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ORIGINAL PAPER

Effects of root watering system on yield, water use efficiency and fruit quality of date palm (c.v. Siwi): a case study in the arid climate, Egypt

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Abstract

The objective of the study is to determine the effects of root watering systems (RWS) with drip irrigation systems (DIS) and bubbler irrigation systems (BIS) on yield, water use efficiency (WUE) and fruit date palm (*Phoenix dactylifera* L.) quality under the different water regimes of 60, 80 and 100% of total water requirements (TWR). The experimental fieldwork was conducted during two successive seasons (2019/2020–2020/2021) in a farm at El-kharga Oasis, New Valley Governorate, Egypt. The evapotranspiration (ET_o) was calculated based on the Penman–Monteith (P–M) equation from which the climatic data was retrieved from the El-kharga climatic station. The results showed that, the maximum productivity was 103 kg/tree in the second season under RWS at 100% of TWR, while, the minimum productivity was 62 kg/tree in the first season under BIS at 60% of TWR. Furthermore, the maximum WUE was 1.61 kg/m^3 under RWS for 60%. The minimum WUE was 0.94 kg/m^3 under BIS for 100%. The percentage of increase in WUE between the maximum and minimum values under three systems was 41.6%. The results indicated that the amounts of applied water markedly decreased in the order of RWS < DIS < BIS and increased productivity and WUE in the order of RWS > DIS > BIS. Fruit quality was significantly affected by the type of irrigation system, with the best quality obtained with the RWS followed by the DIS and then by the BIS. The RWS system, through its positive impact on water use efficiency and enhancement on fruit yield and fruit quality of date palm, seems quite suitable for the irrigation of palm trees in arid and semi-arid regions.

Introduction

Water is one of the most important limited natural resources and it is an essential substance for sustaining life on the earth. Water scarcity is a growing global problem; challenging sustainable development and constraining efforts to produce enough food to meet increasing populations (Molden et al. 2007). Thus, the FAO calls for a "revolution" in water management in order to improve the generally low water use efficiency in irrigation (Diouf 2003).

Egypt has a total land area of approximately one million square kilometers, most of which is desert and only 6% is inhabited. Settlements are mostly concentrated in and around the Nile Delta. Total cultivated land is around 3.36 million hectares. The climate is arid with very low rainfall (Mohamed et al. 2012). Drought or insufficient water resources is one of the most non-biological stressful factors in arid and semi-arid climate areas which significantly constrain supplies of other inputs and their efficiency (Ucan et al. 2007). The future will require even greater improvements as competition for limited water supplies continues to challenge water use efficiency and productivity. Now, conserving irrigation water is considered a strategic target in Egypt. Therefore, the efficient use of water through modern irrigation systems is becoming increasingly important in arid and semi-arid regions with limited water resources (El-Hendawy et al. 2008).

Irrigation water management (IWM) is the practice of monitoring and managing the rate, volume, and timing of water application according to seasonal crop needs, giving consideration to the soil intake and water holding capacities. Soil moisture should be managed to obtain optimum yields, without deep percolation losses or runoff. Poor management has been cited as the most frequent irrigation problem leading to sub-optimal use of limited water (El-Agha et al. 2011).

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Management of an irrigation system depends on water availability, soil characteristics, type of crop, topography, and costs in arid and semi-arid regions, where water for irrigation of crops is vital for complete or partial substitution of crop water requirements. Therefore, adequate methods of irrigation scheduling are necessary to improve WUE. This is especially important in the context of increasing competition between the environment and the various end users of water resources (Jones 2004).

The date palm plays an important socio-economic role in Egypt and supports about 1 million families. Date palm cultivation is a labor-intensive industry which can contribute to job creation in the oases and areas of date palm plantations. Most farmers in Egypt care little about date palm irrigation because they believe that date palms can give full production under water stress conditions and do not require much irrigation. But studies and experiments indicate that in order for date palms to grow and produce quality fruit and yield, their full water requirements must be met. Although the highest date palm production is achieved when providing full irrigation water requirements by traditional methods, the same production can be achieved with significantly less water application, up to 50% less, by using modern irrigation systems (FAO 2007). In a study by Amiri et al. (2007), the response of the date palm 'Zahidi cultivar' was studied under three different irrigation systems: basin, bubbler and sprinkler (Amiri et al. 2007). Their results revealed that the mean values of the number of leaves per tree, leaf area index, tree height and leaf mineral content were significantly influenced by the type of irrigation system. Furthermore, the effect of different irrigation water management methods was studied on the vegetative growth of date palm offshoots under two irrigation systems—the conventional basin and bubbler irrigation systems using three irrigation levels of '50%, 75% and 100%' of full crop water requirements (Ibrahim et al. 2012). The imported bubbler with 100% ET_c recorded the highest average values of the number of leaves, plant height and stem diameter while the basin irrigation with 50% ET_c recorded the lowest values. By contrast, a field experiment was conducted using three irrigation systems: drip, bubbler and basin to study the effect of different irrigation rates—150%, 100% and 50% of date palm water requirement on yield (Al Amuod et al. 2000). The results indicated that the maximum yield was obtained under the drip irrigation system followed by the basin system. Also, it was indicated that the total water requirements by one date palm as 136 m^3/year (Al-Ghobari 2000). In Saudi Arabia, Alazba (2004) reported that the total annual water use by farmers for flood irrigation was 137 m^3/tree in the Eastern region and 195 m^3/tree/year in the central region, compared to 55 and 78 m^3/tree for the same regions, respectively, using drip irrigation (Alazba 2004). While in another study, the total irrigation water used by one date palm under drip irrigation was 164 m^3/year based on a soil water balance method in the Qassim region (Kassem 2007). Al-Amoud et al. (2012) estimated the total annual water requirements in the western part of Saudi Arabia to range between 59.4 and 80 m^3/tree (Al-Amoud et al. 2012). In Algeria, the annual total water requirement was 145 m^3/ tree by trickle irrigation compared to 217 m^3/tree by surface irrigation (Adil et al. 2015). Mazahrih et al. (2012) reported that the amount of applied irrigation water per date palm tree was 27, 40, 53 and 67 m^3 for the irrigation treatments of 50, 75, 100 and 125% ET_c, respectively for date palms in the Jordan Valley (Mazahrih et al. 2012). By contrast, the annual water requirement estimated for date palm using remote sensing data ranged from 11,000 to 13,000 m^3/ha^{-1} (Biro et al. 2020).

For water-use efficiency (WUE), the maximum values in two seasons were 1.55 kg/m^3 and 1.62 kg/m^3 under deep drip irrigation systems, with water levels of 70% of total water requirements and mulched soil in the El-Baharia Oasis area, Egypt (Mohamed et al. 2018). Also, Al-Omran et al. (2019) estimated the total water requirements for one date palm (m^3/tree) by using bubbler irrigation system in eight different regions of Saudi Arabia as 73.4, 73.95, 80, 85, 85.7, 86 and 89 m^3/tree (Al-Omran et al. 2019). The root watering system (RWS) is imperative to ensure the efficient use of irrigation water. This system was constructed to efficiently deliver the irrigation water directly to the functional root zone of the palm tree. Hence, it provides a means to save irrigation water by reducing evaporation and deep percolation. The objective of this study was to determine the effect of the RWS in comparison with traditional surface drip irrigation (DIS) and bubbler irrigation systems (BIS) on date palm yield, quality and water use efficiency (WUE) under different irrigation levels.

Materials and methods

Study area

The field experiments were carried out during the 20,192,020/ and 2020 2021/growing seasons at the farm of date palm trees in the arid region of west Egypt, El-Kharga Oasis, New Valley Governorate. The site was located between 25°39′32.3″N latitude and 30°39′01.2″E longitude, and the altitude was 73 m. The chemical and physical soil

Table 1 Irrigation water and soil chemical characteristics of the experimental site

Sample data	EC ds/m	Soluble cations, meq/L				Soluble anions, meq/L				pH
		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{-}	Hco_3^{-}	So_4^{-}	CL^{-}	
Soil	0.8	1	0.5	6.4	0.12	ND	1.2	1.5	4.5	7.4
Water	0.44	1.5	0.3	2.9	0.3	ND	2.2	0.3	2.5	6.9

EC electric conductivity

properties are given in Tables 1 and 2. The soil samples were tested in the Agriculture Research Center (ARC).

Weather conditions

The climate variables (hourly temperature, relative humidity, solar radiation and wind speed) were retrieved from the meteorological station that was located in EL-Kharga, New Valley Governorate. The annual rainfall was zero mm during the period of the experiment. The mean monthly temperature ranged from 42.1 to 24.4 °C during July, while, it ranged from 5.2 to 21.2 °C during January in the two seasons. The wind speed ranged from 3.33 m/s in December to 5.10 m/s in June. The sun hour increased from 8.3 h per day in January to 11 h per day in June with an average value 9.6 h per day. The maximum mean daily value of evapotranspiration was 11.84 mm/day in June 2020 and the minimum mean daily value of evapotranspiration was 3.82 mm/day in January 2020. The daily climate variables were used to calculate reference evapotranspiration (ET_o) according to FAO-56 Penman–Monteith method (Allen 1998; Mokhtar et al. 2020, 2021) (Fig. 1).

Layout and treatments

The study area of 5184 m^2 (72 m × 72 m) was assigned for the experiments, and divided into three separated blocks (Figs. 2 ands 3). The blocks were divided into three sub plots, where each sub plot (8 × 8 m) contained 9 replicates of date palms (*Phoenix dactylifera*), cv. Siwi. The age of the date palm trees was 10 years. Three sub plots were irrigated by RWS, another three by DIS, and the last three by BIS. Each system applied three water ingrates (60%, 80% and 100% of ETc) (Fig. 3). These laterals were placed above ground surface in surface drip irrigation and bubbler methods study, while these were buried in RWS system. Each sub-area was divided into three wings fitted with a separate set of valves.

Irrigation systems

The components of the irrigation network were as follows:

1. The water source is an underground well (m^3/h)
2. Electrical submersible pump with discharge rate of 40 m^3/h at 50 m pressure head (19 kW).
3. Control head contains filtration unit, fertilizer unit, flow meter, pressure gauges, pressure relieve valve, check valve, and butter flay valve.
4. Main line (125 mm OD) UPVC pipe used to convey and distribute irrigation water from control head to the sub main line.
5. Sub Main line (90 mm OD) UPVC pipe
6. Control valve and a flow meter for each plot to measure the amount of water applied.
7. Lateral line (63 mm OD) UPVC pipe
8. Polyethylene drip line 16 mm diameter used to convey and distribute irrigation water from the sub line to the RWS, DIS and BIS.

The root watering system (model RWS-B-1401, Rain Bird, Azusa, CA) RWS was constructed to efficiently deliver the irrigation water directly to the functional root zone of the palm tree (Fig. 4a). The RWS consisted of perforated mesh tube, a water flow regulator, and gravel around the perforated pipe. The diameter of the pipe was 4 in. (10.2 cm) and the length was 36 in. (91.4 cm). The pipe was wrapped with a filtering cloth and gravel placed along its length to prevent the movement of fine soil and root into the perforated pipe. The gravitational forces play an important role in water movement in the soil with steady-state water flow. The flow rate of the RWS was 57 l/h and RWS. Two RWS tubes were buried around the date palm tree within a circle of diameter of 2 m. On the other hand, drip irrigation system (DIS), four drippers were designed around the palm tree. The dripper flow rate was 16 L/h, the pressure head of dripper was 10 m (1 bar). The dripper head was installed on surface PE pipe 16 (mm OD) around date palm tree within a circle with 2 m diameter. Moreover, the bubbler irrigation (BIS), it was an adjustable bubbler (0–120 L/h) used to

Table 2 Physical analyses of the soil samples

Depth, cm	Soil particles distribution				Soil texture	Bulk density, g/cm^3	Field capacity, %	Wilting point, %	Available water, %
	Sand%		Silt%	Clay %					
	Coarse Sand	Fine Sand							
0–30	3.4	67.08	15.73	17.20	Sandy loam	1.55	15	7.5	7.5
30–60	3.5	70.82	13.94	15.24	Sandy loam	1.57	15.3	7.7	7.6
60–120	1.83	64.03	17.11	16.23	Loam sandy	1.58	13.9	6.95	7.4

deliver irrigation water around the palm. The bubbler flow rate was adjusted to 60 L/h by twisting the bubbler head at a pressure of 10 m (1 bar). The bubbler was connected to the lateral line by using a flexible plastic tube with a length of 1 m and diameter of 16 mm OD.

P-M calculation

Estimation of evapotranspiration ETo by using P–M equation FAO56 to estimate the total irrigation water requirements (TWR):

$$ET_O = \frac{0.408\ \Delta(Rn - G) + \ \gamma\left(\frac{900}{T+273}\right)\ U_2\ \left(e_s - e_a\right)}{\Delta + \ \gamma\left(1 + 0.34U_2\right)}$$

where: ETo: Reference evapotranspiration (mm/day), G: Soil heat flux density (MJ/m^2 per day), Rn: net radiation at the crop surface (MJ/m^2 per day), U_2: Wind speed at 2 m height (m/sec) T:, mean temperature at 2 m height (°C), ea: actual vapour pressure (kPa),es: saturation vapour pressure (kPa), $e_s - e_a$: slope of saturation vapour pressure curve at temperature T (kPa/°C) and γ = Psychrometric constant (kPa/°C).

While, the crop evapotranspiration (ET_c) was calculated as

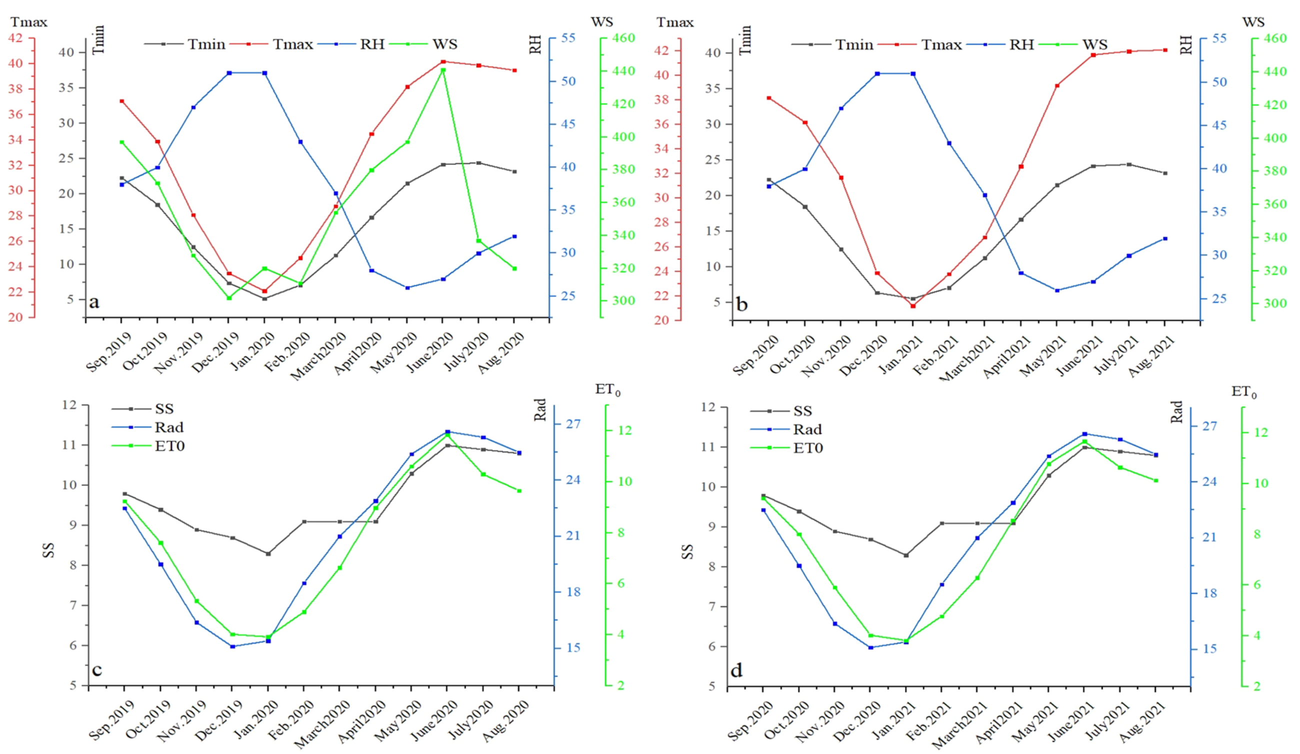

Fig. 1 The mean monthly values of the climatic parameters and reference evapotranspiration in the first season (**a**, **c**) and second season (**b**, **d**) It is notable that there is no rain fall

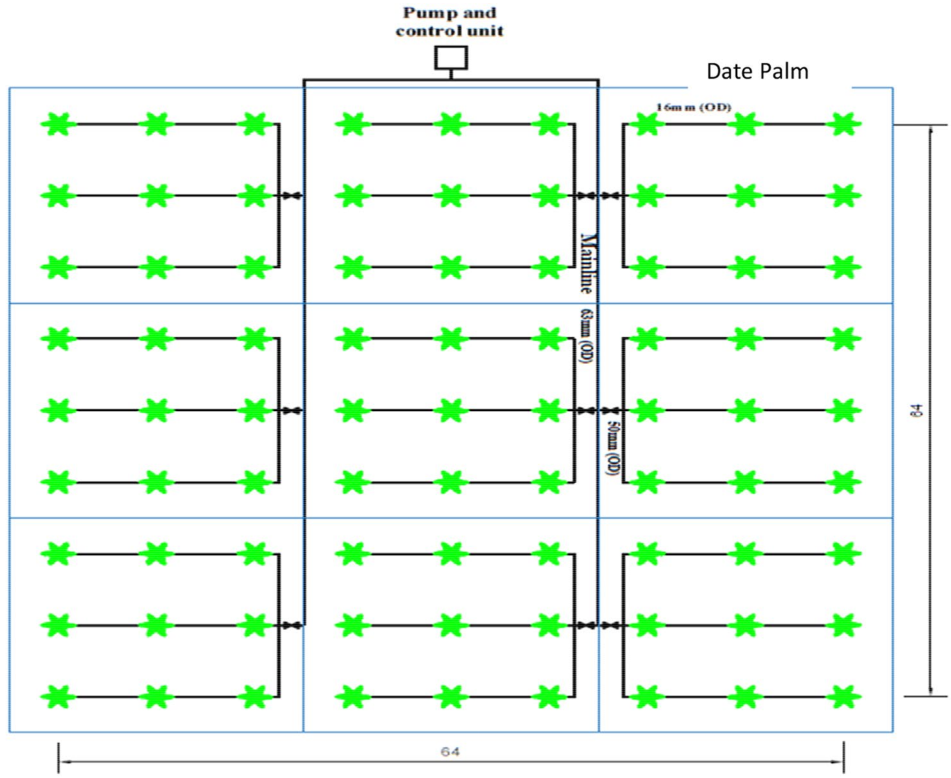

Fig. 2 Layout of date palm experiment and irrigation systems

RWS 100%	RWS 80%	BIS 60%
RWS 60%	BIS 100%	BIS 80%
DIS 100%	DIS 60%	DIS 80%

Fig. 3 Statistical design of the experiment

$$\mathrm{ET_c} = \mathrm{Kc} \times \mathrm{ETo} = \mathrm{IR_n}$$

where, IR_n = net irrigation requirement (K_c) crop coefficient values ranged from 0.8 to 1.0 for date palm (FAO 56).

Gross irrigation requirement (IR_g) was applied using a flow meter (0.0001 m^3 accuracy) set for each subplot.

$$IR_g = \frac{IR_n}{E_a}$$

where E_a (%) is application efficiency, where, it was calculated from the following formula (Saad Eddin 2016):

$$\mathrm{Ea} = [\mathrm{WDZ}/\mathrm{IRg}] * 100$$

where: WDZ = Depth of water stored in the root zone, mm; IRg = The gross irrigation requirement, mm.

Depth of water stored in the root zone of the date palm was determined according to Levin et al. (1979). The soil water content was determined using the gravimetric method. Soil moisture content (SMC) was identified at three depths in the root zone (0–30, 30–60 and 60–90 cm) before and after irrigation. Soil samples were collected by soil auger. Moisture content for each treatment was measured at before irrigation and 6 h after irrigation. Soil moisture content percentage was determined from the following equation:

$$\mathrm{SMC} = (W_1 - W_2)/W_2 * 100$$

where: W_1 = weight of the wet soil sample (g), W_2 = weight of the oven dried soil sample (g) at 105 °C for 24 h.

Find the depth of water that entered the root zone during the irrigation process according to equation

$$\mathrm{WDZ} = (\mathrm{S.M.C2{-}S.M.C1})\, D * 100$$

where: ρ; is the specific weight of soil, S.M.C2; is moisture content at field 6 hours after irrigation. S.M.C1; is moisture content at field before irrigation. *D*; is the root depth (mm)

Evapotranspiration of the actual tree area (S_e) was calculated from the following formula of Hellman (2010):

$$S_e = \pi R^2$$

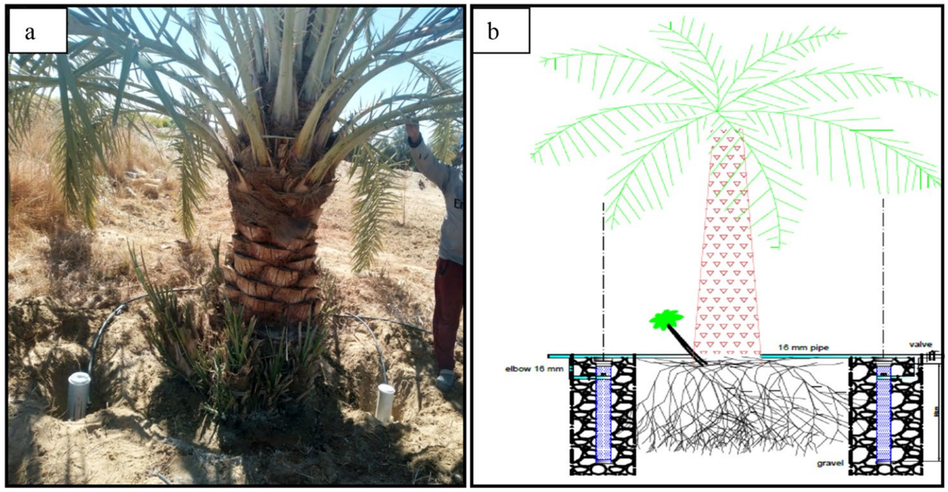

Fig. 4 **a** Image of root watering system and **b** sketch of toot watering system showing below grade details.

where, S_e was measured at noon (representing maximum net radiation time), and R actual radius of the tree. The total water requirement (TWR) L/day for each tree was calculated using the following equation:

$$\mathrm{TWR} = \mathrm{IRg}\ (\mathrm{m/day}) \times \mathrm{Se}\left(\mathrm{m}^2\right) = \left(\mathrm{m}^3/\mathrm{tree\ day}\right).$$

Annual TWR = Σ TWR = (m^3/tree year).Irrigation water-use efficiency (WUE) (kg m^{-3}) was calculated using the equation according to Michael (1978):

$$\mathrm{WUE} = \mathrm{MY}/\mathrm{TWR}$$

where, MY = represents the marketable yield of date palm trees, (kg /tree).

Volume of fruit and moisture content

Average fruit size was determined by immersing samples, each of ten fruits, in a known quantity of water in a graduated jar. By replacement, the difference between the new reading of water in the jar and the initial reading indicated the volume of each fruit. Then average fruit size was calculated in cm^3. The fruit samples (10 fruits from each replicate) were cleaned and seeds were removed. The date flesh was dried at 60–65 °C for 48–72 h until a constant weight was achieved. The difference between fresh weight and dry weight was divided by fresh weight to give a percentage of fruit moisture.

Statistical analysis

The date palm yield, quality and WUE were statistically analyzed. Analysis of variance (ANOVA) was performed using two-way ANOVA from MSTAT software (Fig. 3). All the treatment means were compared for any significant differences using the Duncan's multiple range tests at significant level of $P_{0.05}$.

Results and discussion

Field experiments were applied to study the effect of the root watering system on date palm yield and water use efficiency under water shortage. The aim is the sustainability of groundwater yield through the management and scheduling of irrigation water for date palm under water shortages.

Water applied

The total water requirements TWR in the first season were 3002.7, 2298.7 and 1670.2 mm/year under RWS_{100}, RWS_{80} and RWS_{60}, respectively. Under DIS, TWR were 3107.4, 2323.7and 1687.8 mm/year for DIS_{100}, DIS_{80} and DIS_{60}, respectively. Finally for the BIS, TWR was3299.3, 2402.0 and 1762.0 mm/year for BIS_{100}, BIS_{80} and BIS_{60}, respectively. These results indicated that the TWR increased by 104.7 and 296.6 mm/year under DIS_{100} and BIS_{100} respectively, compared with RWS_{100}. Also, irrigation increased by 25.0 and 103.3 mm/year under DIS_{80} and BIS_{80} respectively, compared with RWS_{80}. Irrigation increased by 17.6 and 91.8 mm/year under DIS_{60} and BIS_{60} respectively, compared with RWS_{60}. In the second season, the TWR were 2969.6, 2273.5 and 1651.9 mm/year under RWS_{100}, RWS_{80} and RWS_{60}, respectively. Under DIS, TWR were 3073.1, 2298.3 and 1687.0 mm/year under DIS_{100}, DIS_{80} and $DIS_{60,}$ respectively. While for the BIS, TWR were 3262.8, 2375.7 and 1742.6 mm/ year for BIS_{100}, BIS_{80} and BIS_{60}, respectively, as shown in (Fig. 5) and (Table 3). The results indicated that the TWR in the second season increased by 103.6 and 293.3 mm/year under DIS_{100} and BIS_{100} respectively as compared with RWS_{100}. Also, irrigation increased by 24.7 and 102.2 mm/year under DIS_{80} and BIS_{80} respectively, compared with RWS_{80}. Finally, irrigation increased by 35.1 and 90.8 mm/year under DIS_{60} and BIS_{60}, respectively, compared with RWS_{60}, however, the number of irrigations N was the same (203) in the two seasons under the three systems. The reason may be related to the application efficiency for the three systems, and it was the best one for RWS. These results are in agreement with those obtained by (AL-Omran et al. 2019; Mohamed et al. 2018).

Results in Fig. 6 indicated that the minimum water applied was obtained under RWS_{100}, RWS_{80} and RWS_{60}, while the maximum water applied was obtained under BIS_{100}, BIS_{80} and BIS_{60}. The annual water consumption of each palm tree was 84.92, 65.01 and 47.23 m^3/tree in the first season and 83.98, 64.30 and 46.72 m^3/tree in the second season under the RWS_{100}, RWS_{80} and RWS_{60}, respectively. DIS consumed 87.88, 65.71 and 47.73 m^3/tree in the first season and 86.91, 64.99 and 47.71 m^3/tree in the second season under DIS_{100}, DIS_{80} and DIS_{60}, respectively. Also, BIS consumed 93.30, 67.93 and 49.83 m^3/tree in the first season and 92.27, 67.19 and 49.28 m^3/tree in the second season under the BIS_{100}, BIS_{80} and BIS_{60}, respectively. The results indicated that the water saving under RWS_{60}, DIS_{60} and BIS_{60} were 44.38%, 45.68% and 46.59% compared with RWS_{100}, DIS_{100} and BIS_{100}, respectively. While the water saving under RWS_{80}, DIS_{80} and BIS_{80} were 23.44%, 25.22% and 27.91% compared with RWS_{100}, DIS_{100} and BIS_{100}, respectively.

Application efficiency (Ea)

Application efficiency (Ea) a general indicator of the irrigation system performance. Application efficiency (Ea) as affected by the irrigation systems types and irrigation water regime is shown in Fig. 7. It could be seen that the application efficiency increased when decreasing the irrigation water applied, where it increased from 89 to 96% when the TWR decreased from 100 to 60% under RWS_{60} and RWS_{100}, respectively. And it increased from 86 to 95% when the TWR decreased from 100 to 60% under DIS_{60} and DIS_{100}, respectively. While it increased from 81 to 91%, when the TWR decreased from 100 to 60% under BIS_{60} and $BIS_{100,}$ respectively. Also, RWS recorded the highest value of Ea, while BIS recorded the lowest value of Ea. The increase in the Ea is due to the RWS significantly reducing evaporation and deep percolation. These results agreed with these values are similar compared to estimates reported from other studies (Amosson et al. 2001; Howell 2003; Irmak et al. 2011).

Date palm production and water use efficiency

Table 4 indicates that the fruit productivity under RWS_{100}, RWS_{80} and RWS_{60}were 100, 84 and 69 kg/tree in the first season and 103, 86 and 75 kg/tree in the second season, respectively. While, under DIS_{100}, DIS_{80} and DIS_{60}fruit

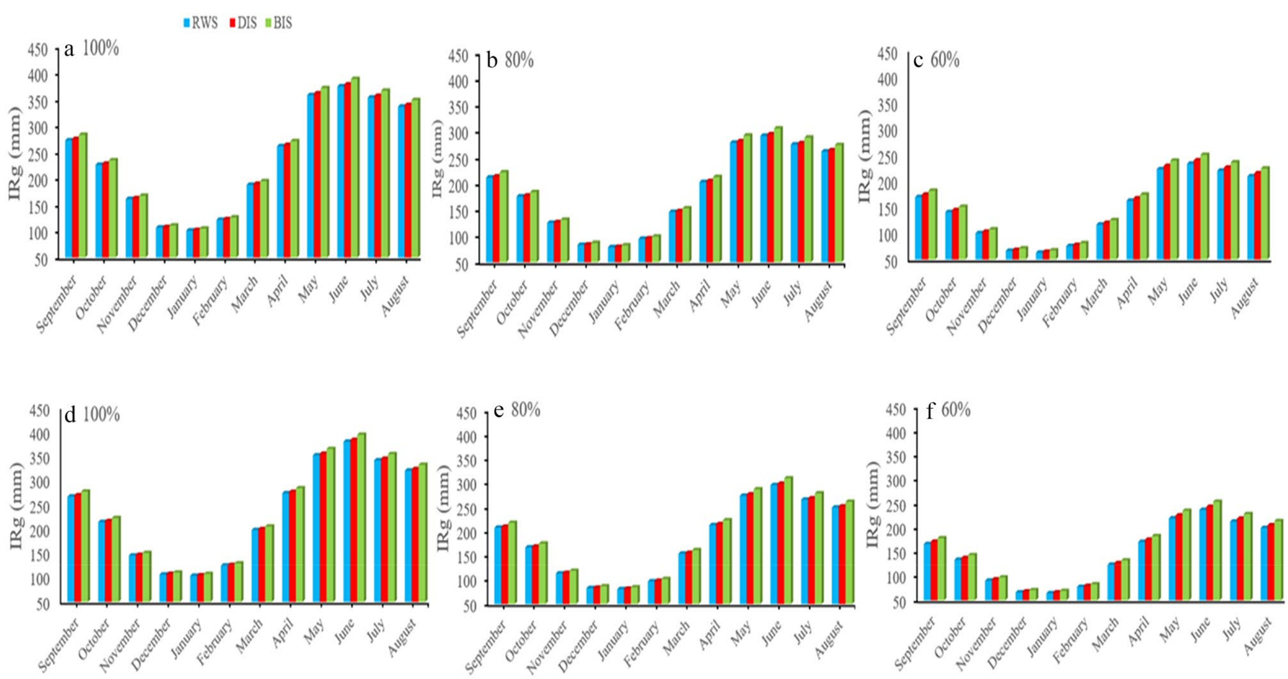

Fig. 5 Gross irrigation requirements (IR_g) under the three irrigation systems, during first (**a**–**c**) and second seasons (**d**–**f**)

Table 3 Net irrigation requirement, IR_n (mm), number of irrigations, *N*, and irrigation efficiency, E_a under the three irrigation systems, during the first and second seasons

Month	N	1st season			2nd season		
		IR_n 100%	IR_n 80%	IR_n 60%	IR_n 100%	IR_n 80%	IR_n 60%
September	15	254.4	203.5	152.7	249.6	199.7	149.8
October	15	211.1	168.9	126.7	200.6	160.5	120.4
November	15	150.6	120.5	90.4	135.9	108.7	81.6
December	7	99.8	79.9	59.9	99.5	79.6	59.7
January	7	94.6	75.6	56.8	97.0	77.6	58.2
February	7	113.7	90.9	68.2	116.5	93.2	69.9
March	15	175.5	140.4	105.3	185.1	148.1	111.1
April	15	243.9	195.1	146.4	255.9	204.7	153.6
May	15	334.5	267.6	200.7	328.9	263.1	197.4
June	30	350.1	280.1	210.1	355.2	284.2	213.1
July	31	330.2	264.1	198.1	319.3	255.4	191.6
August	31	314.0	251.2	188.4	299.5	239.6	179.7
Total	203	2672.4	2137.8	1603.4	2642.9	2114.4	1585.8
E_a %	RWS	89	93	96	89	93	96
	DIS	86	92	95	86	92	94
	BIS	81	89	91	81	89	91

productivity was93, 79 and 68 kg/tree in the first season and 95, 82 and 69 kg/tree in the second season respectively. Finally, the fruit productivity under BIS_{100}, BIS_{80} and BIS_{60} was 88, 78 and 62 kg/ tree in the first season and 90, 79 and 64 kg/tree in the second season, respectively. These results indicated that the productivity increased by 7% and 12% under RWS_{100} compared with DIS_{100} and BIS_{100} respectively, in the first season. While it increased by 5.9% and 7.1% under RWS_{80} compared with DIS_{80} and BIS_{80}, respectively, and by 8% and 14.6% underRWS_{60} compared with DIS_{60} and BIS_{60}, respectively. The results recorded the same trend for the second season, indicating that the best productivity was obtained from RWS under all treatments in both years. The maximum productivity was 103 kg/tree under RWS_{100}, while, the minimum productivity was 62 kg/ tree under BIS_{60}. The percentage of increase in productivity between the maximum and minimum value was 39.8%.

WUE considered an indicator of the capability of an irrigation system to convert irrigation water to crop. The WUE considered a tool of maximizing productivity per each unit of water applied. So, values of WUE for date palm were calculated under RWS, DIS and BIS. Table 4 illustrates the effects of RWS, DIS and BIS on WUE. The results indicated that the RWS treatment markedly increased WUE in the order RWS > DIS > BIS. The highest value of WUE was 1.61 kg/m^3under the RWS_{60} in the second season because the productivity was higher than the DIS_{60} and BIS_{60} and water consumption was less than the DIS_{60} and BIS_{60}. The lowest WUE (0.94 kg/m^3) realized in the first season for the BIS_{100} treatment can be ascribed to the fact that the water was applied to this treatment more than other treatments, while yield of the BIS_{100} was less than $RWS_{100}$and DIS_{100}.

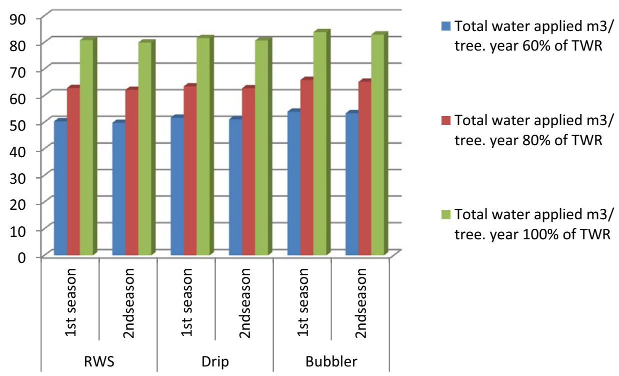

Fig. 6 Water applied to the date palm m^3/tree under three systems during the two seasons

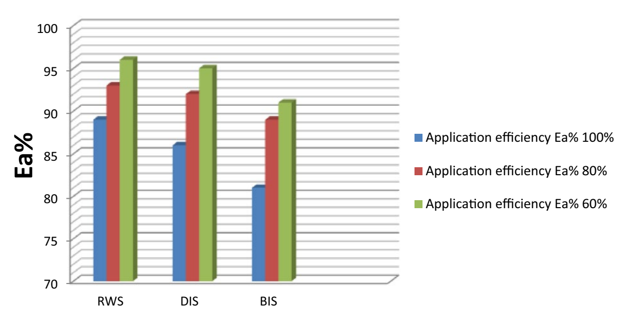

Fig. 7 Application efficiency (Ea) under RWS, DIS and BIS

These results are in agreement with results mentioned by Mohamed et al. (2018).

Statistical analyses conducted on productivity and WUE by using F-test showed significant differences between treatments at 0.05 level (Table 4). The results showed that the maximum productivity and WUE of date palm were obtained with RWS followed by DIS and then by BIS. The data revealed the significant superiority of the RWS as compared to the DIS and BIS for all treatments. The increase in fruit productivity and WUE could be due to the high application efficiency of the root watering system compared to the DIS and BIS. Also the RWS reduces water loss through soil evaporation and deep percolation as water is applied below the soil and nearer to the root zone as compared to the surface application of the DIS and BIs. These results are in agreement with results mentioned by Ahmed Mohammed et al. (2020), who reported that a the maximum WUF was obtained under new subsurface irrigation system (SSI), This is due to increase water distribution beneath the soil directly resulting in faster date palm crop development. Increasing yield could have occurred due to the increase in oxygen percentage and ventilation in the root zone and the increase in fertilizer uptake due to the application of fertilizers directly beneath the soil surface. This may have resulted in an enhancement of the soil environment around the root system, which led to increasing plant growth and, hence, increasing nutrients uptake. Furthermore, the increase in fruit productivity under all treatments in the second season was because the palm tree age was one year older. Although, the best water use efficiency were obtained under RWS $_{60}$, DIS_{60} and BIS_{60} treatments, the productivity was decreased by 27.18%, 27.63% and 28.88% compared with RWS $_{100}$, DIS_{100} and BIS_{100} respectively. This reduction in productivity is due to the water stress on the plant.

Date palm quality

Fruit weight of date palm

The fruit weight of (Siwi) date palm was affected by irrigation system and the amount of water applied. The fruit obtained for RWS, DIS and BIS (Table 5). The maximum fruit weight was 9.29 g in the second season under RWS_{100} and the minimum fruit weight was 5.48 g in the first season under BIS_{60}.The percentage of increase in fruit weight between the maximum and minimum value was 41.01%. According to the previous results, the fruit weight of date palm was significantly affected by irrigation system. Whereas, the maximum weight was obtained under RWS compared with DIS and BIS respectively. Also, this explains the reason of the productivity increase under RWS.

Table 4 Total net water applied, yield and water use efficiency for the two seasons under the three water levels. Statistical differences between means were evaluated using the Duncan test

System		Treatments								
		Total water applied m^3/tree. year			Yield Kg/tree			Water use efficiency, kg/m^3		
		60% of TWR	80% of TWR	100% of TWR	60% of TWR	80% of TWR	100% of TWR	60% of TWR	80% of TWR	100% of TWR
RWS	1st season	47.23	65.01	84.92	$69^{cb} \pm 0.318$	$84^{bb} \pm 0.318$	$100^{ab} \pm 0.318$	$1.46^{ab} \pm 0.006$	$1.04^{bb} \pm 0.006$	$1.18^{bb} \pm 0.006$
	2nd season	46.72	64.30	83.98	$75^{ca} \pm 0.435$	$86^{ba} \pm 0.389$	$103^{aa} \pm 0.389$	$1.61^{aa} \pm 0.009$	$1.34^{ba} \pm 0.008$	$1.23^{ba} \pm 0.008$
DIS	1st season	47.73	65.71	87.88	$68^{cb} \pm 0.153$	$79^{bb} \pm 0.153$	$93^{ab} \pm 0.153$	$1.42^{ab} \pm 0.029$	$1.20^{ab} \pm 0.029$	$1.06^{bb} \pm 0.029$
	2nd season	47.71	64.99	86.91	$69^{ca} \pm 0.187$	$82^{ba} \pm 0.187$	$95^{aa} \pm 0.187$	$1.45^{aa} \pm 0.035$	$1.26^{aa} \pm 0.035$	$1.09^{ba} \pm 0.035$
BIS	1st season	49.83	67.93	93.30	$62^{cb} \pm 0.019$	$78^{bb} \pm 0.019$	$88^{ab} \pm 0.019$	$1.24^{ab} \pm 0.009$	$1.15^{bb} \pm 0.019$	$0.94^{cb} \pm 0.019$
	2nd season	49.28	67.19	92.27	$64^{ca} \pm 0.019$	$79^{ba} \pm 0.019$	$90^{aa} \pm 0.019$	$1.30^{aa} \pm 0.019$	$1.18^{ba} \pm 0.019$	$0.98^{ca} \pm 0.019$
F test*					51.0981			13.317		

First letter denotes the difference between treatments and the second letter denotes the difference between two seasons at $P < 0.05$ under the same system irrigation, respectively. Values represent means whereas ± values indicate standard error

Table 5 Duncan test of Yield (Kg/tree) and Fruit weight (gm/tree) of date palm under different methods sites

System		Fruit weight (g)		
		60%	80%	100%
RWS	1st season	$7.18^{ca} \pm 0.201$	$8.17^{ba} \pm 0.201$	$9.25^{aa} \pm 0.201$
	2nd season	$7.29^{ca} \pm 0.201$	$8.31^{ba} \pm 0.201$	$9.29^{aa} \pm 0.201$
DIS	1st season	$6.62^{cb} \pm 0.061$	$7.84^{bb} \pm 0.061$	$8.95^{ab} \pm 0.061$
	2nd season	$6.69^{cb} \pm 0.061$	$7.91^{bb} \pm 0.061$	$8.99^{ab} \pm 0.061$
BIS	1st season	$5.48^{cc} \pm 0.108$	$6.91^{bc} \pm 0.108$	$8.08^{ac} \pm 0.108$
	2nd season	$5.69^{cc} \pm 0.108$	$7.01^{bc} \pm 0.108$	$8.16^{ac} \pm 0.108$
F* test		19.706		

First letter denotes the difference between treatments and the second letter denotes the difference between irrigation systems at $P<0.05$ under the same system irrigation, respectively. Values represent means whereas ± values indicate standard error

Fruit length, diameter and ratio (L/D)

Table 6 showed that the Siwi date palm fruit length/diameter ratio (L/D) was significantly affected by type of irrigation system and amount of water where, the maximum fruit length was 34.75 mm under $RWS_{100\%}$ and the minimum fruit length was 29.78 mm under $BIS_{60\%}$. The percentage of increase in fruit length between the maximum and minimum value was 14.30%. The maximum fruit diameter was 21.62 mm under $RWS_{100\%}$ and the minimum fruit length was 18.17 mm under $BIS_{60\%}$. The percentage of increase in fruit diameter between the maximum and minimum value was 15.95%. The maximum (L/D) Ratio was 1.70 under $RWS_{60\%}$ and the minimum (L/D) Ratio was 1.52 under $BIS_{60\%.}$ According to the previous results, the length and diameter of the fruit were significantly affected by irrigation system. Whereas, the maximum length and diameter were obtained under RWS compared with DIS and BIS, respectively. The difference in fruit length and diameter was due to the type of irrigation system used because all factors that can affect fruit in length and diameter, such as fertilization rate, ripening stage, and time of harvest were similar among irrigation systems.

Volume of fruits and moisture contents

The maximum fruit volume was 9.3 cm^3 in the second season under RWS100 and the minimum fruit volume was 6.3 cm^3 in the first season under BIS60 (Table 7). The percentage of increase in fruit volume between the maximum and minimum volume was 32.25%. Also, fruit moisture content was affected by the type of irrigation system and amount of water applied. The maximum moisture content was 23.29% in the second season under $RWS_{100\%}$ and the minimum moisture content was 15.95% in the first season under $BIS_{60\%}$. The percentage of increase in moisture content between the maximum and minimum ratio was 31.51%. As moisture content increases in dates, the fruit is more palatable to the consumer. The difference in moisture content was due to the type of irrigation system used because all factors that can affect the moisture content, such as fertilization rate, ripening stage, time of harvest, and the management that the palm trees received were neutralized. These results are in agreements with data recorded by Mohamed et al. (2018), who recorded that the moisture content was affected by the type of irrigation system.

Generally, the results indicated that the RWS system improved fruit quality parameters. These findings may be due to the efficient use of water within the functional absorbing root zone. Proper utilization of water within the tree system likely enhances and improves plant nutrient uptake. Bainbridge (2006) and Ibrahim et al. (2012) reported that the improvement in both parameters was highly probable due to the efficient use of water by the root system since it was directly provided to the absorbing functional zone. Also, Mohamed, 2018 reported that physical characters of date palm fruit were improved with subsurface irrigation system. These results are comparable with our present study (Mohamed et al. 2018).

Conclusion

This study was conducted in El-kharga Oasis, New Valley Governorate, Egypt to determine the effects of a RWS compared with drip and bubbler irrigation systems on yield, water use efficiency and fruit quality of date palm under different water regimes- 100, 80 and 60% of TWR. The results indicated that the maximum fruit productivity of date palm and the minimum water applied was obtained with RWS followed by DIS and then by BIS. The increase in productivity and WUE under RWS could be due to the high application efficiency of the root watering system compared to the DIS and BIS. The RWS reduces water loss through soil evaporation. The results indicated that the water saving under RWS_{60}, DIS_{60} and BIS_{60} were

Table 6 Duncan test of Fruit diameter, fruit length, mm and ratio, % in different treatments

System	Season	Diameter, (mm)			Length, (mm)			Ratio		
		60%	80%	100%	60%	80%	100%	60%	80%	100%
RWS	1^{st}	$19.02^{ba} \pm 0.126$	$21.24^{aa} \pm 0.158$	$21.62^{aa} \pm 0.177$	$32.43^{ba} \pm 0.282$	$33.76^{aa} \pm 0.266$	$34.75^{aa} \pm 0.203$	1.70	1.58	1.60
	2^{nd}	$19.11^{ba} \pm 0.126$	$21.29^{aa} \pm 0.158$	$21.68^{aa} \pm 0.177$	$32.52^{ba} \pm 0.282$	$33.91^{aa} \pm 0.266$	$34.91^{aa} \pm 0.203$	1.70	1.59	1.61
Drip	1^{st}	$18.56^{cb} \pm 0.126$	$20.36^{bb} \pm 0.158$	$21.24^{aa} \pm 0.177$	$30.89^{cb} \pm 0.282$	$31.41^{cb} \pm 0.266$	$33.64^{ab} \pm 0.203$	1.66	1.54	1.58
	2^{nd}	$18.57^{cb} \pm 0.126$	$20.35^{bb} \pm 0.158$	$21.26^{aa} \pm 0.177$	$30.95^{cb} \pm 0.282$	$31.55^{cb} \pm 0.266$	$33.69^{ab} \pm 0.203$	1.66	1.55	1.58
Bubbler	1^{st}	$18.17^{cc} \pm 0.126$	$19.89^{bb} \pm 0.158$	$20.96^{ab} \pm 0.177$	$29.78^{cc} \pm 0.282$	$30.33^{cc} \pm 0.266$	$32.49^{bc} \pm 0.203$	1.63	1.52	1.55
	2^{nd}	18.18 cc ± 0.126	$19.90^{bb} \pm 0.158$	$20.98^{ab} \pm 0.177$	$29.86^{cc} \pm 0.282$	$30.51^{cc} \pm 0.266$	$32.54^{bc} \pm 0.203$	1.64	1.53	1.55
F* test		21.31			51.54			82.87		

First letter denotes the difference between treatments and the second letter denotes the difference between irrigation systems at $P < 0.05$ under the same system irrigation, respectively. Values represent means whereas ± values indicate standard error

Table 7 Volume of fruits, cm^3 and moisture contents, % in different treatments

System	Season	Volume of fruits (cm^3)			Moisture contents %		
		60%	80%	100%	60%	80%	100%
RWS	1st	$7.0^{caa} \pm 0.082$	$8.1^{baa} \pm 0.082$	$8.9^{aa} \pm 0.082$	$19.89^{ba} \pm 0.204$	$22.14^{aa} \pm 0.133$	$23.21^{aa} \pm 0.133$
	2nd	$7.0^{caa} \pm 0.082$	$8.2^{baa} \pm 0.082$	$9.3^{aa} \pm 0.082$	$19.90^{ba} \pm 0.204$	$22.22^{aa} \pm 0.133$	$23.29^{aa} \pm 0.133$
Drip	1st	$6.5^{cb} \pm 0.082$	$8.0^{ba} \pm 0.082$	$8.6^{ab} \pm 0.082$	$17.64^{cb} \pm 0.204$	$20.86^{bb} \pm 0.133$	$21.89^{ab} \pm 0.133$
	2nd	$6.6^{cb} \pm 0.082$	$7.9^{ba} \pm 0.082$	$8.8^{aa} \pm 0.082$	$17.59^{cb} \pm 0.204$	$20.99^{bb} \pm 0.133$	$21.93^{ab} \pm 0.133$
Bubbler	1st	$6.3^{cb} \pm 0.093$	$7.6^{bb} \pm 0.093$	$8.1^{bc} \pm 0.082$	$15.95^{cc} \pm 0.204$	$20.12^{bc} \pm 0.133$	$21.11^{bb} \pm 0.133$
	2nd	$6.4^{cb} \pm 0.093$	$7.8^{bb} \pm 0.093$	$8.2^{bc} \pm 0.082$	$16.01^{cc} \pm 0.204$	$20.23^{bc} \pm 0.133$	$21.31^{bb} \pm 0.133$
F test		5.89			12.60		

First letter denote the difference between treatments and the second letter denote the difference between irrigation systems at $P < 0.05$ under the same system irrigation, respectively. Values represent means whereas ± values indicate standard error

44.38%, 45.68% and 46.59% compared with RWS_{100}, DIS_{100} and BIS_{100}, respectively. While the water saving under RWS_{80}, DIS_{80} and BIS_{80} were 23.44%, 25.22% and 27.91% compared with RWS_{100}, DIS_{100} and BIS_{100}, respectively. Although, the best water use efficiency were obtained under RWS_{60}, DIS_{60} and BIS_{60} treatments, the fruit productivity was decreased by 27.18%, 27.63% and 28.88% compared with RWS_{100},DIS_{100} and $BIS_{100,}$ respectively. Fruit quality was significantly affected by the type of irrigation system; the best quality was obtained with RWS followed by DIS and then by BIS. Generally, the RWS system, through its positive impact on water use efficiency and enhancement on fruit yield and fruit quality of date palm, seems quite suitable for the irrigation of palm trees in arid and semi-arid regions.

Author contributions SMR and AH collected and analyzed the research data and wrote the draft manuscript. AM, AH and SMR designed the research and provided suggestions regarding data analysis. SMR, AM, AAH and SFME generated the figures in the main manuscript. SMR, AH and AM read and edited the draft and final manuscript with suggested changes. All authors have read and agreed to the published version of the manuscript.

Data Availability The data that support the findings of this study are available upon reasonable request from the authors.

References

Adil M, Samia H, Sakher M, El-Hafed K, Naima K, Kawther L, Yamina K (2015) Date palm (*Phoenix dactylifera* L.) irrigation water requirements as affected by salinity in Oued Righ conditions, North Eastern Sahara. Algeria Asian J Crop Sci 7(3):174–185

Ahmed Mohammed ME, Refdan Alhajhoj M, Ali-Dinar HM, Munir M (2020) Impact of a novel water-saving subsurface irrigation system on water productivity, photosynthetic characteristics, yield, and fruit quality of date palm under arid conditions. Agronomy 10(9):1265

Al-Amoud AI, Mohammad FS, Al-Hamed SA, Alabdulkader AM (2012) Reference evapotranspiration and date palm water use in the Kingdom of Saudi Arabia. Int Res J Agric Sci Soil Sci 2(4):155–169

Al-Ghobari HM (2000) Estimation of reference evapotranspiration for southern region of Saudi Arabia. Irrig Sci 19(2):81–86

Al-Omran A, Eid S, Alshammari F (2019) Crop water requirements of date palm based on actual applied water and Penman-Monteith calculations in Saudi Arabia. Appl Water Sci 9(4):1–9

Al Amuod A, Bacha M, Darby A (2000) Seasonal water use of date palms in Saudi Arabia. Int Agric Eng 9(2):52–62

Alazba A (2004) Estimating palm water requirements using Penman-Monteith mathematical model. J King Saud Univ 16(2):137–152

Allen RG, Raes D, Smith M (1998) Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56, 300, D05109.

Amiri M, Panahi M, Aghazadeh G (2007) Comparison of bubbler, sprinkler and basin irrigation for date palms (Phoenix dactylifera, cv Zahdi) growth in Kish Island. Iran. J Food Agric Environ 23:78

Amosson S, Ellis J, Lacewell R, Johnson J, Ethridge D, Segarra E, Johnson PN (2001) Estimating the potential to reduce agricultural irrigation water demand in west central Texas.

Bainbridge D (2006) Deep pipe irrigation. The overstory# 175: Permanent Agriculture Resources: Holualoa.

Biro K, Zeineldin F, Al-Hajhoj M, Dinar H (2020) Estimating irrigation water use for date palm using remote sensing over an Oasis in arid region. Iraqi J Agric Sci 51(4):1173–1187

Diouf J (2003) Agriculture, food security and water: towards a blue revolution: growing enough food to feed the world depends on water supply. In: The challenge can be met, though there are conditions (Spotlight). oecd Observer, pp. 21–23.

El-Agha DE, Molden DJ, Ghanem AM (2011) Performance assessment of irrigation water management in old lands of the Nile delta of Egypt. Irrig Drain Syst 25(4):215–236

El-Hendawy SE, Abd El-Lattief EA, Ahmed MS, Schmidhalter U (2008) Irrigation rate and plant density effects on yield and water use efficiency of drip-irrigated corn. Agric Water Manag 95(7):836–844

FAO (2007) International Center for Advanced Mediterranean Agronomic Studies (CIHEAM).Workshop on “Irrigation of Date Palm and Associated Crops” Faculty of Agriculture; Damascus University: Damascus, Syrian Arab Republic, ISBN 9789251059975.

Howell T (2003) Irrigation Efficiency. Encyclopedia of Water Science. Marcel-Dekker Inc, BA Stewart and TA Howell

Ibrahim YM, Saeed AB, Elamin A (2012) Effect of irrigation water management on growth of date palm offshoots (Phoenix dactylifera) under the River Nile state conditions. Univ Khartoum J Agric Sci 20(3):275–285

Irmak S, Odhiambo LO, Kranz WL, Eisenhauer DE (2011) Irrigation efficiency and uniformity, and crop water use efficiency.

Jones HG (2004) Irrigation scheduling: advantages and pitfalls of plant-based methods. J Exp Bot 55(407):2427–2436

Kassem M (2007) Water requirements and crop coefficient of date palm trees Sukariah CV. Misr J Agric Eng 24(2):339–359

Levin I, Van Rooyen P, Van Rooyen F (1979) The effect of discharge rate and intermittent water application by point-source irrigation on the soil moisture distribution pattern. Soil Sci Soc Am J 43(1):8–16

Mazahrih NT, Al-Zubi Y, Ghnaim H, Lababdeh L, Ghananeem M, Ahmadeh HA (2012) Determination actual evapotranspiration and crop coefficients of date palm trees (*Phoenix dactylifera* L.) in the Jordan Valley.

Mohamed AS, Ali AA, El-Ghany A, Yosri A (2018) Irrigation water management of date palm under El-Baharia Oasis conditions. Egypt J Soil Sci 58(1):27–44

Mohamed RM, El-Gindy A, Arafa Y, Salah A (2012) J Soil Sci Agric Eng. 23:56

Mokhtar A, He H, Alsafadi K, Li Y, Zhao H, Keo S, He Q (2020) Evapotranspiration as a response to climate variability and ecosystem changes in southwest. China Environ Earth Sci 79(12):312. https://doi.org/10.1007/s12665-020-09007-1

Mokhtar A, He H, He W, Elbeltagi A, Maroufpoor S, Azad N, Gyasi-Agyei Y (2021) Estimation of the rice water footprint based on machine learning algorithms. Comput Electron Agric 191:106501

Molden D, Frenken K, Barker R, De Fraiture C, Mati B, Svendsen M, Giordano M (2007) Trends in water and agricultural development. In: Water for food, water for life: A comprehensive assessment of water management in agriculture, pp. 57–89

Saad Eddin M, El-Ansary M, Awaad M, Mohammed A (2016) Evaluation of integrated surface irrigation management in the old lands. J Soil Sci Agric Eng 7(7):509–515

Ucan K, Kıllı F, Gençoğlan C, Merdun H (2007) Effect of irrigation frequency and amount on water use efficiency and yield of sesame (*Sesamum indicum* L.) under field conditions. Field Crops Res 101(3):249–258