horticulturae

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Modifying Walk-In Tunnels through Solar Energy, Fogging, and Evaporative Cooling to Mitigate Heat Stress on Tomato

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Abstract: Global warming is by far the most significant issue caused by climate change. Over the past few decades, heat stress has intensified into a serious issue that has a negative impact on crop production. Hence, it is crucial to modify cultivation systems to cope with this kind of stress, particularly in arid dry regions. In comparison to open-field cultivation, tomato production under protected cultivation techniques in walk-in tunnels that are suited for different farmers' financial abilities was evaluated during the late summer season. The studied tunnels included a shaded net tunnel with natural ventilation, net tunnel with a fogging system and plastic tunnel with evaporative cooling (wet pad and fans). For the operation of fogging and evaporative cooling systems, solar energy was used as a sustainable, eco-friendly energy source. The results indicated that the solar energy system successfully operated the studied cooling systems. All studied protective cultivation techniques mitigated heat stress on tomato plant and improved the microclimate under walk-in tunnels. Moreover, evaporative cooling and fogging systems significantly increased plant leaf area, cell membrane efficiency and the contents of chlorophyll, relative water and proline compared to the net tunnel with natural ventilation. Furthermore, a marked reduction in physiological disorders was noticed. Improved physiological and biochemical parameters and limited physiological diseases led to higher fruit set, marketable fruit yield and total productivity. The percentage of marketable fruit yield increased by around 31.5% with an evaporative cooling system, 28.8% with a fogging system and 17% with a shaded net tunnel with no positive cooling as compared to an open field. However, the plants grown in open-field cultivation without protection significantly deteriorated from heat stress and had a high incidence of physiological disorders. The most incident physiological disorders were blossom-end rot, cracking, internal white tissues, sunscald, puffiness, blotchy ripening, cat face and exserted stigma. It is recommended to use a solar energy system to modify microclimate conditions through fogging or evaporative cooling under walk-in tunnels to ameliorate heat stress on grown tomato in the late summer season for higher fruit yield and fewer physiological disorders.

Keywords: *Solanum lycopersicon*; protected cultivation; fogging; pad–fan cooling; microclimate; physiological disorders; productivity

Citation: Sharaf-Eldin, M.A.; Yaseen, Z.M.; Elmetwalli, A.H.; Elsayed, S.; Scholz, M.; Al-Khafaji, Z.; Omar, G.F. Modifying Walk-In Tunnels through Solar Energy, Fogging, and Evaporative Cooling to Mitigate Heat Stress on Tomato. *Horticulturae* **2023**, *9*, 77. https://doi.org/10.3390/horticulturae9010077

Academic Editor: Domenico Ronga

Received: 1 November 2022
Revised: 4 December 2022
Accepted: 12 December 2022
Published: 6 January 2023

1. Introduction

The growing global population accompanied by climate change has increased food and energy demand. Moreover, the war between Russia and Ukraine has pushed the world to seriously secure food and renewable energy sources. The use of solar energy systems in protected cultivation is one of the most promising solutions for the development of the agricultural sector to address the issues posed by traditional energy sources and climate change, hence reducing environmental pollution and securing food [1]. Climate change has become the core focus of the world in the last decades due to the observed risks to human life [2]. Human activity through burning fossil fuels, cutting down forests and farming livestock are the main causes of gas emissions and global warming, which is known as the "greenhouse effect" [3]. Global warming negatively affects human life and food security. The Mediterranean region's climate, as a "hot spot" of climate change, is described by hot summer with high solar radiation and low relative humidity that is accompanied by limited water resources [4]. Global warming extremely affects ecosystems, including the quantity and quality of food supply [5]. As one of the most important vegetable crops, tomato is not far from these adverse impacts since its yield and quality are affected by heat stress [6]. Fruit set percentage is a crucially sensitive indicator for heat stress since it can fall by 40% with just 2.5 °C over the ideal temperature (about 25 °C) [7]. Reduced fruit set directly correlates with poor yield and quality [8,9]. The harmful effects of heat stress include the production of reactive oxygen species enzymes such as superoxide dismutase and ascorbate peroxidase which negatively affect CO_2 fixation, pollen grain viability, pollen tube growth, pollination and fertilisation function [10–12]. Moreover, a wide range of physiological disorders, including blossom-end rot, cracking, puffiness, cracking and sunscald, are common in incidence under heat stress in open-field cultivation, causing a significant loss in fruit productivity [13,14].

It is necessary to adjust cultivation strategies for better adaptation to climate change. Protected agriculture is suggested to play a crucial part in coping with the adverse effects of climate change and achieving farm sustainability [15,16]. Numerous forms of protected growing facilities, including greenhouses, net houses, tunnels and others, are created based on the needs of the various plant species and climatic conditions. Protected farming has several benefits, such as a reduction in weather-related yield loss, protection from pests, weeds, and diseases, more effective use of resources, improved crop yield and quality and higher farmer incomes [17]. Despite being the best option for changing the microclimate, fully controlled greenhouses face considerable challenges. These include expensive costs and technology as well as energy challenges that cannot be widely applied, particularly for poor farmers and developing countries [1]. In sunny regions, it is common to use unheated plastic greenhouses during the cool season and shaded net houses in the hot ones. However, these methods are still more expensive and need more practical experience than open-field growing. Besides heat stress in these regions, grown tomatoes in the open field in the late summer season suffer from water stress and insect attacks that are critical reasons for viruses transfer and which all increase physiological and biological diseases [18]. These reasons encourage the farmers to establish various kinds of protected cultivation. Low and high tunnels are preferred by the small-holder growers as they are easier and lower-cost options than the greenhouses. According to KC et al. [19], tunnel farming is an efficient low-cost strategy for fending off the effects of climate change, such as severe rainfall and temperature variations, and it enhanced productivity by 32 tons/year/hectare. The walk-in tunnel is appropriate for farmers since it is less expensive than high tunnels and easier for implementing agricultural practices due to its adequate height compared to low tunnels. Mainly, it relies on natural ventilation rather than artificial heating or cooling, which reduces the cost of both construction and maintenance [8,20]. There is a need to incorporate renewable energy systems to modify the microclimate under these types of tunnels to accommodate different farming financial capacities and environments and then to compare the products' productivity and quality. Under hot and sunny conditions, some strategies can be used for cooling the microclimate under protected cultivation, including two techniques. The first does not need energy (passive cooling), including the use of a net cover with different shading levels that provide natural ventilation [21,22] and various kinds of screens and materials to reflect sunlight [23,24]. The second technique needs energy, including forced ventilation [25], evaporative cooling [26] and the use of fogging systems [27].

Shading houses are commonly used by small farmers as a low-cost solution to protect the plants from high summer solar radiation and temperature [19]. El-Bassiony et al. [28] confirmed that shading during the late summer season was effective to boost tomato growth, yield and quality. Under Mediterranean regional conditions, it was also reported that shading during the summer cultivation of tomato was an excellent tool for enhancing the phytochemical quality [29]. Controlling the elevated temperature and low relative humidity around noon, however, is insufficient. Pad–fan evaporative cooling is a low-energy-cost option in hot and dry climates with a favourable effect on plant growth under greenhouse conditions and no negative impact on the environment [30]. Another option is a fog system, which produces small water droplets of 10–20 microns in diameter that are floated in the air before falling onto the crop canopy, causing a reduction in air temperature [31]. Baudoin [32] suggested fogging systems as a cooling method to mitigate the negative impacts of high evapotranspiration and elevated temperatures. According to Leyva et al. [33], using a fogging system on cherry tomatoes grown under a screen house reduced incident radiation by between 30 and 37%, while increasing relative humidity by between 16 and 20% to reduce the occurrence of physiological stress that would have a negative impact on yield and final quality.

Greenhouse modifications for high productivity have been extensively investigated, but for the modification of walk-in tunnels to be suitable for small-holder farmers during the hot summer season, there need to be more studies. Additionally, it is important to compare simple negative cooling with a forced one under these kinds of tunnels, especially when employing a renewable energy source. The evaluation of protected and non-protected tomato growing, as well as the impact of various tunnel covers and cooling techniques that are suitable for different financial abilities of small-holder farmers, were the main goals of this study. Furthermore, we aimed to investigate how far these strategies can modify the microclimate under the low-cost walk-in tunnels. We investigated how far these modifications can alleviate heat stress on grown tomatoes in the late summer season and affect the physiological and biochemical responses as well as the final productivity and physiological disorders in comparison with open-field cultivation.

2. Materials and Methods

2.1. Field Experimental Description

The current experiment was carried out on tomato plant (*Solanum lycopersicon* L.) F1 hybrid of 023 (Sakata seeds Co., Yokohama, Japan) at the International Protected Cultivation Centre, Faculty of Agriculture, Kafrelsheikh Univ., Egypt during the late summer seasons of 2020 and 2021 in silty clay soil (7.8 pH, EC 2.19 ds m^{-1} and 1.9 % organic matter). On the 3rd of June, 35-day-old seedlings were transplanted into rows that were 175 cm wide and had 50 cm between plants. The Agriculture Ministry's recommendations for tomato production including drip irrigation, fertilisers and pest control were followed.

The plants were transplanted in the open field and three walk-in tunnels with the same land area. The tunnels were 2.20 m tall, 6 m wide and 30 m long in the east/west orientation. Galvanised iron pipes were used as a frame. Two tunnels were covered by a white mesh insect-proof net with 35% shade level, 274.3 μm thread diameter, 0.345 m^2 m^{-2} porosity, 236.6 μm diameter of the inside circumference of the pore, 0.171 mm^2 area of the pore and 0.69 ventilation efficiency. The net cover was washed every four weeks to remove the dust. One of these tunnels was equipped with a fogging system under 405 KPa pressure. Three fog lines with 100 cm in between were placed 50 cm below the tunnel roof. The last tunnel was covered by polyethylene plastic film with 200 μm thickness, and a cooling evaporative system with a wet pad and fans was constructed (Figures 1 and S1).

Three fans (1 m in diameter, 300 m^3 per minute capacity) were installed in the tunnel on the east side to exchange the tunnel air once each minute (Figure 1). On the west side, a cooling bed with a pump that circulates water through (30 L/min) and over a porous pad was installed (Figures S1 and S2). To supply the required water, a water tank with a 300 L capacity was placed underground to reduce water temperature (Figure 1). The cooling system was adjusted to work when the outside temperature increases over 25 °C and stop when it reaches 22 °C.

Figure 1. Solar energy cells used in the experiment (**left**), front side of the walk-in tunnel with evaporative cooling system (**right**).

A solar energy system with 2.115 kW photovoltaic was used as an energy source for fogging and evaporative cooling systems (Figure 1).

2.2. Treatments

Four treatments were arranged as follows:

I. Open-field planting (OF).
II. Net house (NH).
III. Fogging under the net house (NF). The system was adjusted to work from 10 p.m. to 4 p.m. for 10 min/h at a rate of 6 S/36 S to lower the energy consumption.
IV. Evaporative cooling system under the plastic house (EP).

2.3. Microclimate Data

RH/Temp data loggers (model BESANTEK BST-DL13, Nanjing, Jiangsu, China) were placed 50 cm above the plant canopy to monitor the minimum, maximum and average air temperatures as well as the relative humidity (RH%). Three devices were randomly distributed in every treatment, and the sensors were shielded from direct sunlight. Additionally, three data loggers—one for each replicate—were dispersed across the open field. The monthly average and the hourly data during the day (3rd July) of peak flowering and fruit set were presented. Since the flowering and fruit set stage extended for two weeks and there were only minor changes (few days) among the studied treatments, an intermediate day was chosen to evaluate the effect of the studied modifications on the microclimate conditions and the related parameters.

2.4. Physiological and Biochemical Measurements

The physiological and biochemical parameters were taken 60 days after transplanting from five random plants from each replicate, and the measurements were carried out for three technical replicates.

2.4.1. Plant Leaf Area

A portable leaf area meter (model LI-3000A, Lincoln, NE, USA) was used to estimate the leaf area per plant (m^2) in the first completely opened leaves of five different random plants from each plot. The leaf area of the first completely developed leaf was multiplied by the overall number of plant leaves to determine the total plant leaf area.

2.4.2. The Relative Water Content (RWC)

The RWC determines a fresh sampled leaf tissue's water content in relation to the maximum amount of water the tissue can contain at full turgidity (condition of being swollen). It was determined for fully formed leaves that had been cut, directly weighed to determine the fresh weight (FW) and then submerged in double-distilled water for 16 h. To calculate the turgid weight (TW) of leaves, extra surface water was removed and dried with paper towels. The leaves were then dried in an oven until the dry weight remained unchanged (DW). According to the following equation [34]:

$$\text{RWC (\%)} = \frac{\text{FW} - \text{DW}}{\text{TW} - \text{DW}} \times \text{W} - \text{D}$$

2.4.3. Membrane Permeability (MP)

MP is a measurement of the plasma membrane's semi-permeability loss. According to the adopted research [35], it was determined by evaluating electrolyte leakage by selecting five plants randomly per replicate, cutting them into uniformly sized discs and taking 0.5 g of the discs from the middle of the youngest fully developed leaf. After that, the discs were cleansed with distilled water to eliminate any surface contaminants. The discs were incubated at 25 °C for 24 h in closed tubes containing 20 mL of deionised water. The bathing solution's electrical conductivity (EC1) was calculated. The samples were then heated to 120 °C in a water bath for 20 min, and when the solution had cooled to room temperature, the electrical conductivity (EC2) was measured. The MP (%) value was calculated as (EC1/EC2) 100.

2.4.4. Relative Chlorophyll Content

Relative chlorophyll content (SPAD) in the first fully developed leaves of five different plants was measured using the SPAD501 equipment (Minolta Corp, Ramsey, NJ, USA), which was used for measuring greenness without destroying the tissues [36].

2.4.5. Proline Content

The method suggested by Bates et al. [37] for determining proline content involved extracting 0.5 g of fresh leaf material, homogenising it in 10 mL of 3% aqueous sulfosalicylic acid and filtering the mixture through Whitman's No. 1 filter paper. Subsequently, 2 mL of the filtered extract was obtained for analysis along with 2 mL of acid ninhydrin and 2 mL of glacial acetic acid. The reaction mixture was first incubated in a bath of boiling water for one hour, and then it was completed in an ice bath. The reaction mixture was given 4 mL of toluene, and the organic phase was extracted and read at 520 nm, using toluene as a blank on a UV-visible spectrophotometer.

2.4.6. Flowering and Fruit Set

Fruit set percentage was taken during two weeks of the peak flowering and fruit set stage. The fully opened flowers of five plants from every replicate were counted and marked, and then the number of flowers converted into fruits was counted daily during this period. Fruit set percentage was calculated as follows:

$$\text{Fruit set\%} = (\text{Number of set flowers}/\text{Total number of marked flowers}) \times 100$$

The percentage of stigma exsertion during this period for the identical plants was also estimated as a sensitive reaction to heat stress damage on flowers according to the following formula:

$$\text{Stigma exertion \%} = (\text{Number of flowers with exserted stigma}/\text{Total number of flowers}) \times 100$$

2.5. Fruit Yield and Quality Parameters

All fruits from the studied plants were picked in the full mature pink stage to estimate the total and marketable yields per plant (kg) and average fruit weight (g). All picked fruits were sorted at every picking to determine the morphological disorders, and 20 fruits from each treatment were cut to estimate the internal defects. The following incident physiological disorders were expressed individually as an average of all pickings:

- Cracking: radial or concentric cracking.
- Sunscald: yellow, sunken areas.
- Blossom-end rot (BER): water-soaked areas at or near the blossom end.
- Puffiness: flat-sided, puffy and/or inside cavities lacking seed gel.
- Internal white tissue (IWT): internal white, hard areas in the outer walls and/or in the cross-wall, without outer symptoms.
- Blotchy ripening: outer uneven ripening or yellow shoulders.
- Cat face shape: brown deep cavities at the blossom end.

2.6. Statistical Analyses

Four treatments were used in three replicates of a complete block randomised design, with three rows in each tunnel and three rows in the open field. One-way analysis of variance was used to analyse the data using the statistical programme SPSS 18.0 for Windows. Duncan's multiple range test was used to compare the main values of the treatments at the $p \leq 0.05$ level.

3. Results

3.1. Microclimate Data

During the peak blooming and fruit set stage of the season, daytime hourly temperature and RH% were registered under the studied tunnels and the open field (Figures 2 and 3). The maximum temperature was extremely high in the open field since it reached 42.1 °C at 2 pm and 41.1 °C at 1 p.m. in the first and second seasons, respectively (Figure 2). In contrast, it dropped, achieving values of 38.8, 35.5 and 25.5 under the uncooled net tunnel, net tunnel with fogging and plastic tunnel with evaporative cooling, respectively. It is obvious that the protection techniques were successful in lowering the temperature during the hot part of the day between the hours of 8 a.m. and 6 p.m. At 8 p.m., the temperature in the open field and all studied tunnels dropped to below 27.5 °C and stayed around 20 °C until sunrise, which was suitable for tomato plant.

Except for when the fogging system was in operation (10 a.m.–4 p.m.) under the net tunnel, where RH% values were higher than those of the evaporative cooling system, the RH% under the plastic tunnel with evaporative cooling was higher than that of the other tunnels and the open field (Figure 3). While the RH% was extremely low in the open field, which dropped to the lowest values of 23.6–24.7% at 2 pm, the other protection techniques successfully improved RH% values. RH% ranged between 33.9 and 36.6% under the uncooled net house, between 60.1 and 62.7% under the net house with fogging and between 82.4 and 86.6% under the plastic house with evaporative cooling in the first and second seasons, respectively. Except for the plastic tunnel, the open field and the net tunnels had close RH% values that ranged between 78 and 80% and 64 and 71% in the first and second growing seasons, respectively. From 6 pm to 12 am, the two studied net tunnels either with or without cooling had close RH% values that ranged between 45 and 81% and 50 and 67% in the first and second seasons, respectively.

The average monthly maximum temperature during the experiment periods from June to September is shown in Figure 4. The open field had the highest values, recording 33.3–35.0 °C and 34.2–36.2 °C in the first and second seasons, respectively. Meanwhile, the studied cooling techniques of walk-in tunnels successfully reduced the maximum temperatures by 2.4–3.1 and 2.3–1.9 °C with the uncooled net tunnel, 5.3–5.0 and 5.5–6.2 °C with fogging under the net tunnel and 8.3–9.5 and 9.2–10.4 °C with evaporative cooling under the plastic tunnel.

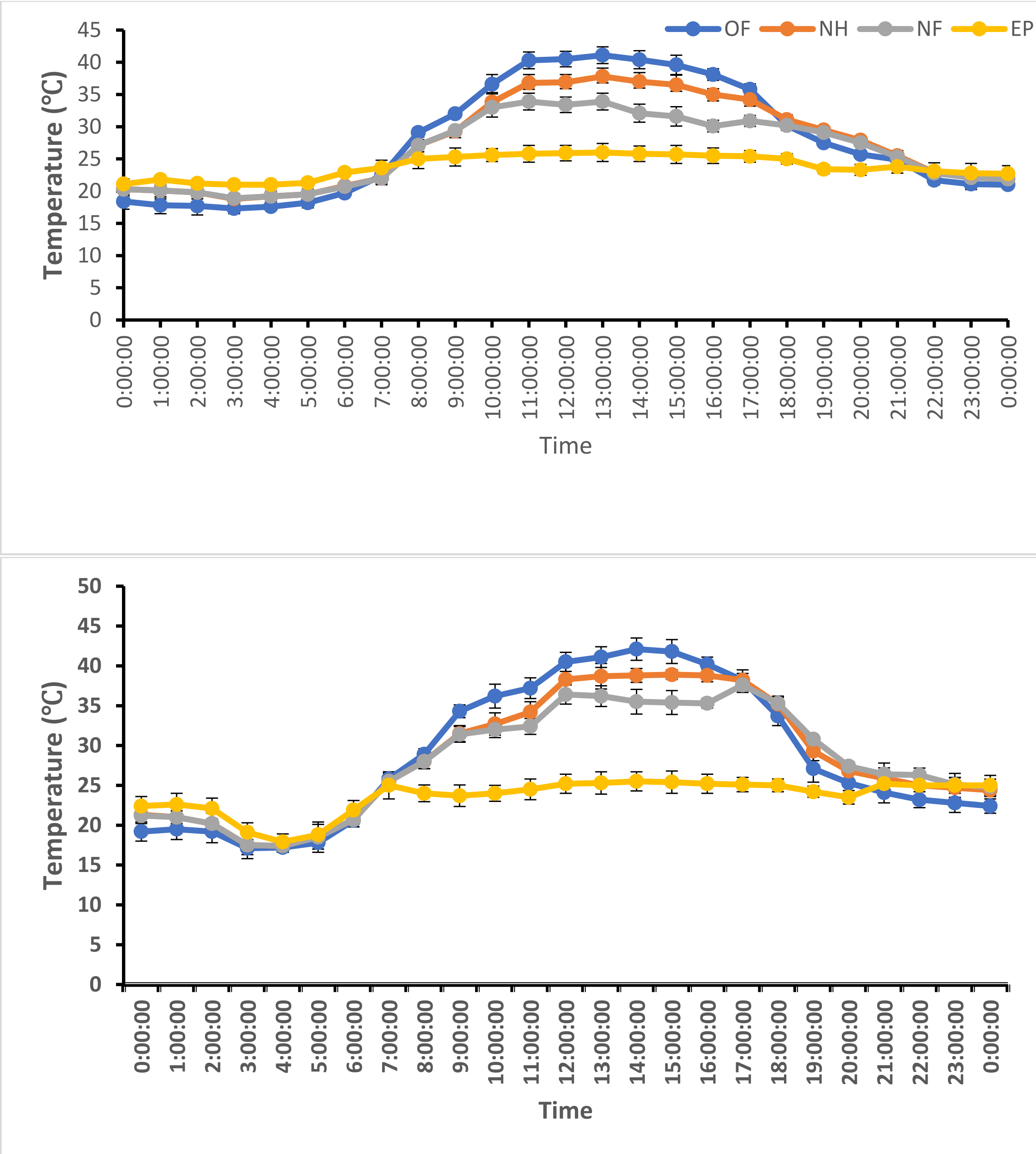

Figure 2. Hourly temperature changes during the peak of flowering and fruit set on 3 August 2020 (**upper figure**) and 5 August 2021 (**lower figure**) registered in the open field (OF), net house (NH), net house with fogging (NF, operating 6 S/36 S from 10 a.m. to 4 p.m.) and evaporative cooling under plastic house (EP). Standard error of the means was derived from three biological replicates.

The average monthly minimum temperature during the experiment period is presented in Figure 5. In the first season, the plastic tunnel kept the lowest minimum temperature ranging between 23 and 24 °C with 1.5–2.2 °C more than the open field, whereas the two studied net tunnels either with or without fogging had intermediate values with slight differences in between them. In the second season, the monthly average in the open field was higher than in the first season and increased up to 26 °C, hence the control system under the plastic tunnel worked to keep the temperature around 25 °C. As a result of the adjustment of the fogging system under the net tunnel to work only during the hottest period of the day (10 a.m.−4 p.m.) to lower the consumed energy, the minimum temperature had almost the same values in the cooled and uncooled tunnels, and it was at an acceptable level (24.5–28 °C).

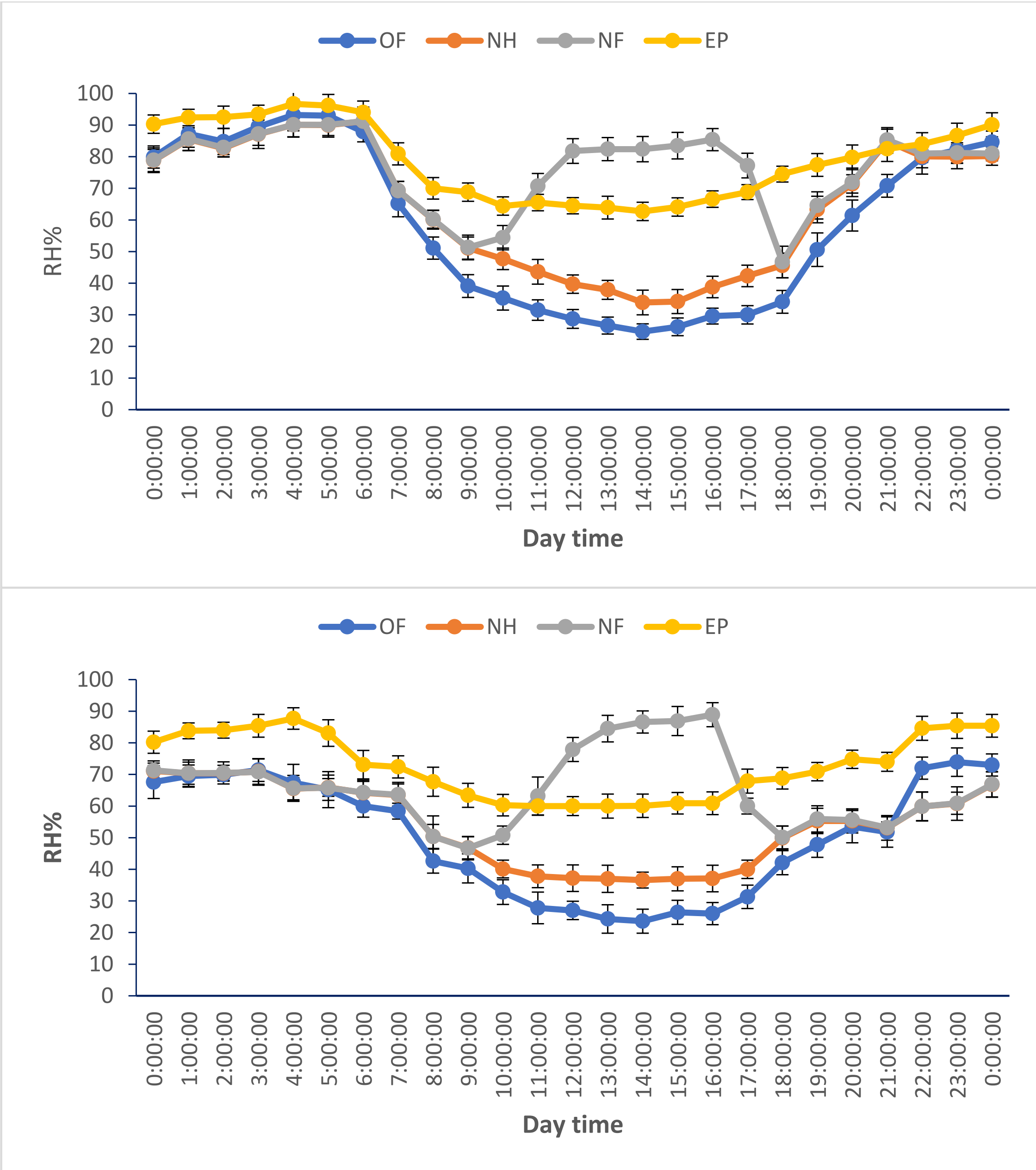

Figure 3. Hourly RH% changes during the peak of flowering and fruit set on 3 August 2020 (**upper figure)** and 5 August 2021 (**lower figure**) registered in the open field (OF), net house (NH), net house with fogging (NF, operating 6 S/36 S from 10 a.m. to 4 p.m.) and evaporative cooling under plastic house (EP). Standard error of the means was derived from three biological replicates.

Water cooling through fogging or evaporative systems enhanced the average monthly maximum RH% under net and plastic tunnels compared with the open field and uncooled net tunnel (Figure 6). Evaporative cooling increased the maximum RH% to 91.2–92.8%; however, fogging increased it to 81.6–89.5%. Meanwhile, the lowest values (81.7–82.2%) were obtained from the open field in the first season, and they were obtained from the uncooled net tunnel in the second one (75.6–77.9%).

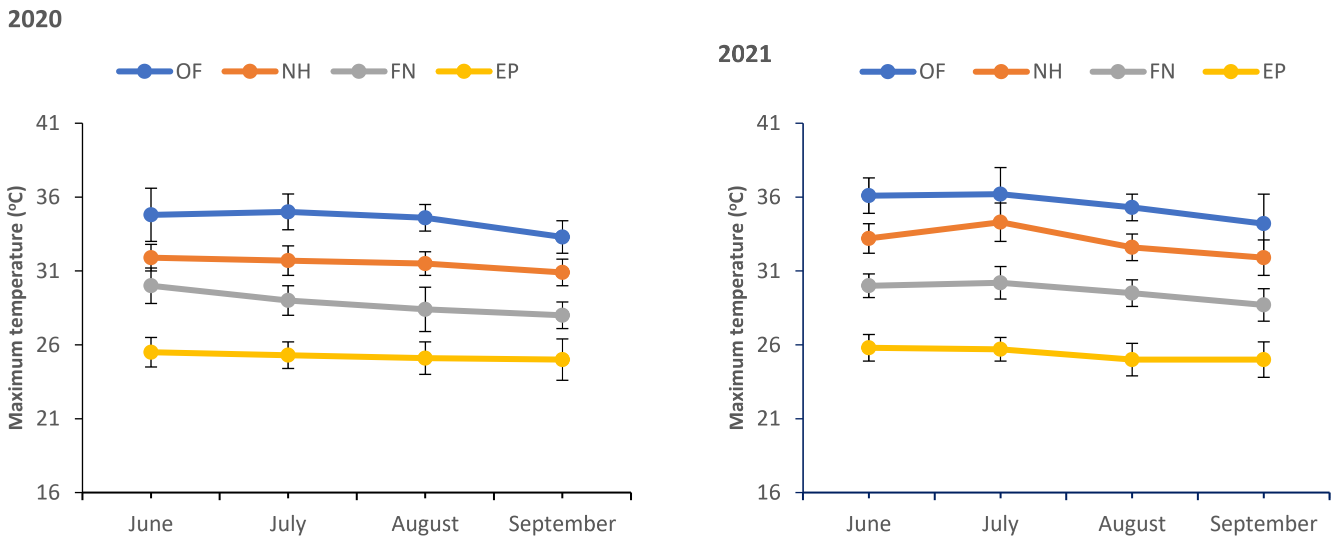

Figure 4. Average monthly maximum temperature during the experiment periods of 2020 and 2021 seasons, registered in the open field (OF), net house (NH), net house with fogging (NF, operating 6 S/36 S from 10 a.m. to 4 p.m.) and evaporative cooling under plastic house (EP). Standard error of the means was derived from three biological replicates.

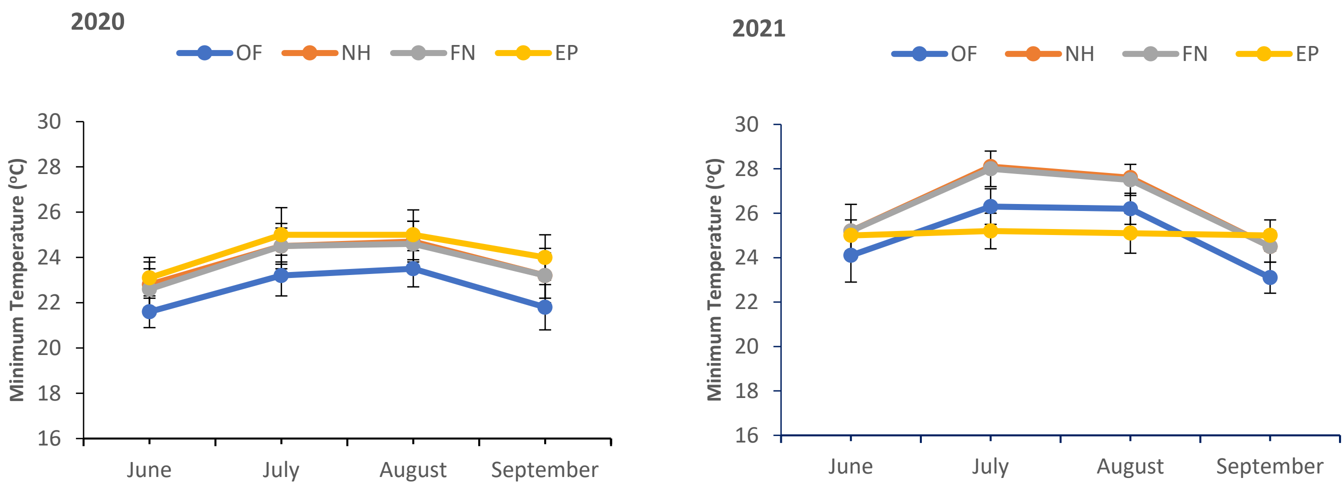

Figure 5. Average monthly minimum temperature during the experiment periods of 2020 and 2021 seasons, registered in the open field (OF), net house (NH), net house with fogging (NF, operating 6 S/36 S from 10 a.m. to 4 p.m.) and evaporative cooling under plastic house (EP). Standard error of the means was derived from three biological replicates.

The monthly average of minimum RH% during the experimental period in Figure 7 indicated that the plastic tunnel with evaporative cooling registered the highest values (65.2–74.2%) followed by the net tunnel with fogging (60.8–70.1%), net tunnel without cooling (49.3–59.0%) and finally the open field (46.3–58.2%).

3.2. Physiological and Biochemical Characteristics

Table 1 indicates that, in comparison to open-field cultivation, all studied physiological and biochemical characteristics of tomato plants including plant leaf area, RWC, MP, relative chlorophyll content and proline content significantly responded to the modification techniques in walk-in tunnels. When the plants were grown under the plastic modified tunnel with the evaporative cooling system, their leaf area was nearly doubled (223.8% and 214.8% in the first and second seasons, respectively, compared with the open field), recording the highest values. Additionally, modifying the net tunnel with a fogging system that operated throughout the hottest period of the day, from 10 a.m. to 4 p.m., was successful in enhancing leaf growth more than the un-fogged net tunnel. Meanwhile, plants grown in the open field without any protection produced the lowest leaf area.

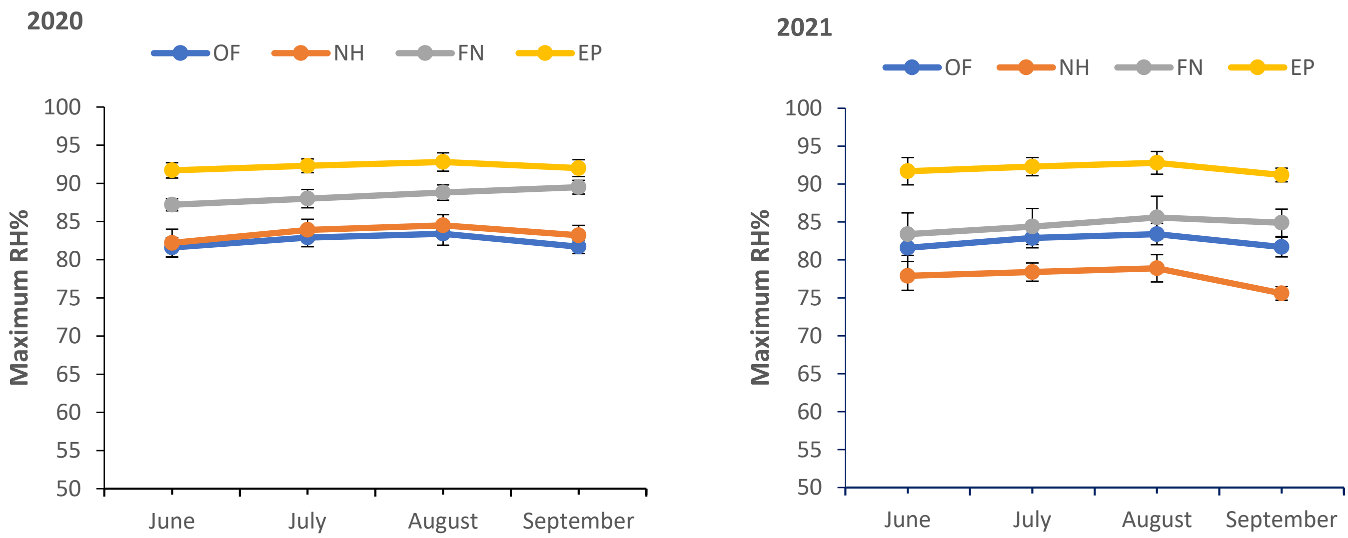

Figure 6. Average monthly maximum relative humidity percentage (RH%) during the experiment periods of 2020 and 2021 seasons, registered in the open field (OF), net house (NH), net house with fogging (NF, operating 6 S/36 S from 10 a.m. to 4 p.m.) and evaporative cooling under plastic house (EP). Standard error of the means was derived three biological replicates.

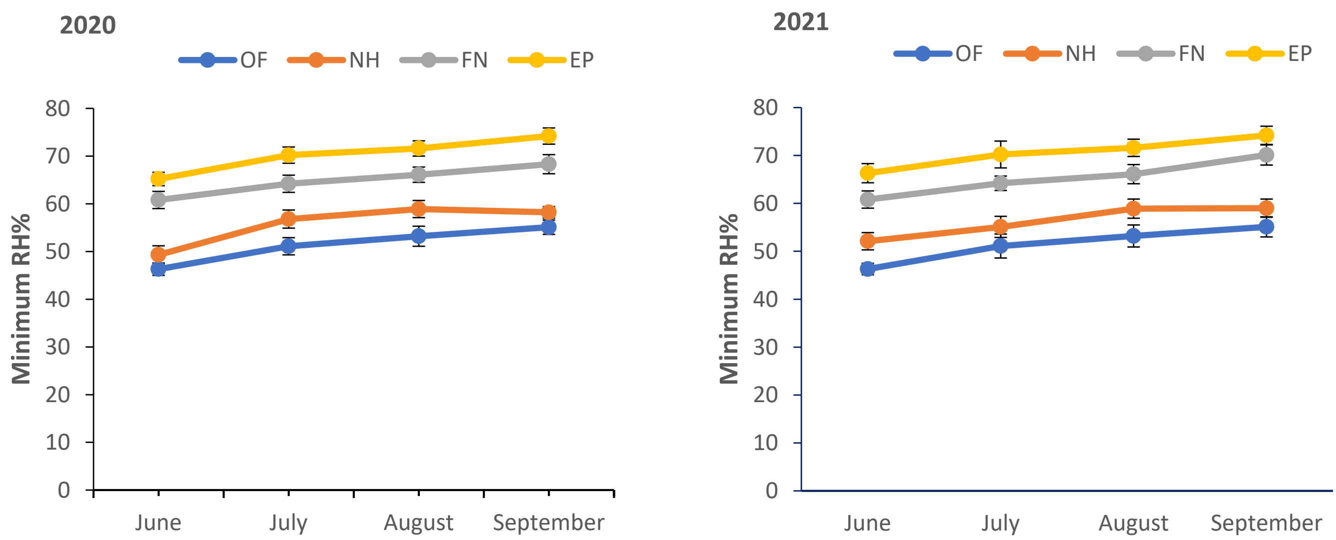

Figure 7. Average monthly minimum relative humidity percentage during the experimental periods of 2020 and 2021 seasons, registered in the open field (OF), net house (NH), net house with fogging (NF, operating 6 S/36 S from 10 a.m. to 4 p.m.) and evaporative cooling under plastic house (EP). Standard error of the means was derived from three biological replicates.

Plant leaf tissue showed a greater ability to hold more water when the microclimate under the tunnels was provided with moisture through fogging or evaporative systems or even with a plastic cover or net cover compared to the unmodified net tunnel or open-field growth (Table 1). Meanwhile, plant leaves that grew in the open field contained the lowest water content compared to the maximum water a leaf can retain (RWC). In the second season only, the differences between the open-field treatment and the un-fogging net tunnel were insignificant.

Leaf cells of the plants grown in the open field showed high membrane permeability compared to in the other studied cultivation protections (Table 1). It was highly effective to protect plants from heat stress to prevent damage to the membrane that could influence their permeability and result in the loss of their internal contents. In comparison to open-field growing, it showed up as decreased membrane permeability in plants cultivated under the net tunnel, net tunnel with fogging and plastic tunnel with an evaporative system, in that sequence.

Table 1. Changes in some physiological and biochemical traits in relation to reduced heat stress on grown tomato under modified walk-in tunnels compared to open-field growing.

Treatment #	Plant Leaf Area (m^2)	Relative Water Content (%)	Membrane Permeability (%)	Chlorophyll (SPAD)	Proline Content (μmol g^{-1})
2020 season					
Open field (OF)	7.02 ± 0.16 d	41.70 ± 0.25 d	15.62 ± 0.22 a	45.24 ± 0.04 d	0.72 ± 0.02 d
Net house (NH)	8.16 ± 0.75 c	53.20 ± 0.47 c	13.34 ± 0.17 b	46.19 ± 0.08 c	0.87 ± 0.03 c
NF	13.57 ± 0.43 b	62.99 ± 0.73 b	11.45 ± 0.06 c	47.29 ± 0.08 b	1.31 ± 0.05 b
EP	15.71 ± 0.19 a	69.65 ± 0.17 a	10.08 ± 0.06 d	49.02 ± 0.43 a	1.46 ± 0.02 a
2021 season					
Open field (OF)	7.43 ± 0.19 d	41.15 ± 0.42 d	14.28 ± 0.04 a	44.74 ± 0.07 d	0.63 ± 0.01 d
Net house (NH)	8.45 ± 0.09 c	49.94 ± 0.03 c	13.69 ± 0.79 a	46.66 ± 0.09 c	0.75 ± 0.02 c
NF	14.20 ± 0.36 b	56.94 ± 0.81 b	11.41 ± 0.16 b	47.49 ± 0.17 b	0.85 ± 0.03 b
EP	15.96 ± 0.12 a	66.25 ± 0.59 a	10.04 ± 0.10 c	48.43 ± 0.23 a	1.36 ± 0.03 a

NH = net house covered by white mesh insect-proof net with 35% shade level, NF = net house with fogging (operating 6 S/36 S from 10 a.m. to 4 p.m.) and EP = evaporative cooling under plastic house. Different letters in the same column indicate that means are significantly different ($p \leq 0.05$). Standard error of the means was derived from three biological replicates.

In the case of the proline content of the leaf as an indicator of stress resistance, there was a significant increase in its content in the plants grown under the plastic tunnel with an evaporative cooling system, net tunnel with a fogging system and net tunnel without fogging, in order, whereas the lowest content was found in the plants grown under open-field conditions. These results were true for both growing seasons.

3.3. Flowering and Fruit Yield

As a sensitive indicator of the impact of heat stress on the flower, stigma exsertion was considered (Figures 8 and 9). Although exserted stigmas were not detectable in the modified tunnels by fogging under net cover and evaporative cooling under plastic cover, they were clearly observable under open-field conditions without any protection from the elevated temperature. They appeared in plants grown under the net tunnel without positive cooling with a lower incidence compared to the open-field plants. In the open field, their percentage ranged between 10.3 and 11.4%, whereas in the plants cultivated in net tunnels without cooling, they were between 0.95 and 1.02%.

An increase in fruit set percentage during the peak blooming and fruit set stages was observed from the cultivated plants under different modified tunnels compared to open-field cultivation in both growing seasons (Table 2). This increase reached about 33.5% with evaporative cooling under the plastic tunnel, 30% with fogging cooling under the net tunnel and 17.5% with the uncooled net tunnel more than the open field. The differences were significant ($p \leq 0.05$) in both growing seasons.

Positive cooling (requiring an energy source, which was solar energy in the current study) throughout evaporative or fogging systems effectively enhanced fruit weight when compared to the uncooled net tunnel and open-field cultivation (Table 2), since evaporative cooling under the plastic tunnel had the highest value (87.6–89.1 g). Nevertheless, open-field cultivation produced the lowest fruit weight (71.6–72.3 g). These results are true and significant in both growing seasons.

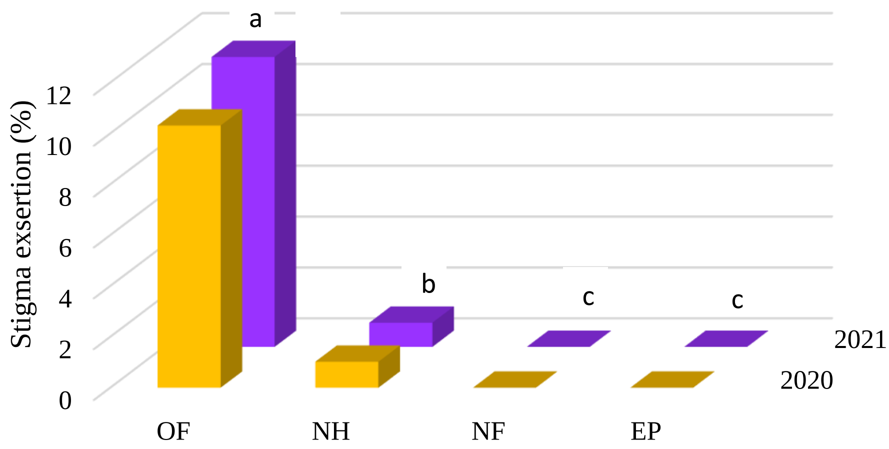

Figure 8. The percentage of flowers with exserted stigmas during the peak flowering period in relation to reduced heat stress by modifying walk-in tunnels (net house, NH; net house with fogging, NF, operating 6 S/36 S from 10 a.m. to 4 p.m.; and evaporative cooling under plastic house, EP) compared to open-field growing (OF). Different letters above the bars indicate that means are significantly different ($p \leq 0.05$). Presented data are the mean of 3 biological replicates, each with 5 plants.

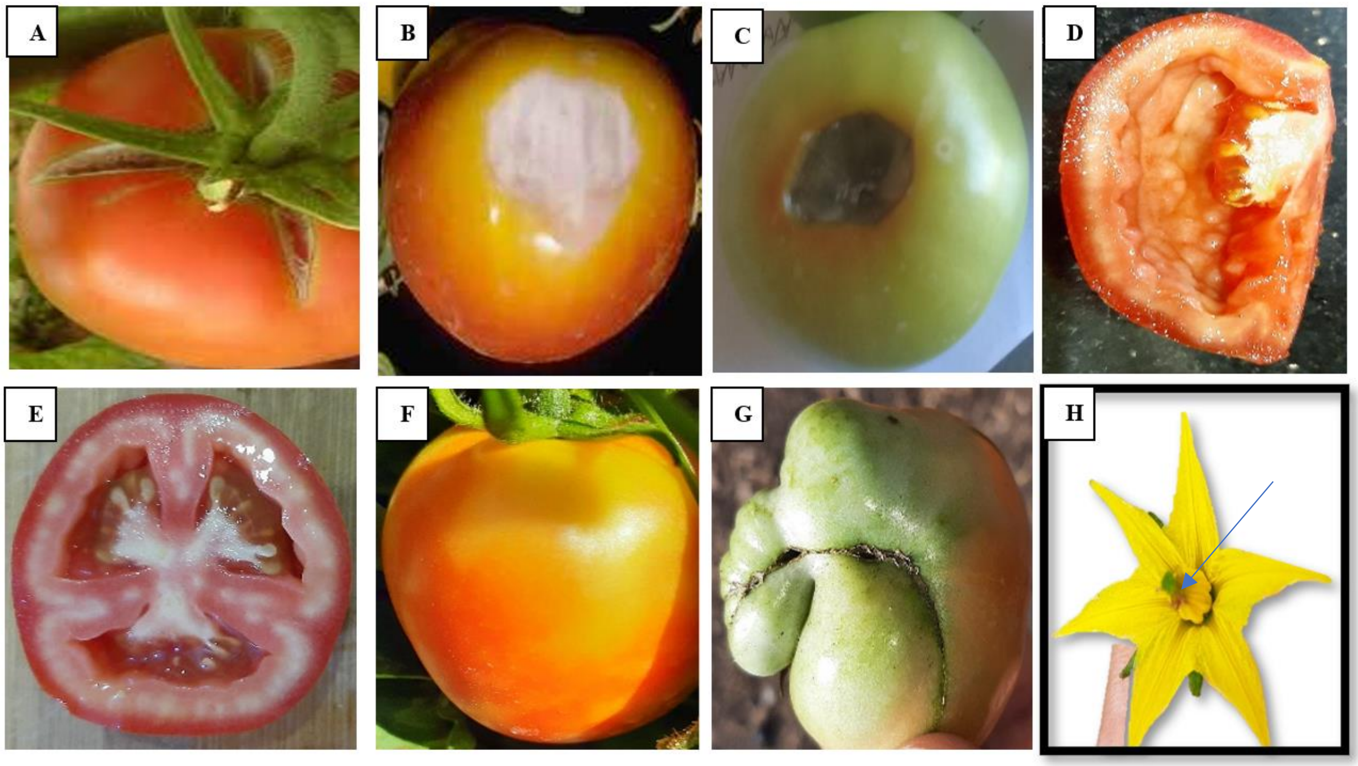

Figure 9. Common physiological diseases during the experiment ((**A**) cracking, (**B**) sunscald, (**C**) blossom-end rot, (**D**) puffiness, (**E**) white internal tissue, (**F**) blotchy ripping, (**G**) cat face and (**H**) exserted stigma).

Cooling treatments using evaporative and fogging techniques reflected a significant increase in marketable fruit yield as a percentage of the total yield compared to open-field cultivation in both growing seasons (Table 2). However, the differences between the two cooling methods were significant only in the second season. When compared to an open field, the percentage of marketable yield rose by around 31.5% with an evaporative cooling system and by 28.8% with a fogging system. With no positive cooling, the shaded net tunnel had intermediate values that were 17% higher than the open field. Modifying microclimate conditions by evaporative or fogging cooling or shade significantly reduced the percentage of physiological diseases in both growing seasons (Table 2). Compared to the open field, the percentage was decreased by 19.4, 17.3 and 12.4%, respectively.

Table 2. Modified walk-in tunnels compared to open-field cultivation to reduce heat stress on tomato plant affecting fruit set, fruit weight, percentages of marketable yield and fruit disorders of tomato.

Treatment #	Fruit Set %	Average Fruit Weight (g)	Marketable Yield	Disorder Fruits
			As Percentage of the Total Yield	
		2020 season		
Open field (OF)	51.0 ± 0.52 d	71.6 ± 0.94 c	55.7 ± 1.19 c	25.0 ± 0.82 a
Net house (NH)	69.2 ± 0.43 c	77.2 ± 1.07 b	72.7 ± 0.72 b	12.7 ± 0.27 b
NF	80.7 ± 0.76 b	84.7 ± 0.56 a	85.0 ± 0.98 a	8.0 ± 0.19 c
EP	84.9 ± 1.63 a	87.6 ± 1.28 a	86.9 ± 0.52 a	6.0 ± 0.33 d
		2021 season		
Open field (OF)	51.9 ± 0.14 d	72.3 ± 0.49 c	55.4 ± 0.38 d	24.7 ± 0.19 a
Net house (NH)	69.0 ± 0.55 c	78.1 ± 0.49 b	72.8 ± 0.61 c	12.2 ± 0.32 b
NF	83.7 ± 1.09 b	86.8 ± 0.86 a	83.7 ± 1.77 b	7.1 ± 0.26 c
EP	85.4 ± 1.48 a	89.1 ± 1.19 a	87.0 ± 0.73 a	5.1 ± 0.06 d

NH = net house covered by white mesh insect-proof net with 35% shade level, NF = net house with fogging (operating 6 S/36 S h from 10 a.m. to 4 p.m.) and EP = evaporative cooling under plastic house. Different letters in the same column indicate that means are significantly different ($p \leq 0.05$). Standard error of the means was derived from three biological replicates.

The most common physiological diseases that were detected in the experiment are shown in Figure 9. They can be summarised as follows: fruit cracking, sunscald, blossom-end rot, puffiness, white internal tissue, blotchy ripping, cat face and exserted stigma. In both growing seasons, heat stress under open-field conditions led to a significant increase in all abovementioned physiological disorders in comparison to the other types of protection techniques (Table 3). The highest incident disorders in the open field were sunscald, blossom-end rot, cracking, white internal tissue, cracking, puffiness, blotchy ripping and cat face, in order, whereas the studied treatments did not significantly differ in the incidence of the cat face defect. Under the uncooled net tunnel, they appeared as follows: blossom-end rot, white internal tissue, cracking, sunscald, puffiness, blotchy ripping and finally cat face. All fruit disorders were the lowest under positive cooling via evaporative and fogging either with a plastic or net cover, with no visible signs of sunscald, and the incidence of fruit physiological disorders was lower under evaporative than fogging cooling. The covered tunnel with a white mesh net had intermediate values between open-field cultivation and the cooled tunnels.

3.4. Fruit Yield

Data about total and marketable fruit yields are shown in Figure 10. All protected cultivation techniques significantly increased total and marketable yields compared with open-field cultivation in both growing seasons. The plastic tunnel with an evaporative cooling system produced the highest yield, reaching 3.6 kg/plant as the marketable yield and 4.2 kg/plant as the total yield, compared to 1.1 kg/plant as the marketable yield and 2.1 as total kg/plant in open-field cultivation. Plant marketable yield increased by 1.0 kg and total yield increased by 1.2 kg when the net tunnel was supplied with the fogging system.

Table 3. Effect of modified walk-in tunnels compared to open field on common fruit disorders of tomato (as a percentage of total yield).

Treatment #	Cracking	Sunscald	BER *	Puffiness	IWT ^	Blotchy	Cat Face
			2020 season				
Open field (OF)	3.20 ± 0.06 a	8.47 ± 0.46 a	6.33 ± 0.06 a	1.58 ± 0.20 a	3.26 ± 0.04 a	1.17 ± 0.02 a	1.00 ± 0.01 a
Net house (NH)	1.68 ± 0.13 b	1.43 ± 0.04 b	4.11 ± 0.05 b	1.11 ± 0.01 b	2.31 ± 0.01 b	1.03 ± 0.03 b	1.00 ± 0.01 a
NF	0.78 ± 0.02 c	0.00 ± 0.00 c	2.20 ± 0.05 c	1.10 ± 0.01 b	1.88 ± 0.08 c	0.81 ± 0.03 c	1.02 ± 0.01 a
EP	0.49 ± 0.15 c	0.00 ± 0.00 c	1.94 ± 0.03 d	1.00 ± 0.03 b	0.81 ± 0.09 d	0.71 ± 0.06 d	0.92 ± 0.03 a
			2021 season				
Open field (OF)	2.65 ± 0.08 a	10.96 ± 0.03 a	3.27 ± 0.20 a	1.78 ± 0.23 a	2.64 ± 0.14 a	2.99 ± 0.09 a	1.04 ± 0.02 a
Net house (NH)	2.63 ± 0.02 a	0.00 ± 0.00 b	3.07 ± 0.04 a	1.47 ± 0.05 a	2.55 ± 0.06 a	2.91 ± 0.05 a	1.04 ± 0.02 a
NF	1.66 ± 0.06 b	0.00 ± 0.00 b	1.79 ± 0.05 b	0.98 ± 0.02 b	1.90 ± 0.05 b	1.68 ± 0.10 b	1.00 ± 0.01 a
EP	1.44 ± 0.06 c	0.00 ± 0.00 b	1.61 ± 0.05 b	0.79 ± 0.07 b	1.72 ± 0.03 b	1.35 ± 0.07 c	1.02 ± 0.01 a

NH = net. house covered by white mesh insect-proof net with 35% shade level, NF = net house with fogging (operating 6 S/36 S from 10 a.m. to 4 p.m.) and EP = evaporative cooling under plastic house. * BER = blossom-end rot. ^ IWT = internal white tissue. Different letters in the same column indicate that means are significantly different ($p \leq 0.05$). Standard error of the means was derived from three biological replicates.

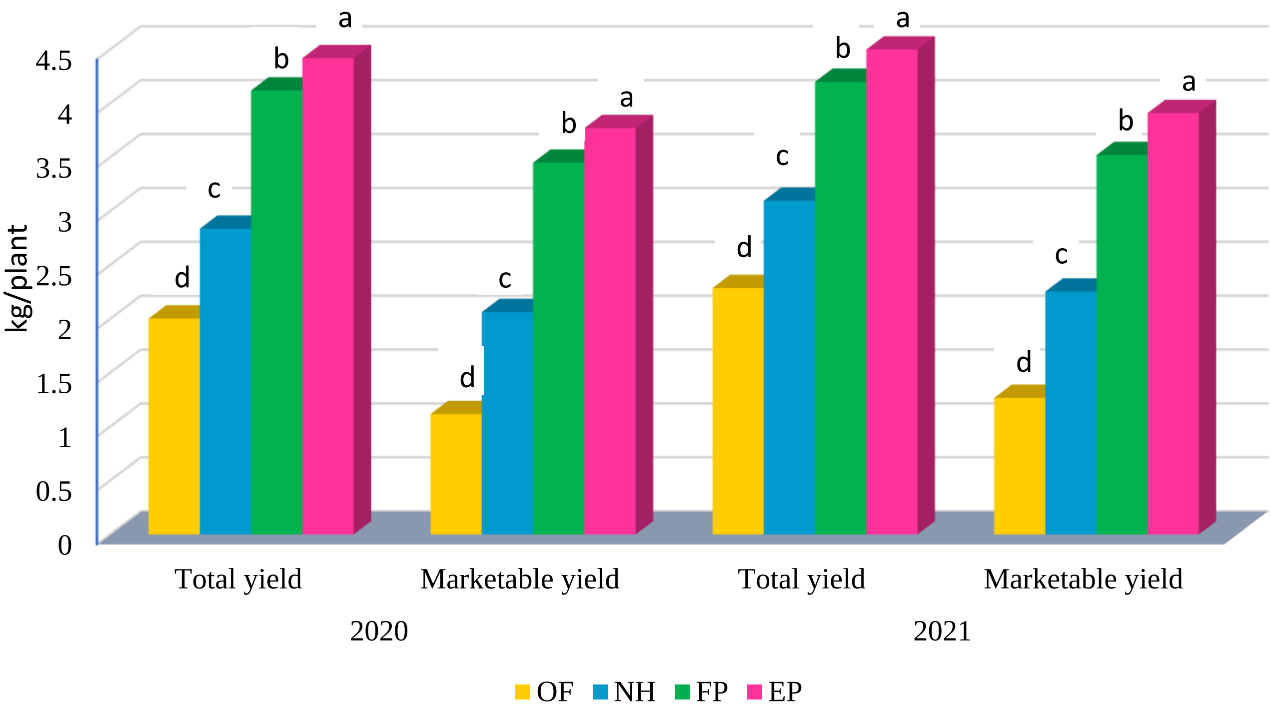

Figure 10. Total and marketable fruit yields of tomato in the open field (OF), net house (NH), net house with fogging (NF) operating 6 S/36 S from 10 a.m. to 4 p.m. and evaporative cooling under plastic house (EP). Different letters above the bars indicate that means are significantly different ($p \leq 0.05$). Presented data are the mean of 3 biological replicates.

4. Discussion

In the current study, we tried to suggest various solutions for the reduction in tomato growth, productivity and quality during the late summer season due to abiotic and biotic stresses, particularly with the severe effects of climate change. Since protected cultivation is the most crucial agricultural technique to protect grown plants from adverse climate changes and pest attacks, it contributes to improving the quality and productivity of plants. Although greenhouses offer the optimum solution to cope with these challenges, they require high technology and financial ability, which are unsuitable for small farmers and developing countries. Low and high tunnels produce a low-cost option without complex technologies compared to greenhouses, but we still need to develop agricultural production strategies to accommodate different farmers' abilities and maximise resource utilisation. Walk-in tunnels have an intermediate height between low and high tunnels that is enough for the workers to manage agricultural practices inside them at a lower cost than in high tunnels. In order to protect the plants from heat and biotic stresses in the late summer season, we investigated tomato production in our study under three types of walk-in tunnels, which are thought to suit different farmers' abilities in comparison with open-field cultivation.

The current results indicate that the shaded tunnel, which is suitable for small farmers, successfully reduced the inside temperature and increased RH% compared to open-field cultivation. However, the fogging system under the shaded tunnel had more efficiency in modifying microclimate conditions. These results are supported by those of [31]. In the hot-summer regions, it was reported that shade alone cannot lower the interior temperature and raise the humidity to levels that are appropriate for plants [8]. According to Abdel-Ghany et al. [23], the shading method effectively reduces solar radiation, but it also reduces photosynthetic radiation, which is important for plant development. It can be the reason for the lower growth and yield of the shaded tunnel without cooling techniques than the modified ones. Sethi and Sharma [38] demonstrated that ventilation systems can operate effectively in conditions of moderate air temperature. In contrast, ventilation systems (natural or forced) cannot function well in areas with high air temperatures and low humidity because they replace the interior air with the hotter ambient air. As a result, ventilation systems rarely cool greenhouses or provide good conditions for plant development [23]. The effectiveness of evaporative cooling systems (wet pad and fans), which are suitable for farmers with higher financial ability, in lowering ambient temperatures and raising air humidity to the desired range for the plant can be linked to the current study's positive outcomes. Evaporative cooling has been proven as the most effective cooling system for regulating the temperature and humidity under protected cultivation in arid regions [39,40]. The alternative is a fogging system, which is also successfully used in arid regions [28,41]. However, in order to wet the pad or create fog, they both need fresh water [27]. Here, we effectively utilised solar energy system for tunnel cooling, which has future prospects in protected cultivation in hot arid climates with minimal environmental effects and maximum utilisation of natural resources [30].

The improvement of physiological and biochemical parameters in relation to protected cultivation methods could be attributed to the amelioration of heat stress compared to open-field cultivation. When plants suffer from extremely high air temperature and low humidity under an open field without protection, it could harm the plants' biochemical and physiological functions [42,43]. Some research stated that tomato photoinhibition can happen between 30 and 40 °C and elevated radiation can occur between 1500 and 1800 mol m^{-2} s^{-1} [44,45]. The damage in physiological and biochemical processes could be attributed to the correlation between high temperature and accelerated senescence [46]. Thus, mesophyll cells underwent considerable damage from heat stress, and the increased permeability of the plasma membrane led to a decrease in stomatal conductance [47]. It is also reported that proline content, chlorophyll (SPAD) and the photosynthetic rate of tomato leaf were reduced under heat stress (45 °C) compared to under an un-stressful temperature of 25 °C; however, electrolyte leakage (membrane permeability) was increased [43]. In response to biotic and abiotic stressors, proline, a non-enzymatic antioxidant, accumulates, playing a beneficial role in metal chelation, antioxidant defense and signalling [48]. It also assists in maintaining membrane stability, osmotic adjustment or cell turgor and protects essential enzymes while reducing the negative effects of ROS and electrolyte leakage [49,50]. Our results support these findings since the higher concentration of protein under protected cultivation helps to maintain water content and cellular membrane permeability as preventing electrolyte leakage is associated with high leaf area and chlorophyll content.

Our results about the favourable effect of cooling the tunnels on tomato growth are supported by those of Sharaf-Eldin [51] and Leyva et al. [33] with shading and fogging techniques on tomato plant and Al-Helal [40] with evaporative cooling. It was also noted that reduced light intensity improved tomato growth and yield in the summer season. Mist application has an effective role in alleviating the negative effect of the double stress of salinity and high temperature on tomato plant, consistent with Romero-Aranda et al.'s [52] finding that intermittent misting for grown tomato under salinity and high-temperature conditions enhanced total leaf area and plant biomass. These findings can help to explain the beneficial effects of fog cooling on plant growth, which were also observed at our experiment site under salinity and elevated temperature. While under open-field cultivation without protection, the plants' leaf area reduced dramatically, indicating a drop in plant growth (Table 1). This reduction can be attributed to the physiological and biological leaf rolls due to severe heat stress and pest infection under unprotected cultivation, which were reflected in small leaf size. The curled, small-size leaf is a reaction from the plant to decrease water transpiration, thus ameliorating the negative impact of heat, light and drought [53,54].

The indirect response to heat stress was tomato flower stigma exsertion (Figure 8). These findings are supported by those of [55–57]. Stigma exsertion obviously appeared in open-field growing under severe heat stress and decreased under shaded, fogged and evaporative cooling tunnels, in order. The severity of this phenomenon relates to the reaction between the genotype and heat stress harshness as an indirect response of pistil development where the style is forced out of the anther tube and results in stigma insertion. In this situation, the stigma cannot be reached by the pollen, preventing successful fertilisation [58]. This is because the male function of tomato flower is generally more exposed to damage than the female one under heat stress [59–61]. Furthermore, Ozores-Hampton [62] indicated that stigma-drying of tomato female flower can also happen when the plants suffer from heat stress. Moreover, it was stated that the initial stages of stamen development are most susceptible to heat stress. In this way, heat inhibits pollen release and transfer to the stigma surface, pollen tube development and fertilisation, which all have a negative impact on pollen viability and quantity, leading to poor fruit set [63,64]. Accordingly, the suppression of fertilisation activity was caused by a decrease in the consistency of seeds, which are thought to be the source of auxin, which increases fruit size through cell division and enlargement [65].

A high occurrence of physiological diseases was obviously noticed in the open field without protection from heat stress compared to the modified tunnels throughout cooling systems (Table 3). The high incidence of sunscalds in the open field may be related to the limited plant leaf area (Table 1), which is unable to adequately cover the fruits and protect them from the intense sun radiation. The leak of fertiliser besides the heat stress in the open field was reported as a reason for puffiness and cat face as per the reported research [66], and the authors monitored tomato physiological disorders in relation to climate warming in Turkey as cat face, scalded, blossom-end rot and cracks increased under non-protected cultivation. However, in the current study, the noticed diseases were blossom-end rot, cracking, internal white tissues, sunscald, puffiness, blotchy ripening and cat face (Figure 9). In Swaziland, blossom-end rot, cat face, cracking, internal white tissue, irregular ripening, puffiness, pox and fleck, rain check, zippering and sunscald were encountered [67]. When pepper plants were irrigated with saline water, a high percentage of blossom-end rot was reported; however, fogging application increased the relative humidity, causing a considerable decrease in infected fruits [31]. These results are in harmony with the current results. In contrast, Gazquez et al. [68] obtained a higher percentage of blossom-end rot with fogging application than un-fogging, which was accompanied by a lower respiration rate under fogging. High air humidity can cause the respiration rate to slow down, which can lead to calcium deficiencies in the fruit, which are known to induce blossom-end rot [69]. The variable salinity conditions that might enhance calcium deficiency when heat and water stresses are present may be the cause of these conflicting findings.

The increased fruit production under tunnel cultivation can be attributed to the high use efficiency of resources and their role in protecting the plant against pest attacks and indirect viral infection. Additionally, with the proper modifications, the tunnels shield plants from the harmful effects of elevated temperatures and low humidity, which can lead to better growth and fruiting with less physiological diseases [19,51]. It is possible that the beneficial effects of fogging and evaporative cooling on tomato production are owed to the high relative humidity's ability to counteract the adverse effects of the salinity that was present at the experiment location and is common in the Mediterranean region. This trend is supported by the obtained results of Romero-Aranda et al. [52] who reported that fruit yield increased by 18% when intermittent misting was applied on grown tomato under saline conditions and high air temperature (36 °C as maximum) with respect to non-misted application, which was attributed to the increase in relative humidity with the mist treatment. Otherwise, Moreno-Teruel et al. [70] indicated that providing a greenhouse with a fogging system along with natural ventilation decreased the yield in comparison to a pad–fan cooling system and only natural ventilation without a cooling system. However, the pad–fan cooling system achieved the highest fruit yield.

5. Conclusions

The obtained findings lead to the following conclusions:

- A solar energy system, which can be used in arid dry regions, successfully operated the cooling systems under the modified walk-in tunnels via fogging and evaporative cooling.
- The studied cooling techniques effectively improved the microclimate conditions by significantly reducing the average monthly maximum temperatures by 2.5 °C with the uncooled net tunnel, 5.6 °C with fogging under the net tunnel and 9.4 °C with evaporative cooling under the plastic tunnel. Moreover, evaporative cooling kept the temperature around 25 °C.
- The tunnels with evaporative cooling and fogging systems significantly improved plant leaf area, water relative content, chlorophyll, membrane functions and proline content compared to the uncooled net tunnel. Moreover, better pollination and fertilisation functions with high fruit set were gained. In constrast, unprotected cultivation had the worst values.
- The percentage of marketable fruit yield increased by around 31.5% with evaporative cooling, 28.8% with the fogging system and 17% with the shaded net tunnel with no positive cooling as compared to an open field. Moreover, the physiological disease percentage decreased by 19.4, 17.3 and 12.4%, respectively.

In brief, the current study developed different eco-friendly techniques for tomato production that are suitable for various farmers' abilities to cope with climate warming. Further studies are needed to adapt agriculture techniques for various crops for climate change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae9010077/s1, Figure S1. Back-side of walk-in tunnel with evaporative cooling system (left) and air cycle system (right). Figure S2. Evaporative cooling system design.

Author Contributions: Conceptualisation, M.A.S.-E., Z.M.Y. and S.E.; Data curation, A.H.E. and G.F.O.; Formal analysis, M.A.S.-E., Z.M.Y., A.H.E., S.E., M.S. and Z.A.-K.; Investigation, A.H.E., S.E. and G.F.O.; Project administration, Z.M.Y.; Resources, G.F.O.; Supervision, Z.M.Y. and M.S.; Validation, M.A.S.-E., Z.M.Y., A.H.E., S.E., M.S. and Z.A.-K.; Visualisation, Z.M.Y., A.H.E., S.E. and G.F.O.; Writing—original draft, M.A.S.-E., A.H.E., S.E., M.S. and Z.A.-K.; Writing—review & editing, M.A.S.-E., Z.M.Y., M.S., Z.A.-K. and G.F.O. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported predominantly by WATERAGRI (European Union Horizon 2020 research and innovation programme under Grant Agreement Number 858735). In addition, the authors acknowledge the facility support by Al-Mustaqbal University College for providing technical and financial support for this research through the Grant Number: MUC-E-0122.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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