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The effect of photovoltaic panels on the microclimate and on the tomato production under photovoltaic canarian greenhouses

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ABSTRACT

Photovoltaic greenhouses are mixed systems, combining electricity and agricultural production in the same area. Moreover, this type of greenhouse conserves all the properties of a conventional greenhouse, as well as offering the possibility of producing and selling electricity.

The aim of the present study is to assess both the impact of the shade caused by the photovoltaic panels on the microclimate and the quality of fruits in the greenhouse. Measurements were carried out in an experimental Canary type greenhouse covered with flexible photovoltaic panels on 10% of its total roof area.

Results illustrate that this occupancy rate of the photovoltaic panels arranged in checkerboard pattern does not have a significant effect on the agronomic parameters e.g. height, stem diameter and tomato yield, and climatic parameters under the greenhouse cover. Additionally, the presence of photovoltaic panels has a negative effect on the development of the population of *Tuta absoluta*.

1. Introduction

Greenhouse technology is a major breakthrough in agriculture, because it favors off-season cultivation and also gives greater crop productivity. The greenhouse is used to protect crops from severe weather conditions such as rain or wind (Dannehl et al., 2014). The greenhouse microclimate is characterized by a set of climatic parameters, such as temperature (Sethi and Sharma, 2008), relative humidity (Kim et al., 2008), carbon dioxide (CO_2) concentration (Körner et al., 2007) and solar radiation (Ioslovich, 2009); which are different from the outside conditions. Each of these parameters is strongly linked to the outside weather conditions as well as the particular characteristics of the greenhouse.

The greenhouse like all agricultural structures consumes energy either in a direct way i.e. irrigation, artificial lighting, heating, air cooling, aeration (Vox et al., 2010; Hardin et al., 2008), or in an indirect way i.e. nitrogen fixation technology and acquisition of fertilizers ‘transport’ (Allardyce et al., 2017; Sonneveld et al.,2010; Stanghellini, 1987; Bot et al., 2005). Currently most of this energy is fossil (Campiotti et al., 2010; Vourdoubas, 2015) e.g. oil, coal, natural gas. Although diversified and very abundant, these resources are becoming harmful on human the health and the environment. Their use generates considerable carbon dioxide, partly responsible for global warming. This effect threatens many populations around the world, endangering the geopolitical stability in certain regions of the globe due to major climatic phenomena.

To address these concerns, more and more countries are putting into place incentives not only to save energy but also to produce energy by other means, often referred to as “clean” in reference to the fact that it does not generate carbon dioxide. These means of production are mainly derived from renewable energies, that is to say, whose resources are sustainable. These include “solar” energy. The latter term actually covers many technologies, including photovoltaic energy. This system transforms sunlight directly creating electricity immediately.

Photovoltaic energy is renewable, natural (Wand and Leuthold, 2011), readily available, sustainable, clean and cheaper than fossil energy (Ftenakis and Kim, 2009). This energy is becoming increasingly used. Moreover, this energy is the most used and the most widespread in the world. Therefore, the use of photovoltaic energy in greenhouses is a major objective for sustainable greenhouse crop production (Kadowaki et al., 2012).

Within this context, in the last few years, manufacturers and

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researchers have had the idea of covering greenhouses with photovoltaic panels (Al-Ibrahim et al., 2006; Al-Shamiry et al., 2007; Campiotti et al., 2008; Kuo et al., 2012; Marucci et al.,2012; Nayak & Tiwari, 2009; Rocamora & Tripanagnostopoulos, 2006; Sonneveld et al., 2010; Yano et al., 2010; Cossu et al., 2014). It is an easily modeled and reliable solution. In addition to the production of electricity; photovoltaic panels can provide shading to reduce or to limit excess solar radiation penetrating into the greenhouse in the summer, particularly in areas with high solar radiations (Garcia et al., 2011; Baille et al., 2001).

However, shading induced by the photovoltaic panels can have a negative impact on crop yields and on the microclimate inside the greenhouse (Bertin et al., 2015).

To date, research on this subject is lacking and refers mainly to the effects of PV panels according to the degree of shade in greenhouses and the positioning of these panels. For instance, Ureña-Sánchez et al. (20012) studied the effects of flexible photovoltaic modules mounted on top of a 'raspa y amagado' greenhouse using two different PV layouts covering 9.8% of the greenhouse roof. The results illustrated that the presence of the photovoltaic panels did not negatively affect the yield, nor the mean fruit mass, nor the tomato production cost.

For their part, Kadowaki et al. (2012) carried out a study to evaluate the influence of PV shading mounted inside the south roof of a single-span plastic greenhouse, on the growth of the onion (*Allium fistulosum L*). Two types of the photovoltaic panel distribution, checkerboard and straight-line were tested, each one covering 12.9% of the roof area. Study results indicated that the electricity generated by the PV array for checkerboard and straight-line was similar. Moreover, the straight-line arranged PV-array decreased dry matter weight (DW) and fresh weight (FW) of Welsh onion compared to the checkerboard PV-array and control. Conversely, the solar radiation inside the checkerboard PV greenhouse was more uniform than in the straight-line PV greenhouse because the former layout improved the unbalanced spatial distribution of solar radiation received in the greenhouse (Yano et al., 2010).

Kuo et al., (2012) investigated the properties of transparent light in a greenhouse located in Taiwan, using the different integrated photovoltaic modules i.e. crystalline light-through module, colorful module, and see-through module, to examine the ideal spectrum and light distributions for plant growth. Results showed that the appropriate selection of the integrated photovoltaic modules produced transparent light with a wavelength distribution that is favorable for plant growth in a greenhouse.

More recently, Cossu et al., (2014) have studied the climate conditions in an east-west oriented greenhouse in Sardinia which was equipped with photovoltaic modules on 50% of its roof area; the south oriented roofs were completely covered with multi-crystalline silicon photovoltaic panels. Study results showed that the presence of PV panels on roof reduced solar radiation inside the greenhouse by 64%; with a total rated power of 68 Kwp.

Fatnassi et al. (2014, 2015) studied the distributed climate parameters in an Asymmetric and Venlo greenhouses equipped with photovoltaic panels on their roofs. Solar radiation distribution, thermal, water vapor and dynamic fields were investigated using CFD. The results of this experiment showed that the transmission of solar radiation in the Asymmetric greenhouse is 41.6% while that in the Venlo greenhouse is 46%. The temperature inside the Venlo type greenhouse varies between −3 °C in summer and −3 °C in winter, so this type of greenhouse is colder than the Asymmetric. When the temperature is monitored, it varies between 5 °C in summer and 3.3 °C in winter.

To back up the previous studies and for the purposes of eco-development of sustainable agriculture in Morocco, through the integration of PV technology in agriculture and its adaptation to the local conventional greenhouses, the effects of providing shade by photovoltaic panels on tomato production and the microclimate of canary greenhouses in the southern Mediterranean climate will be investigated.

2. Materials and methods

2.1. Experimental greenhouses

The canarian greenhouse (Fig. 1) under investigation is a plastic-house equipped with wooden frames and covered with a polyethylene plastic characterized by a height ranging between 3 and 5 m. It is particularly widespread in the Mediterranean Basin.

The experiments were performed in two adjacent canarian greenhouses. Each greenhouse occupies a surface area of 172 m^2, and its maximum height reaches 5 m. These greenhouses were located in the experimental site at the Regional Center of Agricultural Research (INRA) in Agadir (Latitude: 30° 13, Longitude: 9° 23, Altitude: 80 m) on the Atlantic coast of Morocco. The average annual temperature is 18 °C and the highest and lowest temperatures are 24.8 °C and 11.5 °C, respectively. The coverage of the greenhouse roof is in polyethylene

Fig. 1. The conventional canarian greenhouse.

Table 1
characteristics of the photovoltaic panels.

Name	MX-FLEX Protect
Peak power (Pmax)	100 W
Open Circuit Voltage (Voc)	23.4 V
Short circuit Current (Icc)	5.4 A
Voltage (Vmp)	19.8 V
Current (Imp)	5.05 A
dimensions	1000 × 500 × 3 mm
Weight	1.7 kg
Module efficiency	19%

Table 2
Physico-chemical characteristics of the substrate.

Apparent density	650–700 Kg m^{-3}
Content of dry matter	45–55%
Content of organic matter	75–90%
Ash content	10–25%
Carbon content (dry mass)	40–50%
PH (H_2O)	5.0–6.0
Macro-nutrients	N, P, K, Ca, Mg
Micro- nutrients	Fe, Mn, Cu, Zn, B, Mo

plastic film (thickness 200 μm; transmittance is 75%), and the side walls were covered by insect-proof netting, made of mono-filament polythene threads, 0.1 mm in diameter with a square mesh 0.6 mm across. Passive ventilation was provided by manually-operated side openings.

One of the two greenhouses was equipped with photovoltaic panels on the roof. The PV covers 10% of the total surface area of the roof. These PV panels were arranged in East-West oriented strips; whereas the other greenhouse was considered a control.

For this experiment, 32 flexible photovoltaic (PV) panels (1 m Length and 0.5 m Width each) were used (Table 1). The PV panels were fitted onto the roof using a checkerboard pattern (Fig. 2). This configuration was chosen because it improves the unbalanced spatial distribution of solar radiation received inside the greenhouse (Yano et al., 2010; Kuo et al., 2012). We have used the flexible solar panels because they are heavy and easy mounting on the roof of the canarian greenhouses.

2.2. Crop

The Tomato crop (*Solanum lycopersicon* cultivar: Zayda, Rijk Zwaan Company) was planted in each greenhouse. We chose this crop as a model plant because of its high sensitivity to light reduction (Wittwer and Honna, 1979). The plantation date was on January 9, 2017 in a soilless location (Table 2). The tomatoes were arranged in four rows, oriented north-south, perpendicular to the prevailing wind direction. The distances between rows and plants were 1.20 m, 0.3 m, respectively. The drip irrigation system was used to irrigate the plants.

2.3. Climatic parameters measurements

The climatic parameters of the greenhouse were studied throughout a crop cycle. However, in this study, only one main measurement period has been presented, namely, from 12 to 15 April 2017. The main outside climatic variables, such as temperature, humidity, global solar radiation, wind speed and direction were measured every 15 min. The distribution of the internal climatic parameters was measured simultaneously in the two greenhouses. Air temperature and the humidity were measured at three different heights in the center of the photovoltaic greenhouse and at one point in the control greenhouse. The vertical distribution of temperature and humidity in the crop rows was determined using a mast equipped with three temperature and humidity sensors located at 1 m, 2 m and 3 m.

In addition, solar radiation was measured on 9 points on horizontal plane 3 m above the ground level inside the photovoltaic greenhouse (Fig. 3), and on a single point in the control greenhouse during the clear and cloudy days.

All measurements were recorded on a data logger (Campbell CR3000), collected every 10 s and the average noted after one hour.

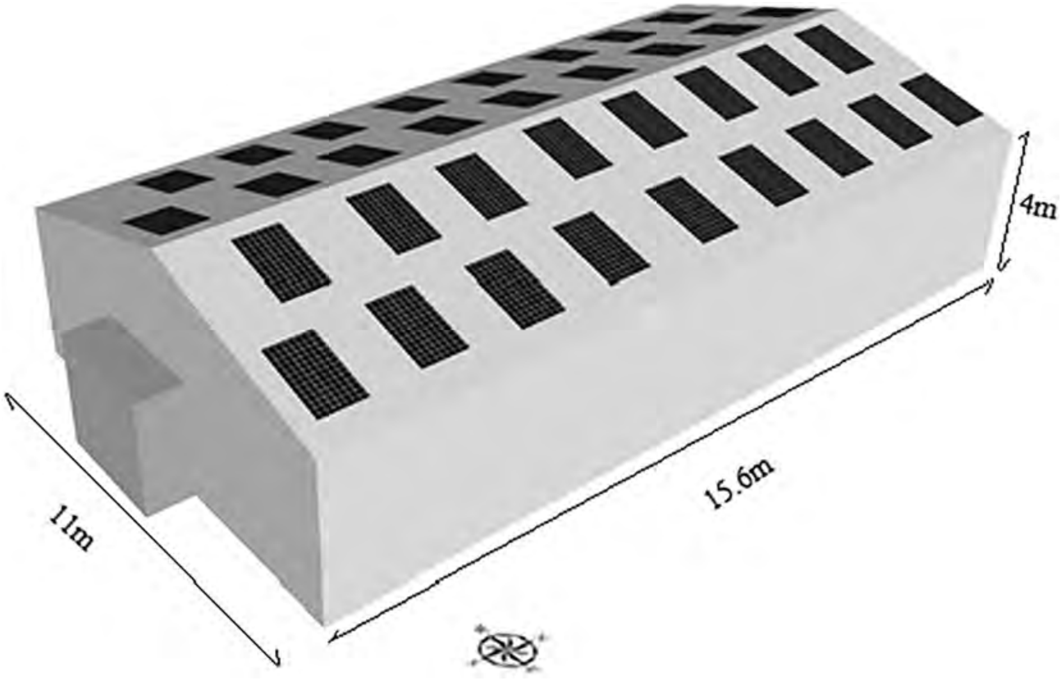

Fig. 2. Arrangement position of the flexible photovoltaic panels on the roof of the greenhouse.

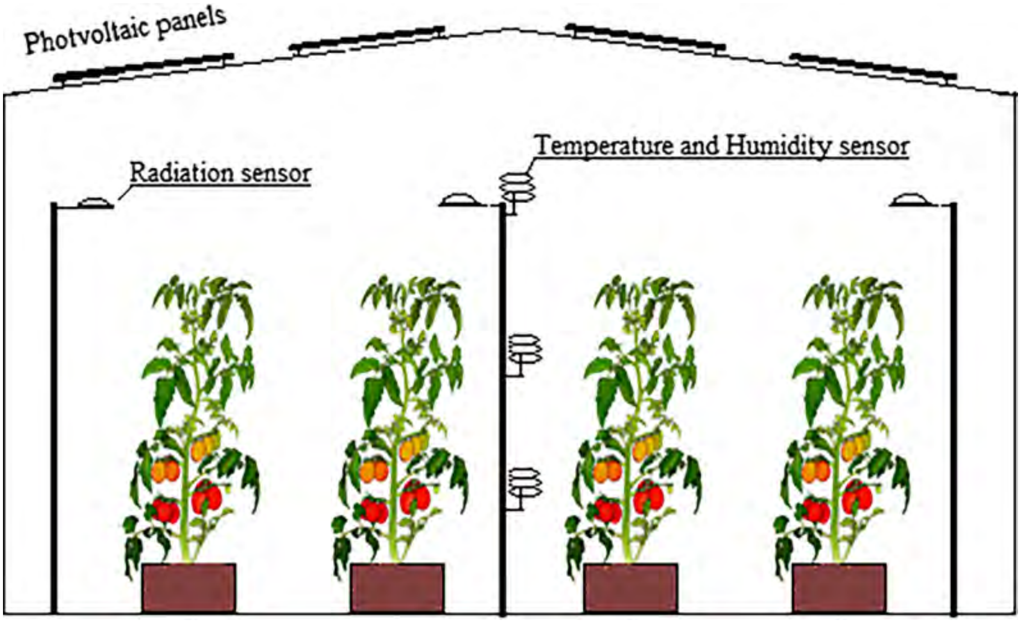

Fig. 3. Section of the photovoltaic greenhouse and the location of the experimental sensors used in the present work.

Table 3
Accuracy of measuring sensors and its range use.

Sensor	Measurement range	Accuracy
Pyranometer CMP3	Up 2000 $W\,m^{-2}$	5% from −10 °C to +40 °C
Pyranometer SP1110	Up 3000 $W\,m^{-2}$	± 5% (typically < ± 3%)
Vaisala HMP50	T: −40 °C to +60 °C RH: 0–100%	± 5% (typically < ± 3%) ± 3% RH (0–90%) ± 5% RH (90–98%)
PT100	−40 °C to +105 °C	0.1 °C
2D anemometer Ltd	0 at 60 $m\,s^{-1}$	± 2%
HFP01 Heat flux	± 2000 $W\,m^{-2}$	Within −15% to +5%

Sensors accuracy is shown in Table 3.

2.4. Agronomic parameter measurements

All agronomic parameter measurements were recorded from the beginning until the end of the crop cycle. The parameters measured were: the average height of the plant (Hp) measured using a wood ruler, the stem diameter (Ds) measured by a digital vernier caliper, the number of fruits per plant (Nf) and the total yield (Ty) determined using an electronic balance which has a resolution of 0.5 g. Data analyses were performed using the SPSS general linear model (GLM) and the software (IBM SPSS statistics 23) procedure for ANOVA at a level of $P < 0.01$. Then, when significance was confirmed, resulting means were compared using Newman-keuls test.

2.5. Monitoring population dynamics of *T. absoluta*

The tomato leafminer *Tuta absoluta* (Lepidoptera: Gelechiidae) is a highly destructive pest in tomato crops. The percentage of damage caused by this pest on tomato can reach 100% (França, 1993) under weak control.

In order to monitor the *T. absoluta* population dynamics both in the photovoltaic and in the control greenhouses, pheromone traps Russel IPM, PH-937-1RR, UK were used (Fig. 4). After abnormal increase of *T. absoluta*, two water traps were implemented in each greenhouse in order to reduce the population of this threatening pest inside the greenhouse.

3. Results and discussions

3.1. Climatic parameters

3.1.1. Air temperature

Fig. 5 shows the variation of the air temperature outside and inside the two greenhouses, with the time frame. Measurements were carried out over a period of four days i.e. from 12 to 15 April 2017.

The results indicate that the variation of temperatures was very high during daytime, and decrease at nighttime. The difference between the maximum temperatures inside and outside the two greenhouses may be explained both by the greenhouse effect, plant activities and the thermal characteristics of the cover. According to Fig. 4, this difference was relatively low at night and early morning.

Indeed, the minimum temperature recorded in the photovoltaic greenhouse ranged between 11.91 °C and 14.32 °C, while the maximum temperature varied from 30.19 °C to 33.17 °C. The minimum temperature in the control greenhouse was between 11.90 °C and 14.37 °C, and the maximum temperature varied between 31.07 °C and 34.64 °C. Therefore, the maximum difference between the photovoltaic greenhouse and the control greenhouse was 1.47 °C.

Marucci et al. (2016) reported that for the different percentages of shading, from 0% to 78%, of the photovoltaic panels, the internal temperature range measured during the hottest period and on days in clear sky conditions; are within the optimal ranges for major vegetables species. This may be due to the type of photovoltaic panels and their relative tilt angles.

Ureña-Sánchez et al. (2012) reported similar findings. These demonstrated that the use of photovoltaic panels occupying 9.8% of the greenhouse roofs provoked a slight decrease in air temperature inside the greenhouse.

It is reported that the tomato plants growing in a protected environment have a required average air temperature between 13 °C and 25 °C and the temperature of the substrate must be higher than 14 °C. Photosynthesis activity occurs between 22 °C and 25 °C (Navez, 2011). Outside this temperature range, photosynthesis decreases significantly. The indoor air temperatures measured in the photovoltaic greenhouse were suitable at nighttime, but high in daytime. To deal with this

Fig. 4. Pheromone trap used to monitor the *T. absoluta* population dynamics.

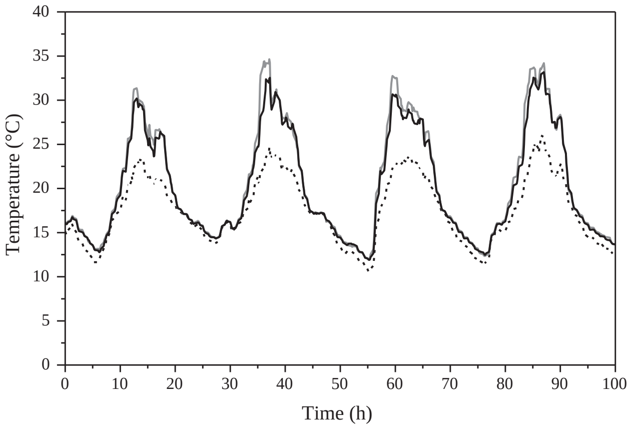

Fig. 5. Evolution of air temperature: (——) inside the photovoltaic greenhouse, (——) the control greenhouse and (—) outside.

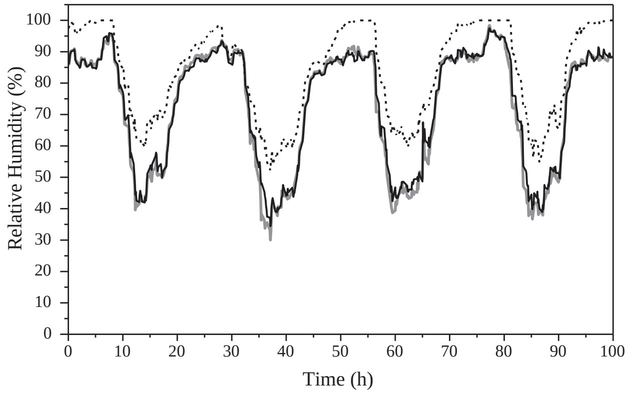

Fig. 6. Evolution of measured air relative humidity: (——) inside the photovoltaic greenhouse, (——) the control greenhouse and (—) outside.

setback, the side opening should to be increased to maximize the natural ventilation rate. During the measurement period, the internal air temperature in the photovoltaic greenhouse is lower compared to the control greenhouse; this suggested that the photovoltaic panels placed on the roof of greenhouse act as shading screens. This effect is very beneficial on the tomato crop cycle during the higher temperature periods. During the lower temperature periods, the energy generated by the photovoltaic panels will also have beneficial consequences for the ambient air inside the greenhouse since it could be used to heat the greenhouse.

3.1.2. *Relative humidity*

Fig. 6 depicts the hourly air relative humidity evolution inside the photovoltaic and control greenhouses together with the outside one, during the period from 12 to 15 April. According to this figure, air relative humidity follows a quasi-periodicity, roughly as found for the variation of the temperature. The increase in the relative humidity is a sign of decreased air temperature. Moreover, relative humidity decreases during the daytime to the minimum values and increases at nighttime to the maximum values (100% in the exterior).

Furthermore, the values of the relative humidity recorded ranged between 97.5–34.4%, and 98.4–30% for inside the photovoltaic and the control greenhouse, respectively. The maximum difference observed for the air relative humidity between the two greenhouses was 5%.

The result of Marucci et al. (2016) illustrates that the average values of relative humidity inside the photovoltaic greenhouse which ranged from 60 to 90% is suitable for a majority of crops. Ureña-Sánchez et al. (2012) found that the mean daily relative humidity in the control zone was lower than in the zone equipped with the photovoltaic panels. This is probably due to the nature of the photovoltaic panels used in both studies. In our case, flexible photovoltaic panels have been used, while in the Ureña-Sánchez et al. (2012) study it was an Amorphous-Silicon thin film.

Lower relative humidity is unsuitable for cultivation resulting in the closure of the stomata and restricts plant-environment gas exchanges thus immediately impacting photosynthesis as well as many physiological processes. Moreover, a too moist air fosters the development of fungal diseases and poor pollination of flowers. The excess or lack of moisture will strongly influence the crop productivity. For growth, the optimal value of relative humidity is 75%, for beyond that the plants

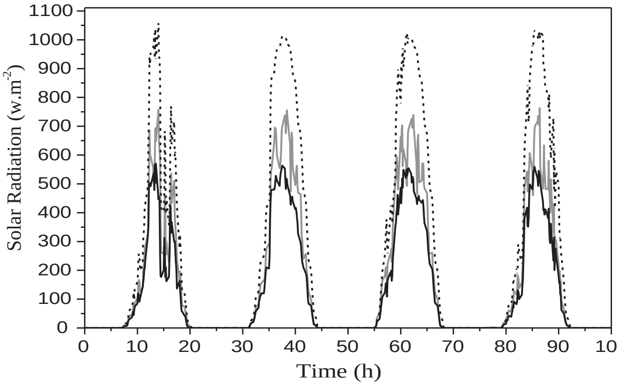

Fig. 7. Evolution of the average solar radiation measured (━) inside the photovoltaic greenhouse, (━) in the control greenhouse and (—) outside during the period April 12 to 15, 2017.

begin to stress (Wacquant et al., 1995). The values measured for the inside air relative humidity in the photovoltaic greenhouse in the present study were quite high compared to the values of suitable relative humidity for the development of tomato; especially on hot days, when the morning aeration can reduce the air humidity and thereby eliminates the small condensation droplets that form on the plastic wall.

3.1.3. Solar radiation

3.1.3.1. Average solar radiation. Fig. 7 shows the hourly variation of the solar radiation inside and outside the two greenhouses for four days, from 12 to 15 April.

The power of solar radiation increases from sunrise reaching maximum value at noon when the sun is at its peak. The sudden fall of solar radiation observed on the first day is due to the passing clouds. Moreover, the maximum value obtained outside is 1050 W m^{-2}, and inside the photovoltaic and control greenhouse, reaching 590 W m^{-2}, 760 W m^{-2} respectively. After that the maximum ratio of the solar radiation between inside and outside the photovoltaic greenhouse is about 56%.

This is in line with Ureña-Sánchez et al. (2012) who reported 65% solar radiation inside the photovoltaic greenhouse during April.

Cossu et al. (2014) reported a reduction of 82% in the greenhouse in which 50% of the roof area had been replaced by the photovoltaic panels. Fatnassi et al. (2015) illustrate that the radiation received was reduced by 41.6% in the Asymmetric greenhouse and by 46% in the Venlo greenhouse.

This reduction in solar radiation could have a negative impact on photosynthesis (Marrou et al., 2013) because solar radiation is important for the photosynthesis process since it allows the assimilation of atmospheric CO_2 (Klaring et al., 2012), and healthy plant activity.

3.1.3.2. Distributed solar radiation. Fig. 8 illustrated the top-view contour maps of the solar radiation distributed in the photovoltaic greenhouse, measured by the nine pyranometers in the morning (Fig. 8a), at noon (Fig. 8b) and in the evening (Fig. 8c). The quantities of energies measured in the nine points were strongly modified during the day; this variation is due to the sun movement and to how the shading provided shifts according to the photovoltaic panels. The highest value of solar radiation was recorded at noon, while the lowest value was obtained in the morning. The sunniest area is located on the east side; therefore, the distribution of solar radiation is not uniform. These results are not in line with those found by Fatnassi et al. (2015) who found that the checkerboard arrangement of photovoltaic panels on the top of the greenhouse improves the uniformity of the spatial distribution of the solar radiation received inside.

3.2. Agronomic parameters

3.2.1. Height of the plant

Fig. 9 shows the average values of plant height Hp in the two greenhouses, on different dates.

According to this figure, after 17 days from the planting date (26 January), under the photovoltaic greenhouse, the tomato plant height is 19 cm compared to that measured in the control greenhouse 18 cm (p-value = 0.071; F = 3.455). After 101 days (20 April), the average height of tomato plants grown in the photovoltaic greenhouse had significantly increased by 25.4 cm compared to the control greenhouse ones (p-value = 0.000; F = 28.403). The mean height of the plants in the photovoltaic greenhouse is always superior to that found in the control greenhouse. This effect is probably due to the climatic conditions inside the photovoltaic greenhouse which favour good plant growth. Furthermore, under the shade, the plants look for light which acts as a kind of stimulus for stem growth.

Under the shading of photovoltaic panels, as well as that produced by the tallest plants, the maximum difference between the height of plants in the photovoltaic greenhouse and that of the control greenhouse is 63 cm. This is in line with the results given by Paez and Lopez (2000), Thangam and Thamburaj (2008) who both found that the plants grown under shading presented superior growth in terms of plant height compared to those in non-shaded areas.

3.2.2. Stem diameter and number of fruits per plant

The data regarding the average values of stem diameter Ds in cm and number of fruits per plant Nf under the photovoltaic and control greenhouse are given respectively in Figs. 10 and 11. The Ds of tomato plants did not differ significantly between the two greenhouses. In addition, the number of fruits Nf in the control greenhouse is a little higher than that in the photovoltaic greenhouse. This may be due to shading effect that has reduced the intake of nutrients and water (Gent, 2008; El-Nemr, 2006). Paez and Lopez (2000) reported that shading did not affect fruit production. Thangam and Thamburaj (2008) illustrated that the number of fruits per plant was lower when shading is provided than in the open field. Sandri et al (2003) found that the number of fruits remains the same in the control and on shaded plants.

3.2.3. Total yield

The data regarding total yield Ty, in kg/greenhouse, of each harvest from the two greenhouses are given in Fig. 12. Eight harvests were performed in all. The first one was on April 11th, and the last one on June 8th. During the first, second, third, and fourth harvest, the average weight of the tomatoes harvested from the photovoltaic greenhouse is (58.9, 65.5, 68.6, 67.1 kg) respectively and remains higher compared with the harvest in the control greenhouse (56.9, 65.1, 61.9, 61.2 kg), and for the fifth and seventh harvests, the average weight of the tomatoes collected from the two greenhouses is the same. Furthermore, during the last harvest, yield differences appear between those in the photovoltaic greenhouse and in the control greenhouse. This is due to great damage caused by the *T. absoluta* in the control greenhouse compared to the photovoltaic greenhouse.

According to Fig. 12, it was found that the yield of tomatoes gathered in the photovoltaic greenhouse was higher than to that in the control greenhouse, and sometimes was almost the same as that of the control. This result is in line with Abdel-Mawgoud et al. (1996) who stated that the shade did not affect tomato fruit yield. As reported by Thangam and Thamburaj (2008), the tomato fruit yield under shade was low compared to that in an open field.

Photovoltaic panels can play a positive role in reducing excess temperature, which improves tomato yield.

3.3. Population dynamics of *T. absoluta*

Fig. 13 illustrates the dynamics of the *T. absoluta* population in the

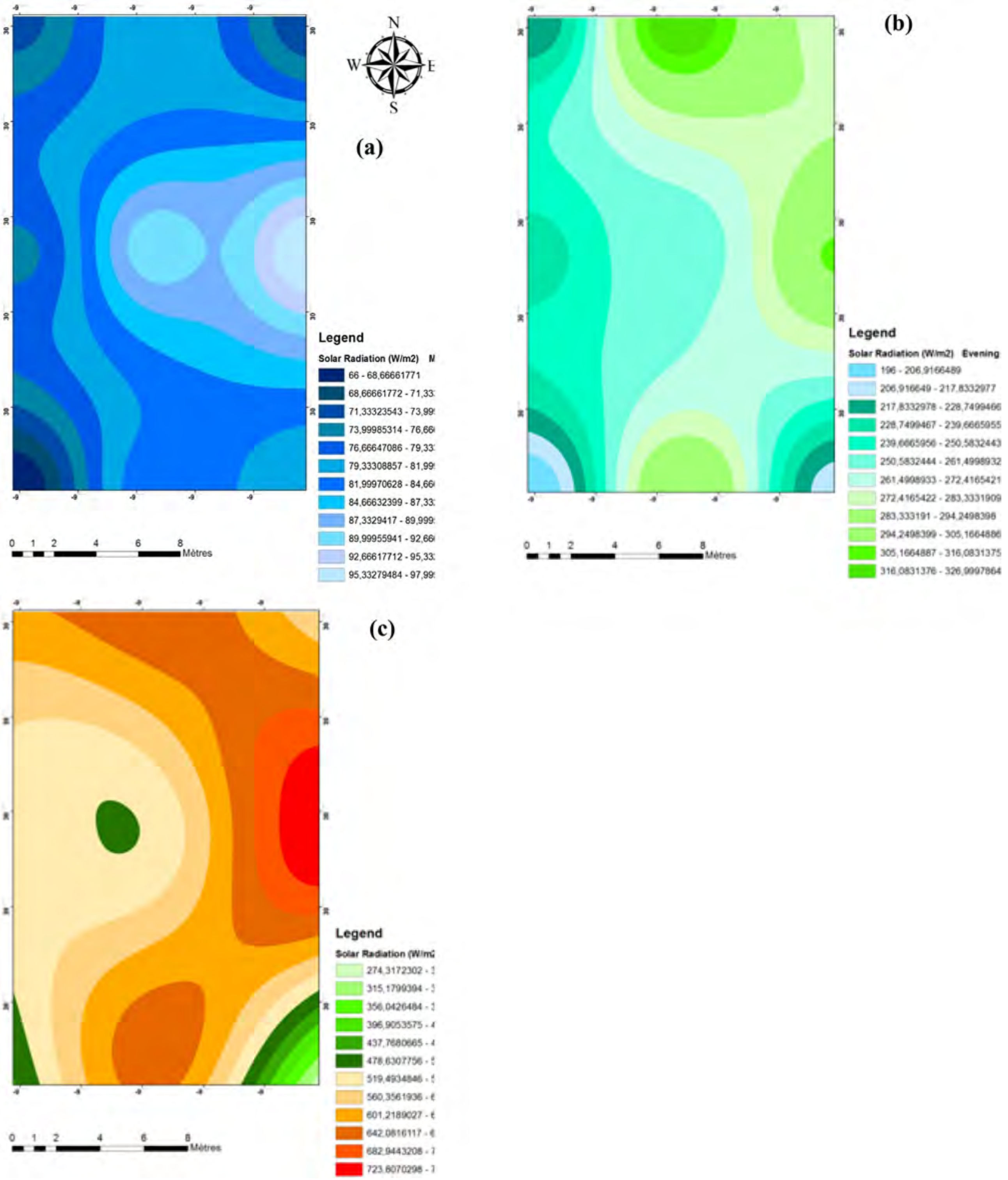

Fig. 8. Top-view contour maps of solar radiation intensity inside the photovoltaic greenhouse measured by the nine pyranometers; in the morning (a), at noon (b) and in the evening (c).

two greenhouses, control and photovoltaic. Analysis of the figure shows that the pressure of *T. absoluta* was relatively low in the photovoltaic greenhouse compared to the control greenhouse. Sampling showed that the individuals of *T. absoluta* trapped in the photovoltaic greenhouse and in the control greenhouse were between 0 and 3, and 3 and 20 respectively. From March 27, 2017, *T. absoluta* increased abnormally in the two greenhouses. With some exception, it appears that the photovoltaic panels system has a negative effect on the development of *T. absoluta*. At the beginning of the cycle until 06 March 2017, the reduction was very significant reaching 100%. This reduction rate decreased after 20 March 2017 and reached 73% on 29 May.

4. Conclusion

The presence of photovoltaic panels on the roof of the Canarian greenhouse with an occupancy rate of 10% in checkerboard patterns

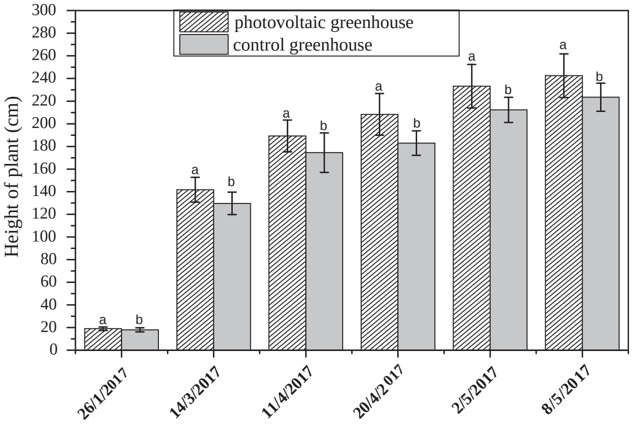

Fig. 9. Evolution of plant height in the photovoltaic and the control greenhouses.

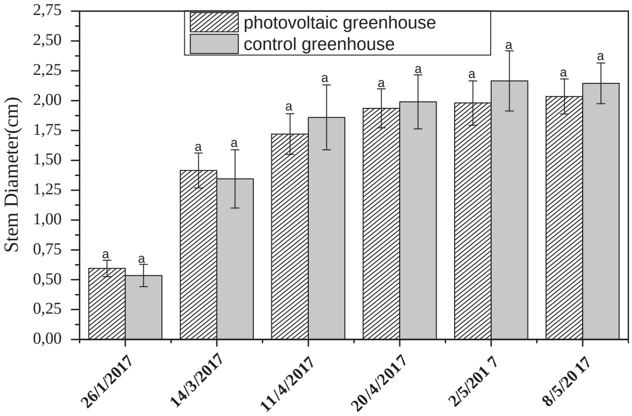

Fig. 10. Evolution of stem diameter in the photovoltaic and the control greenhouses.

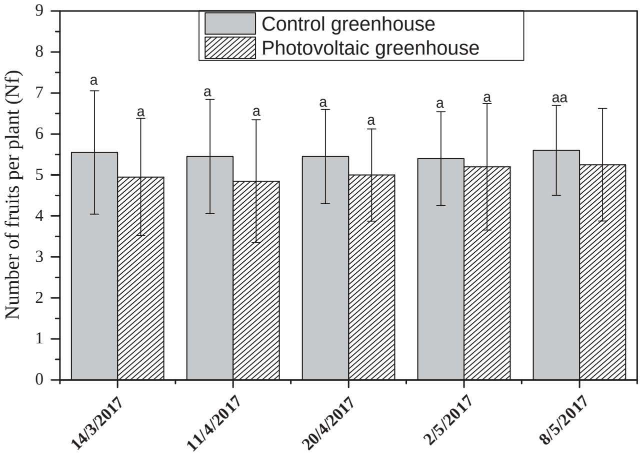

Fig. 11. Variation of number of fruits per plant in the photovoltaic and the control greenhouse.

does not have a significant effect on the microclimate or on the tomato yield. Consequently, farmers of warm climates can install flexible solar panels on 10% of the roof of their tomato greenhouses to produce electricity, without harming their agricultural production in spring-summer crop cycles. Surprisingly, this study also reveals that the use of the photovoltaic panels on the roof of the greenhouse plays a positive role in term of reducing the development of *T. absoluta*.

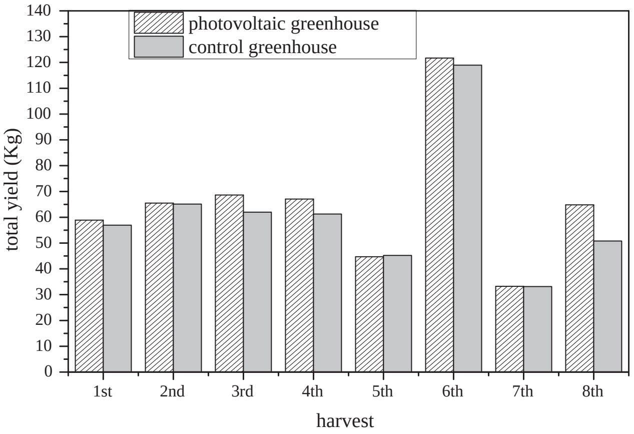

Fig.12. Comparison of the tomato yield in experimental and control greenhouses from 1st to last harvest.

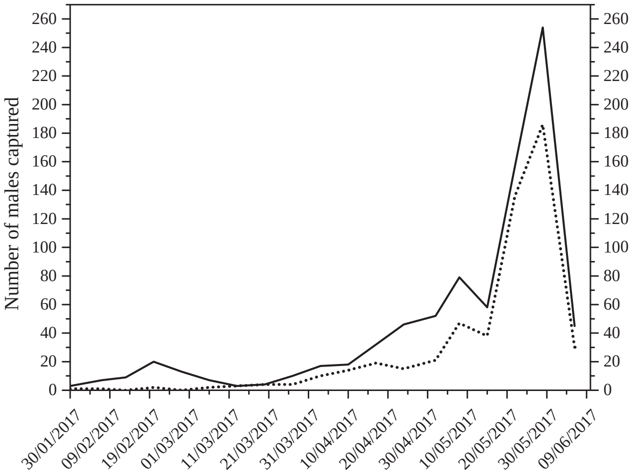

Fig. 13. Evolution of captured males of *T. absoluta* indoor of the two greenhouses control (——) and photovoltaic (…).

Future research should focus on extending the use of photovoltaic panels to find the threshold of negative effects on the crops.

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