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# Surface and Sub-Surface Irrigation Techniques Effects on Water Use Efficiency of Valencia Orange Trees

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**Abstract**: A trial ten-year-old Valencia orange (*Citrus sinensis* Osbeck) trees budded on sour orange (*Citrus aurantium* L.) rootstock grown in this experimental research, was conducted over two seasons in 2021-2022, in the Nubaria area, EL-Beheira, Egypt, in sandy loamy soil. This experimental research was conducted to evaluate surface and sub-surface irrigation techniques on Valencia orange trees under different water stress conditions. In addition, the optimal irrigation technique was specified by comparing different irrigation techniques (surface and sub-surface) under different water provided conditions of estimated crop water requirements (ETc) (60-80-100% of ETc). The present research indicated that irrigation water for Valencia orange trees could be reduced by 20% without compromising their productivity. In addition, sub-surface irrigation techniques may allow increased production. As a result, sub-surface irrigation techniques below ETc-80% showed an improvement in water use efficiency (WUE), producing 4.04 and 3.96kg fruit per cubic meter of irrigation water in the first and second seasons, respectively. Our results showed that the use of sub-surface irrigation technique in combination with ETc-80% achieved a high economic return by increasing total production while raising WUE and water unit return (WUR) at the same time, which reached 16.15 and 15.86 Egyptian pounds per every cube meter of irrigation water in the first and second seasons, respectively, while 20% less water is consumed. Therefore, we recommend using the ETc-80%application in conjunction with the sub-surface irrigation technique for Valencia orange trees budded on sour orange rootstock so that we can obtain a high economic return while maintains rationalized irrigation water.

**Key words**: Orange, irrigation techniques, Surface irrigation, sub-surface irrigation, Evapotranspiration, Water Use Efficiency

## 1. Introduction

Citrus fruits are widely spread between the latitudes of roughly 30° N and 30° S, and constitute among the most significant world fruits **(Liu *et al.*, 2022; Xie *et al.*, 2023 and Youssef *et al.*, 2023a-b)**. It is one of the most widely grown and varied fruits in the world **(Trigueros *et al.*,**

**2020 and Jamshidi *et al.*, 2021)**. Nearly 158 million tons are produced annually worldwide at this point **(Chen *et al.*, 2022)**. It's classified as a crop that is vulnerable to water scarcity, which is a major cause of citrus orchard deterioration and low yield. Water lack in citrus crops inhibits growth and, in certain situations, quality, which can cause large financial losses according to **Panigrahi (2023)**. Citrus fruits are the uppermost fruit crop in Egypt. As compared to other fruit crops, they are quite important economically, especially for export. The citrus extent recorded 493,925 feddan, of which 440,210 were fruitful feddans yielding 4,503,226 tons (38.73 % of the total fruit trees production) with an average 10.20 tons per each feddan. There were 329,729 feddans total under orange trees, of which 302,064 were productive feddans yielding 3,173,430 tons on average (10.51 tons for each feddan). In contrast, there were 140,194 feddans under Valencia trees, of which 126,907 were productive feddans yielding 1,299,685 tons on average (10.42 tons for each feddan) according to **Agriculture Ministry (2022)**. The irrigation rate required for orange trees orchards under Egyptian circumstances has been shown in previous research to vary widely, sometimes reaching more than 8000 $m^3$ per each feddan / year **(Youssef *et al.*, 2023a-b)**. The overall pattern of those experiments demonstrated that raising the irrigation rate promoted a number of traits that increased growth, fruiting and economic yield **(Panigrahi, 2023)**.

Nile River provides Egypt annual with 55.50 billion $m^3$, but it is under tremendous pressure, particularly given the competitive environment with its neighbors. Thus, it is imperative to take multiple actions to be able to maintain the amount and water quality, while creating suitable plans to prevent jeopardizing future water supplies. Moreover, 38.25 billion $m^3$, or 68.97%, of Egypt's total water usage is utilized for agriculture **(Central Agency for Statistics and Public Mobilization, 2021)**. Therefore, the important thing is using irrigation water efficiently while lowering its amount without compromising yield, quantity or quality.

Since the 1980s, sub-surface irrigation has become popular as the uppermost effective irrigation technique. Sub-surface irrigation is an irrigation type applied directly to plant roots at low pressure, with several potential benefits. A well-managed sub-surface irrigation technique can minimize nutrient leaching and water evaporation from soil; maintain a uniform distribution of water, giving more control over the nutrients and irrigation water; reduce deep percolation losses, which can reduce pollution of ground water; and be more flexible to accommodate different soil kinds and plant rooting depths. Several studies have demonstrated that sub-surface irrigation, which use less water and generates comparable or higher agricultural yields than other irrigation techniques, can improve crop water use efficiency **(Robles *et al.*, 2016; Martínez-Gimeno *et al.*, 2018 and Franco *et al.*, 2022)**.

The aim of this investigate was to enhance the effectiveness of water utilization and maximize water use and identify the most efficient application for Valencia orange trees through the use of various irrigation techniques (surface and sub-surface) at varying water levels of estimated water requirements (60- 80-100%).

## 2. Material and Methods

The present paper deals with increasing the effectiveness of various irrigation techniques (surface and sub-surface) at varying water levels (60-80-100% of ETc) on growth also flowering and yielding of Valencia trees (*Citrus sinensis* Osbeck) rooted on sour orange (*Citrus aurantium* L.) rootstock. The investigation was conducted over the course of two consecutive seasons 2021 and 2022. Ten-year-old experimental trees planted at distance four by five meters were cultivated in private orchard with sandy-loam soil located in Nobaria region, El-Beheira, Egypt, using Nile River water under surface and sub-surface irrigation techniques. With the exception of the experimental applications, all trees in this research were subjected to the similar horticultural practices.

The investigational pattern for this study was a split plot arrangement in randomized complete block layout by three replicates and every replicate contained two trees. The $1^{st}$ factor (main plot) had three irrigation levels (60-80-100% of ETc) and the 2nd factor (sub-plot) included two irrigation techniques (surface and sub-surface). The Surface irrigation technique was built in drip lines technique (GR) with 50 cm emitters spacing. Moreover, 16 mm diameter laterals were used at 200 cm spacing. The irrigation technique was sub-surface drip irrigation, the same were practices used for laterals but they were buried at 25-30 cm depth from soil surface and the emitters were covered with geotextile to prevent clogging of the emitters throughout the experimental seasons.

Furthermore, as indicated in Tables 1&2, the investigated irrigation levels were based on various irrigation water rates, i.e., 4382, 3505, and 2629 $m^3$ per each feddan in 1st season, while were 4243, 3314, and 2546 $m^3$ per each feddan in 2nd season. The results were computed using the region's meteorological data (from the years 2020 and 2021) and a computer algorithm **(CROPWAT, 2012)**. Also, the estimated crop water requirement (ETc) was determined by multiplying citrus coefficient (Kc) by evapotranspiration reference (ETo). ETc = Kc x ETo.

**Table (1). The rate of reference crop evapotranspiration (ETo) determined with computer program (CROPWAT V.8.00) by climatic data under Nobaria region, EL- Beheira Governorate using FAO – Penman-Monteith equation by Ndulue and Ramanathan, 2021 method (season 2021)**

| Month | Jan. | Feb. | Mar. | Apr. | May. | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ETo-100% | 1.09 | 2.39 | 3.33 | 4.57 | 5.63 | 6.43 | 6.22 | 5.77 | 4.77 | 3.69 | 2.57 | 2.01 | |
| 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% | 0.66 | 1.53 | 2.23 | 3.29 | 4.39 | 5.21 | 4.98 | 5.60 | 2.19 | 1.88 | 1.64 | 1.17 | |
| W.R ($m^3$/fed./Day) | 2.79 | 6.42 | 9.37 | 13.82 | 18.44 | 21.87 | 20.90 | 23.51 | 9.22 | 7.90 | 6.91 | 4.90 | |
| W.R ($m^3$/ fed. Month) | 84 | 193 | 281 | 415 | 553 | 656 | 627 | 705 | 276 | 237 | 207 | 147 | 4382 |
| ETo-80% | 0.87 | 1.91 | 2.66 | 3.66 | 4.50 | 5.14 | 4.98 | 4.62 | 3.82 | 2.95 | 2.06 | 1.61 | |
| ETc-80% | 0.53 | 1.22 | 1.78 | 2.63 | 3.51 | 4.17 | 3.98 | 4.48 | 1.76 | 1.51 | 1.32 | 0.93 | |
| W.R ($m^3$/fed./Day) | 2.23 | 5.14 | 7.50 | 11.06 | 14.76 | 17.50 | 16.72 | 18.81 | 7.37 | 6.32 | 5.53 | 3.92 | |
| W.R ($m^3$/ fed. Month) | 67 | 154 | 225 | 332 | 443 | 525 | 502 | 564 | 221 | 190 | 166 | 118 | 3505 |
| ETo-60% | 0.65 | 1.43 | 2.00 | 2.74 | 3.38 | 3.86 | 3.73 | 3.46 | 2.86 | 2.21 | 1.54 | 1.21 | |
| ETc-60% | 0.40 | 0.92 | 1.34 | 1.97 | 2.63 | 3.12 | 2.99 | 3.36 | 1.32 | 1.13 | 0.99 | 0.70 | |
| W.R ($m^3$/fed./Day) | 1.68 | 3.85 | 5.62 | 8.29 | 11.07 | 13.12 | 12.54 | 14.10 | 5.53 | 4.74 | 4.14 | 2.94 | |
| W.R ($m^3$/ fed. Month) | 50 | 116 | 169 | 249 | 332 | 394 | 376 | 423 | 166 | 142 | 124 | 88 | 2629 |

**Table (2). The rate of reference crop evapotranspiration (ETo) determined with computer program (CROPWAT V.8.00) by climatic data under Nobaria region, EL- Beheira Governorate using FAO – Penman-Monteith equation by Ndulue and Ramanathan, 2021 method (season 2022)**

| Month | Jan. | Feb. | Mar. | Apr. | May. | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ETo-100% | 1.05 | 2.25 | 3.06 | 4.76 | 5.10 | 6.46 | 5.96 | 5.36 | 4.72 | 3.65 | 2.62 | 2.12 | |
| 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% | 0.64 | 1.44 | 2.05 | 3.43 | 3.98 | 5.23 | 4.77 | 5.20 | 2.17 | 1.86 | 1.68 | 1.23 | |
| W.R ($m^3$/fed./Day) | 2.69 | 6.05 | 8.61 | 14.39 | 16.71 | 21.98 | 20.03 | 21.84 | 9.12 | 7.82 | 7.05 | 5.16 | |
| W.R ($m^3$/ fed. Month) | 81 | 181 | 258 | 432 | 501 | 659 | 601 | 655 | 274 | 235 | 212 | 155 | 4243 |
| ETo-80% | 0.82 | 1.76 | 2.39 | 3.71 | 3.98 | 5.04 | 4.65 | 4.18 | 3.68 | 2.85 | 2.10 | 1.65 | |
| ETc-80% | 0.50 | 1.12 | 1.60 | 2.67 | 3.10 | 4.08 | 3.72 | 4.06 | 1.69 | 1.45 | 1.34 | 0.96 | |
| W.R ($m^3$/fed./Day) | 2.10 | 4.72 | 6.72 | 11.23 | 13.03 | 17.14 | 15.62 | 17.03 | 7.11 | 6.10 | 5.64 | 4.03 | |
| W.R ($m^3$/ fed. Month) | 63 | 142 | 201 | 337 | 391 | 514 | 469 | 511 | 213 | 183 | 169 | 121 | 3314 |
| ETo-60% | 0.63 | 1.35 | 1.84 | 2.86 | 3.06 | 3.88 | 3.58 | 3.22 | 2.83 | 2.19 | 1.57 | 1.27 | |
| ETc-60% | 0.38 | 0.86 | 1.23 | 2.06 | 2.39 | 3.14 | 2.86 | 3.12 | 1.30 | 1.12 | 1.01 | 0.74 | |
| W.R ($m^3$/fed./Day) | 1.61 | 3.63 | 5.17 | 8.64 | 10.02 | 13.19 | 12.02 | 13.10 | 5.47 | 4.69 | 4.23 | 3.10 | |
| W.R ($m^3$/ fed. Month) | 48 | 109 | 155 | 259 | 301 | 396 | 360 | 393 | 164 | 141 | 127 | 93 | 2546 |

The characteristics below were used for assess the therapies that were tried:

### 2.1. Tree canopy size and leaf area as well as fibrous roots length

Throughout both research seasons, tree high (m), canopy size ($m^3$) and circumference (m) were measured. The volume of tree canopy was got by the equation: canopy size ($m^3$) =1.33 * 0.50 * circumference (m) * 3.14 * 0.50 * tree high (m) according to **Turell (1965)**. Furthermore, in December of each season, the fibrous roots length of in 500 $cm^3$ of soil sample were measured at levels 0-30 and 30-60 cm from the soil surface. Also, leaf area ($cm^2$) was calculated using disks from the leaf as described by **Bremner and Taha (1966)**.

### 2.2. Flowering and fruit set characteristics

The data were collected using 16 twigs for every tree in the study (four on every side). The leafy & leafless inflorescences per twig were recorded and the percentages of leafy inflorescences were calculated using the equation: Leafy inflorescences (%) = (100* Leafy inflorescences) /Total inflorescences. Additionally, throughout full bloom, the number of flowers were computed and recorded for twigs. Simultaneously, the set fruitlets numbers for twig were computed and recorded following the fruit set stage. Also, the fruit set % was calculated using the equation: Fruit set (%) = (100* numbers of set fruitlet)/Numbers of total flowers.

### 2.3. Leaf photosynthetic, osmotic pressure, proline and stomata characteristics

The contents of photosynthetic pigment (mg/ 100 g of fresh weight) were assessed in fresh leaf blades in August as mentioned by on **Von-Wettestein (1957)**. Additionally, the content of proline in fresh weight of leaves (µmoles/g) was assessed using **Bates *et al.* (1973)** method, while cell sap osmotic pressure was assessed by **Gosov, 1960**. The total number of stomata and the number of opened stomata /$cm^2$ of leaf area were assessed by **Stino *et al.* (1974)** method then the opened stomata% was computed by the equation: Opened stomata = (100* numbers of opened stomata)/numbers of total stomata.

### 2.4. Physical properties of Fruit

For each replication, 32 fruits at random were chosen (16 fruits for each tree), and the studied characteristics under investigation were fruit weight (g) and juice volume.

### 2.5. Juice chemical constituents

The following criteria were taken into account: Juice ascorbic acid content (mg/100 ml) was got by 2, 6-dichlorophenol-indophenol titration (mg/100 ml) following **AOAC (2016)** method. The total soluble solids (TSS%) was measured by a hand-refractometer. Also, total acidity as citric acid (g/100 ml) was got by sodium hydroxide titration (0.1 N) in the phenolphthalin presence as indicator and the TSS/acid ratio was calculated.

### 2.6. Yield, water use efficiency and water unit return

The quantity of fruits harvested from each tree in April was counted, the total weight of the fruits from each tree was calculated and recorded in kilograms, and the estimated yield per each feddan—which was based on 210 trees per faddan spaced 4x5 meters apart—was calculated. The following formula was used to compute the water usage efficiency (WUE) values **(Jensen, 1983)**.

WUE= yield (kg per each feddan)/seasonal ETc ($m^3$ per each feddan).

Water unit return (WUR) was computed according to the equation: Water unit return = WUE × price of 1kg orange (4 EGP).

### 2.7. Statistical analysis

The experimental study design consisted of a split-plot design of a completely randomized block. The design contains three replicates, and each replicate contain two trees. The main plot had three degrees of water irrigation (60, 80, and 100% ETc), whereas the sub-plot had distinct irrigation techniques (surface and sub-surface). The obtained data were statistically analyzed using the variance method analysis according to **Snedecor and Cochran (1989)**. The means differences were calculated according to **Duncan (1955)**.

### 3. Results

Data in Table (3) summarize the water deficiency and two kinds of irrigation technique impact on the characteristics of morpho-phenological, starting with tree volume and leaf area also, leafy inflorescence%, that considered preliminary predictor for yield quantity. Moreover, fruit set% and fibrous roots length that were probably going to improve the tree fruits numbers.

Regarding, water stress rates, the highest tree canopy was 63.56 with ETc-100 and 60.68 with ETc-80 $m^3$ compared with ETc-60% that got the least value that recorded 44.95 $m^3$ under 1st season. The 2nd season also achieved the same trends. Leaf area parameter got the same direction for the volume of tree canopy. Leaf area greatest values were obtained by ETc-100 and 80%, which recorded 19.58 and 18.54 $cm^2$, respectively, while the minimal value was obtained by ETc-60% that recorded 15.21 $cm^2$ under 1st season. Also, the 2nd season achieved the same trends. Additionally, fibrous roots total length, leafy inflorescence%, fruit set and the tree fruits numbers characteristics got the same direction. Concerning, fibrous roots length (cm/500 in soil layer 0-30 cm), the biggest value was recorded by ETc-100% by a value reached to 195.37 cm. Also, the least value was 106.72 cm for ETc-60%. Moreover, 2nd season got similar pattern.

Regarding, irrigation techniques under 1st season, there were no statical differences among the irrigation techniques throughout experimental seasons for tree canopy and leaf area, while the sub-surface irrigation technique for the fibrous roots length of (cm/500 in soil layer 0-30 cm), leafy inflorescence%, fruit set and the fruits number for tree attained the best values. As contrary the total length of fibrous roots (cm/500 in soil layer 30-60 cm) had the greatest value with surface irrigation technique. Concerning the tree fruit number, they reached 363.68 with sub-surface irrigation technique as compared with surface irrigation technique which reached 343.95. The same trend was recorded in the second season.

Regarding the interaction under 1st season, the tree volume reached 64.82 $m^3$ for ETc-100% shared with the sub-surface irrigation technique, while the 2nd grade came from ETc-100% shared with the surface irrigation technique and ETc-80% with the sub-surface irrigation technique, which recorded 62.26 and 61.52 $m^3$. The leaf area, leafy inflorescence% and fruit set as well as the tree fruits number characteristics got the same direction to tree volume. Regarding, the best application for the fibrous roots length of (cm/500 in soil layer 0-30 cm) was ETc-100% with the surface irrigation technique, as it came in the 1st grade, recording 199.75 cm, while the application of ETc-100% with the surface irrigation and ETc-80% with the sub-surface irrigation techniques came in the 2nd grade by a value of 190.99 and 187.78 cm. In the 2nd season, a similar pattern was also seen. Furthermore, ETc-100% with the sub-surface irrigation technique achieved the best results for the total length of fibrous roots (cm/500 in soil layer 30-600 cm), coming in 1st grade by 193.49 cm. In 2nd grade was ETc-80% with the sub-surface irrigation technique and ETc-100% with the surface irrigation technique with values of 181.40 and 180.63 cm. A similar pattern was also seen in 2nd season.

Data show in Table (4) demonstrated how various irrigation techniques and rates of water deficit affected water relations metrics such leaf proline, chlorophyll a&b, osmotic pressure and percent of opened stomata.

Generally speaking, adding more water raised the characteristics of leaf chlorophyll a&b as well as the percentage of opened stomata. In contrast, increased water amount resulted in a reduction in leaf proline and osmotic pressure in cell sap; this trend held true in both seasons.

Regarding, the smallest significant result was 123.20 (mg/100 g of leaf F. W.) with ETc-60%, while the greatest values were 157.49 and 151.12 (mg/100 g of leaf F. W.) with ETc-100 or 80%. Regarding irrigation technique kinds, no statistically significant variations were found through the two types over the two distinct seasons. For the interaction through Water deficit amount and irrigation technique kinds, the 1st grade was ETc-100 or 80% shared with surface or sub-surface irrigation technique, which recorded 159.65, 155.33, 152.19 and 150.06 (mg/100 g of leaf F. W.) for ETc-100% with sub-surface, ETc-100% with surface, ETc-80% with sub-surface and ETc-80% with surface, respectively, while the 2nd grade was ETc-60% shared with surface or sub-surface irrigation technique, which recorded 125.42 and 120.99 (mg/100 g of leaf F. W.) for 60% with sub-surface and ETc-60% with surface; this came true in both seasons.

**Table (3). Water deficit amount and a few irrigations techniques impact on morpho-phenological (growth, fruit set and yield) characteristics of Valencia orange trees (2021-2022 seasons)**

| Treatments | Tree canopy size ($m^3$) | Leaf area ($cm^2$) | Fibrous roots length (cm) / 500 $cm^3$ soil in 0-30 cm soil layer | Fibrous roots length (cm) / 500 $cm^3$ soil in 30-60 cm soil layer | Leafy inflorescences % | Overall fruit set % per twig | Tree fruits number |
|---|---|---|---|---|---|---|---|
| | **First season (2021)** | | | | | | |
| **ETc-100%** | $63.56^{a}$ | $19.58^{a}$ | $195.37^{a}$ | $187.45^{a}$ | $70.21^{a}$ | $17.46^{a}$ | $432.86^{a}$ |
| **ETc-80%** | $60.68^{a}$ | $18.54^{a}$ | $178.27^{b}$ | $175.32^{b}$ | $65.90^{b}$ | $16.88^{b}$ | $408.26^{b}$ |
| **ETc-60%** | $44.95^{b}$ | $15.21^{b}$ | $106.72^{c}$ | $98.66^{c}$ | $46.21^{c}$ | $12.71^{c}$ | $220.32^{c}$ |
| **SIT** | $55.44^{a}$ | $17.50^{a}$ | $167.42^{a}$ | $149.38^{b}$ | $59.23^{b}$ | $15.42^{b}$ | $343.95^{b}$ |
| **Sub-SIT** | $57.35^{a}$ | $18.06^{a}$ | $152.82^{b}$ | $158.23^{a}$ | $62.32^{a}$ | $15.95^{a}$ | $363.68^{a}$ |
| **ETc-100%×SIT** | $62.29^{b}$ | $19.26^{a}$ | $199.75^{a}$ | $181.40^{b}$ | $68.78^{b}$ | $17.30^{ab}$ | $425.84^{b}$ |
| **ETc-100%×Sub-SIT** | $64.82^{a}$ | $19.91^{a}$ | $190.99^{b}$ | $193.49^{a}$ | $71.64^{a}$ | $17.63^{a}$ | $439.88^{a}$ |
| **ETc-80%×SIT** | $59.85^{c}$ | $18.21^{a}$ | $187.78^{b}$ | $170.01^{c}$ | $64.82^{c}$ | $16.85^{b}$ | $396.97^{c}$ |
| **ETc-80%×Sub-SIT** | $61.52^{b}$ | $18.87^{a}$ | $168.75^{c}$ | $180.63^{b}$ | $66.98^{b}$ | $16.91^{b}$ | $419.55^{b}$ |
| **ETc-60%×SIT** | $44.19^{d}$ | $15.04^{b}$ | $114.73^{d}$ | $96.74^{d}$ | $44.09^{e}$ | $12.10^{d}$ | $209.03^{e}$ |
| **ETc-60%×Sub-SIT** | $45.71^{d}$ | $15.38^{b}$ | $98.71^{e}$ | $100.58^{d}$ | $48.34^{d}$ | $13.32^{c}$ | $231.61^{d}$ |
| | **Second season (2022)** | | | | | | |
| **ETc-100%** | $63.97^{a}$ | $19.82^{a}$ | $187.50^{a}$ | $190.30^{a}$ | $70.48^{a}$ | $16.50^{a}$ | $419.39^{a}$ |
| **ETc-80%** | $61.47^{a}$ | $19.25^{a}$ | $174.84^{b}$ | $173.13^{b}$ | $67.01^{b}$ | $15.86^{b}$ | $378.12^{b}$ |
| **ETc-60%** | $45.42^{b}$ | $15.48^{b}$ | $101.52^{c}$ | $100.73^{c}$ | $44.56^{c}$ | $12.19^{c}$ | $215.28^{c}$ |
| **SIT** | $56.03^{a}$ | $17.97^{a}$ | $158.27^{a}$ | $149.83^{b}$ | $59.59^{b}$ | $14.60^{b}$ | $325.20^{b}$ |
| **Sub-SIT** | $57.88^{a}$ | $18.40^{a}$ | $150.97^{b}$ | $159.61^{a}$ | $61.78^{a}$ | $15.09^{a}$ | $349.99^{a}$ |
| **ETc-100%×SIT** | $62.93^{b}$ | $19.68^{a}$ | $191.81^{a}$ | $186.52^{b}$ | $69.26^{b}$ | $16.21^{b}$ | $406.08^{b}$ |
| **ETc-100%×Sub-SIT** | $65.01^{a}$ | $19.95^{a}$ | $183.20^{b}$ | $194.08^{a}$ | $71.70^{a}$ | $16.80^{a}$ | $432.71^{a}$ |
| **ETc-80%×SIT** | $60.74^{c}$ | $18.91^{a}$ | $178.10^{bc}$ | $167.35^{d}$ | $66.08^{c}$ | $15.93^{c}$ | $362.85^{c}$ |
| **ETc-80%×Sub-SIT** | $62.21^{b}$ | $19.58^{a}$ | $171.58^{c}$ | $178.92^{c}$ | $67.95^{b}$ | $15.78^{c}$ | $393.39^{b}$ |
| **ETc-60%×SIT** | $44.41^{d}$ | $15.31^{b}$ | $104.90^{d}$ | $95.62^{e}$ | $43.43^{e}$ | $11.68^{e}$ | $206.67^{e}$ |
| **ETc-60%×Sub-SIT** | $46.44^{d}$ | $15.66^{b}$ | $98.13^{d}$ | $105.84^{e}$ | $45.69^{d}$ | $12.69^{d}$ | $223.89^{d}$ |

ETc = evapotranspiration, SIT = Surface irrigation technique and Sub-SIT = Sub-surface irrigation technique.

On the contrary, the least value for leaf proline contents was got by ETc-100% application with a value of 31.03 (µmoles/g), while the uppermost significant value was recorded by ETc-60% application with a value of 96.93 (µmoles/g). As for the irrigation techniques, no statistically significant variations were found among the irrigation techniques throughout the two seasons of the experiment.

Regarding, the interaction through water deficit amount and irrigation techniques, the proline least value was obtained by ETc-100% and sub-surface irrigation technique with a value of 28.44 µmoles/g, while the greatest value was 98.86 (µmoles/g) and was obtained by ETc-60% application with surface irrigation technique. The same pattern was observed in the 2nd season.

**Table (4). Water deficit amount and a few irrigations techniques impact on leaf photosynthetic pigments and proline contents, cell sap osmotic pressure and opened stomata percentage of Valencia orange leaves (2021-2022 seasons)**

| Treatments | 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 (µmoles/ g of leaf F. W.) | Leaf cell sap osmotic pressure (atm.) | Opened stomata % |
|---|---|---|---|---|---|
| | First season (2021) | | | | |
| ETc-100% | 157.49ᵃ | 59.03ᵃ | 31.03ᶜ | 18.24ᶜ | 89.09ᵃ |
| ETc-80% | 151.12ᵃ | 56.82ᵃ | 39.05ᵇ | 19.11 ᵇ | 87.19ᵃ |
| ETc-60% | 123.20ᵇ | 46.02ᵇ | 96.93ᵃ | 22.75 ᵃ | 75.71ᵇ |
| SIT | 142.13ᵃ | 53.33ᵃ | 57.75ᵃ | 20.18 ᵃ | 83.40ᵃ |
| Sub-SIT | 145.75ᵃ | 54.58ᵃ | 53.59ᵃ | 19.88 ᵃ | 84.59ᵃ |
| ETc-100%×SIT | 155.33ᵃ | 58.37ᵃ | 33.61ᵇ | 18.35 ᵇ | 88.59ᵃ |
| ETc-100%×Sub-SIT | 159.65ᵃ | 59.68ᵃ | 28.44ᵇ | 18.13 ᵇ | 89.60ᵃ |
| ETc-80%×SIT | 150.06ᵃ | 55.97ᵃ | 40.77ᵇ | 19.31 ᵇ | 86.31ᵃ |
| ETc-80%×Sub-SIT | 152.19ᵃ | 57.67ᵃ | 37.34ᵇ | 18.90 ᵇ | 88.07ᵃ |
| ETc-60%×SIT | 120.99ᵇ | 45.66ᵇ | 98.86ᵃ | 22.87 ᵃ | 75.31ᵇ |
| ETc-60%×Sub-SIT | 125.42ᵇ | 46.38ᵇ | 95.00ᵃ | 22.62 ᵃ | 76.11ᵇ |
| | Second season (2022) | | | | |
| ETc-100% | 155.67ᵃ | 58.88ᵃ | 29.73ᶜ | 18.36ᵇ | 89.45ᵃ |
| ETc-80% | 149.59ᵇ | 56.24ᵃ | 38.70ᵇ | 18.95ᵇ | 87.91ᵃ |
| ETc-60% | 124.63ᶜ | 45.94ᵇ | 89.47ᵃ | 22.77ᵃ | 76.34ᵇ |
| SIT | 140.95ᵇ | 52.89ᵃ | 56.98ᵃ | 20.21ᵃ | 84.03ᵃ |
| Sub-SIT | 145.64ᵃ | 54.48ᵃ | 48.28ᵃ | 19.85ᵃ | 85.10ᵃ |
| ETc-100%×SIT | 152.79ᵇ | 58.33ᵃ | 33.03ᵇ | 18.58ᵇ | 89.10ᵃ |
| ETc-100%×Sub-SIT | 158.54ᵃ | 59.43ᵃ | 26.43ᵇ | 18.13ᵇ | 89.80ᵃ |
| ETc-80%×SIT | 147.39ᵇ | 55.17ᵃ | 40.99ᵇ | 19.12ᵇ | 87.24ᵃ |
| ETc-80%×Sub-SIT | 151.79ᵇ | 57.32ᵃ | 36.42ᵇ | 18.79ᵇ | 88.58ᵃ |
| ETc-60%×SIT | 122.68ᶜ | 45.18ᵇ | 96.93ᵃ | 22.93ᵃ | 75.74ᵇ |
| ETc-60%×Sub-SIT | 126.59ᶜ | 46.70ᵇ | 82.00ᵃ | 22.62ᵃ | 76.94ᵇ |

ETc = evapotranspiration, SIT = Surface irrigation technique and Sub-SIT = Sub-surface irrigation technique.

While irrigation techniques had no influence on the majority of metrics, the data presented in Table (5) clearly demonstrated the ETc impact on all chemical and physical fruit characteristics with substantial variations in both seasons. Regarding fruit weight, 167.86 and 165.20g with ETc-100 and 80%, respectively, were the biggest significant values, whereas 151.79g with ETc-60% was the smallest significant number. Regarding irrigation technique types, they had no impact on any of the fruit's physical or chemical characteristics throughout the study. The uppermost important application was ETc-100% paired with sub-surface irrigation, which got 169.62 g, according to the interaction through water shortage rates and irrigation technique kinds.

**Table (5). Water deficit amount and a few irrigations techniques impact on fruit weight, juice volume, juice TSS, juice acidity, TSS/acid ratio and ascorbic acid of Valencia orange fruits (2021-2022 seasons)**

| Treatments | 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%** | 167.86$^a$ | 95.13$^a$ | 9.09$^b$ | 0.99$^a$ | 9.21$^b$ | 35.17$^b$ |
| **ETc-80%** | 165.20$^a$ | 93.52$^a$ | 9.43$^b$ | 0.96$^a$ | 9.78$^b$ | 35.59$^b$ |
| **ETc-60%** | 151.79$^b$ | 86.20$^b$ | 10.79$^a$ | 0.81$^b$ | 13.32$^a$ | 39.02$^a$ |
| **SIT** | 160.37$^a$ | 90.88$^a$ | 9.87$^a$ | 0.91$^a$ | 10.95$^a$ | 36.85$^a$ |
| **Sub-SIT** | 162.74$^a$ | 92.23$^a$ | 9.67$^a$ | 0.93$^a$ | 10.59$^a$ | 36.34$^a$ |
| **ETc-100%×SIT** | 166.60$^a$ | 94.13$^a$ | 9.18$^b$ | 0.98$^a$ | 9.37$^b$ | 35.30$^b$ |
| **ETc-100%×Sub-SIT** | 169.62$^a$ | 96.13$^a$ | 9.01$^b$ | 1.00$^a$ | 9.05$^b$ | 35.04$^b$ |
| **ETc-80%×SIT** | 164.63$^a$ | 93.30$^a$ | 9.59$^b$ | 0.96$^a$ | 10.02$^b$ | 35.79$^b$ |
| **ETc-80%×Sub-SIT** | 165.41$^a$ | 93.74$^a$ | 9.27$^b$ | 0.97$^a$ | 9.55$^b$ | 35.39$^b$ |
| **ETc-60%×SIT** | 150.38$^b$ | 85.22$^b$ | 10.86$^a$ | 0.81$^b$ | 13.46$^a$ | 39.47$^a$ |
| **ETc-60%×Sub-SIT** | 153.20$^b$ | 86.82$^b$ | 10.72$^a$ | 0.81$^b$ | 13.18$^a$ | 38.58$^a$ |
| | **Second season (2022)** | | | | | |
| **ETc-100%** | 169.11$^a$ | 95.84$^a$ | 9.17$^b$ | 0.99$^a$ | 9.26$^b$ | 35.62$^b$ |
| **ETc-80%** | 165.39$^a$ | 93.73$^a$ | 9.46$^b$ | 0.96$^a$ | 9.82$^b$ | 36.33$^b$ |
| **ETc-60%** | 152.68$^b$ | 86.53$^b$ | 10.82$^a$ | 0.82$^b$ | 13.22$^a$ | 39.61$^a$ |
| **SIT** | 161.34$^a$ | 91.44$^a$ | 9.93$^a$ | 0.91$^a$ | 11.01$^a$ | 37.46$^a$ |
| **Sub-SIT** | 163.45$^a$ | 92.63$^a$ | 9.71$^a$ | 0.94$^a$ | 10.52$^a$ | 36.91$^a$ |
| **ETc-100%×SIT** | 168.50$^a$ | 95.49$^a$ | 9.28$^b$ | 0.98$^a$ | 9.46$^b$ | 36.05$^b$ |
| **ETc-100%×Sub-SIT** | 169.72$^a$ | 96.18$^a$ | 9.06$^b$ | 1.00$^a$ | 9.06$^b$ | 35.18$^b$ |
| **ETc-80%×SIT** | 163.83$^a$ | 92.84$^a$ | 9.60$^b$ | 0.95$^a$ | 10.07$^b$ | 36.45$^b$ |
| **ETc-80%×Sub-SIT** | 166.96$^a$ | 94.62$^a$ | 9.32$^b$ | 0.97$^a$ | 9.57$^b$ | 36.22$^b$ |
| **ETc-60%×SIT** | 151.71$^b$ | 85.97$^b$ | 10.90$^a$ | 0.81$^b$ | 13.51$^a$ | 39.89$^a$ |
| **ETc-60%×Sub-SIT** | 153.66$^b$ | 87.08$^b$ | 10.75$^a$ | 0.83$^b$ | 12.92$^a$ | 39.33$^a$ |

ETc = evapotranspiration, SIT = Surface irrigation technique and Sub-SIT = Sub-surface irrigation technique.

The advantages of this experimental investigation are outlined in Table (6) using ETc-100% have resulted in 15.26 tons of hypothetic yield per each feddan (ton / feddan), the uppermost significant enhancement in hypothetic yield per each feddan (ton / feddan), whereas ETc-60% application only recorded 7.03 tons of feddan. Regarding the different kinds of irrigation techniques, sub-surface irrigation generated 12.56 tons of hypothetic yield per each feddan (ton/ feddan), which recorded the largest significant increase in hypothetic yield per each feddan, while surface irrigation produced only 11.73 tons. This (ton / feddan).

**Table (6). Water deficit amount and a few irrigations techniques impact on tree yield, hypothetic yield per each feddan, water use efficiency and water unit return of Valencia orange trees (2021-2022 seasons)**

| Treatments | Tree yield (kg) | Hypothetic yield per each feddan (ton) | Water use efficiency (kg fruit /$m^3$ water) | Water unit return (EGP/$m^3$ of water) |
|---|---|---|---|---|
| | **First season (2021)** | | | |
| **ETc-100%** | 72.67[a] | 15.26[a] | 3.48[b] | 13.93[b] |
| **ETc-80%** | 67.38[b] | 14.15[b] | 4.04[a] | 16.15[a] |
| **ETc-60%** | 33.46[c] | 7.03[c] | 2.67[c] | 10.69[c] |
| **SIT** | 55.84[b] | 11.73[b] | 3.27[b] | 13.09[b] |
| **Sub-SIT** | 59.83[a] | 12.56[a] | 3.52[a] | 14.09[a] |
| **ETc-100%×SIT** | 70.73[b] | 14.85[b] | 3.39[d] | 13.56[d] |
| **ETc-100%×Sub-SIT** | 74.61[a] | 15.67[a] | 3.58[c] | 14.30[c] |
| **ETc-80%×SIT** | 65.35[c] | 13.72[c] | 3.92[b] | 15.66[b] |
| **ETc-80%×Sub-SIT** | 69.40[b] | 14.57[b] | 4.16[a] | 16.63[a] |
| **ETc-60%×SIT** | 31.43[e] | 6.60[e] | 2.51[f] | 10.04[f] |
| **ETc-60%×Sub-SIT** | 35.48[d] | 7.45[d] | 2.83[e] | 11.34[e] |
| | **Second season (2022)** | | | |
| **ETc-100%** | 70.93[a] | 14.90[a] | 3.51[b] | 14.04[b] |
| **ETc-80%** | 62.56[b] | 13.14[b] | 3.96[a] | 15.86[a] |
| **ETc-60%** | 32.88[c] | 6.90[c] | 2.71[c] | 10.85[c] |
| **SIT** | 53.08[b] | 11.15[b] | 3.25[b] | 12.99[b] |
| **Sub-SIT** | 57.84[a] | 12.15[a] | 3.54[a] | 14.18[a] |
| **ETc-100%×SIT** | 68.42[b] | 14.37 [b] | 3.39[c] | 13.55[d] |
| **ETc-100%×Sub-SIT** | 73.44[a] | 15.42[a] | 3.63[b] | 14.54[c] |
| **ETc-80%×SIT** | 59.45[c] | 12.48[c] | 3.77[b] | 15.07[b] |
| **ETc-80%×Sub-SIT** | 65.68[b] | 13.79[b] | 4.16[a] | 16.65[a] |
| **ETc-60%×SIT** | 31.36[e] | 6.58[e] | 2.59[e] | 10.35[f] |
| **ETc-60%×Sub-SIT** | 34.40[d] | 7.22[d] | 2.84[d] | 11.35[e] |

ETc = evapotranspiration, SIT = Surface irrigation technique and Sub-SIT = Sub-surface irrigation technique.

Additionally, the interaction through water deficit amount and irrigation technique kinds showed that ETc-100% shared with sub-surface irrigation technique resulted in 15.67 tons / feddan, while ETc-100% shared with surface irrigation technique which produced 14.85 tons / feddan, which means that sub-surface irrigation technique increased yield by 5.5 % by using the same amount of irrigation water. This pattern was factual in both seasons.

To economically translate these findings into a monetary output for the water unit, a more thorough evaluation of these results is necessary. The results generally indicate that the sub-surface irrigation technique is superior in WUE and WUR, have the interaction explained so that the sub-surface irrigation technique shared with ETc-80%, which recorded 4.16 for WUE and 16.63 EGP for WUR, was better than the ETc-100% shared with surface irrigation, which got 3.39 for WUE and 13.56 for WUR. The 2nd season further supported this tendency.

To summarizes, based on the results obtained, it can be said that the sub-surface irrigation technique achieved the goals set forth for citrus in the Sustainable Agricultural Development Strategy toward 2030 (Sustainable Agricultural Development Strategy toward 2030) by reducing the rate of water used to irrigate citrus orchards by 20 to 40% while increasing the water unit return (WUR) to reach 10.69 EGP / one cubic meter of irrigation water at 40% saved water and could reach 16.15 EGP / one cubic meter of irrigation water at 20% saved water.

## 4. Discussion

Table (3) displays water stress impact and specific irrigation techniques on morpho-phenological characteristics, starting with tree volume and leaf area as well as leafy inflorescence%, which are considered preliminary predictor for the quantity of yield. Moreover, fruit set% and fibrous roots length that were probably responsible of improving the tree fruits numbers. In this concern, it can be seen that sub-surface irrigation technique got the best values, which cause increasing water use efficiency by reducing the soil surface evaporation and reducing runoff as well as the possibility of directly wetting root spreading areas, thus further reducing unnecessary irrigation water losses. Near the end of the cropping season, the innate capacity to apply small irrigation amounts can enable more water-efficient decisions to be made regarding irrigation events, according to **Robles *et al.* (2016), Martínez-Gimeno *et al.* (2018) and Franco *et al.* (2022). Youssef *et al.* (2023a-b)** found that increasing ETo rates generally improved the aforementioned characteristics. This improvement may have been caused by an increase in availability of soil moisture, which led to soil surface moderate evaporation, low temperature of soil, N, P, and K availability. The findings pertaining to water provide conservation aligned with the findings reported by **Youssef *et al.* (2023a-b)**.

Data in Table (4) obviously reveal the influence of water shortage rates and irrigation technique types along water relations measures such as leaf chlorophyll a&b, proline, osmotic pressure, opened stomata also leaf bound water. Once the water amount was rose, the characteristics of leaf chlorophyll a&b and opened stomata increased. On the opposite, when water quantity rose, proline, osmotic pressure and bound water content dropped; this was factual in both seasons. In terms of water provide levels, the results show that water levels have a major impact on leaf photosynthetic pigments. The results obtained are consistent with those published by **Trigueros *et al.* (2021); Panigrahi (2023), Youssef *et al.* (2023a-b) and Xie *et al.* (2023)**.

Results in Table (5) show the ETc applications impact on all chemical and physical characteristics of fruit with considerable differences in both seasons, while irrigation techniques did not affect most of the characteristics. Moreover, the results of the present investigation for water provide confirmed with 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.* (2023a-b)**.

The data disclosed in Table (6) cause of high-water irrigation provide, which rise soil moisture availability agreeing with **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.* (2023a-b)**. Furthermore, increasing soil moisture may have increased N, K, and P availability and absorption in the root zone, as well as enhanced photosynthetic activities, carbohydrate generation, and yield. The current study found that water levels had a substantial impact on yield characteristics. The foregoing results agree with the findings of **Tie *et al.* (2022); Panigrahi (2023) and Youssef *et al.* (2023a-b)**. Moreover, sub-surface irrigation technique increased yield as a result of increasing water use efficiency by reducing soil evaporation, runoff and the possibility of directly wetting root spreading areas, thus further reducing unnecessary irrigation water losses, which showed increasing in fruits weight and their number per tree according to **Robles *et al.* (2016); Martínez-Gimeno *et al.* (2018) and Franco *et al.* (2022)**.

## 5. Conclusions

Conclusively, it could be mentioned on the basis of the obtained results that using sub-surface irrigation techniques along with ETc-80% had a great economic return and obvious impact in terms of rising yield, water use efficiency, and water unit return (WUR), which reached 16.63 EGP / one cubic meter of irrigation water and consequently required 20% less of water irrigation. To get a good economic return, we thus advise growers of Valencia oranges budded on sour orange rootstock to treat their trees at ETc-80% in conjunction with subsurface watering techniques.

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