nutrients from the vicinity of the plant root zones. The drip irrigation system has the potential of enabling farmers to use water resources more efficiently to produce vegetables when operated properly (Locascio 2005). Subsurface drip irrigation is the most advanced kind of drip irrigation technology, which applies water and nutrients within the vicinity of the crop root zone for maximum plant benefits (Santosh et al. 2017). Moreover, subsurface drip irrigation (SDI) is capable of maintaining a higher soil water content in the crop root zone and providing favourable conditions for improving plant growth. SDI is recognised by having many significant benefits over surface drip irrigation (DI), such as an increased yield, reduced applied water and improved water productivity (Devasirvatham 2009; El-Gindy et al. 2009; Ayars et al. 2015). Also, SDI has the potential to reduce deep percolation, surface evaporation losses, and, in turn, minimise the seasonal water usage (Aliasghar et al. 2017). The yield of squash and water use efficiency were found to be higher under SDI than of the DI system (Ahmed et al. 2017).

Optimising irrigation water use on open-field vegetable crops altogether with improving the water-holding capacity of the sandy soils is highly in demand in arid regions like the Al-Ahsa oasis of KSA. Several studies showed that the water holding capacity of the sandy soils and the availability of soil water improved due to the addition of polymers (El-Rehim et al. 2004; Bhardwaj et al. 2007; Kashkuli & Zahrabi 2013). Polymer addition (PA), such as polyacrylamide, improved the water-holding capacity of the sandy soil by 47% when the drip line of the SDI was placed at a depth of 15 cm with an operating pressure of 1 kPa (Zin-El-Abedin et al. 2015). Besides, it increased the soil moisture by 20% above and by 7.4% below the drip line when placed in a layer at 30 cm depth. Soil moisture distribution and its uniformity in the sandy soil profile under the DI were affected by the dripper-spacing and under the SDI by the lateral location (Badr & Abuarab 2013). In an arid oasis region of northwest China, the lower soil water content limits of melon crops during blooming to fruit setting are recommended being 55% of field capacity (FC) and 65% of FC for the fruit swelling stages (Wang et al. 2016) under furrow irrigation. The muskmelon fruit yield (MFY) and vitamin C content are highly sensitive to low soil water content limits from 45 to 65% FC during the fruit swelling stage.

Deficit irrigation is a regime to apply the amount of irrigation water at the level below the full crop requirement (Al-Solaimani et al. 2017). Such practice assists in saving irrigation water, sustaining productivity and alleviating pressures of water resource-scarcities (Sharma et al. 2014). Imposing deficit irrigation regimes (DIRs) at 50% for the actual evapotranspiration (ETc) increased the root length density of muskmelons, but caused a 30% decrease in the yield. This indicates the DIR command can potentially save 37–45% of the irrigation water with a moderate reduction in the economic value of the melon yield. In another study, a DIR of 75% ETc saved 25% of the irrigation water, but reduced the melon yield by 34% (Leskovar et al. 2004). Crop water productivity was maximised due to the practice of combing DIR and PA soil amendments (Satriani et al. 2018). The objective of the study was to assess the influence of variable levels of DIR and PA (K-highly crossed polyacrylamide) along with their combination on the fruit yield and WUE of muskmelons under two methods of drip irrigation (DI and SDI). The aim was to determine the most efficient irrigation method, the optimal deficit irrigation regime, a better polymer addition rate, or their combination that enhanced the fruit yield and water productivity of the muskmelon.

https://doi.org/10.17221/94/2020-SWR

MATERIAL AND METHODS

Experimental site conditions. The experimental site is located in the Al-Ahsa oasis of the eastern region of KSA, and it is characterised by an extreme dry arid climate with high temperatures, about 50 °C in the summer and a low average annual rainfall of 50 mm (FAO 2009). The study trials were carried out in one of the open fields of the Research and Training Station of King Faisal University, Saudi Arabia (25°16'N, 49°42'E, 148.4 m a.s.l.). The soil of the site was identified as a medium-coarse sandy soil, based on the sieve soil mechanical analysis and classification of the United States Department of Agriculture (USDA). The muskmelon (*Cucumis melo* L.) was cultivated during the growing season of the year 2015. Initially, before the disc harrowing of the site's soil and the addition of an organic fertiliser, the physical properties of the soil profile were determined for three depths as shown in Table 1. The soil properties included the field capacity, permanent wilting point, available water content, organic matter, and distribution of the soil particles.

The reference evapotranspiration (ET_o) plays an essential role in the planning, management, and efficiency of irrigation. The experimental site's ET_o was estimated with the FAO CROPWAT model and the monthly average daily climatic data over five years (2010–2014) prior to the study. The modified Penman-Monteith equation (MPM) in the Food and Agriculture Organization of the United Nations (FAO) Irrigation and Drainage Paper 56 (Allen et al. 1998) has been recommended as the standard method for the estimation of ET_o worldwide for a variety of climatic situations (Phad et al. 2020). As shown in Equation (1), the estimation is based on physical principles, such as the incoming energy, outgoing energy, aerodynamics, and weighing factor.

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma\frac{900}{T+273}u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \quad (1)$$

where:
ET_o – reference evapotranspiration (mm/day);
R_n – net radiation at the crop surface (MJ/m^2/day);
G – soil flux heat density (MJ/m^2/day);
T – mean daily air temperature at 2 m height (°C);
u – wind speed at 2 m height (m/s);
e_s – saturation vapour pressure (kPa);
e_a – actual vapour pressure (kPa);
$e_s - e_a$ – saturation vapour pressure deficit (kPa);
Δ – slope vapour pressure curve (kPa °C);
γ – psychometric constant (kPa °C).

Experimental design. A complete randomised block design (CRBD) was used to evaluate the influence of the PA and DIR on the MFY (t/ha) and WUE (kg/m^3) of the muskmelon. Three levels of PA (0, 0.2, and 0.4%) and two rates of DIR (50 and 75% of ET_o) were randomly imposed within the alternating drip lateral lines of the DI and SDI systems (blocks). Each treatment was replicated three times.

Irrigation system description. The irrigation system, as shown in Figure 1, was made of six alternating subplots, three for SD and three for SDI; each subplot was subdivided into two units of four and five laterals, i.e., nine laterals per subplot. Each subplot received one of the deficit irrigation regime treatments (100%, 75% and 50% ET_o). The main components of the irrigation system were comprised of the main pipeline, sub-main pipeline, a screen filter (200 meshes), a horizontal bypass fertiliser tank (200 L), a pressure gauge, six water control stations, and inline drip laterals. The main and sub-main pipelines were made of high-density polyethylene (HDPE) (PE100) with a nominal outside diameter of 50.8 mm, a wall thickness of 1.8 mm, and a nominal pressure of 5 MPa. The inline drip laterals were made of low-density polyethylene (LDPE) with a 16 mm nominal inside diameter and can stand up to 300 kPa (3 bars) maximum working pressure at a 30 °C water temperature.

Each of the six-water control stations was located between the two units of a subplot. A station consists

Table 1. Soil profile's physical properties of the experimental site

Soil depth (cm)	Θ_{FC}	Θ_{PWP}	AWC	OM (%)	Soil particle distribution (%)			
	(cm^3/cm^3)				2–0.5 mm	0.5–0.25 mm	0.25–0.05 mm	< 0.05 mm
0–20	0.089	0.026	0.063	2	31.3	49.5	17.2	2.0
20–60	0.078	0.022	0.056	1	29.0	51.2	18.3	1.5
60–80	0.072	0.021	0.051	0	28.0	51.9	19.1	1.0

Θ_{FC} – field capacity; Θ_{PWP} – permanent wilting point; AWC – available water content; OM – organic matter

https://doi.org/10.17221/94/2020-SWR

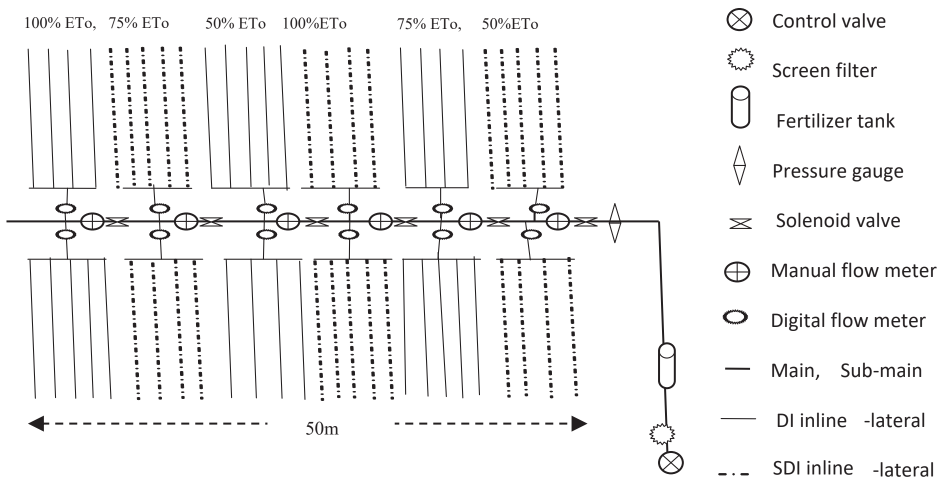

Figure 1. Irrigation system with units of the surface and subsurface drip irrigation with inline drip laterals under the deficit irrigation regimes

DI – surface drip irrigation; SDI – subsurface drip irrigation; ET_o – reference evapotranspiration

of a solenoid control valve connected to a timer, a manual flow meter and two digital volume flow meters, each for a unit. As shown in Figure 2, the inline drip laterals of the SDI units were placed on ridges, while the DIs were located 15 cm below the soil surface. The inline drip laterals of the SDI were wrapped by a sack of plastic mesh to protect them from clogging.

The water application uniformity of the inline drip laterals of the SDI and DI was measured using a hydraulic bench in order to determine the average flows (q_{med}) and the standard deviations. Then by employing the American Society of Agricultural Engineers standard (ASAE 2003), the inline drip laterals of the DI and SDI were classified accord-

(A)

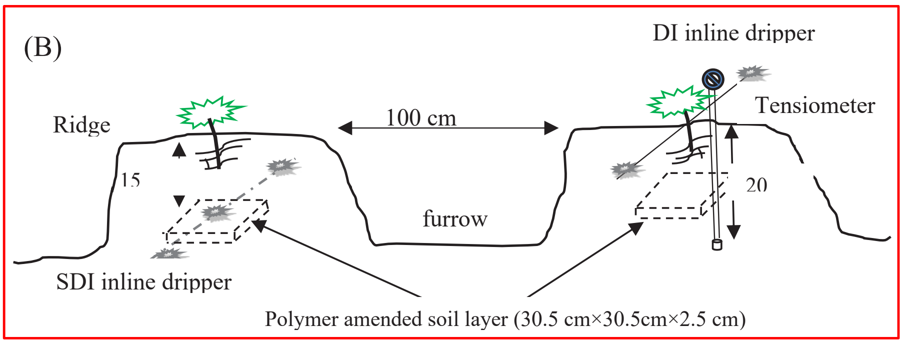

Figure 2. Polymer addition: applying an amended soil layer under the dripper location (A), schematic diagram of the locations of the polymer amended soil layer with respect to the surface drip irrigation (DI) and subsurface drip irrigation (SDI) methods (B)

https://doi.org/10.17221/94/2020-SWR

ing to the coefficient of variation (*CV*) as Excellent (< 5%), Medium (5–7%), Marginal (7–11%) and Poor (> 11%) using the following equation (ASAE 2003).

$$CV = \frac{\sigma}{q_{\text{med}}} \times 100 \qquad (2)$$

where:
CV – coefficient of variation (%);
q_{med} – average of all the flows (L/h);
σ – standard deviation (L/h).

Polymer addition. A super hydrogel polymer, namely K-highly cross-linked polyacrylamide (K-HCP), was utilised for the soil amendment of the experimental site within the vicinity of the inline drippers. This polymer is made up of a water-insoluble acrylamide and potassium acrylate, (-CH_2-CH (COOK)-)n and globally used in agriculture to enhance the water-holding capacity of sandy soils (Bhardwaj et al. 2007). The K-HCP polymer is capable of absorbing, swelling and retaining about 400–500 times its own weight in water and takes five to seven years to degrade completely (Buchholz 1998; Dahri et al. 2019). However, it has an adverse effect in increasing the saturated conductivity of sandy soils.

In the laboratory of the Water Studies Center at King Faisal University, samples of the K-HCP polymer were prepared by weighing 2 and 4 g of dry powder (Stockosorb® 500 micro) to represent the PA treatments of 0.2% and 0.4%. Each sample treatment was added to a kilogram of soil, mixed thoroughly, and poured into a square wood frame as a layer of soil of c.s.a of 30.48 by 30.48 cm and a depth of 2.54 cm. Initially, the wood frame was placed 15 cm below the soil surface as shown in Figure 2A, then filled with the amended soil. This means that the polymer amended soil layers were embedded 15 cm beneath the DI drippers and at the localities of the SDI drippers as illustrated in Figure 2B.

Soil water content and saturated hydraulic conductivity. During the growing season, soil samples were taken from the experimental site to determine the soil bulk density. In addition, randomly disturbed soil samples were collected, air-dried, and passed through a 2 mm sieve. The samples were then used to assess the effects of PA on the relationship between the soil water content (SWC) and pressure head (-h) and on the soil saturated hydraulic conductivity (K_s). A pressure plate extractor was used to determine the SWC of the site soil and polymer amended soils against eight levels of pressure heads (0, 5, 10, 20, 30, 35, 40, and 50 cbar) (Dane & Hopmans 2002).

On the other hand, K_s was determined with a KSAT advanced benchtop device using packed soil samples (1.6 g/cm^3) in the METER sample rings. The method of the KSAT device is based on the German standards DIN 19683-9:1998-05, DIN 18130-1:1998-05, and Darcy's equation (Darcy 1856).

In addition, twelve tensiometers were placed at a depth of 10 cm, two in a subplot to measure the soil pressure heads for the 0.0% and 0.4% PA treatments, daily before irrigation. The subplots of the DI and SDI, three for each method, were under the treatment of the DIRs of 100%, 75%, and 50% of the ET_o. As shown in Figure 3, the relationship between the SWC and the pressure heads was established for the site soil, which was obtained during the growing season. Then the relationship was utilised to determine the equivalent SWC of the soil pressure heads for the 0.0% and 0.4% PA treatments.

Irrigation regime strategies. After transplanting the seedlings, all the treatments received the same daily amount of irrigation water (5.9 mm/day) for three weeks to ensure adequate plant establishment and attain homogeneity. Solenoid valves and a timer were set up to enforce the DIR treatments (100%, 75%, and 50% of ET_o) in the units. The required irrigation water for each unit was determined using the following equation (Doorenobos & Pruitt 1992):

$$I = ET_o \times A \times f_C \qquad (3)$$

where:
I – represents the irrigation amount (L);
ET_o – the reference crop evapotranspiration (mm);
A – the experimental unit area (m^2);
f_C – faction of plant cover.

Cropping. In the first week of February 2015, muskmelon seeds (*Cucumis melo L.*) were sown into pots in a greenhouse and allowed to grow for 27 days. On the 29th of February when the plants had grown into two-leaf seedlings, they were taken and transplanted at dripper locations of the inline drip laterals. A week before transplanting, 140 g of organic fertiliser was added in at the location of each dripper. The organic fertiliser contained 40% organic matter, a 20 : 25 C/N ratio, 2% total N of 2%, 1.1% total P, 0.8% total K, and a pH of 7.0. Also, via fertigation fertilisation, recommended fertilisers for the different growth stages of muskmelon were applied to enhance the vegetative and root growth and improve the quantity and quality of the production. Initially, during the crop establishment stage, the muskmelon plants were

https://doi.org/10.17221/94/2020-SWR

Table 2. Measured actual applied irrigation regimes vs. the potential evapotranspiration (ET_o)

Month	Pen-Mon ET_o (mm)	Measured applied irrigation water (mm/day)					
		100% of ET_o		75% of ET_o		50% of ET_o	
		SDI	DI	SDI	DI	SDI	DI
March	5.9	5.86	5.25	4.35	4.38	2.97	3.05
April	7.1	4.93	5.89	4.60	4.62	3.42	3.24
May	8.7	6.44	10.01	7.83	8.94	6.36	7.06
June	10.3	11.61	12.69	10.30	10.57	6.76	7.21

SDI – subsurface drip irrigation; DI – surface drip irrigation

covered with a cloth for protection against viruses and insects.

Statistical analysis. A complete randomised block design was used for the experimental treatments, which were replicated three times. The differences in the measured values among the main treatments, blocks (DI and SDI), and sub-main treatments (PAs and DIRs) in the units were analysed using an analysis of variance (ANOVA) of the SAS package (Ver. 8.0 e, 2001) and regression tests at $P < 0.05$.

RESULTS AND DISCUSSION

The site reference evapotranspiration. The monthly average daily climatic data of the study area during the period (2010–2014), which used the FAO-PM method, resulted in the ET_o estimated values as reported in Table 2. (Zahra & Seyed 2020) indicated that the ET_o has a vital role in irrigation planning and water management. Therefore, in this study, the estimated ET_o values were used in planning the irrigation of the muskmelons in 2015. The humidity during the growing season, March to June, was 31% and 14%, respectively. The maximum air temperature and radiation during the same months increased by 46.1% and 21.9%, respectively. Accordingly, the results indicated that the monthly average daily ET_o values over the period (2010–2014) for the growth cycle of the muskmelon ranged from 5.9 to 10.3 mm/day. This revealed that the ET_o values could increase by 74.6% from March to June of 2015, due to possible increases in the maximum air temperature, wind, hours of sun per day, and the solar radiation. The growth seasonal average ET_o over the study area was 728.8 mm.

Measurement of the applied irrigation water. Based on the ASAE EP 405.1 standard (ASAE 2003), the *CV* of the DI drippers of the inline drip lateral was assessed to be 4% and classified as excellent, while the SDI was 7% and classified as medium. Covering the drippers of the SDI inline drip lateral with a sack of plastic mesh decreased the discharge by 15.5% and increased the *CV* by 3%. The results showed there were discrepancies between the actual applied irrigation water and the timely scheduled irrigation amounts based on the ET_o, which were delivered to the DI and SDI units (Table 2). This could be attributed to the clogging of the emitters by the fertiliser concentration and the use of ammonium sulphate which is known for its adverse effects on reducing emitter flow rates (Zhou et al. 2016; Liu et al. 2019). Besides, irrespective of the same scheduling times of the two methods, the applied irrigation amounts by the SDI were found to be less by 16.3%, 35.7% and 8.5% than the DI in April, May, and June, respectively. This could be assigned to the high initial soil moisture content (θ_o) surrounding the SDI emitters because they were located near the polymer amended soil layer (Figure 2a). Therefore, consequently, their flow rates decreased relatively compared to the flow rates of the DI emitters, which were located on the soil surface, 15 cm away from the polymer-amended layer. A study showed the hydraulic properties of the SDI embedded emitters in a soil were susceptible to changes in the θ_o and bulk density of the adjacent soil (Fan & Li 2018).

Polymer addition effects on SWC and K_s. The soil water content of the experimental site increased with an increasing amount of the polymer addition (Figure 3). The 0.4% polymer addition changed the field water-holding capacity of the site medium-sand from 0.186 to 0.330 cm^3/cm^3, thus turning out to be similar to the field water holding capacity of loam soils. This outcome agreed with previous studies conducted by Huttermann et al. (1999) and Sivapalan (2001).

The combined impacts of the irrigation methods and the PA on the pressure head and SWC of

https://doi.org/10.17221/94/2020-SWR

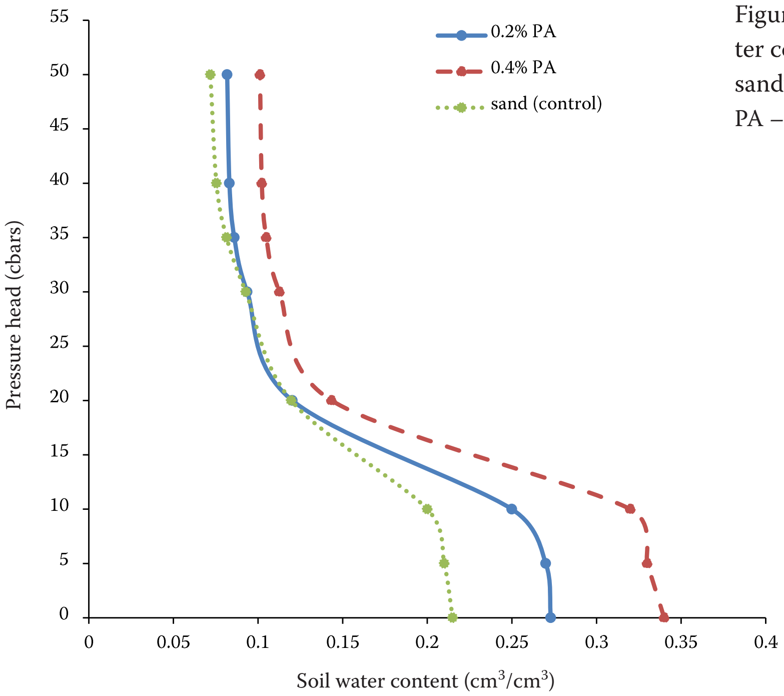

Figure 3. Polymer addition effects on the soil water content and pressure head of the site medium sandy soil
PA – polymer addition

the top surface layer (0–15 cm) before the irrigation are illustrated in Table (3). The pressure head with 0.0% PA was found to be higher under the SDI (12–14.3 cbar) than the DI (10.3–12 cbar). However, with the combined effects of the 0.4% PA and DIR of 50% ET_o, the pressure head was reduced by 21% under the SDI and by 10.8% under the DI.

Based on the SWC-pressure head relationship in Figure 3, the SWC in the surface layer, 5 cm above the amended soil layer, increased in a range of 72.4% to 99.4% due to the 0.4% PA under both drip irrigation methods. Under the SDI method, the SWC increased by 82.2%, 88.2%, and 99.4% while under the DI by 72.4%, 74.5%, and 80.6%, respectively, for the DIRs of 100%, 75%, and 50% of the ET_o. Therefore, the influences of the PA on the SWC under the SDI were more marked. Thus, the impacts of the PA on SWC under the SDI more pronounced. This was attributed to the adjacent location of the subsurface drippers to the polymer-amended layer below the soil surface, acting like a water reservoir. Besides, the matric potential in the top surface layer was higher with the subsurface laterals than the surface laterals, which resulted in an upward soil water flow from the reservoir by the capillary effect.

On the other hand, the K_s increased with an increasing amount of PA. A positive linear relationship developed between the K_s and the PA (Figure 4), which agreed with a previous study carried out by Kodadadi et al. (2013). This indicates that an over-irrigation practice in the top layer (0–15cm) leads to saturation of the polymer-amended layer and, in turn, increases the K_s. Therefore, the practice of imposing a proper deficit irrigation regime (DIR) along with

Table 3. Polymer addition (PA) and deficit irrigation regime (DIR) influences on the soil water content (SWC) under the surface drip irrigation (DI) and subsurface drip irrigation (SDI) methods

Irrigation method	DIR (% of ET_o)	PA (% of soil mass)	Pressure head (cbar)	SWC (cm^3/cm^3)	PA (% of soil mass)	Pressure head (cbar)	SWC (cm^3/cm^3)
SDI	100	0	12.0	0.180	0.4	10.0	0.328
DI	100	0	10.3	0.192	0.4	8.0	0.331
SDI	75	0	13.7	0.170	0.4	10.9	0.323
DI	75	0	11.0	0.188	0.4	10.0	0.328
SDI	50	0	14.3	0.162	0.4	11.3	0.320
DI	50	0	12.0	0.180	0.4	10.7	0.325

https://doi.org/10.17221/94/2020-SWR

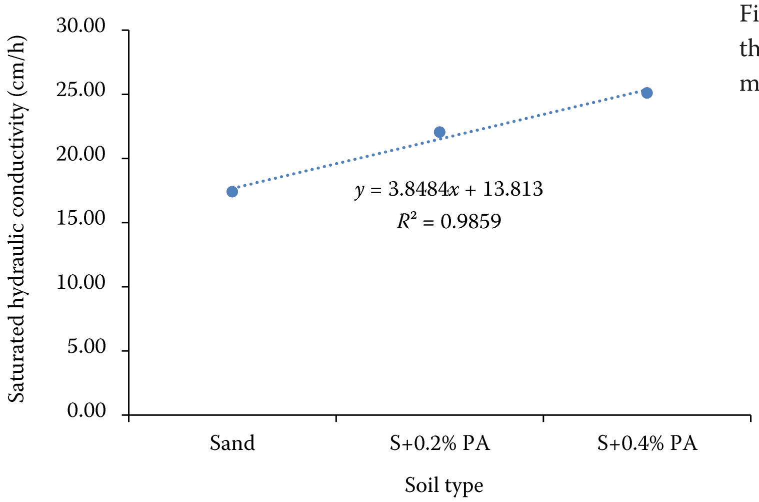

Figure 4. Impact of the polymer additions on the saturated hydraulic conductivity of the site's medium sandy soil

the best polymer addition rate, can enhance the soil water availability within the polymer amended soil layer and capable of counteracting the adverse effect of the K_s increase.

Melon fruit yield. The melon fruit yield was determined by the average weight of a single fruit (grams) and with a plant density of 10 989 per ha. As shown in Figure 5, without the polymer addition (0.0% PA), the MFY significantly ($P < 0.05$) decreased with an increase in the DIR under the DI and SDI methods. The MFY decreased by 32.1% and 47.1% under the DI and by 11.4% and 43.3% under SDI at 75% ET_o and 50% ET_o, respectively. The lowest decrease in the MFY was under the SDI, 11.4%, which was caused by the DIR of 75% ET_o. This indicated that the 75% ET_o irrigation regime provided the appropriate soil moisture for the water and nutrient uptake by the plant roots, which was reflected on the positive yield response. The result was in line with the (Wang et al. 2017) findings, which indicated that the MFY is sensitive to the soil moisture content. Therefore, the SDI method could save up to 25–50% of the irrigation water with moderate reductions (11.4–43.3%) in the economic value of the MFY. The highest MFY obtained (29.2 t/ha) was with the 100% ET_o under the DI method, while the lowest yield (14.1 t/ha) was with the 50% ET_o under the SDI method. As shown in Figure 5, the regression test results of the muskmelons due to the deficit irrigation regimes (100%, 75% and 50% of ET_o) under the DI and SDI methods indicated the best fit are linear equations, with R^2 of 0.958 and 0.9306 for the DI and SDI, respectively.

The effects of the 0.4% polymer addition on the soil water content and on the MFY are presented in Figure 6. The increases in the SWC and corresponding increases in the MFY are due to the 0.4% PA under the DIRs (100%, 75% and 50% of ET_o) were found to be more marked under the SDI than the DI method.

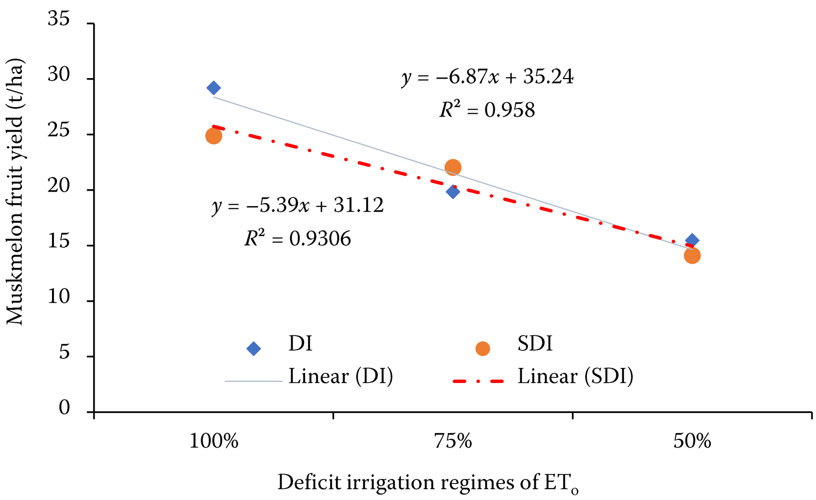

Figure 5. Effect of the deficit irrigation regimes on the muskmelon fruit yield
DI – surface drip irrigation; SDI – subsurface drip irrigation; ET_o – reference evapotranspiration

https://doi.org/10.17221/94/2020-SWR

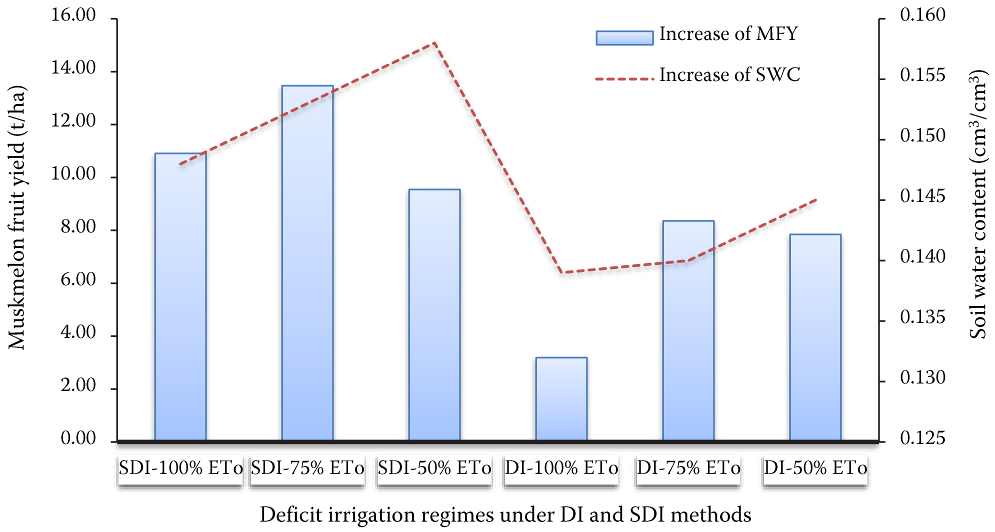

Figure 6. Combined effects of the 0.4% polymer addition and deficit irrigation regimes on the soil water content (SWC) and muskmelon fruit yield (MFY) under the subsurface drip irrigation (SDI) and drip irrigation (DI) methods
ET_o – reference evapotranspiration

The 0.2% polymer addition under the DI method and the DIR of 75% of the ET_o resulted in the highest reduction of the MFY (23.1%), and the lowest under the SDI method (13.6), Figure 7. The regression test results of the MFY due to the irrigation deficit regimes showed the best fit of the linear equation was under the SDI method than the DI method.

The combined effects of the full irrigation rate of 100% ET_o with the polymer addition significantly ($P < 0.05$) enhanced the MFY under the SD compared to the SDI method (Figure 8). The combination effects of the full irrigation rate with the polymer addition of 0.2% and 0.4% increased the fruit yield by 2.4% and 10.9% under the DI method, and by 21.5% and 43.9% under SDI method, respectively. This proved that the addition of a polymer under the SDI has positive impacts on the MFY more than the DI method. The regression test results of the MFY with the 100% ET_o vary with the PA treatments and show the best fit as a positive linear relation with R^2 values of 0.99 for the SDI and 0.90 for the DI method. The highest attained yield (35.8 t/ha) was with the combination of the full irrigation rate and 0.4% PA, and the lowest was (24.9 t/ha) with 0.0% PA both under the SDI method (Figure 6).

Based on the ANOVA, Tables 4 and 5 show the analysis of variance results obtained for the muskmelon fruit yield (kg/ha) and water use efficiency

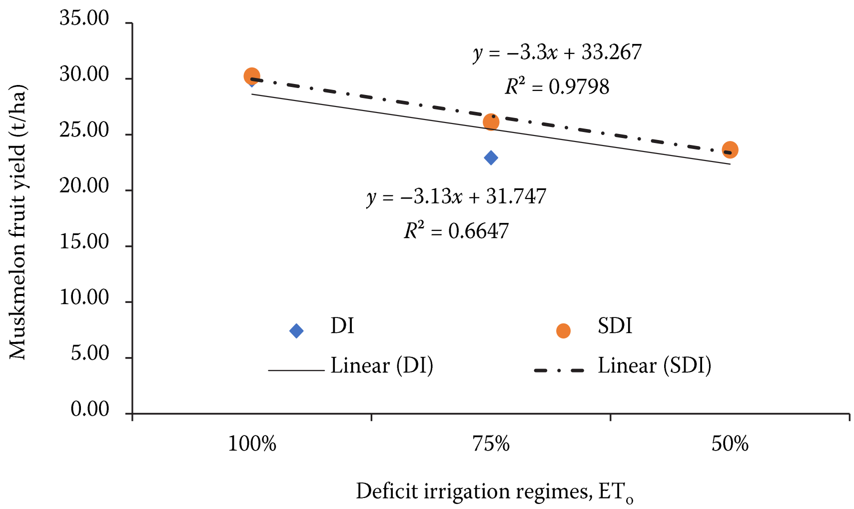

Figure 7. Influence of 0.the 2% polymer addition on the muskmelon fruit under the surface and subsurface drip irrigation methods
DI – surface drip irrigation; SDI – subsurface drip irrigation; ET_o – reference evapotranspiration

https://doi.org/10.17221/94/2020-SWR

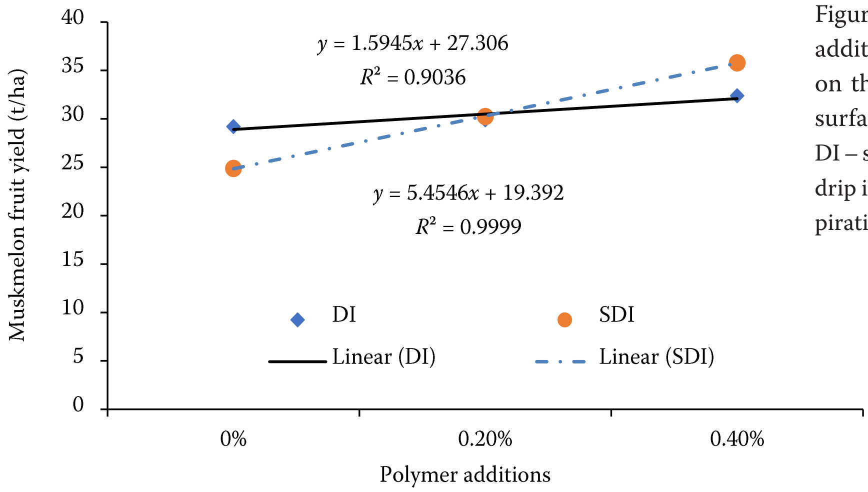

Figure 8. Combined effects of the polymer additions and full irrigation (100% of ET_o) on the muskmelon fruit yield under the surface and subsurface drip irrigation

DI – surface drip irrigation; SDI – subsurface drip irrigation; ET_o – reference evapotranspiration

(kg/m^3) DIR and PA under both the DI and SDI methods. The independent treatment factors, DIR and PA, had significant effects on the MFY at a 5% significance level ($P < 0.05$) for both irrigation methods (DI and SDI). Although there were no significant interaction effects between the two factors on the yield at a 5% significance level ($P > 0.05$) under the DI, they were observed under the SDI. As shown in Table 4, both the DIR and PA and their interaction had significant impacts on the muskmelon WUE under both irrigation methods at a 5% significance level ($P < 0.05$). This implied the positive potential impacts of the combined effects of the PA with the DIR on saving irrigation water and enhancing the yield under both the DI and SDI. Table 6 shows the analysis of variance results obtained for the mean fruit weight (FW) based on the impacts of the DIR and PA under the DI and

Table 4. Analysis of variance for the muskmelon fruit yield (kg/ha)

Irrigation method	Source	df	ANOVA	Mean square	*F* value	*P* value
DI	DIR	2	593 095 584.9	296 547 792.4	17.95	< 0.0001
	PA	2	170 513 033.4	85 256 516.7	5.16	0.0186
	DIR × PA	4	47 538 155.2	11 884 538.8	0.72	0.5911
SDI	DIR	2	44 815 894.0	22 407 947.0	27.09	< 0.0001
	PA	2	967 094 508.2	483 547 254.1	584.64	< 0.0001
	DIR × PA	4	170 913 646.2	42 728 411.6	51.66	< 0.0001

SDI – subsurface drip irrigation; DI – surface drip irrigation; DIR – deficit irrigation regime; PA – polymer addition; df – degree of freedom

Table 5. Analysis of variance for the muskmelon water use efficiency (kg/m^3)

Irrigation method	Source	df	ANOVA	Mean square	*F* value	*P* value
DI	DIR	2	13.2	6.62	10.2	0.0014
	PA	2	0.68	0.34	0.52	0.6040
	DIR × PA	4	0.68	0.17	0.26	0.8981
SDI	DIR	2	1.85	0.93	14.4	< 0.0003
	PA	2	6.78	3.39	52.7	< 0.0001
	DIR × PA	4	4.48	1.12	17.4	< 0.0001

SDI – subsurface drip irrigation; DI – surface drip irrigation; DIR – deficit irrigation regime; PA – polymer addition; df – degree of freedom

https://doi.org/10.17221/94/2020-SWR

Table 6. Analysis of variance for the mean fruit weight (g)

Irrigation method	Source	df	ANOVA	Mean square	*F* value	*P* value
DI	DIR	2	706 662.4	353 331.2	17.43	< 0.0001
	PA	2	205 854.5	102 927.2	5.08	0.0196
	DIR × PA	4	52 180.6	13 045.1	0.64	0.6393
SDI	DIR	2	150 113.8	75 056.9	77.4	< 0.0001
	PA	2	717 663.5	358 831.8	370.1	< 0.0001
	DIR × PA	4	444 296.3	111 074.1	114.6	< 0.0001

SDI – subsurface drip irrigation; DI – surface drip irrigation; DIR – deficit irrigation regime; PA – polymer addition; df – degree of freedom

SDI methods. The results indicated that DIR and PA had significant implications on the mean FW at a 5% significance level ($P < 0.05$) under both irrigation methods. However, their interaction had a significant effect on the FW under the SDI, but not under the DI method. The combined impact of the polymer addition and DIR on the muskmelon fruit components was more pronounced under the SDI than the DI method. These outcomes show the potential positive influences of the DIR and PA on the FW which are more profound with the SDI than the DI method.

Table 7 shows the statistical analysis by the one-way ANOVA for the t-test at the probability levels of 0.05 for the means of the MFY, WUE and FW. The data of the t-test pointed out there are significant differences in the means of the MFY and FW under the DI and in the means of the FW and WUE under the SDI for all the irrigation rate levels (50%, 75%, and 100% of ET_o). In addition, there are significant differences among the means of the MFY, WUE and FW for all the PA levels (0.0%, 0.2%, and 0.4%) under the subsurface drip irrigation. However, under the surface drip irrigation, the MFY, WUE and FW were insignificantly affected by the 0.0% PA and 0.2% PA in contrast to the significant effect under the 0.4% PA. Under both irrigation methods, the mean values of the WUE increased with an increase in the DIR, while the MFY mean values decreased. As shown in Table 7, imposing the 75% ET_o on the muskmelon crop resulted in enhancing the WUE by 48.3%, and reducing the MFY by 11% under the SDI method. While under the DI, the WUE improved by 10% and the muskmelon fruit yield was reduced by 22.3% with the 75% ET_o DIR. The highest increase in the WUE was 62.1% and the lowest MFY was 7.8% by imposing a 50% ET_o. On the other hand, increasing the polymer addition level to 0.4% resulted in enhancing the muskmelon WUE and MFY, by 67.7% and 70.4% under the SDI and by 58.6% and 24.4% under the DI, respectively. Therefore, the data obtained by the analyses of one-way ANOVA are in agreement with the findings that illustrated the positive impacts of the DIR and PA as being more pronounced under the subsurface drip irrigation than the surface drip irrigation method.

Table 7. Combined influence of the deficit irrigation regime and polymer addition on the means of the muskmelon fruit yield (MFY), water use efficiency (WUE) and fruit weight (FW) based on a one-way ANOVA

Treatment	DI			SDI		
	MFY (t/ha)	WUE (kg/m^3)	FW (g)	MFY (t/ha)	WUE (kg/m^3)	FW (g)
100% of ET_o DIR	30.5^a	3.0^b	1 065.9^a	28.3^a	2.9^a	990.5^a
75% of ET_o DIR	23.7^b	3.3^b	827.9^b	25.2^b	4.3^b	883.5^b
50% of ET_o DIR	19.1^c	4.3^a	672.5^c	26.1^b	4.7^c	808.8^c
0.0% PA	22.5^b	2.9^b	788.1^b	20.3^c	3.1^c	711.8^c
0.2% PA	22.8^b	3.2^b	799.5^b	24.7^b	3.7^b	863.5^b
0.4% PA	28.0^a	4.6^a	978.7^a	34.6^a	5.2^a	1 107.6^a

Values with the same letters within one column are not significantly different; SDI – subsurface drip irrigation; DI – surface drip irrigation; PA – polymer addition; ET_o – reference evapotranspiration; DIR – deficit irrigation regime

https://doi.org/10.17221/94/2020-SWR

CONCLUSIONS

Amending the soil layer within the vicinity of emitters of inline drip laterals by K-highly crossed-linked polyacrylamide enhanced the water holding capacity of the medium sandy soil and turned it into being similar to a loamy soil. Moreover, the soil water content of the top layer above the polymer-amended layer increased under both the surface and subsurface drip irrigation methods, but was more pronounced with the latter. The observed increase in the saturated hydraulic conductivity of the polymer amended soil layer could be counteracted by imposing a deficit irrigation regime practice.

The combined effects of the polymer addition and the deficit irrigation regime profoundly improved the muskmelon fruit yield, the fruit weight and the water use efficiency under the subsurface drip irrigation method. In conclusion, imposing a deficit irrigation regime with a polymer addition under a subsurface drip irrigation is an appropriate practice for vegetable production in open fields of arid regions dominated by sandy soils like the Kingdom of Saudi Arabia. This practice has the potential to enhance the water and nutrient availability for the plants' uptake, to minimise the evaporation and deep percolation and to improve the crop water productivity.

REFERENCES

Ahmed E.M., Barakat Ragheb M.M.A., Rushdi M.K. (2017): Impact of surface and subsurface drip irrigation systems and fertigation managements on yield and water use efficiencies of two squash varieties. Assiut Journal of Agricultural Sciences, 48: 303–318.

Aliasghar M., Daniele Z., Khaled B., Daniel P. (2017): A model to assess the economic viability of alfalfa production under subsurface drip irrigation in California. Irrigation and Drainage, 66: 90–102.

Allen R.G., Pereira L.S., Raes D., Smith M. (1998): Crop Evapotranspiration Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper No. 56, Rome, FAO.

Alkhasha A., Al-Omran A., Aly A. (2018): Effects of biochar and synthetic polymer on the hydro-physical properties of sandy soils. Sustainability, 10: 4642.

Al-Solaimani S.G., Alghabari F., Ihsan M.Z., Fahad S. (2017): Water deficit irrigation and nitrogen response of Sudan grass under arid land drip irrigation conditions. Irrigation and Drainage, 66: 365–376.

ASAE (2003): Design and Installation of Micro-irrigation Systems. ASAE Standards Engineering Practices data: EP 405.1, St. Joseph, American Society of Agricultural Engineers.

Ayars J.E., Fulton A., Taylor B. (2015): Subsurface drip irrigation in California – Here to stay? Agricultural Water Management, 157: 39–47.

Badr A.E., Abuarab M.E. (2013): Soil moisture distribution patterns under surface and subsurface drip irrigation systems in sandy soil using neutron scattering technique. Irrigation Science, 31: 317–332.

Bhardwaj A.K., Shainberg I., Goldstein D., Warrington D.N., Levy G.J. (2007): Water retention and hydraulic conductivity of cross-linked polyacrylamides in sandy soils. Soil Science Society of American Journal, 71: 406.

Buchholz F.L. (1998): The structure and properties of superabsorbents polyacrylates. In: Buchholz F.L., Graham A.T. (eds.): Modern Superabsorbent Polymer Technology. New York, Wiley: 167–221.

Dahri S.H., Mangrio M.A., Shaikh I.A., Dahri S.A., Steenbergen F.V. (2019): Effect of different forms of super absorbent polymers on soil physical & chemical properties in orchard field. World Academics Journal of Engineering Sciences, 6: 12–20.

Dane J.H., Hopmans J.W. (2002): Water retention and storage. In: Dane J.H., Topp G.C. (eds.): Methods of Soil Analysis. Part 4. Physical Methods. Madison, SSSA: 671–720.

Darcy H. (1856): Les fontaines publiques de la ville de Dijon. Paris, Dalmont.

Devasirvatham V. (2009): A Review of Subsurface Drip Irrigation in Vegetable Production. Irrigation Matters Series No. 03/09. Darling Heights, Cooperative Research Center for Irrigation Futures.

Doorenbos J., Pruitt W.O. (1992): Crop Water Requirements. Rome, FAO.

Dorraji S.S., Golchin A., Ahmad S. (2010): The effects of hydrophilic polymer and soil salinity on corn growth in sandy and loamy soils. Clean – Soil, Air, Water, 38: 584–591.

El-Gindy A.G.M., El-Banna E.S., El-Adl M.A., Metwally M.F. (2009): Effect of fertilization and irrigation water levels on summer squash yield under drip irrigation. Misr Journal of Agricultural Engineering, 26: 94–106.

El-Rehim A.H.A., El-Sayed A.H., Abd El-Mohdy H.L. (2004): Radiation synthesis of hydrogels to enhance sandy, soils water retention and increase plant performance. Journal of Applied Polymer Science, 93: 1360–1371.

Fan W., Li G. (2018): Effect of soil properties on hydraulic characteristics under subsurface drip irrigation. IOP Conf. Series: Earth and Environmental Science, 121: 052042.

FAO (2009): Irrigation in the Middle East region in Figures. FAO Water Reports No. 34, Rome, FAO.

https://doi.org/10.17221/94/2020-SWR

Huttermann A.M., Zommorodi M., Reise K. (1999): Addition of hydrogels to soil for prolonging the survival of *Pinus halepensis* seedlings subjected to drought. Soil and Tillage Research, 50: 295–304.

Kashkuli H.A., Zohrabi N. (2013): The effect of superabsorbent polymers on the water holding capacity and water potential of Karkhe Noor sandy soils. International Journal of Scientific Research in Knowledge, 1: 317–324.

LeskovarD.I., Bang A., Crosby K.M, Maness N., Franco J., Perkins Veazie P. (2004): Lycopene, carbohydrates, ascorbic acid and yield components of diploid and triploid watermelon cultivars affected by deficit irrigation. Journal Horticultural Science & Biotechnology, 79: 75–81.

Liu L., Niu W., Gun Y., Wu Z., Ayantobo S. (2019): Effects of urea fertigation on emitter clogging in drip irrigation system with muddy water. Journal of Irrigation and Drainage Engeneering, 145: 04019020.

Locascio J.S. (2005): Management of irrigation for vegetables: past, present, future, HortTechnology, 15: 482–485.

MEWA (2018): Statistical Book of MEWA. Riyadh, Ministry of Environment Water and Agriculture.

Phad S.V., Dakhore K.K., Sayyad R.S. (2020): Estimation of reference evapotranspiration (ET_o) at Parbhani, Maharashtra. MAUSAM, 71: 145–148.

Santosh S.M., Jha B.K., Singh R., Meena M. (2017): Bitter gourd response to surface and subsurface drip irrigation under different fertigation levels. Irrigation and Drainage, 66: 615–625.

Satriani A., Catalano M., Scaleiore E. (2018): The role of superabsorbent hydrogel in bean cultivar under deficit irrigation conditions: A case study in Southern Italy. Agricultural Water Management, 195: 114–119.

Sharma S.P., Leskovar D.I., Crosby K.M., Volder A., Ibrahim A.M.H. (2014): Root growth, yield and fruit responses reticulatus and indorus melons (*Cucumis melo* L.) to deficit subsurface drip irrigation. Agricultural Water Management, 136: 75–85.

SIO (2019): Annual Report, Al-Ahsa, Kingdom of Saudi Arabia. Saudi Irrigation Organization.

Sivapalan S. (2001): Effect of polymer on soil water holding capacity and plant water use efficiency. In: Proc. 10^{th} Australian Agronomy Conf., Australian Society of Agronomy, Hobart, Jan 29–Feb 1, 2001.

Wang J., Huang G., Li J., Zheng J., Huang Q. (2017): Effect of soil moisture-based furrow irrigation scheduling on melon (*Cucumis melo* L.) yield, quality in arid region of Northwest China. Agricultural Water Management, 179: 167–176.

Zahra S.A., Seyed F.S. (2020): Evaluating of eight evapotranspiration estimation methods in arid regions of Iran. Agricultural Water Management, 239: 106243.

Zhou B., Li Y., Song P., Xu Z., Bralts V. (2106): A kinetic model for biofilm growth inside non-PC emitters under reclaimed water drip irrigation. Agricultural Water Management, 168: 23–34.

Zin El-Abdein T.K., Matter M.A., Alazba A.A. (2015): Soil wetting pattern from subsurface drip irrigation as affected application of polyacrylamide layer. Irrigation and Drainage, 64: 609–618.

Received: July 13, 2020
Accepted: April 15, 2021
Published online: May 31, 2021