Producing of Tomato Crop using Solar Energy in Hydroponic System

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ABSTRACT

This study was designed to investigate the effect of applied some engineering parameters, such as three different level of ambient temperature (25, 30, and 35°C), and three different levels of nutrient irrigation flow rates (10, 15, and 20 l.hr^{-1}), and three different plant densities (1, 2, and 3plant.pot^{-1}), on some productive and vegetative characters for*(Redgaida Bl 1-16)* is a variety of tomato in hydroponic system. In addition, the effect of the treatments on water uses efficiency (WUE), the power requirements (PR), specific power (SP), and the operation costs were estimated. Where the results showed that the best results under the chosen variety of tomato were obtained at ambient temperature average about 25°C, it was producing the total yield about 26.33 kg.m^{-2},consumed total power about 940.11watt, with specific power of 35.7watt.kg^{-1}, with water use efficiency 31.92 g.l^{-1}, and it costs about 5.22LE.kg^{-1} of tomato. The optimum level of nutrient irrigation flow rate was at the average of 10 l.hr^{-1},it was producing the total yield about 27.06 kg.m^{-2}, consumed total power about 940.11watt, with specific power of 34.74 watt.kg^{-1}, with water use efficiency 32.72 g.l^{-1}, and it costs about 5.08LE.kg^{-1}. The plant densities 3 plants.pot^{-1} considered the best treatment for the studied tomato variety. It was producing the average about 24.8 kg.m^{-2}, consumed total power about 940.11watt, with specific power of 37.91 watt.kg^{-1}, with water use efficiency 24.78 g.l^{-1}, and it costs about 5.54 LE.kg^{-1}

Key words: Temperature- irrigation flow rate**-** plant densities**-**solar energy- hydroponic system

INTRODUCTION

Egypt's population is gradually growing, this is with the agricultural land area remaining almost constant, making it necessary to develop new strategies to close the gap between agricultural output and needs of population *(Derbala, et al., 2022).*

The Government had taken many steps encouraged by the availability of plenty of underground brackish water in those large desert areas for agriculture. Unfortunately, large quantities of this water are of high salinity and are not suitable for agriculture unless distilled. As is known, desalination industry is a large energy intensive since it needs huge amount of energy which is not available in most remote desert areas *(Perakis et al., 2017)*.

So the main two challenges facing the Government to develop agriculture activities are to supply those areas with the necessary energy and water. Implementing agriculture activities in those areas need special kind of management between the three issues; energy, water and agriculture. A sustainable solution for one usually has an impact on the others. The solution for this interact problem is not practical by building more conventional power plants or water delivery with the required normal treatment or to use the ordinary ways to grow crops *(Hassanien et al., 2016)*.

Nowadays, these challenges pose a serious threat to traditional farming systems for which food production has become a challenge. Therefore, the efficiency of traditional agricultural practices must be raised to improve water saving, productivity and environmental sustainability *(Lambin and Meyfroidt, 2011)*. Therefor the modern forms of agriculture must include solutions to low soil productivity, depleted soil nutrient reserves, and limited water availability, as well as help meet the challenges of climate change *(Lavhelesani, et al. 2021)*.

The procedure of growing plants without soil is referred to "hydroponics" and is one of the innovative techniques. *(Sharma et al., 2018 and Kummer et al., 2022)*. Alongside the need to produce healthy food, there is the need to find solutions to reduce the environmental impact of cultivation. Traditional agriculture, especially intensive agriculture, causes soil consumption and often damages soil and environment due to the use of chemical fertilizers and pesticides *(Baiyin et al., 2021a)*.

Energy management is by using sustainable renewable energy sources and making full use of all the produced energy by cogeneration and heat recovery of one type of fuel energy *(El-Awady, et al., 2014)*. Solar that is sustainable abundant energy in those places can play this role in different agriculture applications. Water management would be by using clean energy, storage water, advanced techniques in desalination, irrigation and cultivation *(Tavakoli et al., 2017)*. From the sustainable development point of view, solar thermal is the most sustainable energy resource *(Cartelle, et al., 2015)*. Since the greenhouse itself is a solar collector, utilizing solar energy can lead to a reduction in production cost *(Ntinas et al., 2014)*. Solar greenhouses mostly rely on passive solar design but may use active energy systems and operate as a semi-passive system. Thus, solar greenhouses can be considered as a practical solution for the energy problem of greenhouses. *(El- Maghlany et al., 2015)*. Conventional agriculture faces major challenges, the most important of which is the depletion of soil productivity in cultivable areas, poor soil fertility due to continuous cultivation over the years, and most importantly reduce capital and availability, *(Lehman et al., 2015)*.

Furthermore, high air temperatures inside the greenhouse during summer can decrease the photosynthetic rate, and, therefore, plant growth and crop yield *(Trypanagnostopoulos et al., 2017)*. The low level of tomato production is associated with many problems in relation with poor agronomic management practices, such as plant density, light level and quantity, irrigation water management, and the suitable temperature for tomato growing *(Nadia 2022)*. Plant spacing is one of the agronomic factors, which significantly affect tomato production. Optimum plant spacing enhances better utilization of spaces, high yield and quality production *(Ara et al., 2007)*. Another factor affects on tomato growth and fruit yield is the suitable temperature, during the development of plants, *(Adams et al., 2001)* pointed out that tomato fruits ripened 95, 65, 46, and 42 days after flower opening when plants were grown under controlled environmental conditions at 14, 18, 22 and 26°c, respectively. They added that a similar response to temperature was observed when the temperature of individual trusses was modified while the plants were grown at 20°c, as well as, temperature also affected the shoot dry matter content and partitioning *(Yang et al., 2020)*. *Abelmageed et al. (2003)*, reported that the reproductive processes in tomato were more sensitive to high temperature than the vegetative one.

MATERIALS AND METHODS

The present study was conducted in hydroponic unit inside the greenhouse at Faculty of Technology and Development Zagazig University Egypt, to producing tomato using solar energy in hydroponic system on the *(Redgaida BI 1-16)* variety of tomato. The effect of some engineering parameters (ambient temperatures, and quantity of nutrient irrigation fluid) and plant densities on some characteristics plant growth were considered. According to the above goals, an applied research experiment was carried out to

achieve these aims. An experiment was carried out through successive season 2023/ 2024. The main plot was ambient temperatures, the sub plot was the rates of nutrient solution irrigation, and sub– sub plot was plant densities.The experiment was repeated three consecutive seasons to allow for varying temperatures inside the greenhouse, with each season lasting three months. The first growing season began in mid-September 2023 and continued until mid-December 2023, and the ambient temperature 25°C was applied. Followed by the second season until mid-March 2024 and the ambient temperature 30 °C was applied. And finally the third season, which ended in mid-June 2024, and the ambient temperature 35°C was applied.

- The three different levels of nutrient irrigation flow rates were 10, 15, and   20 l.hr^{-1}. The three different levels of plant densities were 1, 2, and 3 plants.pot^{-1}. The different flow rates and plant densities treatments were repeated under the three mentioned growing seasons.

Materials:

Solar cells:

It consists of an aluminum frame with a length of 2 m ×1 m with layers of silicon and germanium, to which two main elements were added: phosphorus and boron. The silicon cells have a positive charge on one side and a negative charge on the other side. All of this was covered with a spectrum of non-reflective glass for sunlight. Solar photovoltaic panels capture sunlight, which causes the electronics in the silicon cells in the power panel to fire, to work on the flow of continuous electrical current (DC). The inverter was connected to convert direct current (DC) into alternating current (AC), which is used for all electrical purposes. It is an electronic device that regulates the electrical voltage coming from the solar cells before it passes to the solar batteries, as well as the voltage coming from the battery to the electrical load, in order to preserve the used battery and ensure that it is charged and used optimally ***Fig. (1).***

Hydroponic and irrigation unit:

The hydroponic system consists 8 perforated tubes are made of polyethylene. The length of every tube is 3 m, and stand 1.2 m high above the ground, with row spacing about 30 cm ***Fig. (2).*** Every tube has 12 holes. Perforated pot has 12cm bottom diameter, and about 18 cm upper band diameter, was putted in every hole (96pots in every hydroponic unit). So that the plant root was contact with the solution.

Supplementary irrigation unit for hydroponic unit consists of water storage tank having dimensions of 70 cm diameter and 75 cm height, (about 200-liter size) for storing nutrient irrigation solution ***Fig.(3).***

Floating (submersible) pump (Hmax:2.8M type, with power:90 watt, and a water column height of 2.8 m) was used to transfer the nutrient irrigation solution from the storage tank to the pipes, the pump was connected to the irrigation system (perforated tubes) using polyethylene tubing of 16 mm outside diameter, with 8 valves to control the flow rates of nutrient irrigation solution inside every pipe.The pump delivered the three flow rates of irrigation solution were about 10, 15, and 20 where, (liter. hour^{-1}). The timing and duration of opening/closing of the pump was applied with using intermittent flow system (half hour "on" and 2.5 hours "off") using a time switch (Grasslin Talento 111 DIN Mount Analogue Time Switch). The solution delivered from the tank to the upper end of the tubes, and then the nutrient irrigation solution flow to the end of tube by gravity. Nutrient irrigation solution is circulated in closed system. The tank of the nutrient solution will use for collecting of drained solution (N.F.T system).

Cooling and air-condition unit:

Cooling and air condition unit was use to concave the appropriate microclimate to safe healthy plant and equipment, aeration system, to enhance the root zone media with its air balance. Addition to aeration unit was installed to provide oxygen to the system for plant growth. The aeration unit (glass ventilator) with 34 cm vane diameter, and cooling fan 1200 rpm speed*Fig. (4)*. To adjust the required temperatures degree inside the experimental unit, the system was calibrate several times before the experiment to reach the most suitable position for the cooling system sensor to operate during the experiment.

Heating system:

Solar energy was use directly for heating inside the agricultural unit. If direct solar energy is not sufficient to reach the required temperature, artificial heating unit using operating lamps. Thermometer (KT-201,Digital LCD Thermometer) used to determine the measurements of the temperature and humidity *Fig. (5)*.The humidity ranged between 10-50%.

Plant materials and growth condition:

Tomato were planted at 25 cm spacing in each row. The nutrient solution (irrigation solution) consists of N.P.K nutrient solution with concentration of 20-20-20 % (*v/v*). The all-traditional methods for growing methods for the two types of plants were apply. The properties of Vermiculite soil and irrigation solution, which used in the experiments, were shown in *Table (1).*

Table (1): Properties of Vermiculite soil and irrigation solution.

Medium	pH	EC (ds m^{-1})
Vermiculite Soil	6.6	2.04
Irrigation solution	7.2	3.00
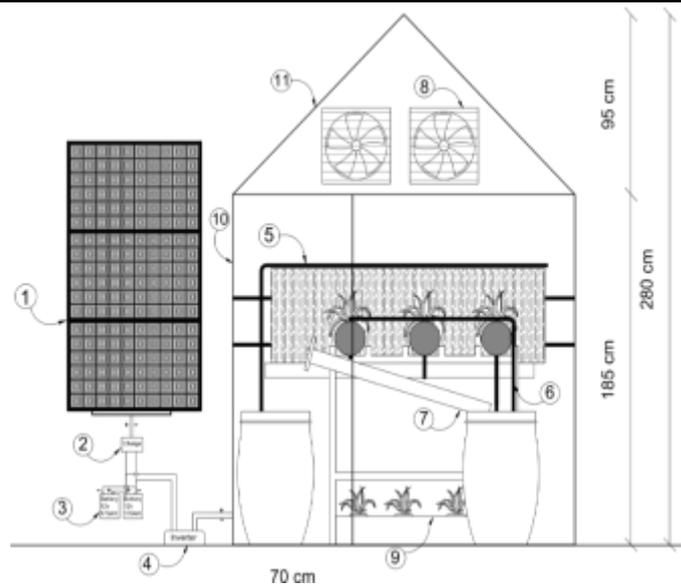
1.Solar cells modules,2.Charge Controller, 3. Battery, 4. Inverter (converts direct current (DC) coming from the battery or solar panels into alternating current (AC)),, 5. Cooling Pad6. Hydroponic feeding unit, 7. Hydroponic exchange unit, 8. Cool air fan9. Deep water culture, 10. Gable-even-span greenhouse,11 Polyethylene sheet to cover greenhouse

Fig. (1): Schematic diagram showing the basic dimensions and component of the constructed greenhouse.

Fig. (2): The hydroponic system

Fig. (3): Supplementary irrigation unit. *(a) water storage tank; (b) mount analogue time switch.*

Fig. (4): Glass ventilator.

Fig. (5): Thermometer and humidity measurement.

Measurements:

To measure the flow rate of the irrigation nutrient fluid, the 16 mm diameter liquid delivery pipes were removed and the pump was operated to push the fluid so that it would be received in a special tanks , then the amount of collected fluid in a certain time was determined. The amount of fluid collected per minute and the flow rate was calculated using ***Equation (3-1)***. To adjust the flow rate to reach the desired rate, the valve installed on each pipe was used until the desired rates of 10, 15 and 20 liters/minute were reached.

$$\textit{Flow rate} = \frac{\textit{The amount of fluid collected}}{\textit{Time taken}} \qquad \text{(3-1)}$$

Water use efficiency.

Water use efficiency (W.U.E) is an indicator of efficiency of irrigation unit for increasing crop yield. W.U.E was calculated, according to Jensen (1981) as follows:

Power requirements:

1-Power of Solar Energy:

$$Pi = G \; x \; A \; (w) \qquad \text{(3-2)}$$

$$P_o = v \; x \; 1 \; (w) \qquad \text{(3-3)}$$

$$E_a \; (\%) = \frac{Po}{Pi} \times 100 \qquad \text{(3-4)}$$

Where:

P_i= input power, P_o = output power, E_a = array efficiency,

G = solar radiation (w.m^{-2}), and A = effective module cell area (m^2).

The energy produced by the solar power unit is stored in special batteries to be used to operate the irrigation pump and other energy requirements such as lighting, cooling, etc., and is compensated from the main electrical power grid.

2- Power requirements for irrigation:

Power consumed in pump to deliver the amounts of nutrient solution from the tank to all plants tubes were calculated as:

$$\textbf{Power requirements } (PR) = \frac{F.w.H}{constant} \qquad \textbf{(3-5)}$$

$$\textbf{Require motor power } (P_{motor}) = P.R. / \eta_m \qquad \textbf{(3-6)}$$

Where:

F: amount of irrigation solution (nutrient solution) delivered to eachtreatment.w: specific weight of nutrient solution (1000 kg.m^{-3}).H: the total pressure head (2.8m), η_m: motor efficiency (assume = 75%).

The total power required = pumping power+ heating power +ventilating power (3-7)

2.a.Specific Power:

It's a key indicator of performance.

$$\textbf{Specific power} = \frac{Total\ power\ required}{Total\ crop\ yield} \qquad \textbf{(3- 8)}$$

3. Operations costs:

The hourly costs was estimated according to 2023prices using fixed and operation costs method. The hourly cost was included fixed costs and operating costs. The parameterswhich are considered while cost evaluation are presented

RESULTS AND DISCUSSIONS

Effect of different levels of ambient temperature on some vegetative and productivity characters of tomato plant:

The obtained data in***Table 2, and Fig.6*** revealed that**,** the increasing in degree of ambient temperature from 25 $^\circ$C to 30 $^\circ$C causes significant decreasing in all chosen vegetative and productive characters of tomato. These decreasing were about 5, 15, 12, 13, 25, 7, and 10% for plant height, fruit length, fruit diameter, No. of leaves.plant^{-1}, leaf area, No. of fruit.plant^{-1}, and fruit weight respectively.Where, the ambient temperature increased from 25to 35^{0}C, the decreasing were about 21, 24, 24, 20, 36, 9, and 19% for the same mentioned vegetative characters of tomato respectively. This explains that is the reproductive processes in tomato is more sensitive to high temperature, and agree with ***Adams et al. (2001), and Abelmageed et al. (2003)****.*In addition, it is evident obviously; the total yield has an inverse relationship with ambient temperature.
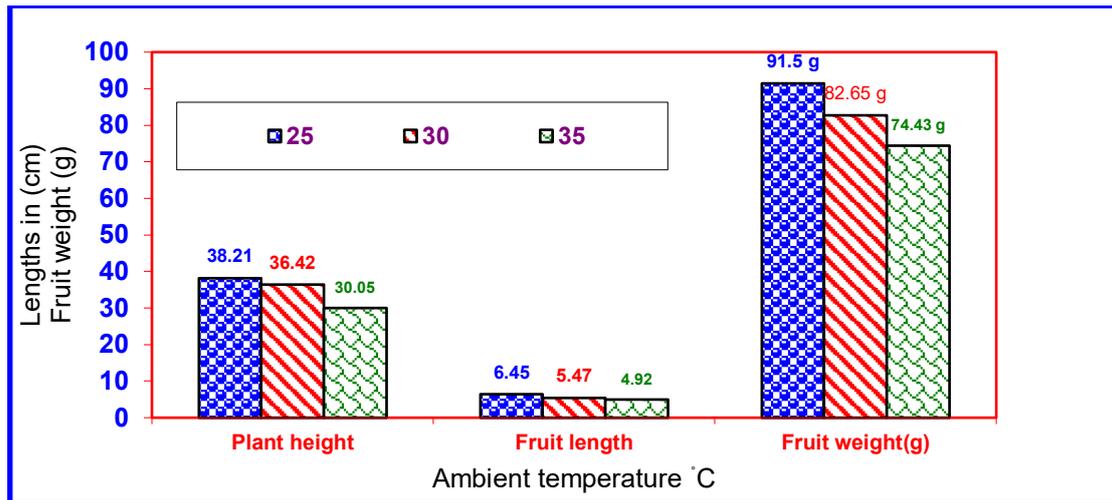
Fig. (6): Effect of ambient temperatures on some plant growth characters of tomato.

Therefore, this variety of tomato gives the best result at ambient temperature of $25°C$, where the total yield was about 26.33 kg.m^{-2} increased by 17, and 33%, when the temperature changed from $25°C$ to 30, and $35°C$ respectively. It consumed about 940.11 watt, specific power 35.7 watt.kg^{-1}, and WUE 31.92 g. l^{-1}, less by about 45, and 89% in total power requirement comparing with the two others ambient temperatures 30 and $35°C$ respectively. With an increase of 16 and 25% in WUE compared to the two others temperature respectively. This treatment (ambient temperature 25 $°C$) costs about 5.22 LE.kg^{-1} decreasing by about 17, 33%, comparing with two others ambient temperatures 30, and 35 $°C$ respectively.

Effect of different levels of nutrient irrigation flow rates on vegetative and productivity characters of tomato plant:

It evident obviously in *Table 2, and Fig.7* that is the, with increasing the flow rates of nutrient solution irrigation from 10 to15 liters.hr.$^{-1}$ causing significant decreasing in all vegetative and productive characters of tomato. These decreasing were about 2, 8, 9, 4, 17, 5, and 9% for same plant characters mention in above paragraph respectively. These decreasing were about 7, 21, 20, 10, 31, 6, and 19% for the same plant characters mention in above paragraph respectively, when the flow rate changing from 10 to 20 l. hr^{-1}. This explains that is the reproductive processes in tomato is more sensitive to high flow rates, and agree with *Adams et al. (2001).* In general the all-vegetative and productive characters of tomato plant highly improving with decreasing the nutrient irrigation flow rates. This indicates that the flow rate affects plant growth by influencing the plant nutrient Percentage. The ideal flow rate provides sufficient contact time and collision frequency for roots and nutrient ions in a nutrient solution.

This can promote nutrient absorption and thus increase plant growth. Conversely, although an increased flow rate can promote turbulent diffusion and affect the transport of nutrient ions to the root surface, a flow rate that is too fast may represent excessive physical stimulation that may have a negative impact on plant growth. These data were in agreement with, *Barbi et al. (2021) and Baiyin et al. (2021a).*

Table (3) showed that, the best treatment to producing the *(Redgaida BI 1-16)* variety of tomato under the circumstances of this experiment was at nutrient irrigation flow rate at 10 l.hr^{-1}, which produced about 27.06 kg.m^{-2}. With an increase of about 14, and 24% compared with two othersnutrient irrigation flow rates 15,and 20 l.hr-1 respectively. This is due to the same reasons which mention above. This treatment improved specific power (SP), and water efficiency (WUE). Where SP was34.74 watt.kg^{-1} with increasing by about 16, and 31 % compared to the others flow rates (15, and 20 l. hr^{-1}) respectively, at the same time the WUE recorded about 32.72 g. l^{-1}, increasing by about 28, 47% compared to the two others flow rates (15, and 20 l.hr^{-1})respectively. This treatment (at flow rate 10l. hr^{-1}) costs about 5.08 LE.kg^{-1} decreasing by about 16, 31%, comparing with two others flow rates 15, and 20 l.hr^{-1} respectively.

Table (2): Effect of engineering parameters and plant densities on total yield of tomato crop.

	No. of fruit.plant^{-1}	Fruit weight (g)	Total yield.plant^{-1} (kg.plant^{-1})	Net area. Pot^{-1} (m^2)*	No. of pot.m^{-2}	Total yield (kg.m^{-2})
**Ambient temperature ($^{\circ}$C)**
25	21.57	91.57	1.98	0.075	13.33	26.33
30	20.15	82.65	1.67	0.075	13.33	22.45
35	19..72	74.43	1.49	0.075	13.33	19.86
**Nutrient irrigation flow rates (l.hr^{-1})**
10	21.9	92.82	2.03	0.075	13.33	27.06
15	20.92	83.65	1.75	0.075	13.33	23.33
20	20.54	75.46	1.55	0.075	13.33	20.66
**Plant densities (plant.pot-1)**
1	20.42	74.93	1.53	0.075	13.33	20.40
2	20.92	82.22	1.72	0.075	13.33	22.93
3	21.86	85.09	1.86	0.075	13.33	24.80

* - Net Area for every pot = 0.25 × 0.3 = 0.075 m^2

Effect of different levels of plant densities on vegetative and productivity characters of tomato plant:

It evident obviously in *Tables 2&3,*and*Fig.8* that is the, with increasing the plant densities (plant.pot^{-1}) from 1 to 3 plant.pot^{-1} causing significant increasing in all vegetative and productive characters of tomato. These increasing were about 10, 19, 18, 9, 23, 7, and 18% for same plant characters mention in above paragraph respectively. These increasing were about 7, 11, 9, 4, 18, 5, and 10% for the same plant characters mention in above paragraph respectively, when the plant densities changing from 2 to 3 plant.pot^{-1}. This explains that is the reproductive processes in tomato is more sensitive to plant densities. In general the all vegetative and productive characters of tomato highly improving with increasing the plant densities. This is due to, may be the crowding of plants and consequently the crowding of their roots and branches in the irrigation pipes has led toobstructing the passage of the irrigation fluid and slowing its passage, allowing the plants to absorb more nutrients, and thus improving the all the plant's vegetative and productivity characteristics.

Table (3): Effect of engineering parameters and plant densities on total yield, total power requirements, and WUE of tomato crop.

	Total power requirement (watt)	crop yield (kg.m^{-2})	Specific power (watt. Kg^{-1})	F. w. (kg.plant^{-1})	*C.W.C. (l.plant^{-1})	W.U.E. (g. l^{-})	Specific costs (LE.kg^{-1})
Ambient temperature ($^{\circ}$C)							
25	940.11	26.33	35.7	1.98	62.04	31.92	5.22
30	1360.11	22.45	60.58	1.67	62.04	26.82	6.12
35	1780.11	19.86	89.63	1.49	62.04	24.02	6.92
Nutrient irrigation flow rates (l.hr^{-1})							
10	940.11	27.06	34.74	2.03	62.04	32.72	5.08
15	940.16	23.33	40.3	1.75	74.45	23.51	5.89
20	940.22	20.66	45.51	1.55	89.34	17.35	6.66
Plant densities (plant.pot-1)							
1	940.11	20.40	46.08	1.53	62.04	24.66	6.74
2	940.11	22.93	41.0	1.72	68.24	25.21	6.00
3	940.11	24.80	37.91	1.86	75.06	24.78	5.54

F.w. = Fresh weight (g.plant^{-1}), *C.W.C.** = cumulative irrigation water consumption, and was appreciated at optimum nutrient flow rate (10 l.hr^{-1}), **W.U.E.** = water use efficiency g.l^{-1}

   Tables (2&3), and *fig. (8),* showed that, the ideal treatment to producing the *(Redgaida BI 1-16)* variety of tomato under the circumstances of this experiment was at plant densities 3plant.pot^{-1}, provides sufficient contact time and collision frequency for roots and nutrient ions in a nutrient solution. This can promote nutrient absorption and thus increase plant growth. It produced about 24.8 kg.m^{-2}. With an increase of about 22, and 8% compared with two others plant densities 1and 2plant.pot^{-1}respectively.This was agreement with***Cardoso et al., 2018.*** This treatment consumed about 940.11watt as a total power requirements and improved specific power (SP), and water use efficiency (WUE). Where SP was 37.91 watt.kg^{-1}with increasing by about 17, and 7 % compared to the others plant densities (2, and 3 plant.pot^{-1}) respectively, at the same time the WUE recorded about 24.78 g. l^{-1}.This treatment (at plant density 3 plant.pot^{-1}) costs about 5.54 LE.kg^{-1} decreasing by about 8,and21%, comparing with two others plant densities2, and 3plant.pot^{-1} respectively.
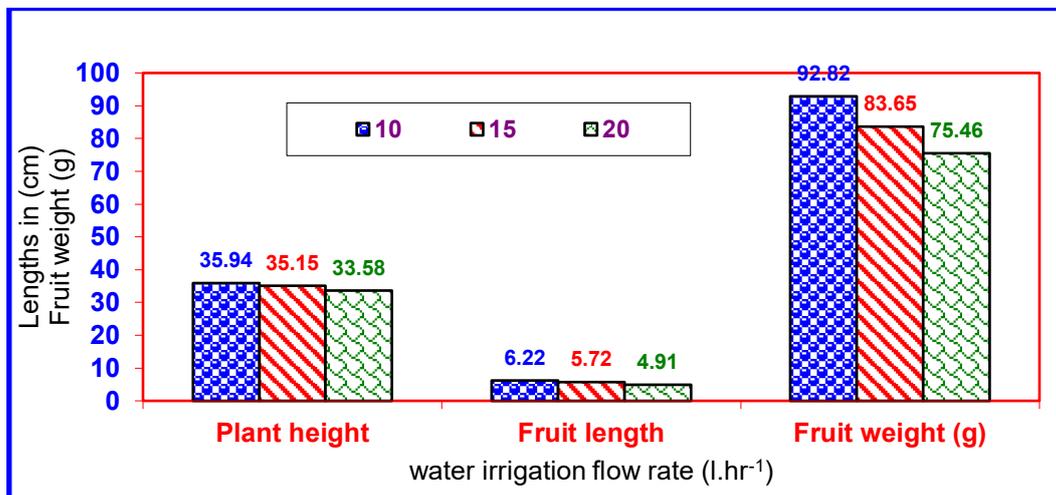

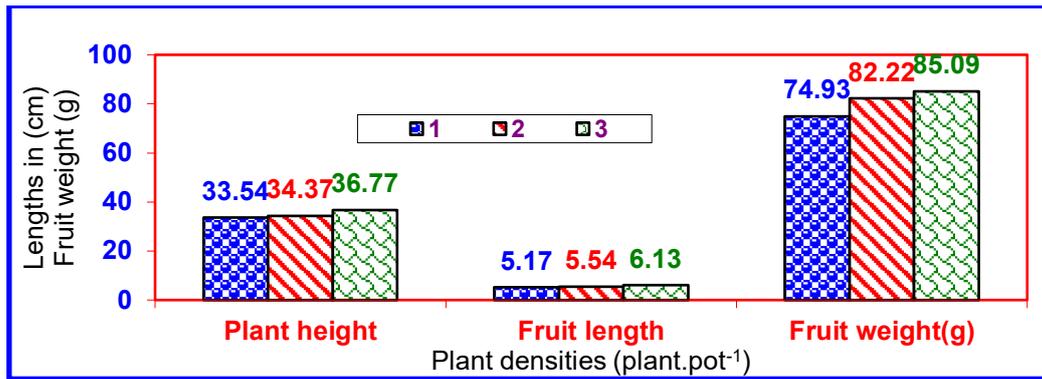**Fig. (7):** Effect of nutrient irrigation flow rate on some plant characters of tomato.

Fig. (8): Effect of plant densities on some plant characters of tomato.

CONCLUSIONS

The best results under the chosen variety of tomato were obtained at ambient temperature average about 25°C, producing the total yield about 26.33 kg.m^{-2}, at total power about 940.11watt, with specific power of 35.7 watt.kg^{-1}, with water use efficiency 31.92 g.l^{-1}, and costs 5.22 LE.kg^{-1}.The optimum level of nutrient irrigation flow rate was the of 10 l.hr^{-1}, produced the total yield about 27.06 kg.m^{-2}, consumed total power about 940.11watt, with specific power of 34.74watt.kg^{-1}, with water use efficiency 32.72 g.l^{-1}, and costs 5.08LE.kg^{-1}. The plant densities 3 plants.pot^{-1} considered the best treatment for the studied tomato variety. It was producing the average about 24.8 kg.m^{-2}, consumed total power about 940.11watt, with specific power of 37.91watt.kg^{-1}, with water use efficiency 24.78 g.l^{-1}, and costs 5.54 LE.kg^{-1}.

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