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Effect of some irrigation systems on water stress levels of Washington navel orange trees

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Abstract

Background This experimental study was conducted during two successive seasons 2021–2022 on 10-year-old Washington navel orange trees (*Citrus sinensis*) budded on sour orange rootstock (*Citrus aurantium*) under sandy loamy soil conditions in Belbeis district, Sharkia Governorate, Egypt. This experimental study was conducted to compare some irrigation systems with different water stress levels on Washington navel trees and to determine the best system in terms of irrigation water use efficiency using different irrigation systems (drip and micro-sprinklers) under different levels of water supply (100, 80, and 60% of ETc, i.e., the estimated water requirements of crops).

Results The included data demonstrated that irrigation water amounts can be reduced by 20% for Washington navel trees, while maintaining production, with the possibility of increasing by using micro-sprinkler irrigation systems. In summary, water use efficiency increased with micro-sprinkler irrigation systems under ETc 80%, which resulted in 2.57 and 2.67 kg of fruit per cubic meter of irrigation water in the first and second seasons, respectively.

Conclusion The results of the present study showed that using ETc 80% combined with micro-sprinklers irrigation system had a high economic return through increasing total yield, water use efficiency, and water unit return (WUR) which reached to 10.26 EGP/one cubic meter of irrigation water and using less water irrigation amount by 20% at the same time. Thus, we recommend applying the treatment of ETc 80% combined with micro-sprinklers irrigation system to Washington navel orange trees budded on sour orange rootstock to gain a high economic return.

Keywords Orange, Irrigation systems, Drip irrigation, Micro-sprinklers irrigation, Evapotranspiration, Water stress

Background

Citrus fruits are some of the most important fruits in the world and are mainly distributed between the latitudes of approximately 30° N and 30° S (Liu et al. 2022; Xie et al. 2023). It is one of the world's most commonly produced and diverse fruits (Trigueros et al. 2020; Jamshidi et al. 2021). Global annual production has now reached 158 million tons (Chen et al. 2022). It is classified as a sensitive crop to water scarcity, which is one of the major causes of low productivity and the decline of citrus orchards. In citrus, water lack reduces vegetative development and, in some cases, quality, resulting in significant economic losses (Trigueros et al. 2021; Ziogas et al. 2021; Panigrahi 2023). In Egypt, citrus trees are the most important fruit crop. They have an outstanding economic importance among fruit crops, particularly for exportation. The citrus area amounted to 493,925 feddans, out of them 440,210 feddans are fruitful producing 4,503,226 tons (38.73% of the total production of fruit trees) with average of 10.23 tons per feddan. The total area under Washington orange trees is 152,806 feddans out of them 145,645 feddans are fruitful producing 1,608,806 tons with an average of 11.05 tons per feddan (Ministry of Agriculture 2022). The previous studies under Egyptian conditions exhibited a wide range of irrigation rate needed for orange orchards that could reach sometimes

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Table 1 Reference crop evapotranspiration rate (ETo) calculated with CROPWAT V.8.00 computer program from meteorological data under Sharkia Governorate conditions using FAO Penman–Monteith equation according to Ndulue and Ramanathan 2021 (season 2021)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
ETo 100%	2.17	2.73	3.69	5.24	6.76	6.79	6.77	6.27	5.05	3.89	2.75	2.07	
Crop coefficient	0.61	0.64	0.67	0.72	0.78	0.81	0.80	0.97	0.46	0.51	0.64	0.58	
ETc 100%	1.32	1.75	2.47	3.77	5.27	5.50	5.42	6.08	2.32	1.98	1.76	1.20	
W.R (m^3/fed./day)	5.56	7.34	10.38	15.85	22.15	23.10	22.75	25.54	9.76	8.33	7.39	5.04	
W.R (m^3/fed. month)	166.79	220.15	311.26	475.37	664.37	692.99	682.42	766.32	292.70	249.97	221.76	151.28	4895.36
ETo 80%	1.74	2.18	2.95	4.19	5.41	5.43	5.42	5.02	4.04	3.11	2.20	1.66	
ETc 80%	1.06	1.40	1.98	3.02	4.22	4.40	4.33	4.87	1.86	1.59	1.41	0.96	
W.R (m^3/fed./day)	4.45	5.87	8.31	12.68	17.72	18.48	18.20	20.44	7.81	6.67	5.91	4.03	
W.R (m^3/fed. month)	133.43	176.12	249.21	380.30	531.50	554.39	545.93	613.06	234.16	199.98	177.41	121.02	3916.49
ETo 60%	1.30	1.64	2.21	3.14	4.06	4.07	4.06	3.76	3.03	2.33	1.65	1.24	
ETc 60%	0.79	1.05	1.48	2.26	3.16	3.30	3.25	3.65	1.39	1.19	1.06	0.72	
W.R (m^3/fed./day)	3.34	4.40	6.23	9.51	13.29	13.86	13.65	15.33	5.85	5.00	4.44	3.03	
W.R (m^3/fed. month)	100.07	132.09	186.91	285.22	398.62	415.79	409.45	459.79	175.62	149.98	133.06	90.77	2937.37

ETo reference crop evapotranspiration rate and ETc estimated crop water requirement

8000 m^3/feddan[1]/year or more (Youssef et al. 2023). The general trend in those studies showed that increasing irrigation rate caused promotions in many characteristics, which lead to an increment in both vegetative growth and fruiting and finally profitable yield (Panigrahi 2023).

The Nile River is the major source of water in Egypt (55.50 billion cubic meters), which puts it under enormous pressure, especially in light of the competitive situation with neighboring countries. Therefore, it is a must to take several steps to preserve the quantity and quality of water, while developing appropriate strategies to avoid endangering future water supplies. Water irrigation accounts for more than 38.25 billion cubic meters (68.97%) of the total water used in Egypt according to the statistics of Central Agency for Public Mobilization and Statistics (2021), so the efficiency of using irrigation water is a top priority, while reducing its quantity without affecting the yield, quantity, and quality.

Lately, some studies evaluated one or more of the irrigation systems (drip and micro-sprinklers), which cleared that the most water use efficiency was drip irrigation, while other reports indicated that micro-sprinkler irrigation was the best according to Ntshidi et al. (2023) and Youssef et al. (2023).

The objective of this study was to improve water use efficiency, maximize water utilization, and determine the most effective treatment by using different irrigation systems (drip and micro-sprinklers) under different levels of water supply (100, 80, and 60% of ETc, i.e., evapotranspiration) to Washington navel orange trees.

[1] Feddan = (0.42 hectare).

Methods

Material preparation and characterization

The present investigation was carried out during two successive seasons (2021 and 2022) to improve water use efficiency and increase water unit return for citrus by studying the effect of different irrigation systems (drip and micro-sprinklers) under different levels of water supply (100, 80, and 60% of ETc) on growth, flowering, fruit set, and yield of Washington navel orange trees (*Citrus sinensis L. Osbeck)* budded on sour orange (*Citrus aurantium*) rootstock. The experimental trees were 10 years old and grown at 4 × 5 m, in sandy loam soil under drip irrigation system using River Nile water in a private orchard at Belbeis region, El Sharkia Governorate, Egypt.

All the trees of this study received the same horticultural practices except experimental treatments. The experimental design was a split-plot arrangement of randomized complete block with three replicates and two trees for each replicate. The main plot (first factor) comprised of three irrigation levels (100, 80, and 60% of ETc) and the sub-plot (second factor) included different irrigation systems (drip and micro-sprinklers). The tested irrigation levels were based on different rates of irrigation water, i.e., 4895, 3916, and 2937 m^3/feddan/year for the first season and 4720, 3776, and 2832 m^3/feddan/year for the second season as shown in Tables 1, 2 and Fig. 1. These values resulted from the CROPWAT (2012) version 8.0.1.1 computer program using the region meteorological data (2020 and 2021 years). Moreover, the estimated crop water requirement (ETc) is obtained by multiplying the specific crop coefficient (Kc) by reference evapotranspiration (ETo), i.e., ETc = ETo x Kc.

Table 2 Reference crop evapotranspiration rate (ETo) calculated with CROPWAT V.8.00 computer program from meteorological data under Sharkia Governorate conditions using FAO Penman–Monteith equation according to Ndulue and Ramanathan 2021 (season 2022)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
ETo 100%	2.10	2.57	3.39	5.46	6.12	6.82	6.49	5.82	5.00	3.85	2.62	2.18	
Crop coefficient	0.61	0.64	0.67	0.72	0.78	0.81	0.80	0.97	0.46	0.51	0.64	0.58	
ETc 100%	1.28	1.64	2.27	3.93	4.77	5.52	5.19	5.65	2.30	1.96	1.68	1.26	
W.R (m^3/fed./day)	5.38	6.91	9.54	16.51	20.05	23.20	21.81	23.71	9.66	8.25	7.04	5.31	
W.R (m^3/fed. month)	161.41	207.24	286.18	495.33	601.47	696.05	654.19	711.32	289.80	247.40	211.28	159.31	4720.99
ETo 80%	1.68	2.06	2.71	4.37	4.90	5.46	5.19	4.66	4.00	3.08	2.10	1.74	
ETc 80%	1.02	1.32	1.82	3.14	3.82	4.42	4.15	4.52	1.84	1.57	1.34	1.01	
W.R (m^3/fed./day)	4.30	5.53	7.63	13.21	16.04	18.56	17.45	18.97	7.73	6.60	5.63	4.25	
W.R (m^3/fed. month)	129.12	165.80	228.95	396.26	481.18	556.84	523.35	569.06	231.84	197.92	169.02	127.45	3776.79
ETo 60%	1.26	1.54	2.03	3.28	3.67	4.09	3.89	3.49	3.00	2.31	1.57	1.31	
ETc 60%	0.77	0.99	1.36	2.36	2.86	3.31	3.12	3.39	1.38	1.18	1.01	0.76	
W.R (m^3/fed./day)	3.23	4.14	5.72	9.91	12.03	13.92	13.08	14.23	5.80	4.95	4.23	3.19	
W.R (m^3/fed. month)	96.84	124.35	171.71	297.20	360.88	417.63	392.52	426.79	173.88	148.44	126.77	95.59	2832.60

ETo reference crop evapotranspiration rate and ETc estimated crop water requirement

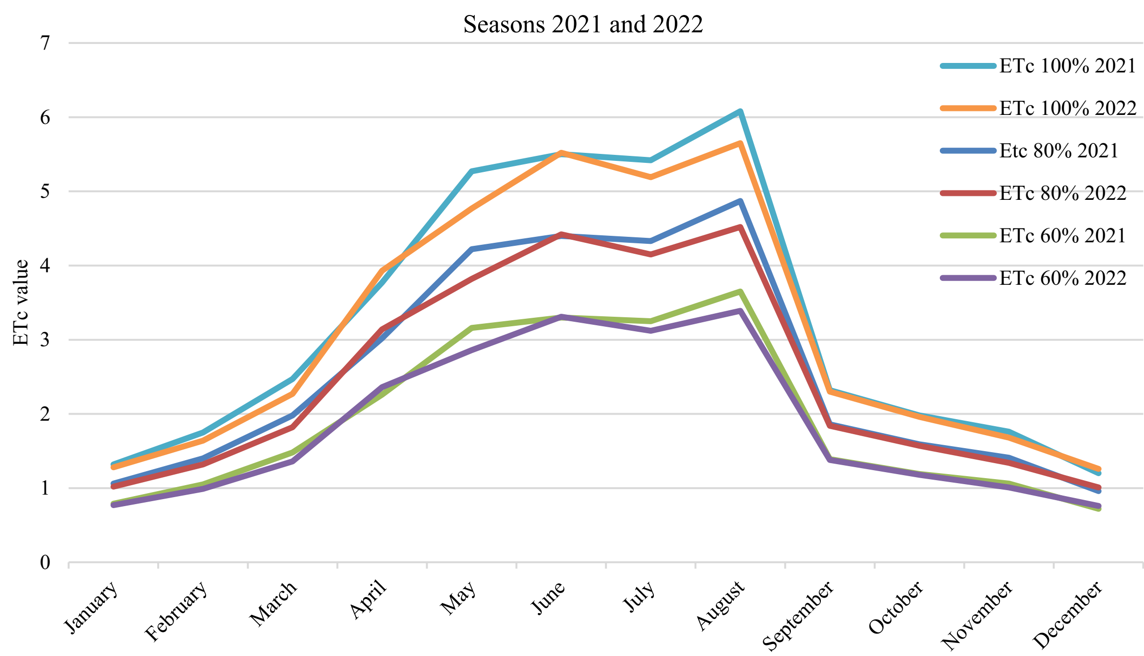


Fig. 1 Monthly estimated crop water requirement (ETc) at the experimental site during the two growing seasons (2021 and 2022)

The tested treatments were evaluated through the following parameters

Tree volume leaf area and root behavior (length of fibrous roots)

The tree height (m), tree circumference (m), and tree canopy volume (m^3) were determined in both investigation seasons. The tree canopy volume was calculated according to the following equation: canopy volume (m^3) = 1.33 × 0.5 x circumference (m) × 3.14 × 0.5 x height (m) (Turell 1965). Tree volume increment had been calculated by subtracting tree volume at the beginning and the end of the season. In addition, the total length of fibrous roots in 500 cm^3 of soil samples was taken from the layers of 0–30 cm from the soil surface at the beginning of the experiment and then at the end of each season (December). Moreover, leaf area (cm^2) was determined using disks of the leaf blades according to Bremner and Taha (1966).

Flowering and fruit set

Sixteen twigs per tree (four twigs in each side) were chosen to collect the data. The number of leafy and leafless inflorescences per twig was counted and recorded then leafy inflorescences percentages were computed according to the following equation:

$$\text{Leafy inflorescences}(\%) = 100 \times \frac{\text{Leafy inflorescences}}{\text{Total inflorescences}}.$$

In addition, the total number of flowers per twig was counted and recorded at full bloom. At the same time, the number of set fruitlets per twig was counted and recorded after the fruit set stage. Finally, the fruit set percentage was computed according to the following equation:

$$\text{Fruit set}(\%) = 100 \times \frac{\text{Number of set fruitlet}}{\text{Number of total flowers}}.$$

Leaf photosynthetic pigments, proline, cell sap osmotic pressure, opened stomata percentage, and leaf bound water percentage

The photosynthetic pigment contents (mg/100 g of fresh weight) were determined in fresh samples of leaf blades collected in August, according to Von-Wettestein (1957). Moreover, the proline content of fresh leaves (µ moles/g fresh weight) was determined following the method adopted by Bates et al. (1973). The leaf osmotic pressure of the cell sap of leaf blades and leaf bound water percentage were determined following the method of Gosov (1960). The total number of stomata and the number of opened stomata/cm^2 of leaf area were determined using the method of Stino et al. (1974) then the percentage of opened stomata was computed according to the following equation:

$$\text{Opened stomata} = 100 \times \frac{\text{Number of opened stomata}}{\text{Number of total stomata}}.$$

Fruit physical properties

Samples of 32 fruits per replicate (16 fruits per tree) were randomly selected, and the studied parameters involved fruit weight (g) and juice volume.

Chemical constituents of the fruit juice

The following parameters were considered: Total soluble solids percentage (TSS) was determined using a hand refractometer; total titratable acidity (g citric acid per 100 ml of juice) was determined by titration against 0.1 N sodium hydroxide in the presence of phenolphthalin as an indicator; values of the TSS/acid ratio were calculated; ascorbic acid content (mg per 100 ml of juice) was determined by titration against 2,6-dichlorophenol indophenol (mg per 100 ml) following the method illustrated in the AOAC (2016).

Yield, water use efficiency, and water unit return

The quantity of fruits collected from each tree at harvest (December) was tallied, the weight of all the fruits from each tree (kg) was determined and noted, and the hypothetical yield per feddan [based on 210 trees per feddan (4×5 m apart)] was computed.

Water use efficiency (WUE) values were calculated according to the following equation (Jensen 1983):

$$\text{WUE} = \frac{\text{Yield (kg per feddan)}}{\text{Seasonal ET (m3 per feddan)}}$$

Water unit returns (WUR) were calculated according to the following equation:

$$\text{Water unit return} = \text{WUE} \times \text{price of 1 kg orange (4 EGP)}.$$

Statistical analysis

The experimental design was a split-plot arrangement of a complete randomized block (factorial experiment with split-plot design) with three replicates and two trees for each replicate. The main plot contained three water irrigation levels (100, 80, and 60% of ETc), and the sub-plot comprised different irrigation systems (drip and micro-sprinklers). The data obtained were statistically analyzed using the analysis of variance method as reported by Snedecor and Cochran (1989). The differences between means were differentiated by using Duncan's range test (Duncan 1955).

Results

The listed data in Table 3 clarified the impact of water deficiency rates and some irrigation system types on morpho-phenological parameters, beginning with tree canopy volume, leaf area, and leafy inflorescence percentage, which are considered as preliminary predictor of yield status, fruit set, and length of fibrous roots, which were likely to increase the number of fruits per tree.

As for tree canopy, the highest significant value was 60.74 m^3 with ETc 100%, while the least significant value was 44.25 m^3 with ETc 60%. As for irrigation systems, the highest significant value for tree canopy was 53.52 m^3 with drip irrigation systems as compared to

Table 3 Water deficiency rates and some irrigation system types effectiveness on morpho-phenological (growth, fruit set, and yield) parameters of Washington navel orange trees (2021–2022 seasons)

	Tree canopy volume (m^3)	Leaf area (cm^2)	Total length of fibrous roots (cm)/500 cm^3 soil in 0–30-cm soil layer	Total length of fibrous roots (cm)/500 cm^3 soil in 30–60-cm soil layer	Percentage of leafy inflorescences	Overall fruit set percentage per twig	Number of fruits per tree
First season (2021)							
ETc 100%	60.74[a]	19.19[a]	177.57[a]	146.71[a]	74.27[a]	10.03[a]	172.85[a]
ETc 80%	47.05[b]	16.73[b]	127.49[b]	104.69[b]	63.85[b]	8.63[b]	167.93[b]
ETc 60%	44.25[c]	16.20[b]	106.32[c]	85.58[c]	51.62[c]	5.50[c]	151.58[c]
DIS	53.52[a]	17.90[a]	126.63[b]	121.72[a]	58.22[b]	6.90[b]	150.84[b]
MSIS	47.84[b]	16.84[b]	147.63[a]	102.94[b]	68.27[a]	9.20[a]	177.39[a]
ETc 100% × DIS	66.81[a]	20.19[a]	162.87[b]	159.57[a]	67.56[b]	8.80[c]	154.38[c]
ETc 100% × MSIS	54.67[b]	18.18[b]	192.28[a]	133.85[b]	80.99[a]	11.26[a]	191.32[a]
ETc 80% × DIS	50.44[c]	17.40[c]	122.38[d]	110.05[c]	58.10[c]	6.89[d]	153.83[c]
ETc 80% × MSIS	43.65[d]	16.06[d]	132.61[c]	99.32[d]	69.61[b]	10.37[b]	182.03[b]
ETc 60% × DIS	43.30[d]	16.11[d]	94.63[f]	95.53[d]	49.02[d]	5.00[e]	144.32[d]
ETc 60% × MSIS	45.21[d]	16.28[d]	118.01[e]	75.64[e]	54.21[c]	5.99[e]	158.84[c]
Second season (2022)							
ETc 100%	74.79[a]	21.25[a]	180.80[a]	149.44[a]	76.47[a]	14.13[a]	189.12[a]
ETc 80%	53.49[b]	17.87[b]	127.59[b]	105.42[b]	68.73[b]	11.31[b]	170.71[b]
ETc 60%	49.48[c]	17.12[b]	104.39[c]	83.57[c]	52.67[c]	7.66[c]	154.73[c]
DIS	64.32[a]	19.59[a]	125.72[b]	122.95[a]	59.29[b]	10.26[b]	156.63[b]
MSIS	54.19[b]	17.90[b]	149.46[a]	102.67[b]	72.62[a]	11.81[a]	186.42[a]
ETc 100% × DIS	86.77[a]	23.02[a]	160.02[b]	167.32[a]	66.67[c]	13.72[b]	160.90[c]
ETc 100% × MSIS	62.81[b]	19.49[b]	201.58[a]	131.56[b]	86.27[a]	14.54[a]	217.35[a]
ETc 80% × DIS	57.63[c]	18.70[c]	121.23[c]	111.17[c]	64.31[c]	10.19[d]	161.53[c]
ETc 80% × MSIS	49.35[d]	17.04[d]	133.94[c]	99.67[d]	73.15[b]	12.43[c]	179.89[b]
ETc 60% × DIS	48.56[d]	17.04[d]	95.92[e]	90.35[d]	46.90[e]	6.86[f]	147.45[d]
ETc 60% × MSIS	50.40[d]	17.19[d]	112.87[d]	76.78[e]	58.44[d]	8.46[e]	162.01[c]

ETc = evapotranspiration, DIS = drip irrigation system, and MSIS = micro-sprinklers irrigation system

Mean followed by the same letter/s within each column is not significantly different from each other at 0.5% level

micro-sprinklers irrigation system, which recorded the least significant value of 47.84 m^3. In regard to the interaction, the best coefficient treatment was ETc 100% with the drip irrigation system, which ranked first with a value of 66.81 m^3, while the ETc 100% with a micro-sprinkler irrigation system treatment came in the second place with a value of 54.67 m^3, this trend held true in the two seasons. The leaf area and total length of fibrous roots (cm/500 cm^3 soil in 30–60-cm soil layer) parameters took the same trend to tree canopy volume. Concerning the drip irrigation system, it scored the highest value, and this may be due to the penetration of moisture into the soil layer from 0–60 cm, which means an increase in the absorption of water and nutrients, and thereby was reflected in the increasing vegetative growth standards.

Moreover, the total length of fibrous roots (cm/500 cc in the soil layer 0–30 cm), the percentage of leafy inflorescences, the percentage of fruits, and the number of fruits per tree had the same trend as that achieved by the previous trait, and this held true in the two seasons. As for the highest significant value of the total length of the fibrous roots, it was achieved with the ETc 100%

Table 4 Water deficiency rates and some irrigation system types effectiveness on leaf photosynthetic pigments and proline contents, cell sap osmotic pressure, opened stomata percentage, and leaf bound water content percentage of Washington navel orange leaves (2021–2022 seasons)

	Leaf chlorophyll a content (mg/100 g of leaf F. W.)	Leaf chlorophyll b content (mg/100 g of leaf F. W.)	Leaf proline content (μ g/moles of leaf F. W.)	Leaf cell sap osmotic pressure (atm.)	Opened stomata percentage	Leaf bound water content percentage
First season (2021)						
ETc 100%	0.22[a]	0.11[a]	35.68[c]	25.95[c]	90.94[a]	45.21[b]
ETc 80%	0.21[b]	0.10[b]	94.83[b]	27.88[b]	83.10[b]	45.52[b]
ETc 60%	0.20[c]	0.09[c]	119.93[a]	28.85[a]	81.88[b]	49.09[a]
DIS	0.21[a]	0.10[a]	79.75[b]	27.19[a]	86.65[a]	47.19[a]
MSIS	0.21[a]	0.10[a]	87.21[a]	27.92[a]	83.96[b]	46.02[b]
ETc 100% × DIS	0.23[a]	0.11[a]	26.35[e]	25.48[e]	93.02[a]	44.86[d]
ETc 100% × MSIS	0.22[b]	0.10[b]	45.00[d]	26.42[d]	88.86[b]	45.57[d]
ETc 80% × DIS	0.21[c]	0.10[b]	81.16[c]	27.09[c]	85.47[c]	46.57[c]
ETc 80% × MSIS	0.20[d]	0.09[c]	108.51[b]	28.67[b]	80.73[d]	44.47[d]
ETc 60% × DIS	0.20[d]	0.09[c]	131.75[a]	29.01[a]	81.46[d]	50.14[a]
ETc 60% × MSIS	0.20[d]	0.09[c]	108.10[b]	28.68[b]	82.30[d]	48.03[b]
Second season (2022)						
ETc 100%	0.22[a]	0.10[a]	34.11[c]	26.32[c]	91.66[a]	44.16[b]
ETc 80%	0.21[b]	0.10[a]	91.81[b]	28.62[b]	85.16[b]	44.74[b]
ETc 60%	0.20[c]	0.09[b]	118.52[a]	29.97[a]	83.20[b]	47.30[a]
DIS	0.22[a]	0.10[a]	78.23[b]	27.76[b]	88.29[a]	46.03[a]
MSIS	0.21[b]	0.10[a]	84.73[a]	28.85[a]	85.07[b]	44.77[b]
ETc 100% × DIS	0.23[a]	0.11[a]	24.74[e]	25.84[c]	93.94[a]	44.15[d]
ETc 100% × MSIS	0.22[b]	0.10[b]	43.48[d]	26.80[b]	89.38[b]	44.18[d]
ETc 80% × DIS	0.21[c]	0.10[b]	79.02[c]	27.52[b]	87.59[c]	45.75[c]
ETc 80% × MSIS	0.20[d]	0.09[c]	104.61[b]	29.72[a]	82.74[d]	43.74[d]
ETc 60% × DIS	0.20[d]	0.09[c]	130.94[a]	29.91[a]	83.33[d]	48.19[a]
ETc 60% × MSIS	0.20[d]	0.09[c]	106.10[b]	30.04[a]	83.07[d]	46.40[b]

ETc = evapotranspiration, DIS = drip irrigation system, and MSIS = micro-sprinklers irrigation system

Mean followed by the same letter/s within each column is not significantly different from each other at 0.5% level

treatment, recording a value of 177.57 cm, while the least significant value was for the ETc 60% treatment, recording a value of 106.32 cm. Regarding the irrigation systems, the highest significant value of the total length of the fibrous roots was 147.63 cm, and the micro-sprinklers irrigation system was achieved compared to the drip irrigation system, which recorded the least significant value of 126.63 cm. As for the interaction between water deficiency rates with irrigation systems, the best treatment was ETc 100% with the micro-sprinkler irrigation system, as it came in the first place, achieving 192.28 cm, while the treatment of ETc 100% with the drip irrigation system came in the second place with a value of 162.87 cm. An analogous trend was also noticed in the second season.

Data in Table 4 clarify the effect of water stress and irrigation system types on water relations parameters such as leaf chlorophyll a, leaf chlorophyll b, leaf proline, leaf cell sap osmotic pressure, opened stomata percentage, and leaf bound water content. Generally, leaf chlorophyll a, leaf chlorophyll b, and opened stomata percentage parameters were increased when water amount was increased. On contrary, leaf proline, leaf cell sap osmotic

Table 5 Water deficiency rates and some irrigation systems types effectiveness on fruit weight, juice volume, juice TSS, juice acidity, TSS/acid ratio, and ascorbic acid of Washington navel orange fruits (2021–2022 seasons)

	Fruit weight (g)	Juice volume/fruit (cm^3)	Juice TSS (%)	Juice acidity (%)	TSS/acid ratio	Ascorbic acid (mg/100 ml)
First season (2021)						
ETc 100%	280.17^{a}	158.77^{a}	10.83^{c}	0.77^{a}	14.15^{b}	36.90^{c}
ETc 80%	266.00^{b}	150.74^{b}	11.52^{b}	0.74^{b}	15.48^{b}	40.90^{b}
ETc 60%	253.83^{c}	143.85^{c}	12.67^{a}	0.69^{c}	18.51^{a}	45.76^{a}
DIS	269.89^{a}	152.95^{a}	11.44^{a}	0.74^{a}	15.47^{a}	39.74^{a}
MSIS	263.44^{a}	149.30^{a}	11.90^{a}	0.72^{a}	16.62^{a}	42.63^{a}
ETc 100% × DIS	284.67^{a}	161.32^{a}	10.61^{d}	0.77^{a}	13.78^{e}	35.53^{c}
ETc 100% × MSIS	275.67^{b}	156.22^{b}	11.05^{c}	0.76^{a}	14.51^{d}	38.27^{c}
ETc 80% × DIS	268.33^{c}	152.07^{c}	11.38^{c}	0.75^{a}	15.13^{c}	39.93^{c}
ETc 80% × MSIS	263.67^{d}	149.42^{d}	11.66^{c}	0.74^{a}	15.84^{c}	41.86^{b}
ETc 60% × DIS	256.67^{e}	145.46^{e}	12.35^{b}	0.71^{a}	17.50^{b}	43.74^{a}
ETc 60% × MSIS	251.00^{f}	142.24^{f}	12.98^{a}	0.67^{a}	19.52^{a}	47.77^{a}
Second season (2022)						
ETc 100%	277.00^{a}	156.98^{a}	11.02^{c}	0.79^{a}	14.01^{b}	37.32^{c}
ETc 80%	259.67^{b}	147.16^{b}	11.67^{b}	0.76^{b}	15.29^{b}	41.59^{b}
ETc 60%	250.17^{c}	141.77^{c}	13.12^{a}	0.72^{c}	18.24^{a}	47.91^{a}
DIS	267.33^{a}	151.50^{a}	11.63^{a}	0.76^{a}	15.25^{a}	40.24^{a}
MSIS	257.22^{a}	145.77^{a}	12.25^{a}	0.75^{a}	16.44^{a}	44.31^{a}
ETc 100% × DIS	287.00^{a}	162.65^{a}	10.88^{d}	0.79^{a}	13.76^{e}	35.82^{d}
ETc 100% × MSIS	267.00^{b}	151.31^{b}	11.15^{c}	0.78^{a}	14.25^{d}	38.82^{d}
ETc 80% × DIS	261.67^{c}	148.29^{c}	11.50^{c}	0.77^{a}	14.91^{d}	40.55^{c}
ETc 80% × MSIS	257.67^{d}	146.02^{d}	11.85^{c}	0.76^{a}	15.66^{c}	42.63^{b}
ETc 60% × DIS	253.33^{e}	143.57^{e}	12.50^{b}	0.73^{a}	17.08^{b}	44.36^{b}
ETc 60% × MSIS	247.00^{f}	139.98^{f}	13.75^{a}	0.71^{a}	19.40^{a}	51.47^{a}

ETc = evapotranspiration, DIS = drip irrigation system, and MSIS = micro-sprinklers irrigation system

Mean followed by the same letter/s within each column is not significantly different from each other at 0.5% level

pressure, and leaf bound water content were decreased when water amount increased; this held true in both seasons.

Regarding, the highest significant value for leaf chlorophyll a was 0.22 (mg/100 g of leaf F. W.) with ETc 100%, while the least significant value was 0.20 (mg/100 g of leaf F. W.) with ETc 60%. For irrigation system types, no significant results were noticed between the two irrigation system types in the two seasons. For the interaction between water stress and irrigation system types, the first rank was ETc 100% combined with drip irrigation system, which record 0.23 (mg/100 g of leaf F. W.), while the second rank was ETc 100% combined with micro-sprinklers irrigation system, which record 0.22 (mg/100 g of leaf F. W.); this came true in both seasons.

On the other hand, the least significant value of leaf proline was achieved by ETc 100% treatment with a value of 35.68 (µ g/moles of leaf F. W.), while the highest significant value was attained with ETc 60% treatment with a value of 119.93 (µ g/moles of leaf F. W.). As for the irrigation systems, the least significant value of leaf proline was 79.75 (µ g/moles of leaf F. W.) with the drip irrigation system, while the highest significant value was 87.21 (µ g/moles of leaf F. W.) and was performed with the micro-sprinklers irrigation system; this came true in the two seasons. Regarding the interaction between water stress and irrigation systems, the least significant value for leaf proline was with ETc 100% and drip irrigation treatment system with a value of 26.35 (µ g/moles of leaf F. W.), while the highest significant value was 131.75 (µ g/moles of leaf F. W.) and was achieved with a treatment of ETc 60% with drip irrigation system, the same trend was recorded in the second season.

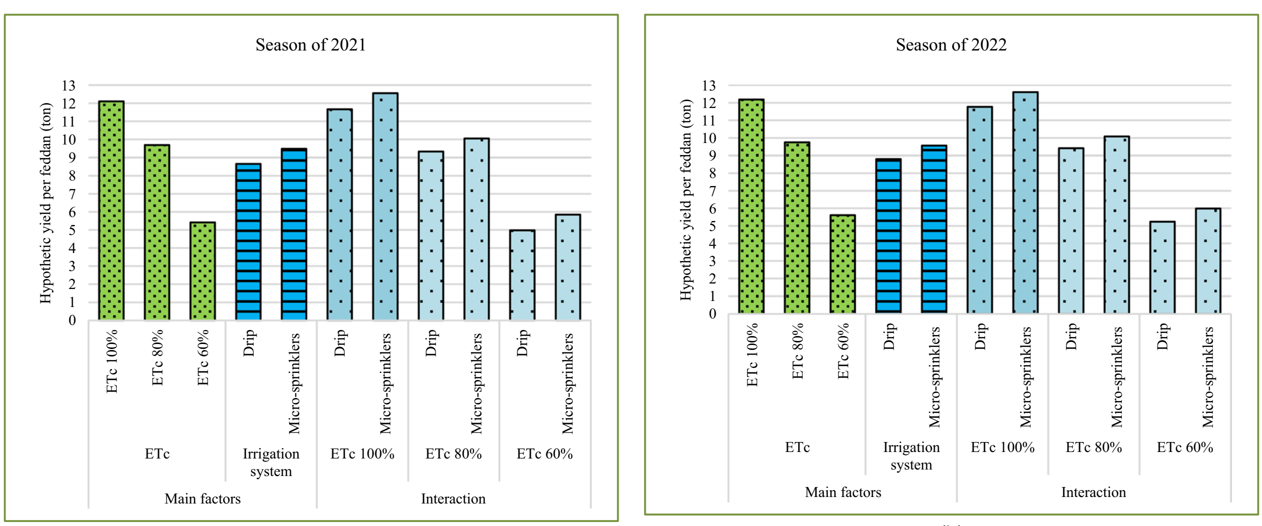
Results recorded in Table 5 strongly cleared the impact of ETc treatments on all physical and chemical fruit parameters with significant differences in both seasons, while irrigation system types had no effect on the most parameters. As for, the highest significant value for fruit weight was 280.17 g with ETc 100%, while the least significant value was 253.83 g with ETc 60%. As for irrigation

Table 6 Water deficiency rates and some irrigation system types effectiveness on tree yield, hypothetic yield per feddan, water use efficiency, and water unit return of Washington navel orange trees (2021–2022 seasons)

	Tree yield (kg)	**Hypothetic yield per feddan (ton)**	**Water use efficiency (kg fruit/ m^3 water)**	**Water unit return (EGP/m^3 of water)**
First season (2021)				
ETc 100%	57.68^{a}	12.11^{a}	2.47^{a}	9.90^{a}
ETc 80%	46.15^{b}	9.69^{b}	2.47^{a}	9.90^{a}
ETc 60%	25.79^{c}	5.42^{c}	1.84^{b}	7.38^{b}
DIS	41.25^{b}	8.66^{b}	2.15^{b}	8.62^{b}
MSIS	45.17^{a}	9.48^{a}	2.37^{a}	9.50^{a}
ETc 100% × DIS	55.56^{b}	11.67^{b}	2.38^{b}	9.53^{b}
ETc 100% × MSIS	59.80^{a}	12.56^{a}	2.57^{a}	10.26^{a}
ETc 80% × DIS	44.45^{d}	9.33^{d}	2.38^{b}	9.53^{b}
ETc 80% × MSIS	47.84^{c}	10.05^{c}	2.57^{a}	10.26^{a}
ETc 60% × DIS	23.73^{f}	4.98^{f}	1.70^{d}	6.79^{d}
ETc 60% × MSIS	27.85^{e}	5.85^{e}	1.99^{c}	7.96^{c}
Second season (2022)				
ETc 100%	58.03^{a}	12.19^{a}	2.58^{a}	10.33^{a}
ETc 80%	46.42^{b}	9.75^{b}	2.58^{a}	10.33^{a}
ETc 60%	26.73^{c}	5.61^{c}	1.98^{b}	7.93^{b}
DIS	41.93^{b}	8.81^{b}	2.28^{b}	9.11^{b}
MSIS	45.53^{a}	9.56^{a}	2.49^{a}	9.94^{a}
ETc 100% × DIS	56.03^{b}	11.77^{b}	2.49^{b}	9.97^{b}
ETc 100% × MSIS	60.03^{a}	12.61^{a}	2.67^{a}	10.68^{a}
ETc 80% × DIS	44.83^{d}	9.41^{d}	2.49^{b}	9.97^{b}
ETc 80% × MSIS	48.02^{c}	10.08^{c}	2.67^{a}	10.68^{a}
ETc 60% × DIS	24.94^{f}	5.24^{f}	1.85^{d}	7.40^{d}
ETc 60% × MSIS	28.53^{e}	5.99^{e}	2.12^{c}	8.46^{c}

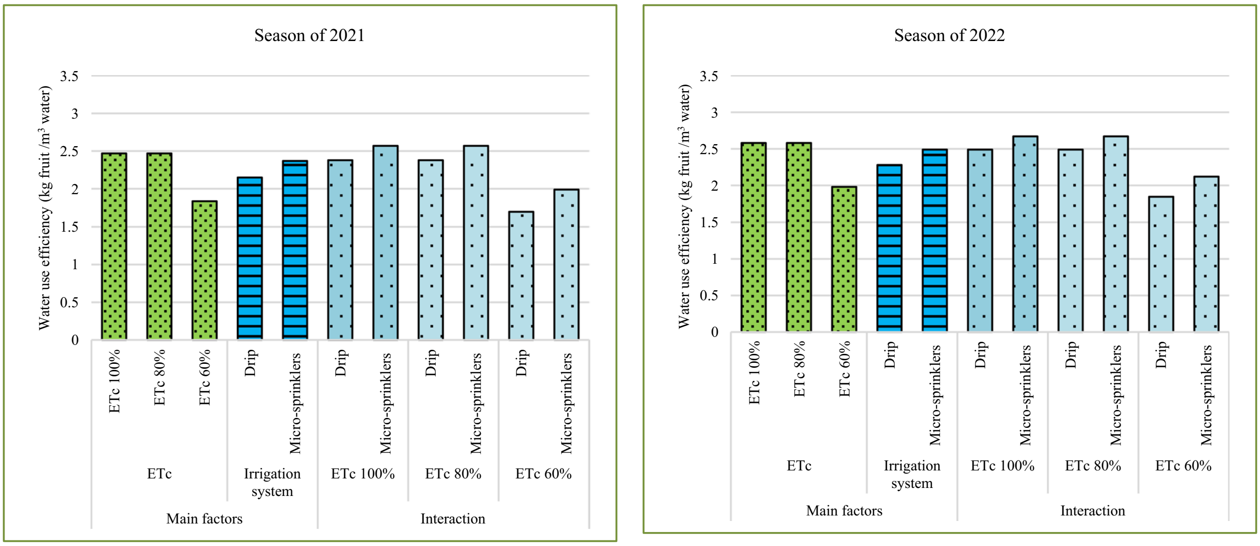
ETc = evapotranspiration, DIS = drip irrigation system, and MSIS = micro-sprinklers irrigation system

Mean followed by the same letter/s within each column is not significantly different from each other at 0.5% level



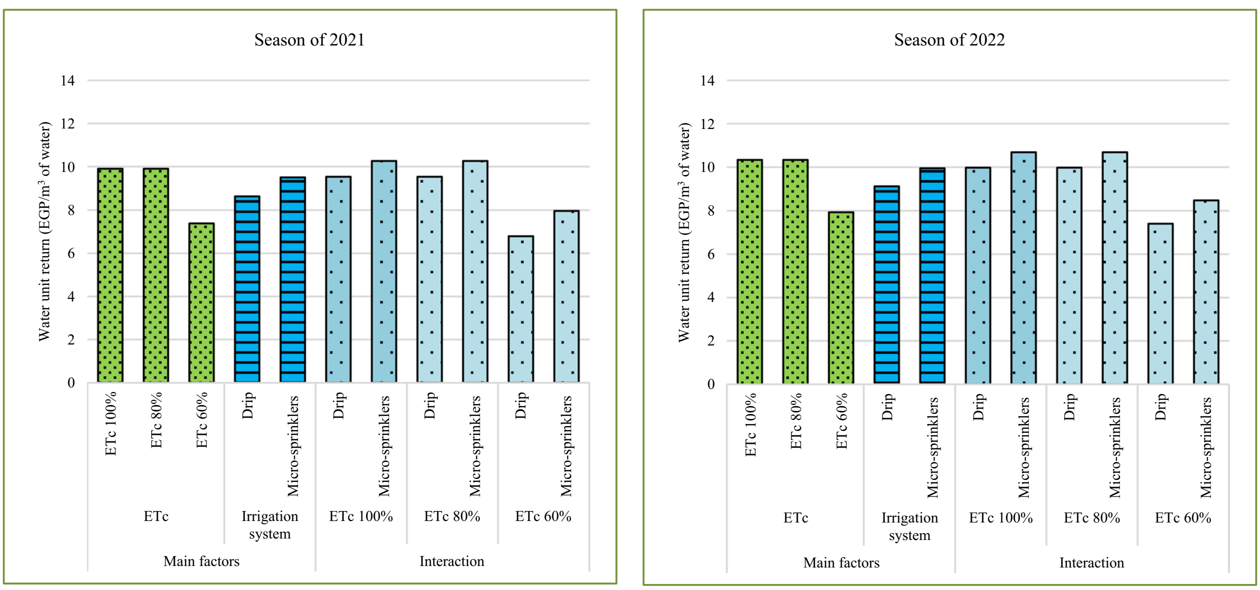
(a) (b)

Fig. 2 **a**, **b** Water deficiency rates and some irrigation system types effectiveness on hypothetic yield per feddan of Washington navel orange trees (2021–2022 seasons)



(a) (b)

Fig. 3 **a**, **b** Water deficiency rates and some irrigation system types effectiveness on water use efficiency of Washington navel orange trees (2021–2022 seasons)



(a) (b)

Fig. 4 **a**, **b** Water deficiency rates and some irrigation system types effectiveness on water unit return of Washington navel orange trees (2021–2022 seasons)

system types, there is no effect for irrigation system types on all physical and chemical fruit parameters in both seasons. The interaction between water stress and irrigation system types obviously indicated that the most significant treatments were ETc 100% combined with drip irrigation, which gained 284.67 g.

Table 6 and Figs. 2, 3, and 4 summarize the benefits of this experimental study. The highest significant increment in hypothetic yield per feddan (ton/feddan) was gained by using ETc at 100%, which produced 10.15 tons/feddan, while ETc at 60% treatment recorded only 8.08 tons/feddan. As for irrigation system types, the highest significant increment in hypothetic yield per feddan (ton/feddan) was gained by using micro-sprinklers irrigation system, which produced 9.84 tons/feddan, while drip irrigation system recorded only 8.56 tons/feddan.

In addition, the interaction between water stress and irrigation system types showed that ETc at 100% combined with micro-sprinklers irrigation system resulted in 11.08 tons/feddan, while ETc at 100% combined with drip irrigation produced 9.23 tons/feddan, which means that micro-sprinklers irrigation system increased yield by 20.04% by using the same amount of irrigation water, this trend was true in both seasons.

With a more comprehensive view, these results cannot be evaluated without reference to WUE (water use efficiency – kg fruit/m^3 water) and WUR (water unit return – EGP/m^3 water) to translate these results economically as a monetary product of the water unit, so, if the results have generally shown superiority of micro-sprinklers irrigation system in WUE and WUR, get the interaction clarified that the micro-sprinklers irrigation system combined with ETc 60%, which recorded for ETc 60% combined with micro-sprinklers irrigation system was 2.93 for WUE and 11.72 for WUR was better than the ETc 100% combined with drip irrigation, that gained 1.94 for WUE and 7.76 for WUR. This trend was also confirmed in the second season. Conclusively, it could be mentioned on the basis of the obtained results that micro-sprinklers irrigation system achieved what is targeted for citrus in SADS (Sustainable Agricultural Development Strategy toward 2030) by decreasing the water amount used to irrigate citrus orchards by a rate ranging from 20 to 40%, at the same time, it increased the water unit return (WUR) to reach 11.72 EGP/one cubic meter of irrigation water at 40% saved water and could reach 10.59 EGP/one cubic meter of irrigation water at 20% saved water.

Discussion

The listed data in Table 3 clarified the impact of water deficiency rates and some irrigation system types on morpho-phenological parameters, beginning with tree canopy volume, leaf area, and leafy inflorescence percentage, which are considered as a preliminary predictor of yield status, fruit set, and length of fibrous roots, thereby were reflected by an increase in the number of fruits per tree. In this scenario, it can be noticed that micro-sprinklers irrigation system resulted in better values that may be due to the greater horizontal extension of the area of wetted soil around the source of water under the tree canopy as well as to the higher soil moisture at the soil layer of 0–30 cm, that increased fruit set percentage and the number of fruits per tree, according to Ennab and Alam-Elden (2020), Parra et al. (2021), Ennab et al. (2023), Kwakye and Kadyampakeni (2023), Ntshidi et al. (2023), and Panigrahi (2023). Generally, the aforementioned parameters were increased by increasing ETo rates, possibly due to the increase in soil moisture availability, moderate evaporation from the soil surface, temperature, N, P, and K values, according to Youssef et al. (2023). Results regarding conserving water supply levels were in agreement with those mentioned by Youssef et al. (2023).

Data shown in Table 4 clearly indicate to the effect of water stress and irrigation system types on water relations parameters such as leaf chlorophyll a, leaf chlorophyll b, leaf proline, leaf cell sap osmotic pressure, opened stomata percentage, and leaf bound water content. Generally, leaf chlorophyll a, leaf chlorophyll b, as well as opened stomata percentage parameters were increased when water amount increased. On contrary, leaf proline, leaf cell sap osmotic pressure, and leaf bound water content were decreased when water amount was increased; this came true in both seasons. Concerning water supply levels, the obtained results reveal that leaf photosynthetic pigments were significantly affected by water supply levels. The obtained results are in line with these reported by Trigueros et al. (2021), Panigrahi (2023), Youssef et al. (2023), and Xie et al. (2023).

Results recorded in Table 5 cleared strongly effect by ETc treatments on all physical and chemical fruit parameters with significant differences in both seasons, while irrigation system types did not affect most of the parameters. For water supply levels, the results of the present investigation confirmed those obtained by Ennab and Alam-Elden (2020), Aydinşakir et al. (2021), Tie et al. (2022), Ennab et al. (2023), Panigrahi (2023), and Youssef et al. (2023).

The results shown in Table 6 and Figs. 2, 3, and 4 may be due to the high water irrigation supply, which increase soil moisture availability according to Ennab and Alam-Elden (2020), Aydinşakir et al. (2021), Parra et al. (2021), Chen et al. (2022), Ennab et al. (2023), and Youssef et al. (2023). Besides, the increase in soil moisture might have increased soil availability of N, K, and P and their uptake in the zone of roots, as well as enhanced photosynthetic processes, carbohydrate production, and yield. Results of the present investigation revealed that yield characteristics were significantly affected by water supply levels. The foregoing results agree with the findings of Tie et al. (2022), Panigrahi (2023), and Youssef et al. (2023). Moreover, micro-sprinkler irrigation systems led to an increase in yield due to an increase in the width of the wetted area with horizontal extension around the water source under the tree canopy, as well as an increase in soil moisture in the soil layer from 0–30 cm, which led to an increase in the percentage of fruits and their number of fruits per tree according to Ntshidi et al. (2023).

Conclusions

We can conclude that, the results of the present study showed that, using ETc 80% combined with micro-sprinklers irrigation system had a high economic return through increasing total yield, water use efficiency, and water unit return (WUR) which reached to 10.26 EGP/one cubic meter of irrigation water and thereby using less water irrigation amount by 20% at the same time. Thus, we recommend applying the treatment of ETc at 80% combined with micro-sprinklers irrigation system to Washington navel orange trees budded on sour orange rootstock to gain a high economic return.

Abbreviations

EGP	Egyptian Pound
ETc	Estimated crop water requirement
ETo	Reference crop evapotranspiration rate
FAO	Food and Agriculture Organization
Kc	Crop coefficient
Kg	Kilogram
Ppm	Parts per million
SA	Salicylic acid
WUE	Water use efficiency
WUR	Water unit returns
DIS	Drip irrigation system
MSIS	Micro-sprinklers irrigation system

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Author contributions

EA, TA, and MA performed the investigations. EA, TA, and MA contributed to writing the original data including analysis and interpretation. EA, TA, and MA performed the editing of the manuscript. All authors have read and approved the manuscript.

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Declarations

Ethics approval and consent to participate

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Competing interests

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References

AOAC (2016) Association of Official Analytical Chemists (2016) Official Methods of Analysis of International. 20th Ed. Benjamin Franklin Station, Washington, D. C.

Aydinşakir K, Ulucab E, Dinç N, Küçükcoşkunc Ş (2021) Effects of different irrigation levels on fruit yield and quality of Valencia Late Orange Under Northern Cyprus Conditions. J Agric Sci (tarim Bilimleri Dergisi) 27(3):276–284. https://doi.org/10.15832/ankutbd.615839

Bates LS, Walren RR, Tears ID (1973) Rapid determination of proline for water stress studies. Plant Soil 39(1):205–207

Bremner PM, Taha MA (1966) Studies in potato agronomy 1—the effects of variety, seed size and spacing on growth, development and yield. J Agric Sci 66(1):241–252

Central Agency for Public Mobilization and Statistics (2021) Indicator Description: Calculating of irrigation water quantities used in three crops lugs or fruits. https://www.capmas.gov.eg/Pages/IndicatorsPage.aspx?page_id=6151&ind_id=2361

Chen F, Cui N, Jiang S, Li H, Wang Y, Gong D, Hu X, Zhao L, Liu C, Qiu R (2022) Effects of water deficit at different growth stages under drip irrigation on fruit quality of citrus in the humid areas of South China. Agric Water Manag 262:107407. https://doi.org/10.1016/j.agwat.2021.107407

CROPWAT (2012) A computer program for irrigation planning and management. https://www.fao.org/land-water/databases-and-software/cropwat/en

Duncan DB (1955) Multiple range and multiple "F" tests. Biometrics 11(1):1–42

Ennab HA, Alam-Eldein SM (2020) Foliar application of biostimulants to improve growth, yield and fruit quality of Valencia orange trees under deficit irrigation conditions. J Am Pom Soc 74(3):118–134

Ennab HA, Khadr AM, Mikhael GB (2023) Effect of irrigation levels, mulching and kaolin on yield and fruit quality of washington navel orange trees grown in clay soil. Ann Agric Sci Moshtohor ASSJM 61(1):177–186. https://doi.org/10.21608/assjm.2023.293857

Gosov NA (1960) Some methods in studying plant water relations. Leningrad. Acad. Of Science, USSR

Jamshidi S, Zand-Parsa S, Niyogi D (2021) Assessing crop water stress index of citrus using in-situ measurements, landsat, and sentinel-2 data. Int J Remote Sens 42(5):1893–1916

Jensen ME (1983) Design and operation of farm irrigation systems. American Society Agriculture Engineers, Michigan, USA

Kwakye S, Kadyampakeni DM (2023) Impact of deficit Irrigation on growth and water relations of HLB-affected citrus trees under greenhouse conditions. Water 15(2085):1–16. https://doi.org/10.3390/w15112085

Liu S, Liu X, Gou B, Wang D, Liu C, Sun J (2022) The interaction between CitMYB52 and CitbHLH2 negatively regulates citrate accumulation by activating CitALMT in citrus fruit. Front Plant Sci. https://doi.org/10.3389/fpls.2022.848869

Ministry of Agriculture (2022) Statistics of Fruit Production in Egypt

Ndulue E, Ramanathan SR (2021) Performance of the FAO Penman–Monteith equation under limiting conditions and fourteen reference evapotranspiration models in southern Manitoba. Theoret Appl Climatol 143:1285–1298

Ntshidi Z, Dzikiti S, Mazvimavi D, Mobe NT (2023) Effect of different irrigation systems on water use partitioning and plant water relations of apple trees growing on deep sandy soils in the Mediterranean climatic conditions, South Africa. Sci Hortic 317(1):1–13

Panigrahi P (2023) Impact of deficit irrigation on citrus production under a sub-humid climate: a case study. Water Supply 23(3):1177. https://doi.org/10.2166/ws.2023.074

Parra M, Hortelano D, García-Sánchez F, Intrigliolo DS, Rubio-Asensio JS (2021) Effects of drip irrigation design on a lemon and a young Persimmon Orchard in semi-arid conditions. Water 13(13):1795. https://doi.org/10.3390/w13131795

Snedecor GW, Cochran WG (1989) Statistical methods.Oxford and J. B. H. Publishing Co. 8th Ed., Iowa State University Press, Ames, Lowa, USA

Stino GR, El-Azzouni MM, Abdalla KM, Mohsen AM (1974) Varietal studies in relation to zone of plantation in ARE. Egypt J Hortic 1(2):145–156

Tie Z, Bin P, Feifei L, Xiaochuan M, Mengjing T, Xuefei L, Yuanyuan C, Yuewen C, Xiaopeng L (2022) Effects of drought stress at enlargement stage on fruit quality formation of satsuma mandarin and the law of water absorption and transportation in tree after re-watering[j]. Acta Horticulturae Sinica 49(1):11–22

Trigueros CR, Alarcón JJ, Nortes PA, Bayona JM, Maestre VJ, Nicolás EM (2020) Mid-long term effects of saline reclaimed water irrigation and regulated deficit irrigation on fruit quality of citrus. J Sci Food Agric 100:1350–1357

Trigueros CR, Gambín JMB, Tortosa PAN, Cabañero JJA, Nicolás EN (2021) Isohydricity of two different citrus species under deficit irrigation and reclaimed water conditions. Plants 10(2121):1–19. https://doi.org/10.3390/plants10102121

Turell FM (1965) Comparative nocturnal thermal budgets of large and small citrus trees. Ecology 46(1):25–34

Von-Wettestein D (1957) Chlorophyll Lethal und Submikroskopischefromivechsel der Plastiden Exptl. Cell Res 12(1):427–433
Xie J, Chen Y, Yu Z, Wang J, Liang G, Gao P, Sun D, Wang W, Shu Z, Yin D, Li J (2023) Estimating stomatal conductance of citrus under water stress based on multispectral imagery and machine learning methods. Front Plant Sci 14:1–16. https://doi.org/10.3389/fpls.2023.1054587
Youssef EA, Mahmoud TA, Abo-Eid MAM (2023) Effect of foliar application of different concentrations of salicylic acid on Washington navel orange trees under water stress. Bull Natl Res Centre 47(98):1–13. https://doi.org/10.1186/s42269-023-01068-z
Ziogas V, Tanou G, Morianou G, Kourgialas N (2021) Drought and salinity in citriculture: optimal practices to alleviate salinity and water stress. Agronomy 11(7):1283. https://doi.org/10.3390/agronomy11071283

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