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Adoption of an intelligent irrigation scheduling technique and its effect on water use efficiency for tomato crops in arid regions

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Abstract

The intelligent irrigation technique is a valuable tool for scheduling irrigation and quantifying water required by plants. This study was carried out during two successive seasons spanning 2010 and 2011. The main objectives were to investigate the effectiveness of the intelligent irrigation system (IIS) on water use efficiency (WUE), irrigation water use efficiency (IWUE) and to assess its potential for monitoring the water status and irrigation schedule of a tomato crop cultivated under severely arid climate conditions. The intelligent irrigation system was implemented and tested under a drip irrigation system for the irrigation of tomato crops (*Lycopersicon esculentum* Mill, GS-12). The results obtained with this system were consequently compared with the control system (ICS), which utilized an automatic weather station. The results reveal that plant growth parameters and water conservation were significantly affected by IIS irrigation. The water use efficiency under IIS was generally higher (7.33 kg m^{-3}) compared to that under ICS (5.33 kg m^{-3}), resulting in maximal water use efficiency for both growing seasons (average 6.44 kg m^{-3}). The application of IIS technology therefore provides significant advantages in terms of both crop yield and WUE. In addition, IIS conserves 26% of the total irrigation water compared to the control treatment, and simultaneously generates higher total yields. These results show that this technique could be a flexible, practical tool for improving scheduled irrigation. Hence, this technology can therefore be recommended for efficient automated irrigation systems because it produces higher yield and conserves large amounts of irrigation water. The intelligent irrigation technique may provide a valuable tool for scheduling irrigation in tomato farming and may be extendable for use in other similar agricultural crops.

Keywords: Smart irrigation; evapotranspiration; tomato yield; water application efficiency; arid region; plant growth parameters.
Abbreviations: AIW- Amount of Seasonal Applied Irrigation Water; Dg- Depth of Irrigation Water; (Dg)t- Total Depth Of Irrigation Water; Ea- Water Application Efficiency; ICS- Irrigation Control System; IIS- Intelligent Irrigation System; IWUE- Irrigation Water Use Efficiency; LR- Leaching Requirement; LSD- Least Significant Difference; Qs- Irrigation Discharge; SMS- Soil Moisture Sensing; WUE- Water Use Efficiency.

Introduction

Tomatoes (*Lycopersicon esculentum* Mill) are an important global vegetable crop (Berova and Zlatev 2000), and require a high water potential for optimal vegetative and reproductive development (Waister and Hudson, 1970). Production areas are typically intensively managed with high inputs of fertilizer and irrigation. Planting tomatoes in Saudi Arabia accounted for 13% of the total land planted with vegetables in 2008 (MOA, 2010). Tomato is one of the most important vegetables because of its special nutritive value, and is the world's largest vegetable crop after potato and sweet potato. Considerable quantities of irrigation water are required, depending on the soil and weather conditions. To reduce the total amount of irrigation water needed by a tomato crop without affecting the yield and fruit quality, the grower must develop management strategies. To achieve better control and management of water in tomato production, irrigation schedules should be based on crop water requirements according to FAO guidelines (Doorenbos and Pruitt, 1977; Allen et al., 1998). Another approach is the development of a daily water balance to calculate ETc and to schedule irrigation events according to effective soil water storage capacity and estimated crop water removal. These methods for irrigation scheduling can be very efficient, but this is difficult and expensive to implement at a farm level. In most of the world, irrigated agriculture has been faced with increased limitations in the water supply over the last few decades. Major efforts have been made by researchers and irrigators to increase and to conserve this vital source by many means. One of these means is the application of irrigation scheduling using sensors and electronic control devices. Irrigation scheduling is a technique designed to accurately give water to a crop in a timely fashion (El-Tantawy, et al., 2007). Irrigation scheduling methods are based on two approaches: soil measurements and crop monitoring (Hoffman et al., 1990). However, the use of more efficient technologies often increases, rather than decreases, water consumption (Whittlesey 2003; English et al. 2002). Improved irrigation scheduling can reduce irrigation costs and increase crop quality. Irrigation scheduling based upon crop water status is more advantageous since crops respond to both the soil and aerial environments (Yazar et al., 1999). Drip irrigation has been practiced for many years due to its effectiveness in reducing soil surface evaporation. It has been used widely for crops in both greenhouses and the field (Du et al. 2008). Uniform water application in drip irrigation is affected by field topography as well as the hydraulic design parameters of the drip system such as energy losses in laterals and emitter characteristics (Mofoke et al. 2004; Yildirim 2007; Zhu et al. 2009). An intelligent irrigation system (IIS) is integrated with intelligent controllers and uses microclimate data to schedule water irrigation. Intelligent irrigation technologies are regarded as a promising tool to achieve landscape water savings and reduce non-point source pollution (Nautiyal et al. 2010). This technique is under evaluation at the trial farm in Dookie, Egypt, and the initial results indicate up to 43% (average 38%) water savings over conventional irrigation control methodologies (Dassanayake et al. 2009). In the past 10 years, intelligent irrigation controllers have been developed by a number of manufacturers and have been promoted by water purveyors in an attempt to reduce over-irrigation (Michael and Dukes 2008). There are many intelligent irrigation systems that compute the amount of water applied and ET based on climate conditions (McCready et al. 2009; Mendez-Barroso et al. 2008; Lozano and Mateos 2007). These systems differ in their accuracy and reliability. Intelligent irrigation systems usually depend on modern electronic sensors, which are capable of collecting data, analyzing and decision making to start/stop irrigation. These devices generally transmit the decisions to electronic controller devices, which control the sprinkler or drip irrigation system. Several moisture sensors are commercially available, such as tensiometers and watermarks. They can generally be used for manual readings to guide irrigation scheduling, while some of them can also be interfaced directly with the irrigation controller in a closed loop control system (Zazueta et al., 1994) to automate irrigation. Some researchers have used tensiometer sensors in irrigation scheduling for tomato under drip irrigation systems (Mendez-Barroso et al. 2008; Smajstrla and Locascio1997). Water use efficiency (WUE) has been reported to decrease with increased irrigation times and the amount of irrigation water per growing season (Qui et al., 2008). Several studies have found that drip irrigation increases yields and WUE by large amounts compared with those with sprinkler or surface irrigation (Kamilov et al., 2003; Nazirbay et al. 2007). The automation of irrigation systems based on soil moisture sensing (SMS) has the potential to provide maximum WUE. Such systems maintain soil moisture within a desired range, which is optimal or adequate for plant growth and/or quality (Munoz-Carpena and Dukes 2005). Therefore, based on prevailing conditions and water shortages, the optimum irrigation schedules for the tomato crop in a region should be determined. The objectives of this study were to investigate the effect of different targets of this intelligent irrigation system on tomato ET, yield, WUE and irrigation water use efficiency (IWUE) in arid climatic conditions.

Results

Tomato evapotranspiration (ETc)

The processor-interfaced IIS was used as an electronic controller to monitor, record ETo based on measured weather parameters and automatically adjust the amount of irrigation water applied. The daily and weekly averages of the ETc rates for tomato crops under IIS and ICS treatments were calculated using the daily records during the two growing seasons (Table 3). The values of ETc for ICS treatment were derived by the product of the reference evapotranspiration (ETo) and the crop coefficient (Kc) for different stages of tomato crop development. From this table, it can be noted that the total ETc values for tomato crops under the IIS and ICS treatments were 540.42 and 671.57 mm, respectively, with significant water saving equal to 20% with IIS treatment compared to ICS. Values of ETc during the first four weeks of crop growth were lower under IIS treatment, then increased during plant booming and development, peaking approximately 55 days (8 weeks) post-transplantation. After this point, values of ETc began to retreat gradually with leaf senescence, most significantly during weeks 9 to 15, and a similar trend took place with ICS management. The accumulated rainfall for the 2010 and 2011 growing seasons were 14 mm and 16.6 mm, respectively, which are considered to be not significant for irrigation.

Irrigation management

In IIS treatment, irrigation was scheduled and initiated automatically based on ETo prediction. This system is equipped with special options, such as the addition more or less water depending on the needs of the plant. The water quantities and timings were monitored and recorded and shown on the monitor. The ETo values for ICS were determined using the modified Penman method, FAO version (Allen et al., 1998) and used efficiently to schedule irrigation at different growth stages. Based on local experience, these stages were approximately 30, 40, 40, and 25 days, respectively, and were considered in the evaluation of Kc. These stages are: initial, crop development, mid-season and late season. Furthermore, as shown in Table 3, ETc determined for the ICS experiment was higher than that of the IIS, with a similar trend during the entire growth season. The averages of weekly irrigation water (Dg) added for both treatments were calculated and tabulated in Table 4. As shown in this table, the average of total irrigation water used during the two growing seasons in the IIS and ICS treatments were 614.26 and 825.47 mm, respectively, with a 26% difference. Therefore, the results of this study show that IIS significantly conserves water compared to ICS. Moreover, the data analysis revealed that ETc values were close in the initial developmental stages, but their values gradually diverged during the rest of the season.

Analysis of agronomical characteristics

The effect of IIS scheduling on tomato growth and productivity parameters were investigated. The growth characteristics of tomato plants grown during the two seasons (2010 and 2011) are shown in Table 5. The results of this study reveal that the IIS had a clear impact on agronomical plant characteristics. The average plant heights were 45.3 and 38.8 cm for the IIS and ICS treatments, respectively. The average branch numbers were 6.31 and 5.05 per plant for the same treatments, and the average yields for the two seasons were 39.55 and 37.05 ton h^{-1} for the IIS and ICS, respectively. The IIS was superior to the ICS in terms of plant height, number of branches, fruit length, average fruit weight, early yield, WUE and IWUE by 16%, 26%, 11%, 6%, 8%, 38% and 43%, respectively. In addition, these results suggest that the tomato yields varied between studied treatments by 7-9% in favor of IIS.

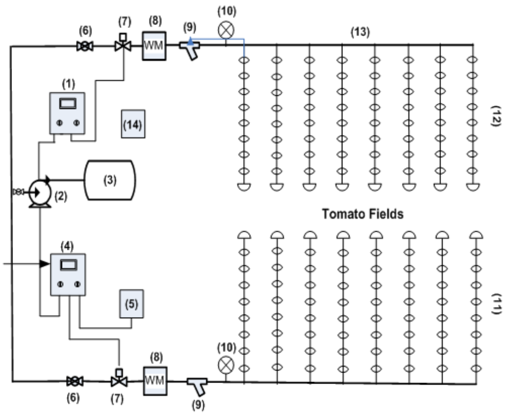
Water use efficiency

Table 6 illustrates the effects of the IIS and ICS on tomato water use efficiency during the growing seasons. Through analysis of this table, we found that the values of WUE and IWUE were higher in the IIS treatment. For instance, regarding the first and second seasons in the IIS and ICS

Table 1. Metrological data of the experimental site.

Month	Tmax (c°)	Tmin (c°)	MRH %	Total Rainfall mm	SR 10^4W^{-2SR}	WS (m/s)	ETommday^{-1}
2010 Season							
February	26.28	13.40	26.96	0.00	41.29	5.76	4.62
March	30.03	16.39	19.02	0.01	51.51	5.53	5.97
April	32.86	21.41	28.53	0.27	46.01	6.94	6.20
May	37.64	25.25	25.06	0.18	48.22	5.93	6.90
2011 Season							
February	23.44	12.41	36.23	0.00	38.71	1.53	4.29
March	25.39	14.77	31.69	0.54	40.34	1.94	5.28
April	30.83	19.86	24.18	0.04	39.59	1.92	6.02
May	35.40	23.29	20.97	0.09	51.63	1.59	6.96

MRH = Maximum relative humidity, SR = Solar radiation.



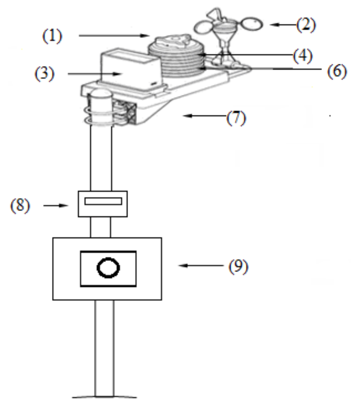
1 ICS Control panel
2 Pump
3 Water Tank
4 IIS Control panel
5 ET sensor (Fig 2)
6 Ball Valve
7 Solenoid Valve
8 Water Meter
9 Filter
10 Pressure Gauge
11 Intelligent irrigation Treatment (IIS)
12 Control Treatment (ICS)
13 Main Lines
14 Weather Station

Fig 1. Schematic diagram of tomato field using drip irrigation systems for both intelligent irrigation (IIS) and control (ICS) systems.

Table 2. Physical properties of different soil layers in the studied field.

Layer depth cm	Particle size distribution (%) Sand %	Silt %	Clay %	Soil texture class	FC % $m^3\ m^{-3}$	PWP % $m^3\ m^{-3}$	BD $g.cm^{-3}$
0 – 20	68.5	12.0	19.5	Sandy clay loam	13.65	6.83	1.48
20 – 30	68.7	11.0	20.3	Sandy clay loam	14.34	7.17	1.46
30 –60	58.7	15.0	26.3	Sandy clay loam	16.67	8.33	1.40
Average	65.3	12.7	22.1	Sandy clay loam	14.89	7.44	1.45

BD = bulk density, PWP = permanent welting point, FC = field capacity.



1 Solar Radiation
2 Wind Speed
3 Rain Gauge
4 Air Temperature
6 Relative Humidity
7 Sensor Base
8 ET Module
9 Irrigation Controller (Pro C)

Fig 2. The Smart System components used in the study.

treatments, these values were 7.50, 6.56 and 7.15, 6.32 kg m^{-3}, respectively. The tomato yields, in the case of IIS treatment, were 39 and 40.08 ton h^{-1} for both seasons, respectively, and a similar trend was observed for WUE and IWUE. Moreover, the amounts of applied irrigation water were 5947.6 and 6337.6 m^{-3} h^{-1} for consecutive seasons, respectively (Table 6). Consequently, the maximum and minimum values of WUE were 7.50 kg m^{-3} and 5.33 kg m^{-3}, respectively. However, the results indicate that irrigation water was used more effectively through IIS treatment. The aforementioned table also shows that the highest and lowest values of IWUE among seasons were 6.56 and 4.30 kg m^{-3} obtained with IIS and ICS, respectively. The comparison of the IIS with the ICS shows that the increases in IWUE were 39% and 47% for the 2010 and 2011 seasons, respectively. In contrast, the smallest amount of irrigation water used was 594.76 mm in case of IIS, while the largest amount applied was 854.79 mm in the control treatment.

Statistical analysis of agronomical factors

Statistical analysis was conducted using CoHort Software (2005) program version 6.311. A *t*- test was used to compare the average agronomical factors with the two methods, following a normal distribution. This test was done to find significant differences between IIS and ICS water treatment. The results of this test clearly show a large influence of the IIS technique on tomato agronomical factors in both years. For instance, the highest amount of irrigation water applied was detected with the ICS in both seasons, while with the ICS less water was applied. The data suggest that the IIS technique had a highly significant effect on the average fruit weight. However, there was no such effect on either fruit diameter (cm) or fruit shape. Meanwhile, the agronomical data for the IIS treatment revealed a significant difference in plant height (cm), branch number, fruit length (cm), average fruit weight (g), total yield (kg m^{-2}), total yield (ton h^{-1}) and WUE/IWUE (kg m^{-3}) compared to the control. WUE and IWUE were significantly affected by the IIS ($p > 0.05$) in both growing seasons, as shown in Table 5. Their averages were different, depending on the schedule of the IIS. However, WUE and IWUE ranged during the two seasons from 5.53 to 7.33 kg m^{-3} and from 4.50 to 6.44 kg m^{-3}, respectively. Furthermore, the results presented in Tables 5 and 6 show that both efficiencies under the IIS were higher than those under the ICS. Maximum values of WUE (7.50 and 7.15 kg m^{-3}) were obtained with the IIS, whereas minimum values (5.72 and 5.33 kg m^{-3}) were obtained with the ICS treatment. This result indicates that water was used more effectively in the IIS. The results also indicate that the IWUE for IIS was higher than that for ICS treatment. The maximum values of IWUE (6.56 and 6.32 kg m^{-3}) were obtained with the IIS in both years, whereas the minimum values (4.70 and 4.30 kg m^{-3}) were obtained with the ICS. IWUE was higher with the IIS compared to ICS by 29% and 32% in the 2010 and 2011 seasons, respectively. Thus, the WUE and IWUE values decreased with increased amounts of applied irrigation water (Table 6). Furthermore, the higher respective values (7.50 and 4.75 kg m^{-3}) in the first season were achieved with the IIS treatment, while the corresponding values for the second season were 7.15 and 4.30 kg m^{-3}.

Discussion

In this study, marked variation in the ETc of the tomato crop was seen between the two treatments over the different seasons; these values were 540.42and 671.57 mm for IIS and ICS, respectively. This led to a 20% savings in irrigation water when using intelligent irrigation technology. These outcomes indicate the importance of adopting IIS due to its effectiveness in providing irrigation water, which requires extraordinary effort to obtain especially in arid regions which suffer from water scarcity, such as Saudi Arabia. As well, this system will improve irrigation practices and ultimately minimize labor efforts. In general, this superiority in saving water may be due to the fact that the IIS has the feature of increasing or reducing irrigation water according to the needs of the plants. Despite this, to initiate the process of irrigation at 80% of ETc, the analysis pointed out that the ETc value of the control treatment was higher than that of the IIS through both seasons. Therefore, a comprehensive understanding of the relationship between the effect of the IIS technique and water content distribution in the root zone is imperative. This may be due to the increased accuracy of the irrigation scheduling which leads to evenly distributed water with sufficient quantities in the root zone. Moreover, the differences could have occurred due to application of the incompatible Kc values which were selected from Allen et al. (1998) and used for the prediction of ETc. Insignificant differences were found in the ETc values between treatments only in the initial development stage, while marked differences were observed in the other stages, with higher values under ICS treatment (Table 3). Simultaneously, the steepness of ETc for the control treatment could have resulted from an erroneous prediction of ETo, especially when selecting some coefficients, particularly the crop coefficient, Kc, and the length of the crop growth stages. Additionally, the intelligent irrigation system was designed especially for scheduling landscape irrigation, although it gave satisfactory results when is used to irrigate a tomato crop. Moreover, the soil distribution could also be responsible for the ICS results, since the field consisted of entirely moved soil. The results of the second season were found to be consistent with the findings of the first season within each treatment, but a significant difference was found among treatments. The consistency was a result of non-significant differences in microclimatic parameters at the sites of the experiments and due to minor variations in available soil moisture depletion levels. The total applied irrigation water, Dg for IIS and ICS, was 614.26 and 825.47 mm, respectively. This indicates that there was a 26% savings in irrigation water in the case of IIS compared to the control treatment. Also, the results indicate that more irrigation water was utilized under ICS treatment. Hence, a change in irrigation frequency and application stage could significantly affect the available soil water during the tomato growing season. In any case, these amounts are greater than the amount of irrigation water usually delivered by the farmers in the area. This study revealed that both irrigation scheduling techniques had a clear impact on the agronomical characteristics of the plants. In the same context, it was found that the average yields for the two seasons were 39.55 and 37.05 ton/ha^{-1} for the IIS and ICS treatments, respectively. This shows that the variation between the yields in the IIS and ICS treatments was 5-9%. The fact that IIS resulted in greater yields than the ICS can be attributed to differences in the amount of water applied with the two treatments. An increased moisture level in the root zone is vital for increasing the agronomical factors, especially when more irrigation water was added (Dg) as in the ICS treatment. The low amount of irrigation water added in the IIS treatment affected all the agronomical parameters compared to the control treatment. The results indicate that each 1 mm of water depth applied by both treatments yielded 65.57 and 63.24 kg/mm for first and second seasons for IIS, while these values were 46.97 and 42.94 kg/mm for ICS. The combined season averages for the IIS and OCS systems were 64.41 and 44.95 kg/mm, respectively. Conserving water is very important in areas experiencing severe drought such as Saudi Arabia. The lower amounts of water used correspond inversely with higher water use efficiency. This agrees with the results noted by Faberio et al. (2001) and Almarshadi and Ismail (2011). Similar findings were also obtained by Oktem et al. (2003) and Wan and Kang (2006), who found that a low irrigation frequency resulted in higher water use efficiency values when compared to a high irrigation frequency. Generally, IWUE can be increased by reducing irrigation water losses (Oktemet, al., 2003). Irrigation water use efficiency can also be affected by soil type, cultural and management practices (Wan and Kang 2006). Generally, in IIS, increased yields are obtained while minimal water is applied, which eventually results in higher IWUE. This finding is consistent with a study by Sammis and Wu (1986), who reported that IWUE increased under soil moisture stress, and is also consistent with the observations of Camp et al. (1989), Howell et al. (1997), Oktem et al. (2003) and Wan and Kang (2006), who reported that low irrigation frequencies result in higher water use efficiency values than do high irrigation frequencies. For both seasons, the IIS resulted in higher WUE and IWUE values compared to the ICS. In general terms, this study suggests that IIS should be implemented to supply irrigation water to crops in the required quantity and at the required time. The decreased WUE and IWUE observed under the ICS treatment can be attributed to the increasing level of applied irrigation water. Hence, it can be concluded that the effects on IWUE accuracy were significant for the IIS, amounting to a 26% decrease in the amount of seasonal irrigation water required (Table 6). The same trend was observed for WUE and IWUE, in which higher values were obtained with the IIS in both seasons (Tables 5 and 6). Therefore, the IIS resulted in higher WUE and IWUE values than the ICS. In general, the results in Table 5 show that all agronomical characteristics of IIS treatments were significantly superior compared to those of ICS. The fact that the yield of 2011 was lower with the ICS treatment could be due to the excess of irrigation water which was applied.

Materials and methods

Experimental site

Field experiments were performed at the King Saud University Experimental Farm of the College of Food and Agriculture Sciences, Riyadh, at 24°43’ N latitude, 46°43’ E longitude and 635 m altitude during the spring seasons of 2010 and 2011. Generally, the climate in this region is classified as arid, and the climatological data measured at the experimental site during this study period are provided (Table 1). The weather station was used to measure the climate parameters that were used to compute evapotranspiration (ETo). These values were then compared with the values obtained from the IIS in the tomato crop fields. The IIS was programmed in situ, taking into account both the crop type and environmental conditions of the area. This device was then calibrated and configured to implement the next phase of the study prior to collecting real data.

Field features and evaluation of irrigation practices

The study site was divided into two equal plots with a 5 m buffer in the middle (Fig. 1). Each tomato plot size was 7.2 m × 12 m (86.4 m^2), and the plots were irrigated via nine drip lines that were 16 mm in diameter at distances of 0.8 m and mounted with 30 drippers. The distance between drippers on the line was 0.4 m. The soil type in the plot area was sandy clay loam; some physical properties of the experimental field soil are presented in Table 2. One of the two fields was irrigated automatically with the IIS, while the other was irrigated manually based on ETc values and using climatological data from the weather station installed at the site. The drip irrigation system was installed for both plots and equipped with controllers to regulate the pressure and a flow meter to quantify the amount of water added during each irrigation event. The drip system was evaluated in the field according to the methodology of ASABE Standard, S346.1 (2007). The intelligent irrigation system required a complete database for each station (or “zone”) to be controlled. It was easy to set up this database with little effort, and the operator was completely responsible for the accuracy of both input information and output results from the database. Every system must be carefully observed and monitored after initial installation for the best results. Generally, most systems require adjustment, at the station level, for some time after installation to provide ideal results. Evaluation tests were conducted by checking the performance index values under the operating field conditions. All evaluation index values were within acceptable limits with good water distribution uniformity (over 90%). The control experiment was used for comparison purposes.

Components, functions, and installation of the intelligent system

The intelligent irrigation system chosen for this study was the Hunter ET-System.[1] The smart controllers integrate many disciplines to produce a significant improvement in crop production and resource management (Norum and Adhikari 2009).This system is not considered the best system, but it was inexpensive and available on the local market. The IIS was installed according to the manufacturer’s instructions in the field for the planned experiments. It can be customized by station (or “zone”) for specific plants, soils and drip types. This type of system uses digital electronic controllers and modules, and its platform can be wired to an ET module that can sense the local climatic conditions via different sensors that measure wind speed, rainfall, solar radiation, air temperature and relative humidity (Fig. 2). The ET module then receives data from the ET sensor and applies it to the individual fields (zones) of irrigation. The IIS automatically calculates crop evapotranspiration (ETc) for local microclimates based on a modified Penman equation (Allen et al., 1998) and creates a scientific program that it downloads to the controller. Here, the ET module was plugged into the irrigation controller Pro C, which was called the Controller Intelligent Port, and adjusted the irrigation run times to only replace the amount of water the plants had lost, at a rate at which could be effectively absorbed by the soil. Hence, the IIS relayed data acquisition of environmental parameters as well as system parameters (pressure, flow, etc.). The state of the system is compared against a specified desired state, and a decision as to whether or not to initiate an action is based on this comparison. In the case of a decision taken by the ET sensor (Fig. 2) to initiate irrigation, a signal

[1]The use of the trade name does not imply promotion of this product; it is mentioned for research purposes only.

Table 3. Daily and weekly averages of tomato ETc for both systems.

Growth Period (Week)	ETc for IIS (mm/day)	ETo (mm/day)	Kc	ETc for ICS (mm/day)
1	2.34	4.22	0.70	2.95
2	3.15	4.65	0.70	3.25
3	3.94	4.98	0.93	4.54
4	3.95	5.56	1.15	6.39
5	4.36	5.61	1.15	6.46
6	4.58	5.78	1.15	6.64
7	4.87	5.28	1.15	6.08
8	4.56	5.92	1.03	6.30
9	5.26	6.71	1.03	6.84
10	5.10	6.67	0.90	6.00
11	4.93	6.54	0.90	5.89
12	5.00	6.87	0.90	6.18
13	4.85	6.56	0.83	5.53
14	4.60	6.64	0.83	5.53
15	5.81	7.49	0.90	6.74
16	4.83	6.96	0.75	5.22
17	5.07	7.17	0.75	5.38
Avg.	4.54			5.64
Sum.	540.42			671.57

Table 4. Averages of irrigation water (Dg) and accumulative depths (Dg)t added to the tomato crop using the intelligent and control systems.

	Avg. (Dg) for Tomato, IIS			Avg. (Dg) for Tomato, ICS		
Growth Period (week)	Water Added (m^3)	Irrigation Depth Dg (mm)	Acc. depth (Dg)t (mm)	Water Added (m^3)	Irrigation Depth Dg (mm)	Acc. depth (Dg)t (mm)
1	0.65	18.83	18.83	0.89	25.81	25.81
2	0.90	25.94	44.77	0.97	28.09	53.90
3	1.07	30.99	75.76	1.32	38.29	92.19
4	1.12	32.53	108.29	1.93	55.91	148.10
5	1.21	35.08	143.37	1.91	55.15	203.25
6	1.26	36.43	179.80	1.91	55.33	258.58
7	1.35	39.18	218.98	1.82	52.54	311.12
8	1.24	35.87	254.85	1.86	53.78	364.90
9	1.41	40.91	295.76	2.07	59.85	424.75
10	1.42	41.03	336.79	1.84	53.16	477.92
11	1.34	38.78	375.57	1.74	50.28	528.20
12	1.34	38.89	414.46	1.85	53.41	581.61
13	1.35	39.02	453.48	1.61	46.64	628.24
14	1.24	35.78	489.26	1.67	48.39	676.63
15	1.60	46.22	535.47	1.92	55.51	732.14
16	1.31	37.99	573.46	1.60	46.25	778.39
17	1.41	40.79	614.26	1.63	47.08	825.47
Sum	21.23	614.26		28.53	825.47	

will be transmitted to open the solenoid valve and pump to supply the required irrigation water. In the ICS, the climatic data are gathered from a weather station, and the daily reference evapotranspiration rate (ETo) is calculated and utilized in making irrigation decisions. Then, the calculated ETo data are integrated with the Kc of crops to determine irrigation water to be added. The determined quantity is fed manually to the control panel, which in turn transmits a signal to the solenoid valve to provide the required water to the field. In some other systems, both soil moisture sensors and climatic measurements are used. However, the IIS was used here to irrigate the tomato crops under the drip irrigation system. Daily tomato ETc data measured from the IIS and ICS experiments to carry out irrigation were monitored and recorded. For ICS, the daily ETo measurements were multiplied by adequate coefficients to provide ETc and used efficiently to schedule the automated microirrigation systems. Furthermore, the total ETc for the intelligent and control irrigation experiments were compared together, and the overall difference was quite significant.

Agronomic practices and observations

Tomato plants (*Lycopersicon esculentum* Mill, GS-12) were transplanted into the fields on February 14, 2010 and February 7, 2011. The seedlings were planted in a single row in each bed, with a row spacing of 0.8 m and an interplant space of 0.4 m per row. Other cultivation practices were performed following a scheduled tomato crop program. Daily and weekly ET_c rates for tomatoes during the growth period were determined for the IIS and ICS treatments. The irrigation water depths (D_g) and accumulative depths added to the tomato crop under the two treatments were monitored

Table 5. Responses of tomato growth yield and water use efficiencies (WUE and IWUE) for irrigation system (IIS and ICS) in the 2012 and 2011 winter seasons.

Treatment						
Character	2010 Season		t- sign	2011 Season		t- sign
	IIS	ICS		IIS	ICS	
Plant height (cm)	44.0	39.0	**	46.7	38.7	**
Number of branches	6.0	5.0	**	6.63	5.10	**
Fruit length (cm)	6.3	5.7	**	7.1	6.3	**
Fruit dia. (cm)	4.6	4.8	**	5.8	5.1	**
Fruit shape index	1.23	1.31	*	1.22	1.30	*
Avg. fruit wt.(gm)	95.0	93.0	**	93	84	**
Early yield (ton ha^{-1})	23.60	24.00	**	26.52	22.60	**
Total yield (ton ha^{-1})	39.00	37.40	*	40.08	36.71	**
WUE (kg m^{-3})	7.50	5.72	**	7.15	5.33	**
IWUE (kg m^{-3})	6.56	4.70	**	6.32	4.30	**

*,** t is significant at 0.05 and 0.01, respectively.

Table 6. Effects of the IIS and ICS on tomato water use efficiency during the growing season.

2010 growing season						
Irrigation	ETc		AIW		WUE	IWUE
treatments	(mm)	m^{-3} h^{-1}	(mm)	m^{-3} h^{-1}	(kg m^{-3})	(kg m^{-3})
IIS	520.30	5203	594.76	5947.60	7.50	6.56
ICS	653.70	6537	796.15	7961.50	5.72	4.70
2011 growing season						
IIS	560.50	5605	633.76	6337.6	7.15	6.32
ICS	689.20	6891.80	854.79	8547.9	5.33	4.30

by flow meters and were recorded through the growing season. The last irrigation was on 31 May and 27 May for the first and second seasons, respectively. Fruit yield and its components were evaluated in eight plants from the central plot rows during the harvest period. Other agronomic parameters, such as total fruit yield, were recorded for each plot to obtain the gross yield (t ha^{-1}).

Operation time required

To calculate the ET_c and the irrigation water requirements of tomatoes, daily ET_o values were first determined using the meteorological station and were then multiplied by the crop coefficients and the water application efficiency. Based on the area of the field (86.4 m^2) and the discharge rate from the drippers (1.220 l/h), the required water quantity per event and actual operation time required could be determined. Accordingly, the actual operation time required could be calculated based on the following relationship.

$$T\,(\min) = \frac{V(\text{Lit})}{Q_s\ (\text{L}/\min)} = \frac{K_c \times E\,T_o\ (\text{mm}) \times A\ (m^2) \times P_w}{E_a \times (1 - L\,R) \times Q_s\ (\text{L}/\min)} \qquad (1)$$

$$T\,(\min) = \frac{K_C \times E\,T_O\ (\text{mm}) \times 86.4 \times 0.40}{0.90 \times (1 - 0.10) \times \frac{1.220}{60}} = K_C \times E\,T_O\ (\text{mm}) \times 2.31 \qquad (2)$$

Here, T (min) is the actual operation time required, V (liter) refers to the water volume to be added, Q (1/min) is the discharge from the irrigation system, Kc represents crop coefficient, A (m^2) refers to the area of the field, ETo (mm) is the reference evapotranspiration, LR refers to the leaching requirement which is equal to 0.1 on the least water area (Stegman et al.,1980), Pw (40%) refers to the wetted area percentage and Ea (90%) refers to the water application efficiency.

$$Ea = Ks\,.\,Eu \qquad (3)$$

Where Ea = irrigation efficiency coefficient (smaller than 1) and expresses the ratio: crop root zone to be used by the crop/applied water. Ks is a coefficient (smaller than 1) which expresses the water storage efficiency soil (0.9 in sandy soils, 1.0 in clay or loam soils). Eu is a coefficient (smaller than 1) which reflects the uniformity of water application (a properly designed and well-managed drip system should reach Eu values of 0.85-0.95). This coefficient should be measured for each system regularly (Vermeiren et al, 1980). The net irrigation requirement Dg must replenish the crop evapotranspiration (ETc), as rainfall and other components of the water balance are normally unimportant in the irrigated area. The gross irrigation requirements $(Dg)_t$ must increase the Dg in order to compensate the irrigation efficiency and to leach salts.

$$(Dg)_t = \frac{Dg}{Ea\,(1 - LR)} \qquad (4)$$

The irrigation system was turned on and off manually in the control experiments in the ICS plots. The net depth of the irrigation water (Dg) for IIS under the drip irrigation system was calculated based on the difference in the flow meter readings before and after irrigation.

Irrigation water efficiencies

Irrigation water used efficiency (IWUE) was calculated as the ratio between the total fresh yield (FY) and the seasonal applied irrigation water $(Dg)_t$ (Michael, 1978). Water use efficiency (WUE) was the relationship between the yield and the ETc (Wanga et al., 2007). Thus, WUE was calculated as the fresh tomato fruit mass (kg) per unit land area (Y, kg m^{-2}) and divided by the units of water consumed by the crop per unit land area (ETc, m^3 m^{-2}, usually reported in mm) to produce that yield. In this case, WUE is presented in kg m^{-3}, and crop evapotranspiration Etc can be expressed as the water depth (mm). Another key parameter for evaluating system efficiency is the irrigation water use efficiency (IWUE, kg m^{-3}). The WUE and IWUE were calculated using Equations 3 and 4, respectively.

$$WUE = \left(\frac{Y}{ETc} \right) \quad (5)$$

$$IWUE = \left(\frac{Y}{(Dg)_t} \right) \quad (6)$$

In these equations, Y is the economical yield (kg m^{-3}), ETc is evapotranspiration (mm) and (Dg)t is the amount of seasonally applied irrigation water (mm). The mature fruits were harvested once or twice a week, and the plant height (cm), branch number, fruit length (cm), fruit diameter (cm), fruit shape index (length/diameter), average fruit weight (g), and total yield (kg.$m^{-2}$and ton/h^{-1}) were measured for each plot at each harvest. The data obtained from the two growing seasons were tabulated and subjected to variance analysis and least significant difference analysis (LSD) using CoHort Software (2005). Treatment mean values were compared using the least significant difference test (LSD) at a 5% probability level. Water consumption was considered in this analysis. Statistical analysis was conducted using CoHort Software (2005) program version 6.311. A *t*- test was used to compare the average of the two methods following a normal distribution. This test was done to find significant differences between IIS and ICS water treatment.

Conclusions

The highest actual yield was observed for the IIS (40.08 ton.ha^{-1} for the second season), which shows the relevance of this system to field crops, although it was only intended for scheduling water in landscaping as instructed by the manufacturer's manual. As a result of this two-year field study and using the IIS for irrigation water scheduling, it was found that the IIS offered a significant advantage in managing the irrigation of tomato crops in both seasons under severely arid conditions. In comparison with the control treatment, the IIS significantly managed water and reduced irrigation water by 26% due to improved moisture distribution in the root zone. The lowest amount of water supplied was recorded with the IIS (614.26 mm), while the highest value was obtained with the ICS (825.47 mm) treatment during the two seasons. To verify the findings of this research, the systems must be assessed for both the same and different crops at different locations and conditions in order to reach a well-established result. Until now, not much scientific work has been carried out on investigating the compatibility of IIS with field crops, but recently studies have assessed its suitability. Therefore, the IIS irrigation method is recommended due to its easy application and greater water savings. Also, the results indicate that the values of WUE (7.50 kg m^{-3}) and IWUE (6.56 kg m^{-3}) were higher with the IIS than the ICS. This result indicates that water was used most effectively with the IIS treatment. A high influence of the IIS on tomato yields and agronomical factors was noted in both years. All agronomical characteristics of the tomato crops with the IIS were significantly superior compared to those crops grown under the ICS. Consequently, the results in both years show that the IIS had significant effects on WUE and IWUE. The IIS technique conserved irrigation water by 26% compared to the amount provided by the control system. Conserving water is very important in areas experiencing severe drought, such as Saudi Arabia. This study has demonstrated possible modifications and developments to the proposed system for improved and more efficient scheduling control. It can be concluded that an economic amount benefit can be achieved with saving large amounts of irrigation water when applying advance scheduling irrigation techniques such as IIS under arid conditions.

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