

Influence of Irrigation Levels on Morphological Attributes and Yield of Tomato under Current and Climate Change Conditions

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ABSTRACT

Water shortage consider on of the main threats facing the agriculture, mainly in the Mediterranean area. So that there is a great need to apply new methods to water resource management. The crop models are used to achieve this objective. Tomato is a significant vegetable crop globally and represent an important part of horticultural production with 180 million tons produced on over five million hectares even though few studies have validated the AquaCrop model, especially in Egypt. This study was conducted in a protected cultivation experimental farm, Agricultural Research Center (ARC), Dokki, Giza, Egypt during the winter seasons of 2019/2020 and 2020/2021. Different irrigation levels (IL): 55%, 70%, 85%, 100%, and 115% of evapotranspiration (Eto) were applied on tomato. Plant growth parameters, relative chlorophyll content (SPAD), yield, fruit quality and plant nutrients (NPK) were recorded at both seasons. Also, the aforementioned irrigation levels were used to validate the AquaCrop model on different climate change scenarios on tomato productivity in 2050 and 2100. The findings revealed that the highest plant growth parameters were obtained in 85% and 100% Eto as compared to all treatments at both seasons. In contrast, the 55% of Eto obtained the lowest values of all plant growth parameters. The number of fruits/plant, early yield, and total yield of 100% Eto were ranked secondly. Fruits quality was significantly affected by the tested ILs. The highest values of TSS, firmness and vit C of tomato fruits were obtained by 55% followed by 70% Eto. The lowest proline content was recorded at 115% of Eto in both seasons. The content of proline in plants of 70% Eto ranked secondly after 55% of Eto in both seasons. The results of AquaCrop model (Version 7.0) revealed that the crop productivity decreased by 4% and 33% of RCP4.5 and RCP8.5 scenarios, respectively, of the years 2050, 14% and 44% for the same scenarios, respectively, of the year 2100.

Keywords: AquaCrop model, climate change scenario, crop simulation model, irrigation requirements, *Solanum Lycopersicon*, tomato.

INTRODUCTION

Agricultural sustainability is limited by various circumstances, such as decreasing crop yield, nutrient depletion, climate change, and limited water supply (Fróna et al., 2019). The global food and nutritional security is faced with great challenges, such as climate change. Important fluctuations in the meteorological factors, such as precipitation, temperature, humidity, and radiation (Malhi et al., 2021). Agricultural sector represents a major water user in nearly every country. Due to its availability (Patanè et al., 2011) and quality (Khapte et al., 2019; Wu

et al., 2023) in the Mediterranean region, water is also a limiting factor. The irrigation water contributes around 75% of the global water resources (Qadir et al. 2007). Such a fraction is unsustainable in light of the rising competition for resources and the requirement for higher agricultural productivity to provide food security. Thus, the water security can be validated by increasing the agricultural water use efficiency (Rana, et al., 2022).

Irrigation is a major factor in Egypt's agricultural production. Insufficient water supplies for irrigation in several agricultural areas of Egypt over the past ten years have become the

rule, rather than the exception. (Hegab, et al., 2019). As a result, increasing the food production with the lowest water use is a great challenge that all sectors of agriculture must overcome by enhancing crop water productivity, which will either produce similar food quantity with less water resources or more food with the same resources (Ding, et al., 2021).

In the near future, food production will face severe risks from water shortage, particularly in arid and semi-arid regions where water considers primary constraint on the growth of arable land. As a result, it is highly desirable to manage water in a way that maximizes productivity per unit of water used by plants. (Srivastav, et al., 2021). Consequently, it is important to upgrade irrigation management in these places, so that the emphasis is placed on maximizing production per unit of water consumed, or water productivity (Eissa et al., 2018; Dehghanisani, et al., 2021). Therefore, it is crucial to figure out how to maintain the best agricultural output when there is a water shortage. This has recently encouraged researchers to develop novel irrigation systems, technologies, and techniques to increase water use effectiveness. One of the most promising ways to increase water use efficacy for strategic crops is the use of set up deficit irrigation designs (Abdalhi et al., 2020). The adoption of contemporary irrigation methods, which increase the water application efficiency of plants, is a second technique. The irrigation management of the major crops may be aided by assessing the water consumption for main crops in the dry region of Egypt using various irrigation techniques (Moursy et al., 2023).

By taking into consideration crop growth pattern and productivity response to meteorological factors and irrigation activities, crop models are a very useful tool for improving irrigation practices. Many parameters and many models have been constructed using physical or semiempirical equations based on simple or sophisticated systems (Jones et al., 2003; Raes, et al., 2012; Vanuytrecht, et al., 2014; Battude, et al., 2016). The AquaCrop model represents one of the models now in use. FAO created it as a crop growth model to examine the impacts of agricultural management, environment, and to address food security (Foster et al., 2017). For herbaceous crops, AquaCrop simulates yield response to water, making it especially useful for the crop production scenarios where water is a limited element (Kamanga, 2020). A wide

range of users, including farmers, agricultural consultants, and policymakers, can easily utilize AquaCrop as a modeling tool. The model is reliant on an array of knowledge that the user provides to it (Kephe et al., 2021). Also García-Vila and Fereres (2012) reported that AquaCrop is the pinnacle of accuracy, simplicity, and resilience in cropping. Previous research has demonstrated that this model can reasonably forecast the production of a variety of crops, as they react to different degrees of irrigation and under water shortage circumstances, such as; sugar beet, wheat barley, potato, maize, sun-flower, oats, cabbage, sorghum, and tomato (Andarzian, et al., 2011; Stricevic, et al., 2011; Abedinpour, et al., 2012; Ahmadi, et al., 2015; Linker, et al., 2016). Research on climate change and food production has also been utilized AquaCrop (Voloudakis, et al., 2015). Many researchers reported that the crop model will plan the optimal watering policies to be followed in the future with tomato crop (Katerji, et al., 2013; Saadi, et al., 2015; Linker and Sylaios, 2016).

Tomato (*Solanum lycopersicum*) is considered is one of main and widely cultivated vegetable crops globally. Tomato production ranks second in the world after the potato in terms of vegetable production. Tomato is consumed either fresh, cooked or processed into different products. Also, tomato fruits are one of the main sources of vitamins C, E and carotenoids i.e beta-carotene and lycopene (Ishiwu, et al., 2014). In Egypt, tomatoes are considered one of the most cultivated vegetable crops either in the old or in the new land. It is cultivated in open land and greenhouse environment (Siam and Abdelhakim, 2018; Wu et al., 2023). It is grown in six seasons either in an open field or under protected cultivation. Its total annual area is approximately 4% of area cultivated in total, and 40% of the whole vegetable cultivated area in Egypt. The total cultivated area in Egypt of tomato was 356896 feddan with a total production of 6389295 tons with an average of 17 tons per feddan (Ministry of Agriculture and Land Reclamation, 2021).

From all the afore-mentioned details, the aim of the research was to evaluate the impact of different irrigation regimes on plant growth parameters, quality and yield of tomato. Moreover, validating Aquacrop model to predict how climate change will affect tomato productivity under Egyptian conditions.

MATERIAL AND METHODS

Study site and plant material

This experiment was carried out in the protected cultivation experimental farm, (ARC), Dokki, Giza, Egypt (the altitude and longitude are 18 meters above sea level, 30°.02'44" N and 31°.12'17" E) during the winter seasons of 2019/2020 and 2020/2021.

The plastic greenhouse dimensions were 9 m in width, 40 m long, and 3.2 m in height. It was divided into five wide ridges with 1m width each, and the distance between the two rows in the same ridge was 0.6 m with 0.3 m space between the plants. The plot area was 12 m². Tomato transplants cv. Agyad 7 Hybrid were transplanted on the 20th and 22nd of October 2019 and 2020, respectively. The experimental soil was clay loam (Table 1 shows the physico-chemical analysis of experimental soil pre planting).

Five irrigation levels (IL) (55%, 70%, 85%, 100%, and 115%) of evapotranspiration (ET_o) were applied. A flow meter was fixed for each irrigation regime; the number of replicates was 3 at each treatment. The experiment was watered by drippers of 4 L·h⁻¹ capacity, the fertilizers were applied in form of nutrient solution injected into the irrigation system according to irrigation time. The chemical analysis of irrigation water is shown in Table 2. All the agricultural practices for tomato were performed as mentioned by the Ministry of Agriculture and Land Reclamation (MALR), Egypt.

Experimental design and treatments

The treatments contained five irrigation levels, i.e., 55%, 70%, 85%, 100%, and 115% of crop evapotranspiration (ET_o). The number of replicates were three in each season and the experimental design was Randomized Complete Block Design (RCBD). Total amount of irrigation

water was calculated according to the methods described by the FAO Penman-Monteith (Allen et al., 1998; Isikwue et al., 2014). ET_o was correctly predicted in a broad range of climate and site conditions by this method. Calculations of irrigation levels were done as follows:

The potential evapotranspiration (ET_o) was calculated first: (1)

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

where: ET_o = reference evapotranspiration (mm day⁻¹);

R_n = net radiation at the crop surface (MJ m⁻² day⁻¹);

G = soil heat flux density (MJ m⁻² day⁻¹);

T = mean daily air temperature at 2 meters height (°C);

U_2 = wind speed at 2 meters height (m s⁻¹);

e_s = saturation vapor pressure (k Pa);

e_a = actual vapor pressure (k Pa);

$e_s - e_a$ = saturation vapor pressure deficit (k Pa);

Δ = slope vapor pressure curve (k Pa °C⁻¹);

γ = psychrometric constant (k Pa °C⁻¹).

According to (FAO 2012), the 2nd step was to determine crop water consumptive use (ET_c), which was calculated by multiplying the reference crop evapotranspiration, ET_o , by a crop coefficient, K_c :

$$ET_c = ET_o * K_c \dots\dots \text{mm / day} \quad (2)$$

where: ET_c crop evapotranspiration [mm day⁻¹], K_c crop coefficient [dimensionless] and ET_o reference crop evapotranspiration [mm day⁻¹].

The irrigation requirements (IR) for each treatment were calculated as follows:

Table 1. Physico-chemical analysis properties of pre-planting soil

| Physical properties | | | | | | | | | |
|---------------------|--------------------------------------|----------------------------------------|----------------------------------------|---------------------------------------|--------------------------------------|-----------------------------------------------------|-----------------------------------------------------|---------------------------------------|-----------------------------------------------------|
| Sand % | Silt % | Clay % | Texture al class | SP % | FC % | WP % | BD Mg m ⁻³ | CaCO ₃ % | OM % |
| 15.9 | 31.8 | 52.2 | Clay loam | 87.9 | 62.2 | 27.9 | 1.37 | 5.62 | 0.83 |
| Chemical properties | | | | | | | | | |
| pH (1:2.5) | EC _e , dS m ⁻¹ | Ca ²⁺ mmolc L ⁻¹ | Mg ²⁺ mmolc L ⁻¹ | Na ⁺ mmolc L ⁻¹ | K ⁺ mmolc L ⁻¹ | CO ₃ ²⁻ mmolc L ⁻¹ | HCO ₃ ⁻ mmolc L ⁻¹ | Cl ⁻ mmolc L ⁻¹ | SO ₄ ²⁻ mmolc L ⁻¹ |
| 7.60 | 2.70 | 10.8 | 7.75 | 11.4 | 5.97 | n.d.* | 7.05 | 12.9 | 13.9 |

Table 2. Chemical analysis of irrigation water

| pH | EC | Soluble cations (meq/l) | | | | Soluble anions (meq/l) | | | |
|-----|------|-------------------------|------------------|-----------------|----------------|------------------------------|-------------------------------|-----------------|------------------------------|
| | dS/m | Ca ⁺⁺ | Mg ⁺⁺ | Na ⁺ | K ⁺ | CO ₃ ⁻ | HCO ₃ ⁻ | Cl ⁻ | SO ₄ ⁻ |
| 7.3 | 0.45 | 1.6 | 1.1 | 0.95 | 0.16 | 0 | 0 | 0.8 | 0.39 |

$$IR = (ET_o \cdot K_c) \cdot (LR) \cdot 4.2 / Ea \quad (3)$$

(m³/feddan/day)

where: *LR* % = Leaching requirement percentage
Ea = efficiency of the irrigation system (assumed to be 85% of total applied water).

Leaching requirements were calculated based on Allen et al., (1998). According to FAO (1982), the water use efficiency (WUE) is the ratio of crop productivity (*y*) to the total amount of irrigation water used in the field throughout the growing season (*IR*),

$$WUE \text{ (kg/m}^3\text{)} = Y \text{ (kg)}/IR \text{ (m}^3\text{)} \quad (1)$$

From all of the pervious data the irrigation quantities for each treatment at this experiment throughout the Dokki site at the two growing seasons are shown in Table 3.

Measurements

The climatic data concerning weather parameters, such as (max. and minim. temperatures, average relative humidity, soil temperature, wind speed and evapotranspiration (*ET_o*) during the both seasons (2019–2020 and 2020–2021) are demonstrated in tables 4 (Weather station, Central Laboratory for Agricultural Climate, (MALR), Egypt)

The plant growth attributes, such as plant height (cm), number of leaves/plant, leaf area (cm²), plant fresh and dry biomass and plant dry matter were recorded 90 days after transplanting (DAT) on five plants of each experimental plot. Relative chlorophyll content (SPAD) was measured in the fully expanded fifth leaf after 90 DAT, using a Minolta Chlorophyll Meter SPAD-501.

Ten readings were recorded from each experimental plot.

The fruits were harvested at 16 pickings time when they had reached full size. Total and early fruit (the first and second pickings) yield was recorded during the harvest time and data were presented as tons per acre. Number of fruits per plant was also recorded. At fully ripe stage, 10 fruit as a random sample from each experimental plot were used to determine fruit quality characters. By using a digital refractometer (Abbe Leica model), (TSS) total soluble solids were determined. Vitamin C was determined as mg/100 g fresh weight using 2,6 dichlorophenols indophenol as a pointer for titration as mentioned by AOAC 2000. Also, the fruit firmness was determined by a TA–1000 instrument for analyzing the firmness of fruit by penetrating a cylinder of 1 mm diameter into the pulp at 3 and 5 mm distance, and by a constant speed of 2 mm s⁻¹, and the peak of resistance was recorded as g cm⁻².

Proline content was determinate in fresh new leaves according to Troll and Lindsley (1955) modified by Petters et al., (1997). Samples of vegetative parts were dried in oven at 70°C for 3 days. The dry samples were pulverized separately and then a sample was digested by acid to determine total NPK. The total N in the plant was determined using the micro-Kjeldahl as described by Chapman and Pratt, (1962). Total P was determined colorimetrically, as mentioned by Watanabe and Olsen, 1965. Total K was determined by using a flamephotometer, as mentioned by Chapman and Pratt, 1962.

AquaCrop model

AquaCrop (ver. 7.0) is a model for water-driven crop growth which simulates crop biomass growth as a linear function of transpiration

Table 3. Water requirements (m³/acre) for tomato during the 2019–2020 and 2020–2021 seasons for different irrigation treatments

| Irrigation treatments (2019–2020) | | | | | Irrigation treatments (2020–2021) | | | | |
|-----------------------------------|------|------|------|------|-----------------------------------|------|------|------|------|
| 55% | 70% | 85% | 100% | 115% | 55% | 70% | 85% | 100% | 115% |
| m ³ / feddan | | | | | m ³ / feddan | | | | |
| 1209 | 1539 | 1868 | 2198 | 2528 | 1211 | 1541 | 1871 | 2201 | 2531 |

Table 4. Meteorological data of the experimental site during the 2019–2020 and 2020–2021 seasons

| First season (2019–2020) | | | | | | |
|---------------------------|---------------|---------------|-----------|---------------|-------------------|------------------------|
| Month | Max. temp. °C | Min. temp. °C | Avg. RH % | Soil temp. °C | Wind speed m/sec. | ET _o Mm/day |
| October | 31.41 | 22.52 | 61.90 | 0.83 | 26.15 | 3.03 |
| November | 25.11 | 15.24 | 68.43 | 0.36 | 20.17 | 1.67 |
| December | 22.82 | 11.81 | 69.13 | 0.24 | 16.85 | 1.19 |
| January | 21.76 | 10.91 | 68.62 | 0.43 | 16.44 | 1.49 |
| February | 22.40 | 10.08 | 68.05 | 0.51 | 16.64 | 1.85 |
| Second season (2020–2021) | | | | | | |
| October | 30.37 | 20.53 | 59.23 | 0.89 | 24.41 | 3.05 |
| November | 27.39 | 16.91 | 69.99 | 0.52 | 21.52 | 1.90 |
| December | 20.64 | 11.63 | 65.26 | 0.50 | 15.85 | 1.30 |
| January | 18.66 | 7.55 | 65.92 | 0.36 | 12.89 | 1.29 |
| February | 20.93 | 8.74 | 66.14 | 0.52 | 14.55 | 1.84 |

through the water productivity function (biomass per unit of water transpired) driven from FAO Paper No. 33, relating yield to the consumed water. It simulates the green canopy cover and uses reference evapotranspiration ET_o and crop coefficient to calculate transpiration. Then, yield was calculated from the dry matter production and harvest index.

Agricultural procedures and field characteristics

AquaCrop model input data were followed standard agricultural procedures for growing tomato crop in Dokki area, Giza Governorate, Egypt during the growing season of 2019–2020, 2020–2021. Input data included site specifications such as soil physical and chemical properties, as well as irrigation water quality, and tomato crop characteristics. Performance of AquaCrop in simulating total dry weight was evaluated by comparing simulated data as compared to observed data from 2019–2020 and 2020–2021 of growing season. Aquacrop model was set to work at the mode of “Calendar days”

until the calibration process was completed, then the mode was set to work on “Growing degree-days” for the testing periods and investigating the new predicted climate scenarios. During calibration, various model parameters were adjusted to match the observed values. These adjustments made the simulation results match the observed values.

Data of three global climate models; namely, CNRM-CM5, EC-Earth, and GFDL-ESM2M, the predicated data of the three models were based on two scenarios of climate change, depending on predicted CO₂ concentration in the year 2100 (Representative Concentration Pathway) (RCP). The optimistic scenario is when CO₂ increase will cease at 550 ppm (RCP 4–5), and the dramatic one is when CO₂ will continue to rise above 900 ppm (RCP 8–5). The two proposed scenarios for the time periods of 2050 and 2100 were ran through the AquaCrop model utilizing the climate data that was generated.

Table 5. Total yield of tomato plants as predicted by the AquaCrop simulator for model under two scenarios of climate change in two different periods compared with the reference period

| CC scenarios | Current | RCP 4.5 | | RCP 8.5 | |
|--------------|---------|--------------|--------------|--------------|--------------|
| | | 2050 | 2100 | 2050 | 2100 |
| Year | 2021 | 2050 | 2100 | 2050 | 2100 |
| 55% ET_o | 17.3 | 16.6 -10% | 14.9 -20% | 12.5 -40% | 6.70 -56% |
| 70% ET_o | 18.3 | 17.5 -9% | 15.7 -19% | 13.2 -39% | 8.23 -55% |
| 85% ET_o | 26.4 | 25.3 -8% | 22.7 -18% | 19.0 -36% | 12.8 -52% |
| 100% ET_o | 19.0 | 18.3 -4% | 16.4 -14% | 13.7 -33% | 11.7 -44% |
| 115% ET_o | 18.8 | 18.0 -4% | 16.2 -14% | 13.5 -32% | 10.5 -39% |

Statistical analyses

The results are expressed as means \pm standard error. All data were evaluated in 3 replications for each parameter. The data were statistically analyzed using the analysis of variance adopting IBM SPSS software. Differences between means were considered significant ($p < 0.05$) at a 95% confidence level according to Duncan’s multiple range test.

RESULTS

Effect of irrigation levels on the morphological attributes of tomato

Figure 1 present the effect of different irrigation levels (ILs) (55 – 70 – 85 – 100 – 115 E_t) on plant height, leaf area and number of leaves/plant (no.leaves/plant). The results revealed there were substantial variances among all treatments at both seasons in all tested plant growth parameters. The greatest plant height was recorded at 85% and 100% IL, as compared to all treatments at both seasons (Fig. 1A). However, the minimum values of plant height were obtained at the 55% and then 115% IL in the two seasons under consideration.

The most extreme values of leaf area were obtained at 85%, followed by 100% IL, as compared to all other treatments at both seasons (Fig. 1B). In contrast, the lowest value of leaf area was obtained at the lowest irrigation level (55% E_t).

The no. leaves/plant at different irrigation levels after 90 days from transplanting is shown in Fig. 1C. The maximum value of number of leaves/plants was obtained by 85% IL. In contrast, the lowest value was recorded by applying the lowest irrigation level of 55% IL.

The impact of various ILs (55 – 70 – 85 – 100 – 115% E_t) on plant fresh weight, plant dry weight and plant dry matter of tomato are presented in Figure 2. The highest values of plant fresh weight were acquired from the plants irrigated with 85% followed by 100% IL, as compared to all other irrigation levels (Fig. 2A). The improvement ratios of plant fresh weight at 85% IL were 10.3% and 17.9% in both seasons, respectively, as compared to 100% IL. On the other hand, the lowest value of plant fresh weight was obtained by 55% E_t in both seasons.

Increasing the IL up to 85% E_t led to increasing plant dry weight significantly in both seasons and then the values decreased (Fig.2B). In turn, the lowest value of plant dry weight was obtained by the lowest irrigation level (55% E_t) during the

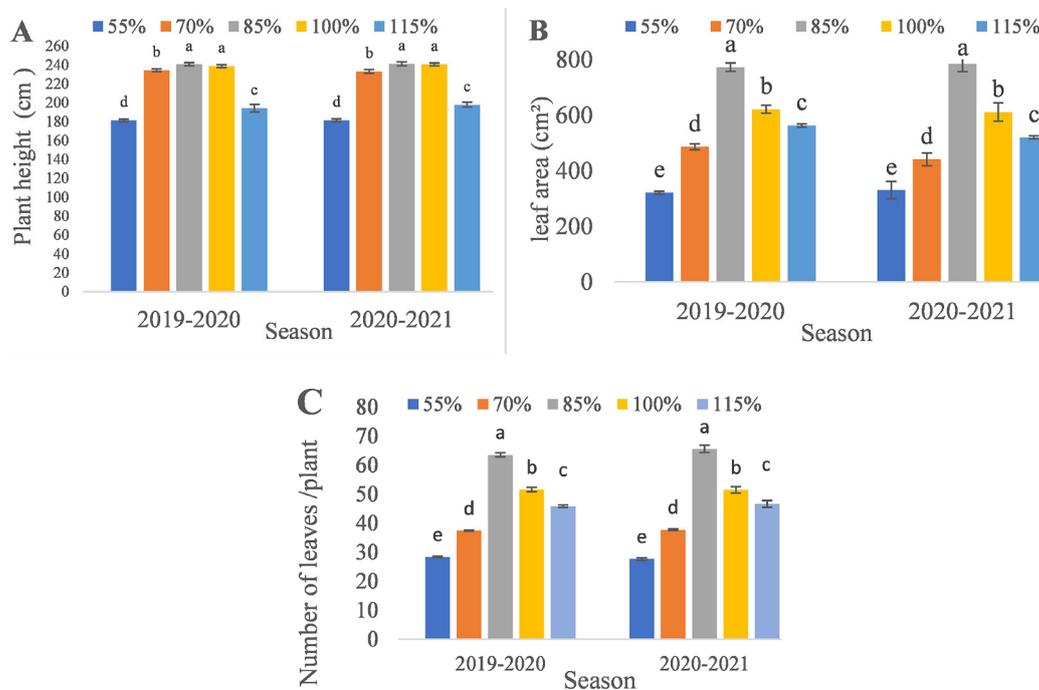


Fig. 1. Effect of different irrigation levels (55%-70%-85%-100%-115% of evapotranspiration (E_t) (mm day-1) on (A) plant height (cm), (B) leaf area (cm²) and (C) number of leaves/plant of tomato plants in both seasons, 90 days after transplanting. Vertical bars represent standard error (\pm SE) (n=3). letters in common are not indicating a significant difference between treatments (Duncan’s multiple range test at 95%).

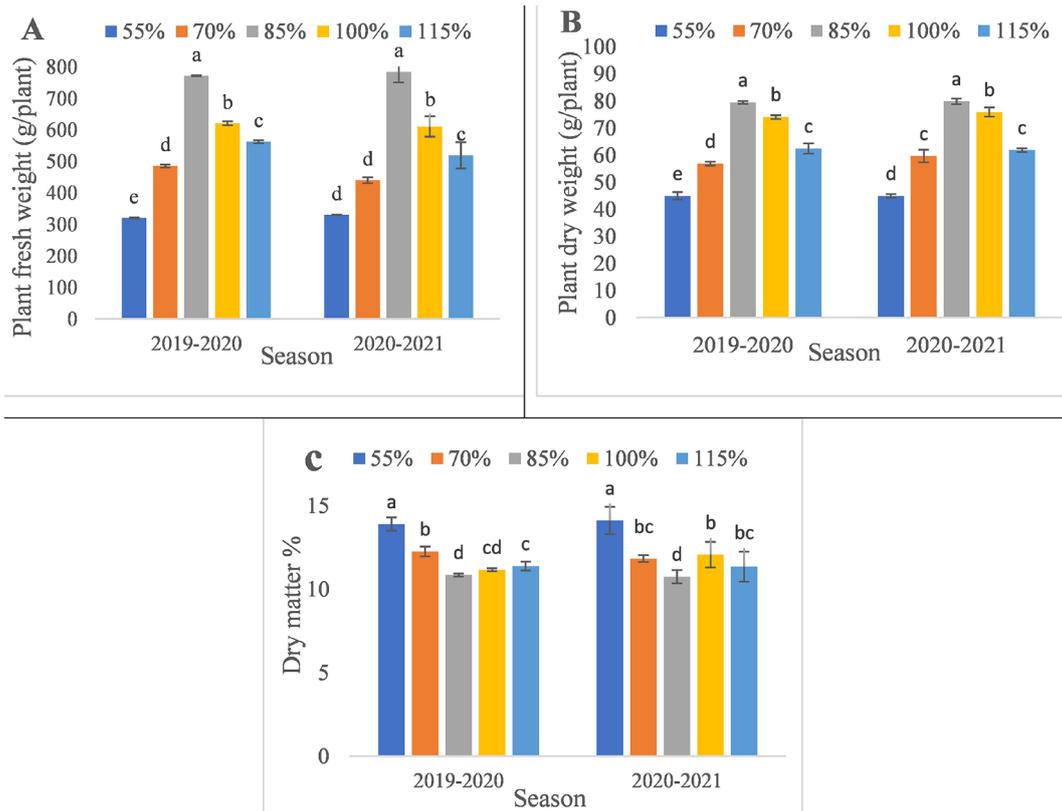


Fig. 2. Effect of different irrigation levels (55%-70%-85%-100%-115% of evapotranspiration (ET_0) ($mm\ day^{-1}$) on (A) plant fresh weight, (B) plant dry weight and (C) plant dry matter of tomato plants in both seasons, 90 days after transplanting. Vertical bars represent standard error ($\pm SE$) ($n=3$). Letters in common are not indicating a significant difference between treatments (Duncan's multiple range test at 95%).

two seasons under study. Generally, the highest plant dry weight was recorded by the (85% ET_0) treatment, followed by 100% ET_0 with significant differences between each other.

The most extreme values of plant dry matter were obtained with 55% ET_0 in the first and second seasons, respectively. In contrast, 85% of ET_0 recorded the lowest plant dry matter in both seasons.

Effect of irrigation levels on yield attributes

The data in Figure 3 show the impact of various irrigation levels (ILs) (55 – 70 – 85 – 100 – 115 ET_0) on fruit number/plant, early yield and total yield of tomato. The highest fruit number / plant was obtained by 85% ET_0 during both seasons (Fig. 3A). The 100% IL ranked second in the no. fruit/plant. In contrast, the lowest value of fruit number/ plant was obtained by 55%. The similar was observed in the second season.

Regarding the early yield (ton/fed) under different ILs (Fig.3B), data exhibited the highest early yield in both seasons was obtained by

85% ET_0 followed by 100% ET_0 with significant differences from each other. Meanwhile, 55% ET_0 recorded the lowest early yield as compared to all treatments except 70% ET_0 .

The highest total yield was acquired through 85% of ET_0 , as compared to all ILs during the two seasons under study. In turn, the yield of 100% IL ranked second without significant differences in comparison to the yield of 115% IL. On the other hand, the lowest value of total yield was obtained by 55% ET_0 . Also, a similar trend was recorded in the second season.

Effect of irrigation levels on quality of tomato fruit

Figure 4 shows the impact of various irrigation levels (ILs) (55 – 70 – 85 – 100 – 115 ET_0) on the TSS, fruit firmness and Vit. C of tomato. Fruit quality was significantly affected by the tested ILs. The highest TSS of tomato fruit was obtained by 55% at both seasons as compared to all treatments but there were notable variations between 55% and 70% in the

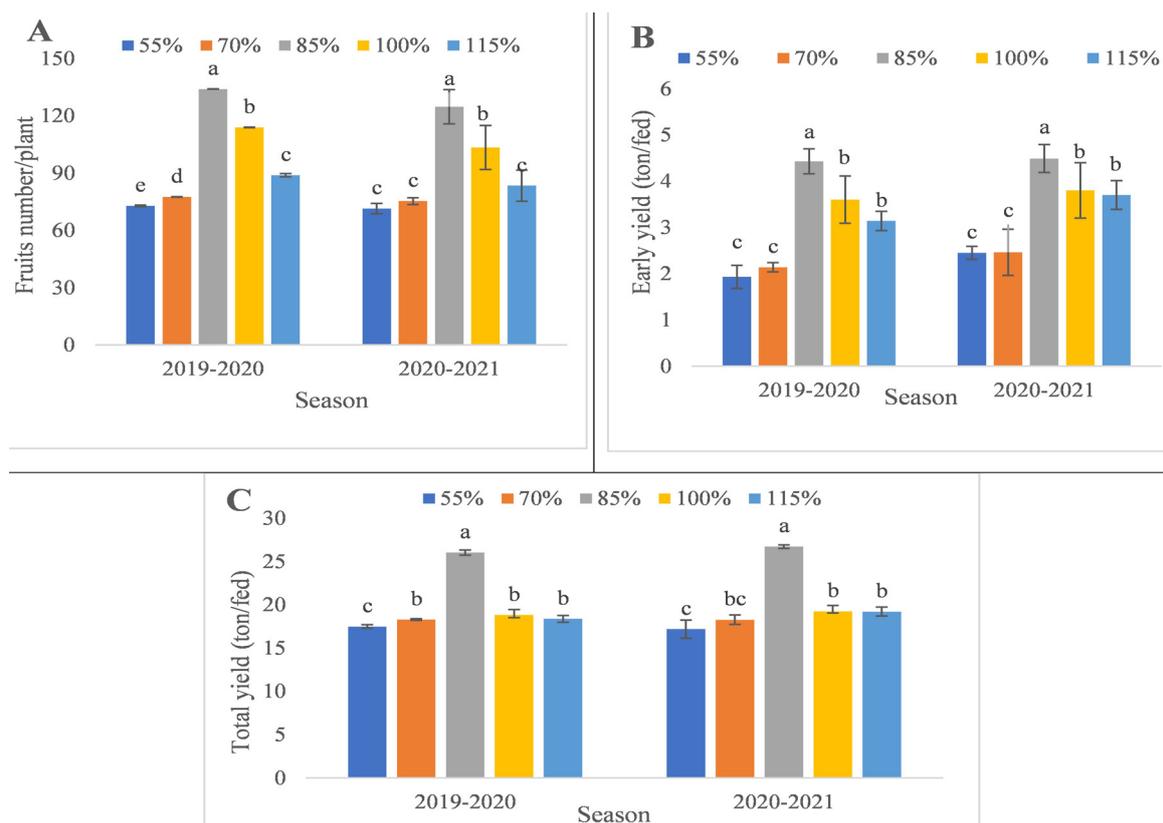


Fig. 3. Effect of different irrigation levels (55%-70%-85%-100%-115% of evapotranspiration (E_t) (mm day^{-1}) on (A) fruits number/plant, (B) Early yield and (C) Total yield of tomato plants in both seasons, 90 days after transplanting. Vertical bars represent standard error (\pm SE) ($n=3$). Letters in common are not indicating a significant difference between treatments (Duncan's multiple range test at 95%)

second season (Fig. 4A). In contrast, the lowest TSS tomato was obtained by 115% of E_t .

The highest firmness of tomato fruit was obtained by 55% E_t in the initial season without significant differences, as compared to 70% and 100% E_t (Fig. 4B). The same trend was recorded in the second season, but without significance, as compared to 70%. The lowest firmness of fruits was recorded by 85% E_t in both seasons. The highest Vit. C content was obtained in fruit at 55% E_t followed by 70% E_t in both seasons, but with an insignificant difference between them at the first season. Contradicting, the lowest Vit. C content was recorded at 115% E_t without significant differences as compared to 100% and 85% in the inaugural season.

Effect of irrigation levels on the content of nutrients of tomato plant (NPK)

Figure 5 shows the effect of different irrigation levels (ILs) (55 – 70 – 85 – 100 – 115 E_t)

on N, P and K of tomato plants after 90 days of transplanting. The highest N content was recorded by the lowest IL (55% E_t) in the initial season as compared to all other levels and the content of plants applied with 70% ranked secondly (Fig. 5A). In turn, the lowest N content was obtained by 115% of E_t . In the second season, the highest N content was recorded at plants in the lowest IL (55% E_t) with insignificance, as compared to all treatments, except 115% of E_t .

The phosphorus content of tomato was statistically significantly influenced by different ILs (Fig. 5B). The highest P content was recorded by the 55% E_t in the first season in comparison with all treatments except 70% of E_t . The identical pattern was seen in the second season with significance to all other treatments. The highest P content was recorded in tomato plants at 55% of E_t followed by 70% of E_t without significant differences between each other in both seasons. However, no significant differences were revealed among the remainder of the ILs in both seasons.

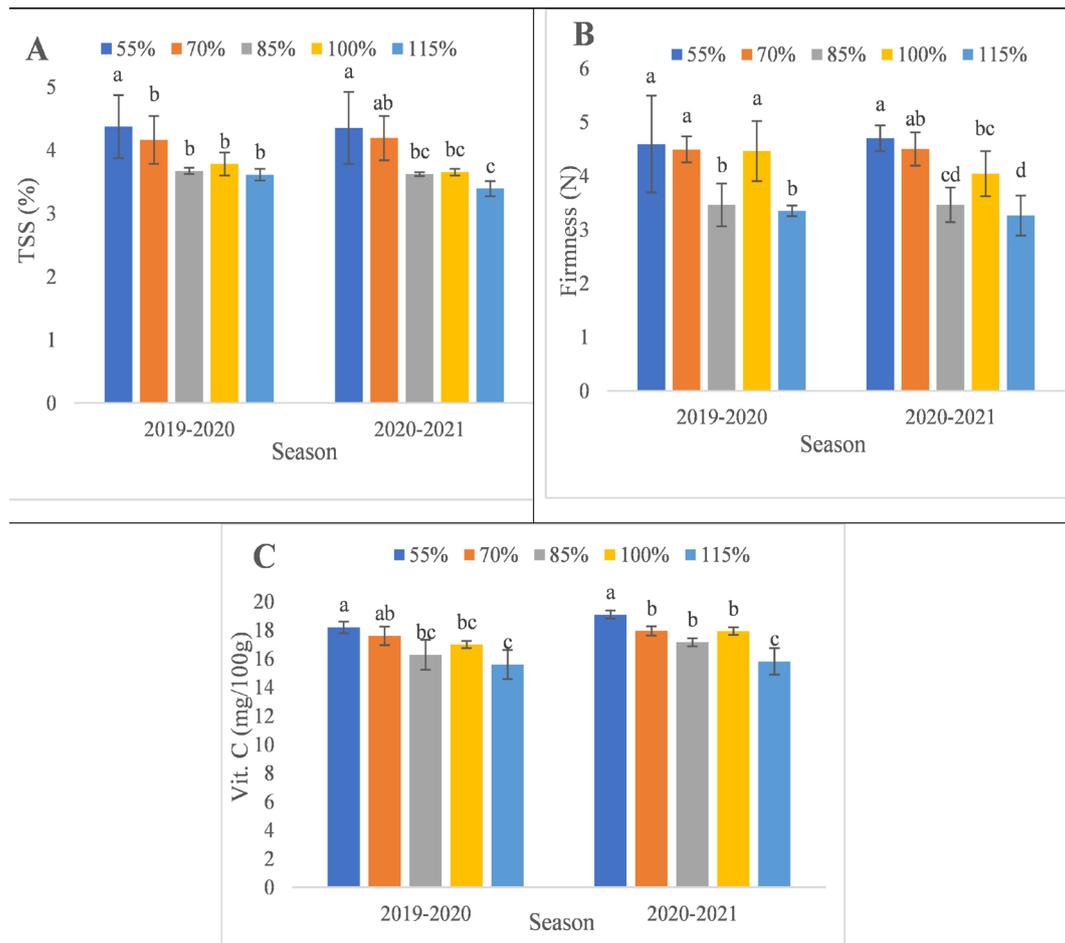


Fig. 4. Effect of different irrigation levels (55%-70%-85%-100%-115% of evapotranspiration (ET_0) (mm day^{-1}) on (A) TSS (B) Fruit firmness and (C) Vit C content of tomato plants in both seasons, 90 days after transplanting. Vertical bars represent standard error (\pm SE) ($n=3$). Letters in common are not indicating a significant difference between treatments (Duncan's multiple range test at 95%)

Effect of irrigation levels on the relative chlorophyll content and proline of tomato plants

The data in Fig.6A show the effect of different irrigation levels (ILs) (55 – 70 – 85 – 100 – 115 ET_0) on the relative chlorophyll content (SPAD) of tomato leaves. The lowest IL (55% ET_0) obtained the highest value of SPAD significantly, as compared to all ILs in the first season. However, at the second season, the SPAD in plants under 55% ET_0 did not differ significantly as compared to 70% ET_0 . The values of SPAD were decreased by increasing the ILs. The data in Fig.6B show the effect of different irrigation levels (ILs) (55 – 70 – 85 – 100 – 115 ET_0) on the proline of tomato leaves. Increasing IL led to decreasing the proline content in tomato leaves. The lowest concentration of proline content was recorded at the highest IL (115% of ET_0) in both seasons. The content of proline in plants in 70% ET_0 ranked second after

55% of ET_0 with significant differences between them in both seasons.

Simulation of crop responses to different climate scenarios

Through the results of the output of the AquaCrop model, it turned out that rising temperatures lead to a decrease in the tomato crop by an amount, since the RCP8.5 scenario achieved the largest values, as evidenced by the falling yield, whereas the worst scenario for the year 2100 and the lowest scenario is the RCP4.5 scenario; the crop productivity decreased by 4% and 33% for the scenarios RCP4.5 and RCP8.5, respectively, for the years 2050, as well as 14% and 44% for the same scenarios, respectively, for the year 2100, compared to the production values of the reference period, which ranged between 19 tons / fed. The application of 55% under irrigation reduced reference period productivity by 10%, and

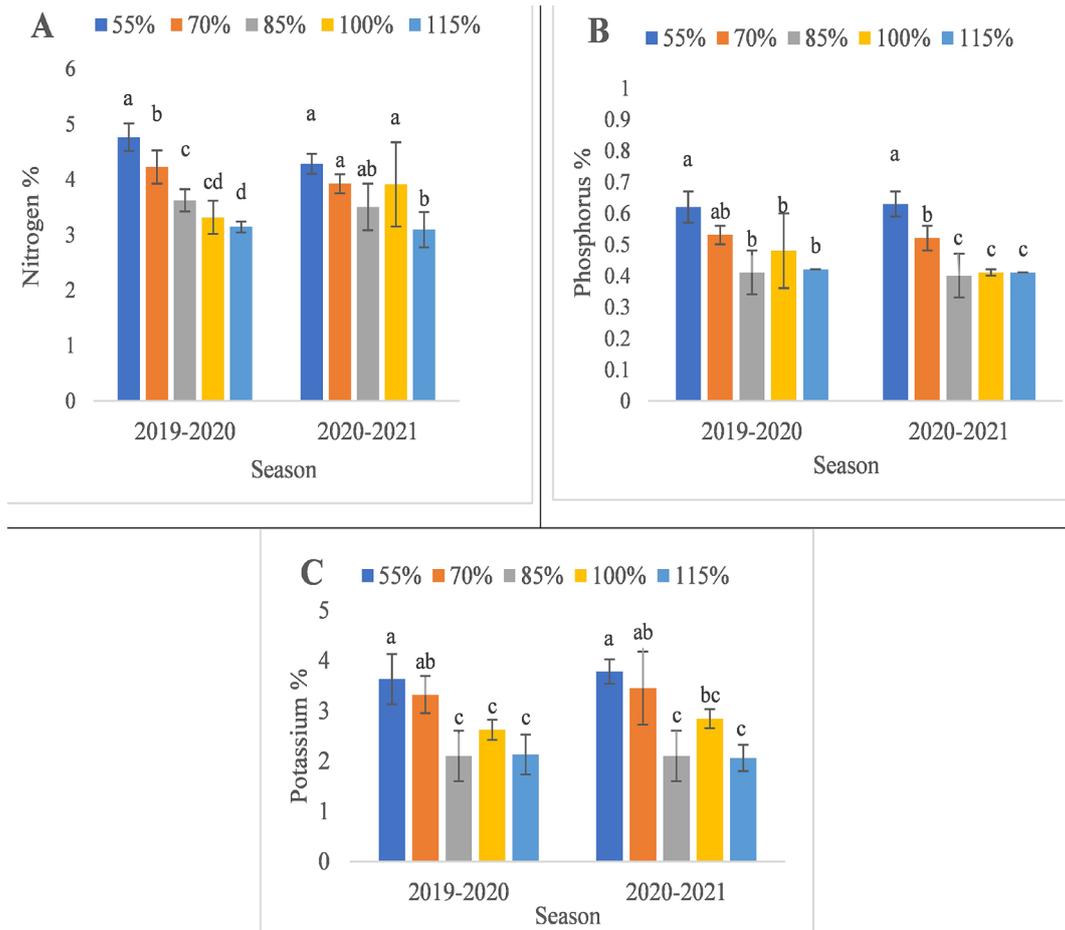


Fig. 5. Effect of different irrigation levels (55%-70%-85%-100%-115% of evapotranspiration (ET_0) ($mm\ day^{-1}$) on (A) Nitrogen, (B) Phosphorous and (C) Potassium of tomato plants in both seasons, 90 days after transplanting. Vertical bars represent standard error ($\pm SE$) ($n=3$). Letters in common are not indicating a significant difference between treatments (Duncan’s multiple range test at 95%)

40% for the RCP4.5 and RCP8.5 scenarios, respectively, for the years 2050 as well as by 20% and 56% for the same scenarios, respectively, for

the year 2100, compared to the similarity values. crop when following the currently applied irrigation schedule.

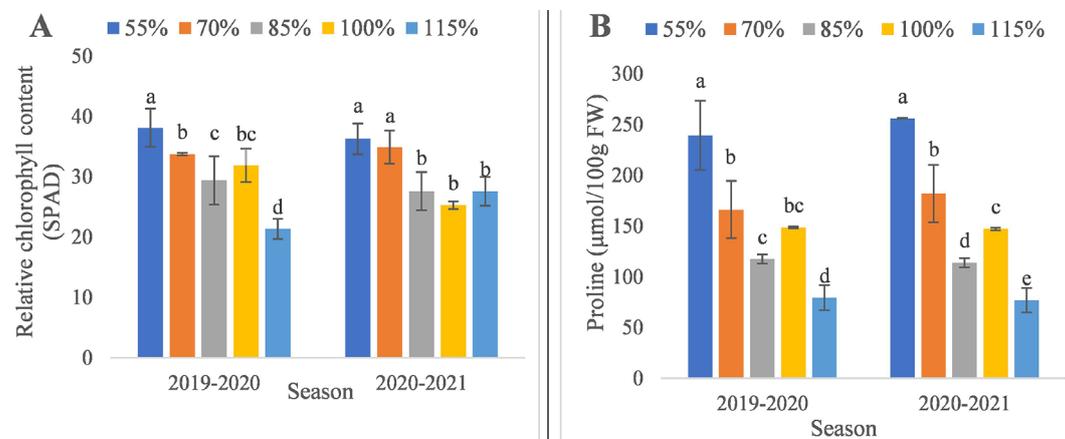


Fig. 6. Effect of different irrigation levels (55%-70%-85%-100%-115% of evapotranspiration (ET_0) ($mm\ day^{-1}$) on (A) Relative chlorophyll content (SPAD) and (B) proline of tomato in both seasons, 90 days after transplanting. Vertical bars represent standard error ($\pm SE$) ($n=3$). Letters in common are not indicating a significant difference between treatments (Duncan’s multiple range test at 95%)

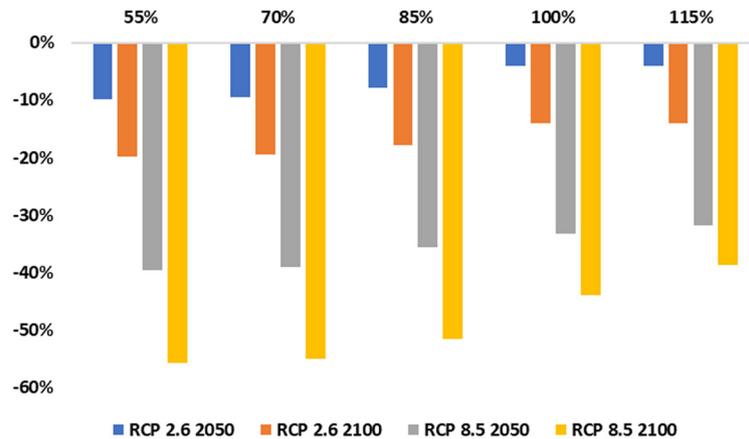


Fig. 7. Total yield of tomato plants as simulated in the AquqaCorp model under two scenarios of climate change in two different periods compared with the reference period

DISCUSSION

The obtained findings revealed that the different amount of irrigation regimes from 55, 75, 85 to 100 and 115% water requirement differed significantly in their effects on all measured morphological aspects at both seasons of a study. The level of 85% ET_0 recorded the most effective ranking of all morphological parameters after 90 DAT at the two tested seasons as compared to all irrigation levels. This is in agreement with Selim and Nady (2011). They reported that 80% of field capacity caused an increase in all plant growth attributes, i.e. root length, no. branches/plant and when compared to 100% FC (control), 60% and 40% FC dramatically reduced tomato plant length and the no. leaves / plant. Under drought stress, the lowering in net photosynthetic rate in plants as a result of stomatal closure, which decreases water loss but reduces CO_2 availability for chloroplast may lead to retarded the growth of tomato plants (Lawlor and Cornic, 2002; Flexas, et al., 2004; Bertamini, et al., 2007). In addition to Erice, et al, 2007, who stated that the well-watered treatments greatly reduced the dry matter of the alfalfa plants. All of these perhaps connected to the fact that water stress conditions increase losses in water content at plants, which retarded the growth, stem elongation and leaf expansion (Shao, et al., 2007). Also, drip irrigation providing plants with their nutrients and requirements of water with high efficiency. The same trend was obtained by several studies, Alomari et al., 2023 recorded that the tomato plant height under water defect (40% of ET_0) reduced the by 24%, and stem diameter by 18%. Also, Abdelraouf and

Ragab, 2018 revealed that raise the watering level from 55% ET_0 to 100% ET_0 obtained an ideal growth of tomato which significantly affected the flowering and productivity, also the highest values of total leaf area were recorded under 100% ET_0 and 85% ET_0 . In the same line, Ragab *et al.* (2018) found that 100% ET_0 recorded significantly the highest values of most of tested plant growth attributes of tomato.

The obtained findings revealed that the 85% ET_0 achieved the highest values of no. fruits/plant, early and total yield comparing to all other irrigation levels. However, 100% ET_0 ranked secondly at the yield attributes. The enhancement of all plant growth parameters reflected to all yield attributes in the present study. A similar trend was obtained by (Shedeed, et al., 2009; Zakher and Abdrabbo, 2014; Ahmed, et al., 2015; Badr, et al., 2016; Kumar et al., 2022). In this concern, Ihuoma and Madramootoo (2019) revealed that there were no significant differences in yield of 80% and 100% AWC (available water for crop) treatments. However, 80% AWC had the maximum value of IWUE (Irrigation Water Use Efficiency), even though the highest value of yield was recorded at 100% AWC treatment. According to the previous study, the 80% AWC is ideal for maximizing tomato plant water use and might be used under the circumstances of water shortage where water efficiency is crucial. The results are in accordance with those of Hartz et al. (2005), who found that tomato can resist a moderate amount of stress without suffering appreciable yield losses. Also, they mentioned that the highest marketable yield was obtained

from 100% AWC, while the lowest marketable yield was recorded at 20% AWC. The yield at 100% AWC did not differ significantly, as compared to the yield of 80% AWC.

Many studies obtained that applying the appropriate irrigation regime help plants to use either water or nutrients from deeper soil; therefore, increasing water and nutrient use efficiency, as well as lowering nitrogen leaching. In addition, the application of irrigation during the period of fruit development had a favorable effect on yield, in addition to the effectiveness of water utilization (Ngouajio, *et al.*, 2007; Zakher and Abdrabbo, 2014; Badr, *et al.*, 2016). However, Vijitha and Mahendran (2010) found that the defect of irrigation levels at this stage had an unfavorable effect on fruit quality characteristics, such as: TSS, acidity and vitamin C. Their findings differ from the results obtained by the authors of this study in that the lowest irrigation levels (55 and 70% ET_0) obtained the most prevalent values of TSS, firmness and Vit. C, as compared to all other irrigation levels. On the other hand, such results are in line with those found by Mors, (2019) and EI-Dolify *et al.* (2016) who reported that the lower water level led to higher contents of TSS and vitamin C content in the fruits. This may be referring to that the drought or water deficit cause lower water accumulation of fruits which led to visible higher contents of vitamin C and TSS. The obtained results are in accordance with those revealed by Vijitha and Mahendran, 2010; Morsy, 2019 in tomato crop.

As regarding to proline, the findings obtained that reducing the irrigation level increased proline contents. Under extreme stress, proline plays an important role as an osmoregulator which rises membrane permeability to water, which affects how turgid a plant is. Additionally, proline increases the production of cytokinins, which improves plant development (Shetty, *et al.*, 1992). Proline can prevent oxidative damage to plant cells by scavenging reactive oxygen species (Nayyar, 2003; Shao, *et al.*, 2008). Also Sibomana and Kahlaoui (Sibomana *et al.*, 2013; Kahlaoui *et al.*, 2014), reported that the chlorophyll content of tomato leaves decreased with increasing water stress.

In AquaCrop, yield is expressed as dry weight which does not indicate the quality of the fruit and whether it is marketable or not. An increase in temperature may cause the quality of fruit to decline, which could harm their chances of being sold. In addition, the incidence of some

physiological disorders to the fruits because of high temperatures such as blossom end rot may affect the partitioning of assimilates (Salman, *et al.*, 2005), and this is not considered in the AquaCrop model. This is due to the decrease in the crop cycle versus to the control, and the high temperature leads to an increase in the values of evaporation and transpiration of the crop, which causes an increment in the crop requirement for irrigation water (Ismael *et al.*, 2021).

CONCLUSIONS

The 85% Et_0 of tomato irrigation requirements improved all plant growth characteristics and yield characteristics of tomato, as compared to 100% Et_0 or all other levels. Reducing the quantity of irrigation needed of tomato up to 15% without adverse effects on productivity of tomato under the same climate conditions can be recommended. Depending on AquaCrop model, tomato yield will be decreased under various climate change scenarios either in best or worst scenarios. The productivity of tomato plants will be affected under the conditions of climate change due to the increase in the temperature cycles, and this decrease may reach a loss of 50% of the crop production in 2100, which requires a new policies or techniques to adapt to climate change conditions.

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