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The Influence of Different Cooling Systems on the Microclimate, Photosynthetic Activity and Yield of a Tomato Crops (*Lycopersicum esculentum* Mill.) in Mediterranean Greenhouses

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Abstract: The purpose of this study was to analyse the effect of different evaporative cooling systems compared to natural ventilation on the microclimate, photosynthetic activity and yield of a tomato crop (*Lycopersicum esculentum* Mill.) in a spring-summer cycle. In this study, the expenditure of electricity and water caused by the different refrigeration systems and their economic cost was analysed. The study was carried out in three multi-span greenhouses: (i) a greenhouse with evaporative pads and fans and natural ventilation (PS + NV); (ii) a greenhouse with a fog system and natural ventilation (FS + NV); (iii) a greenhouse only with natural ventilation (NV). The photosynthetic activity was higher in the greenhouse with natural ventilation (14.7 µmol CO_2 m^{-2} s^{-1}) than in the greenhouse with the pad-fan system (14.6 µmol CO_2 m^{-2} s^{-1}; without a statistically significant difference) and in the greenhouse with fog system (13.4 µmol CO_2 m^{-2} s^{-1}; with a statistically significant difference). The production was higher in the greenhouse with the pad-fan system (5.0 kg m^{-2}) than in the greenhouse with natural ventilation (4.8 kg m^{-2}; without a statistically significant difference) and in the greenhouse with a fog system (4.5 kg m^{-2}; with a statistically significant difference). In general, photosynthetic activity and crop production increased as the maximum temperature (and the number of hours of exposure to high temperatures) decreased. It has been observed that the improvement in temperature conditions inside the greenhouses in spring-summer cycles produces increases in the photosynthetic activity of the tomato crop and, consequently, growth in production. The energy and water consumption derived from the use of active-type cooling systems have not been offset by a representative improvement in photosynthetic activity or crop production.

Keywords: protected crops; ventilation; evaporative systems; photosynthesis; yield

1. Introduction

Photosynthesis is the main physiological process that drives plant growth and crop productivity. This physiological process is heavily influenced by environmental conditions [1]. Air temperature affects not only growth but also nitrogen metabolism in tomato plants, which is related to photosynthetic activity [2]. For most horticultural crops, its yield is adequate in a wide range of temperatures, although the net photosynthesis balance decreases when temperature increases excessively due to a rise in respiration. An augmentation in temperature between 5 and 10 °C above the optimum can produce a notable impact on net photosynthesis [3], which is closely related to crop yields and can be an important variable when selecting one variety or another of cultivation [4].

The average temperature is fundamental in the development of tomato crops, since at average daily temperatures of 29 °C, the number of fruits, the percentage of fruiting and the weight of the fruits per plant decreases compared to tomatoes grown at 25 °C. This reduction in yield is mainly due to reduced pollen viability by excess temperature [5,6]. Another climatic factor that influences the yield of the tomato crop, more specifically the viability of the pollen, is the relative humidity inside the greenhouses. Relative humidity between 50–70% is considered optimal for tomato pollination, although high relative humidity values close to 90% can decrease the viability of heat stress pollen [7].

In the Mediterranean area, the excess temperature from spring to autumn can damage the yield of crops [8]. For this reason, it is necessary to reduce the temperature inside the greenhouses. The cooling system to be chosen will depend on the climatic conditions, the technology, and the available resources [9]. The greenhouses in the province of Almeria (Spain) that use evaporative-cooling systems are around 20%. The most used is the fog system due to the peculiarities of the greenhouses already built, such as the excessive width and lack of hermeticity [10]. Water evaporative cooling systems are also associated with an increase in relative humidity inside the greenhouse, being desirable in dry climate zones [11,12]. The combination of the reduction in temperature and the increase in relative humidity makes cooling systems more efficient than other climatic controls systems such as shading or forced ventilation [13]. Fog systems are less efficient than evaporative pad-fans systems [14]. However, their lower installation cost makes them more attractive for use in greenhouses [13]. The use of evaporative pad-fan systems normally produces non-uniform climatic conditions [13]. Significant temperature gradients of around 0.13–0.27 °C m^{-1} have been observed in the direction of airflow [15].

Although more and more active refrigeration systems are being implemented inside the greenhouses, the reality is that practically all farmers in Almeria develop their crops in greenhouses whose only method of climate control is natural ventilation. At present, the existing ventilation surface in the greenhouses of Almeria is around 15%. This average value is below the real needs in a greenhouse with insect-proof screens. Recommended ventilation surface values in greenhouses without insect-proof nets vary between 15 and 25% of the soil surface [16]. These percentages should be increased to compensate for the decrease of ventilation capacity when insect-proof nets are used [10]. Efficient natural ventilation of greenhouses is crucial to maintain suitable microclimatic conditions for crops and to promote photosynthetic activity, being especially important if the outside temperature, global radiation and indoor humidity have high values [10].

The net rate of photosynthesis increases with the rise of the concentration of CO_2 in a range between 0 and 1000 µmol mol^{-1} [17]. Therefore, the concentration of CO_2 in greenhouses can be increased during the day, using CO_2 enrichment techniques, up to about 1000 µmol mol^{-1} to promote photosynthesis and plant growth inside greenhouses [18,19]. In the absence of this CO_2 enrichment, net rates of photosynthesis may increase, enhancing air circulation by natural ventilation [20,21], allowing the entry of CO_2 from the outside to compensate for the CO_2 consumed by plants. The optimal air circulation depends on the plant species, plant structure, canopy depth and wind direction with respect to the position of the plant in greenhouses [22,23]. On the other hand, insufficient air circulation above the plant canopy causes limited gas exchange due to the increased strength of the leaf boundary layer [24,25].

Cooling greenhouses by means of water evaporative cooling systems implies greater energy and water consumption than the use of the natural ventilation system.

According to Franco et al. [26], despite the existence of higher water consumption in the evaporator panel system, the crop requires less irrigation [27] since its transpiration rate decreases by 31%. Therefore, the total increase in the water requirement is only 19% [15].

The objective of this work was to determine the influence that different refrigeration systems exert on the inside microclimate, the photosynthetic activity, and the production of a tomato crop in a greenhouse. Two water evaporation cooling systems combined with natural ventilation were compared with exclusive natural ventilation.

2. Materials and Methods

2.1. Characteristics of Experimental Greenhouses

The research was carried out in three multi-span greenhouses with NW-SE orientation (Figure 1), located in the experimental farm UAL-ANECOOP "Catedrático Eduardo Fernández" of the University of Almeria (36°51′ N, 2°16′ W and 87 m.a.s.l.). The greenhouses were divided transversely by a polyethylene wall, separating the east sector from the west sector.

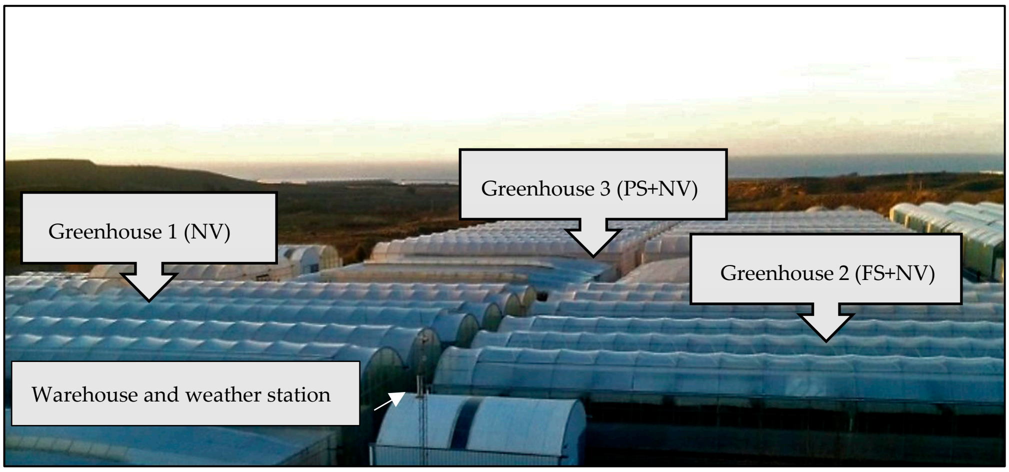

Figure 1. Panoramic view of the experimental greenhouses. Natural ventilation (NV), fog system (FS + NV) and evaporative pads and fans system (PS + NV).

For our trial, we used the experimental sectors located in the east of each greenhouse (Table 1). The west sectors were used for other research work, being the same crop in the two sectors of the greenhouses. Greenhouse 1 consisted of two spans 9 m wide, with two roof windows and two side openings. Greenhouses 2 and 3 have three spans 8 m wide, with three roof windows. While greenhouse 2 has two side openings, greenhouse 3 had a cellulose pad at the south wall and eight fans at the north wall (evaporative pads and fans system).

Table 1. Characteristics of the east sectors of each experimental greenhouse. Total length L_G and width W_G (m), width of each span w_S (m), maximum height of the span h_{max} (m), gutter height h_{gut} (m), surface area S_C (m^2), side ventilation surface S_{VS} (m^2), roof ventilation surface S_{VR} (m^2) and total ventilation surface area S_V/S_C (%).

Greenhouse	Cooling Systems	$L_G \times W_G$	w_S	h_{max}	h_{gut}	S_C	S_{VS}	S_{VR}	S_V/S_C
1	Natural ventilation (NV)	18 × 25	9	6.6	4.6	450	40.5	45.0	19.0
2	Fog system (FS + NV)	24 × 25	8	6.2	4.6	600	34.5	67.5	17.0
3	Pad-fan system (PS + NV)	24 × 25	8	6.2	4.6	600	-	67.5	11.3

The sidewalls of the greenhouses were made up of corrugated sheets of rigid polycarbonate, while for the roof of the greenhouses, a three-layer *Triplast* plastic cover (PE-EVA-PE) of 0.2 mm thickness (Plastimer-Morero and Vallejo Industrial, Almería, Spain) was used. The manufacturer described the technical characteristics of the cover as diffuse colourless, 85% transmittance to visible light, 50% transmittance to diffuse light and 8% transmittance to infrared light. All side and roof openings were protected using insect-proof nets with a density of 10 × 20 threads cm^{-2} and a porosity of 36.0%.

The sector east of the experimental greenhouse 1 was used as control, with only natural ventilation as a climate control method (Table 1). The east sector of greenhouse 2, in addition to natural ventilation, had a low-pressure air/water mist system Clima-Fun (Mondragón Solutions, Albuixech, Spain). It was composed of a network of pipes placed at 4.6 m high and with a nozzle for every 12 m^2. The air was supplied by a rotary screw compressor RTA10-8 (Puska Pneumatic®, Vizcaya, Spain) with a power of 7.5 kW, working pressure of 8 bar and airflow of 1.12 L min^{-1}. The water reaches the system with a 1.7 kW pump PRISMA 5M (ESPA, Innovate Solutions, Gerona, Spain).

The sector east of greenhouse 3, has natural ventilation by roof openings and pads-fans cooling system. The cooling system was compound of an evaporator pad (dimensions 1.9 × 22.5 m^2) CELdek 7090-15 (Munters Spain®, Madrid, Spain) 10 cm thick located in the southern wall of the greenhouse. On the northern wall of the greenhouse, there were eight fans EM50d (Munters Spain®, Madrid, Spain) of 735 W of power with a nominal flow of 32,500 m^3 h^{-1} (for a pressure difference of 25 Pa). The water is supplied by a PRISMA 4 M pump (ESPA, Innovate Solutions, Gerona, Spain; 1.4 kW) from a 5000 L main tank located in the near warehouse to a tank located near the evaporator panel, from there it is pumped to the panel by a submersible pumps LOWARA -DOC 76 (ITT Corporation, Lowara SRL, Montecchio Maggiore, Italy). In this case, the natural ventilation and the cooling system do not work simultaneously since when the pad-fan was activated, the roof openings were closed.

A MultiMa Series II climate controller (Hortimax SL, Almería, Spain) connected to a weather station, and microclimate measuring boxes located inside the experimental sectors (Table 2) managed the different climate control systems.

Table 2. Characteristics of microclimate measurement equipment.

Parameters	Sensor	Manufacturer	Range	Accuracy
Outdoor climatic parameters measured at the weather station located at 9 m height				
Solar radiation	Kipp Solari	HortiMax B.V. (Maasdiijk, Netherlands)	±2000 W m^{-2}	±5%
Wind speed	Anemómetro—MII		0–40 m s^{-1}	±5%
Wind direction	Veleta Meteostation II		0–360°	±5°
Air temperature	Pt1000 IEC 751 1/3B	Vaisala Oyj (Helsinki, Finland)	−25–75 °C	±0.2 °C
Air humidity	HUMICAP HMT100		0–100%	±2.5%
Indoor climatic parameters measured at 2 m height				
Air temperature	Pt1000 Clase A—Ektron III	Elektronik Ges. M.b.H. (Engerwitzdorf, Austria)	−10–60 °C	±0.6 °C
Air humidity	EE07-04 PFT6—Ektron III		0–100%	±2%

Vent openings were managed depending on the climatic conditions. They would open when the inside air temperature rose above 20 °C and close when the wind speed exceeded 8 m s^{-1}, to avoid structural damage to the greenhouses. The pad-fan system was activated when the inside temperature was 10 °C above the outside temperature. The fog system was activated two hours after sunrise and stopped two hours before sunset, at intervals of 10 min.

The control of electricity consumption was carried out by means of three single-phase electricity meters for single-phase low-voltage networks with digital display, model MK-30-LCD-RS485 (Circutor SA, Spain) and seven three-phase energy meters EDMk (Circutor SA, Spain). The control of the water consumption used in each of the two refrigeration systems was determined by means of two MTK-HWV Class B multiple jet meters (Geconta SL, Spain), with a nominal flow of 2.5 m^3 h^{-1}, a maximum flow rate of 5 m^3 h^{-1}, an accuracy of 0.0001 m^3 and a pressure drop of 0.25 bar.

2.2. Crop System

A tomato crop (*Lycopersicum esculentum* Mill.) of the "Marenza" variety (Enza Zaden España S.L., Sta. María del Águila, Spain) was transplanted in April 2013 (density of 1 plant m^{-2}) in artisanal crop bags (30 × 30 cm^2) and 13 m long. The artisanal crop bags were located transversely to the roof of the greenhouse. The type of substrate used was a mixture of coconut fibre and peat (pH: 6.3 and EC: 0.9). All crop management and irrigation water (localised irrigation) were the same in the three greenhouses where the research was carried out.

2.3. Photosynthetic Activity and Production Measurements

To determine the influence of the different climate control systems on crop yields, three crop lines (considered as statistical repetitions) were selected. Marketable and non-marketable fruits were weighed with an EKS Premium electronic balance (EKS Spain, SA, Spain), with a measuring range of 0–40 kg and an accuracy of 10 g.

To compare the effect of different climate control systems on the photosynthetic activity of tomato plants, measurements were carried out with an LCI SD photosynthesis analyser (ADC BioScientific Limited, Hertfordshire, UK) following the methodology used by Jiang et al. [28]. LCI SD equipment (ADC BioScientific Limited, Hertfordshire, UK) consists of a portable console with a blade clamping chamber equipped with a CO_2 and H_2O IRGA concentration sensor (infrared gas analysis) with a CO_2 measurement range of 0–2000 ppm, 0–75 mbar H_2O (accurately $\pm$ 2%), and 0–3000 m^{-2} s^{-1} PAR radiation. CO_2 and water vapour concentrations were measured from the known airflow in the chamber at the entrance and exit of the chamber to calculate CO_2 assimilation (photosynthesis) and leaf transpiration rate. Data collection was done once or twice per week, depending on the daily weather conditions. The camera that measures photosynthesis needs clear and sunny days for proper operation. The process of measuring and observing the data was carried out on fully randomly chosen plants on each measurement day. Measurements were carried out on the last mature leaves of each selected plant (a total of 12 leaves per sector). The path for reading data was different on each measurement day and was executed randomly to prevent the sun's position from having a distorting effect on measurements. In addition, the data were always recorded during the same time interval, between 12:00 and 12:30 h.

2.4. Statistical Analysis

Statistical analysis of the data was performed with the Statgraphics Centurion XVIII software, using an analysis of variance (considered significant if the p-value $\leq$ 0.05) and comparing the mean values with Fisher's minimum significant difference (LSD) procedure. Bartlett, Cochran, and Hartley tests were used to determine whether a sector has similar variation. Where there was a statistically significant difference between standard deviations, parametric analysis was not feasible using analysis of variance. In this case, nonparametric analysis was performed with Friedman's test, in which each row represents a block (the measurement date), using the box and whisker plot [29].

3. Results and Discussion

3.1. Effect of Different Climate Control Systems on the Indoor Temperature of Greenhouses

Average daily temperatures were higher in greenhouse 2 with the fog system for most of the period analysed from April to July (Figure 2). However, the average daily temperatures do not show statistically significant differences between the three greenhouses, being higher than the average daily temperature outside with statistically significant differences. The daily maximum temperature was statistically higher in greenhouse 2 with the fog system and natural ventilation (FS + VN). The minimum temperature was very similar in the three greenhouses, with no statistically significant differences (Table 3).

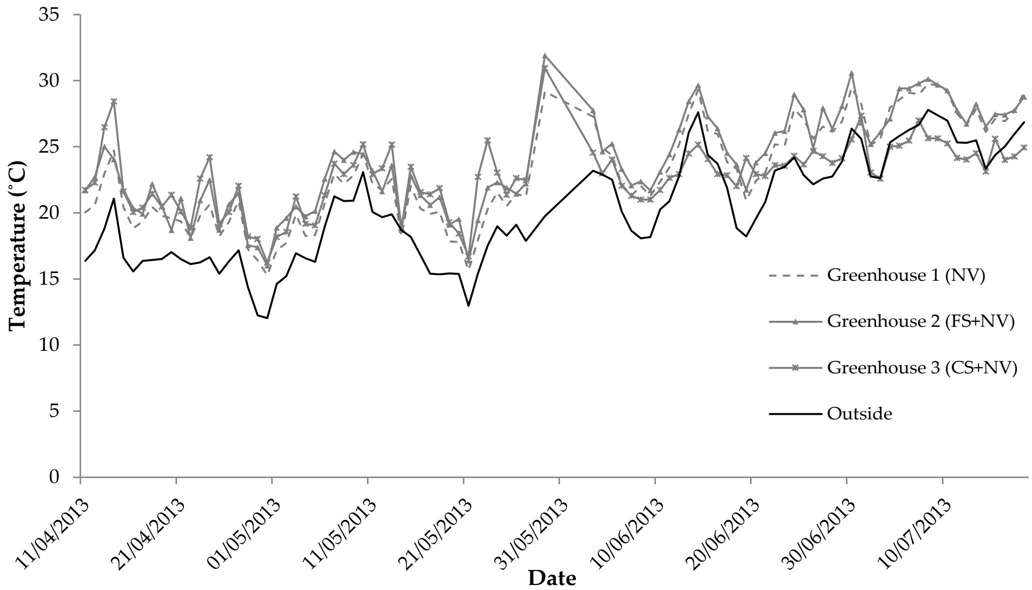

Figure 2. Average daily temperature during the development of the test. Natural ventilation (NV), fog system (FS + NV) and evaporative pads and fans system (PS + NV).

Table 3. Mean (±standard deviation) daily temperature T_M, average daily maximum temperature T_{MAX}, average daily minimum temperature T_{MIN} and hours of exposure to temperatures above 37 °C, N_{H37}.

Greenhouse	Cooling Systems	T_M (°C)	T_{MAX} (°C)	T_{MIN} (°C)	N_{H37} (h)
1	Natural ventilation (NV)	23.0 b ± 3.9	32.0 b ± 4.9	16.3 a ± 3.3	44.7
2	Fog system (FS + NV)	23.8 b ± 3.7	34.0 c ± 5.3	16.6 a ± 3.3	63.7
3	Pad-fan system (PS + NV)	22.7 b ± 5.9	31.8 b ± 5.1	16.7 a ± 2.9	8.9
	Outside	20.2 a ± 4.0	30.5 a ± 4.7	16.1 a ± 3.6	0

a Values accompanied by different letters are significantly different at the 95.0% confidence level (*p*-value 0.05).

In greenhouse 3 equipped with the pads-fans systems, crops were fewer hours above 37 °C (8.9 h), and in greenhouse 2 with the fog system, the crops were exposed for a greater number of hours (63.6 h) to excessive temperature (Table 3). The optimal daily temperature for tomato crops is about 19–20 °C [30]. In the case of our research, the temperature exceeded 32 °C during the development of the crop, a temperature at which pollen formation and viability is reduced [31,32]. Therefore, it could be assumed that the high air temperatures described in greenhouses 1 and 2 affected the development of plants.

3.2. *Effect of Different Climate Control Systems on the Indoor Relative Humidity of Greenhouses*

The average values of relative humidity of the indoor air of the greenhouses are similar from the beginning of the crop in the middle of the month of April until the middle of the month of May. From that moment, the notable increase in the relative humidity in the greenhouses where water evaporation cooling systems are used is revealed. For example, mainly the increase in greenhouse 3 (PS + NV) and the decrease in the relative humidity in greenhouse 1 with exclusive natural ventilation (Figure 3). The behaviour of the relative humidity is normal because the cooling systems by evaporation of water usually increase the humidity of the air to lower the temperature inside the greenhouse.

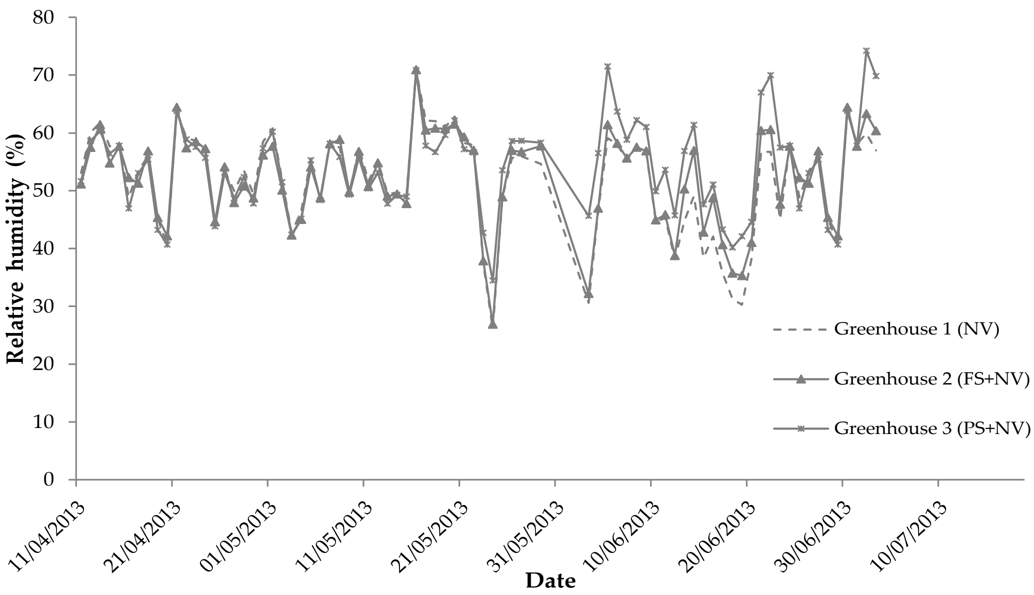

Figure 3. Average daily relative humidity during the development of the test. Natural ventilation (NV), fog system (FS + NV) and evaporative pads and fans system (PS + NV).

The average relative humidity values vary between 51.4% in greenhouse 1 (NV) and 54.2% in greenhouse 3 (PS + NV), with statistically significant differences between them. It was also in this greenhouse where the highest values of the maximum relative humidity (71%) were shown, but without statistically significant differences. In the case of minimum relative humidity, the values show statistically significant differences between the data taken in the greenhouse with pads and fans system (greenhouse 3) and the rest of the greenhouse used in the research (Table 4). Average and maximum relative humidity values vary in the optimal range of 50–70% set by Shamshiri et al. [33] for all tomato development stages. The average conditions of relative humidity are close to 60%, a value that is considered optimal for adequate pollination [34]. Outdoor relative humidity conditions could not be included in the analysis due to an error in the measurement sensor located in the weather station adjacent to the experimental greenhouses.

Table 4. Mean (±standard deviation) daily relative humidity H_M, average daily maximum relative air humidity H_{MAX} and average daily minimum relative air humidity H_{MIN}.

Greenhouse	Cooling Systems	H_M (%)	H_{MAX} (%)	H_{MIN} (%)
1	Natural ventilation (NV)	51.4 a ± 8.8	69.0 a ± 8.6	29.9 a ± 8.3
2	Fog system (FS + NV)	52.2 ab ± 8.2	69.7 a ± 8.2	29.5 a ± 7.9
3	Pad-fan system (PS + NV)	54.2 b ± 7.8	71.0 a ± 7.5	32.3 b ± 9.8

a Values accompanied by different letters are significantly different at the 95.0% confidence level (*p*-value 0.05).

3.3. Effect of Different Climate Control Systems on Photosynthesis Activity

During the development of the research, the photosynthetic activity was very similar between greenhouse 2 (FS + NV) and the greenhouse with exclusive natural ventilation (greenhouse 1), being slightly higher in the latter although without significant differences (Table 5). In this case, the lowest photosynthetic activity was shown in greenhouse 3 (PS + NV), with statistically significant differences from the other two greenhouses.

Table 5. Photosynthetic activity A [μmol CO_2 m^{-2} s^{-1}], radiation PAR R_{PAR} [μmol m^{-2} s^{-1}], concentration of CO_2 C [ppm], leaf temperature T_L [°C], transpiration E_L [mmol m^{-2} s^{-1}], and stomatal conductivity C_E [mol m^{-2} s^{-1}].

Greenhouse	Cooling Systems	A	R_{PAR}	C	T_L	E_L	C_E
1	Natural ventilation (NV)	14.8 b ± 4.1	654.2 b ±189.3	365.3 a ±9.7	33.8 a ± 2.4	4.2 a± 0.8	0.3 a± 0.13
2	Fog system (FS + NV)	14.6 b ± 2.8	586.0 a ± 136.9	364.8 a ± 8.3	33.5 a ± 2.6	4.8 b± 0.9	0.3 a± 0.08
3	Pad-fan system (PS + NV)	13.4 a ± 2.7	570.6 a ± 143.9	361.4 a ± 9.6	34.5 a ± 2.3	4.6 b± 0.7	0.2 a± 0.05

a Values accompanied by different letters are significantly different at the 95.0% confidence level (p-value 0.05).

The two main parameters that define photosynthesis capacity are CO_2 concentration and PAR radiation. The mean CO_2 concentrations measured were statistically similar in the three greenhouses, whereas PAR radiation was statistically higher in greenhouse 1 as a consequence of the different curvature of the roof (wider spans than in greenhouses 2 and 3). As a consequence, photosynthesis was greater in greenhouse 1 but without statistical significance.

Temperature measured at the surface of the plants' leaf was higher in greenhouse 3 (PS + NV). The lower values of CO_2 concentration and PAR radiation and the greater leaf temperature observed in greenhouse 3 produced a reduction in photosynthetic activity (Table 5). The increase of plant temperature above the optimum favours photorespiration, reducing photosynthesis [35]. Adverse temperatures and excessive radiation can lead to a persistent decrease in the efficiency of the conversion of solar energy into photosynthesis, known as photoinhibition [36–39]. Photosynthesis limits growth at warm temperatures and decreases with temperature. Tomato photoinhibition can occur at 30–40 °C and high radiation levels (1500–1800 mol m^{-2} s^{-1}) [40–42].

Furthermore, inside greenhouses, there are stressful thermal regimes and atmospheres of high evaporative demand, which negatively affect crop growth and reduce the quantity and quality of crops [43].

The influence exerted by photosynthesis on crop yield in our case is mainly shown in the greenhouse with exclusive natural ventilation. Santiago et al. [4], in addition to clearly seeing this influence in different tomato varieties, also observed a better use of irrigation water.

The transpiration rate of the leaves shows statistically significant differences between the greenhouse with exclusive natural ventilation (greenhouse 1), where the value is lower (4.2 mmol m^{-2} s^{-1}) and greenhouses with active cooling systems (Table 5). It should be noted that the highest value is reached in greenhouse 2 (FS + NV), where the average relative humidity has an intermediate value (Table 4) and the average and maximum temperature are higher than in the rest of the greenhouses. In addition, the exposure time to temperatures above 37 °C is also longer in that greenhouse (Table 3). In our case, the results do not exactly agree with Kittas et al. [44], who stated that in a greenhouse with air conditions around the leaves too hot and humid, the transpiration of the leaves is ineffective. However, moisture alone does not provide enough information about plant transpiration and cannot be used as a good indicator of stress [33].

Stomatal conductance showed no statistically significant differences between plants grown under the influence of an active cooling system and the use of exclusive natural ventilation (Table 5).

3.4. Effect of Different Climate Control Systems on Production

The marketable production harvested in the three greenhouses was very similar (Figure 4), with differences lower than 10%. Greater production was observed in greenhouse 3 equipped with the pad-fan system, where the exposure of tomato crop to excessive temperatures greater than 37 °C was significantly lower (Table 3).

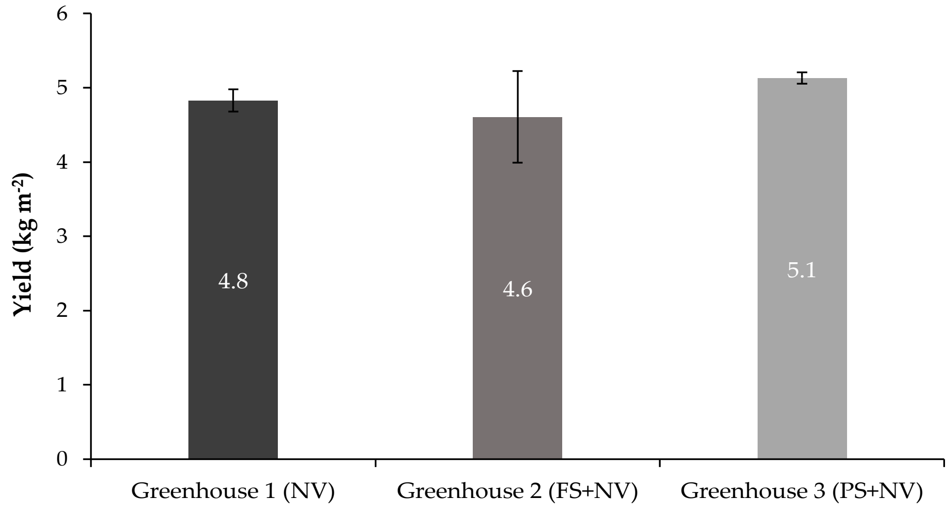

Figure 4. Marketable yield obtained in the experimental sectors under the influence of the different cooling systems. Natural ventilation (NV), fog system (FS + NV) and evaporative pads and fans system (PS + NV).

Tomato production was not significantly increased in the greenhouses with the active cooling systems analysed in this work. Even production developed in greenhouse 1 with wider spans and only natural ventilation was greater than in greenhouse 2 with fog system, but with lower spans width that reduced PAR radiation. In previous works developed in regions with high relative humidity, evaporative water cooling does not improve the production of tomato crops [45]. In addition, it should be noted that greenhouse 1 has a larger ventilation area and several authors have reported increases in production related to the increase in ventilation surface [46–48]. These production levels are well below the yields of 49 to 55 kg m^{-2} for tomatoes obtained in greenhouses with high-tech climate control systems in northern Europe or America [49,50].

3.5. Effect of Different Climate Control Systems on Energy and Water Consumption

Water consumption was notably higher, with 0.14 L m^{-2} consumed in greenhouse 3 (PS + NV) compared to 0.02 L m^{-2} consumed in greenhouse 2 (FS + NV). Electric consumption was also higher in greenhouse 3 (PS + NV) with 4.66 kWh m^{-2}, while in the greenhouse with exclusive natural ventilation, the energy expenditure was 0.06 kWh m^{-2} (Table 6). During the research, electrical energy expenditure and water consumption were lower in greenhouse 1 with exclusive natural ventilation (Table 6).

Table 6. Electricity consumption E_C [kWh m^{-2}] y water consumption W_C [m^3 m^{-2}] of each of the climate control systems installed in the greenhouses.

Greenhouse	Cooling Systems	E_C	W_C
1	Natural ventilation (NV) (	0.06	-
2	Fog system (FS + NV)	1.38	0.02
3	Pad-fan systems (PS + NV)	4.66	0.14

The production costs in this research generated a lower environmental impact, as the energy requirements are below the threshold of 50–80 MJ kg^{-1} set for other regions of Europe. In the case of production in a greenhouse without a heating system in Spain, the cost is 5 MJ kg^{-1} [51]. Regarding the water consumption of each refrigeration system, there have been great differences between treatments. Water consumption increases linearly with the ventilation rate [52]. In our case, the daily water consumption has been 2.75 L m^{-2}, a value below those obtained by Al-Helal and Musalami [53], where under its particular conditions of extreme aridity, it obtained water consumption during the day of 8.4 L m^{-2} and 14 L m^{-2}. Franco et al. [26] registered values between 3.2 and 10.3 L m^{-2}, and, according to Sabeh et al. [54], water consumption can be up to 11 L m^{-2} in a semi-arid region.

In specific cases, the production costs can be offset, depending on the particular conditions, by the corresponding increase in the earliness, quality and yield of the crop, and allows growth in arid areas during the summer period. In addition, producers can produce for a longer period, thus modifying the peak production periods [26].

4. Conclusions

From the results obtained by comparing the different cooling systems combined with the natural ventilation and the exclusive natural ventilation in a Mediterranean greenhouse, the following conclusions can be drawn:

- Pads and fans systems decrease the maximum daily temperatures below 32 °C and decrease the number of hours that the crop is exposed to high temperatures (37 °C), without an excessive increase in relative humidity (maximum relative humidity 71%) on the tomato crop.
- The increase in the width of the greenhouse with exclusive natural ventilation (from 8 to 9 m), which improves the interception capacity of PAR radiation (12% compared to the other two greenhouses) and the increase of ventilation surface that produces an increase in the concentration of CO_2 in the interior of greenhouses (1% compared to the other two greenhouses) are an ideal combination to increase photosynthetic activity (1.4% compared to greenhouse 2 (FS + NV) and 9.5% compared to greenhouse 3 (PS + NV), with statistically significant differences with the greenhouse with pads and fans combined with natural ventilation.
- For the climatic conditions of our research (spring-summer cycle), the combination of natural ventilation with pads and fan system slightly increases tomato production, with production 6% higher than that observed in the greenhouse with exclusive natural ventilation and 9.8% higher than the greenhouse with fog system combined with natural ventilation.

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