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Morphology, yield and quality of greenhouse tomato cultivation with flexible photovoltaic rooftop panels (Almería-Spain)

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A B S T R A C T

Flexible photovoltaic panels are an option to generate renewable energy that could be compatible with the production of greenhouse crops, especially in warm sunny countries. The aim of this study was to evaluate, during two growing seasons, the effect of shading caused by flexible photovoltaic panels mounted on the greenhouse roof on tomato plant morphology and fruit yield and quality. This study was conducted during two growing seasons in a commercial greenhouse for tomato production. Two photovoltaic panel arrays placed on the greenhouse roof were analysed. Both occupied 9.8% of the cover. The parameters studied were PAR, plant morphology, crop yield and fruit quality. The results show that the small reduction in PAR caused by flexible photovoltaic panels on the roof did not affect the total and marketable yield; plant morphology; number of flowers per branch; and fruit colour, firmness and pH. However, the fruit diameter decreased, without affecting the yield (kg·m^{-2}). Both flexible photovoltaic panel arrays on the greenhouse roof produced a similar effect on plant morphology, crop yield and fruit quality.

1. Introduction

Currently, the negative environmental and socioeconomic impacts produced by using fossil fuels motivate the search for clean alternatives to generate energy. One of the current challenges of agriculture is the study of possible available renewable resources (Roslan et al., 2018). Photovoltaic technology is considered one of the best alternatives for electrical generating energy to produce food, especially in warm sunny countries (Fabrizio, 2012; Boxwell, 2015). Using photovoltaic panels could satisfy the energy needs of agricultural holdings of greenhouse crops, in addition to providing additional income for farmers (Djevic and Dimitrijevic, 2009). In south-eastern Spain, the installation of flexible solar panels on greenhouse roofs is an interesting proposal for farmers because of the many annual sunshine hours in the area (Varun and Prakash, 2009; Ureña-Sánchez et al., 2012; Pérez-Alonso et al., 2012). However, one problem is the loss of solar radiation reaching the plants because of roof mounting (shading). This can affect plant growth, crop yield and fruit quality (Cossu et al., 2018; Roslan et al., 2018). For this reason, the problem of shading by photovoltaic panels must be studied in detail.

From the nineties to the present, greenhouse shading caused by different systems and mechanisms has been studied by numerous authors (Aroca-Delgado et al., 2018). Greenhouse shading is a simple and effective method to provide a favourable environment for plant growth and improve the productivity and quality of crops in warm areas with many hours of sunshine per year (Lorenzo et al., 2006; Ahemd et al., 2016). Shading reduces the intensity of solar radiation and thus the temperature inside the greenhouse (Kittas et al., 1999). Shading levels should not greatly reduce solar radiation entering the greenhouse to avoid negative effects on plant growth (Cockshull et al., 1992; Challa and Bakker, 1998; Lorenzo et al., 2006; Cossu et al., 2014). When radiation is reduced, the temperature and relative humidity inside the greenhouse are reduced, which decreases the cost of cooling, water consumption and electricity (Willits and Peet, 2000; Al-Helal and Al-Musalam, 2003; Ahemd et al., 2016). In addition, shading reduces the incidence of blossom-end rot in tomatoes (Abdel-Mawgoud et al., 1996). For example, Gent (2007) found the total yield decreased line-arly with the increase in shading by 15, 30 and 50%, but this difference disappeared when the yield of marketable fruit was considered. Additionally, Abdel-Mawgoud et al. (1996) found that applying 30% shading to tomato plants does not affect the fruit yield. Loik et al.(2017) stated that shading caused by selective photovoltaic systems caused a small decrease in water use, whereas minimal effects were observed on the number of fruits and fresh weight for several market-able tomato species.

Crop yield is linearly related to the amount of solar radiation absorbed by the plants (Newton et al., 1999). Callejón-Ferre et al.(2009) found lower production in tomato plants grown under alumi-nised screens with shading above 40%. Klaring and Krumbein (2013) argue that restricting the intensity of solar radiation, through excessive permanent shading, leads to reduced tomato growth and yield but not to reduced fruit quality. In contrast, Callejón-Ferre et al. (2009) found fruit firmness was significantly greater when shading was above 40% and fruit total soluble solids (TSS) decreased as the shading density increased from 40% to 60%.

In relation to plant morphology, moderate external shading can improve plant homogeneity, especially in warm sunny areas (Al-Helal and Abdel-Ghany, 2011). Cockshull et al. (1992) in a study on three fixed shading treatments (0%, 6.4% and 23.4%) obtained total plant lengths of 9.1, 9.7 and 10 m, respectively, with no significant differences. In contrast, shading above 60% produced elongated plants. The plants reach higher values of length and leaf area and a lower number of leaves under high shading conditions (Bénard et al., 2015). Abdel-Mawgoud et al. (1996) showed that 30% shading increases the main stem length and leaf area but not the number of leaves.

In recent years, some studies have been published on using photovoltaic panels for greenhouse crops (García et al., 2011; Ezzaeri et al., 2018). Also, at the University of Almería (Spain) a research project was carried out during three crop cycles (2009-10, 2010-11 and 2011-12) to evaluate the compatibility of PV electrical energy production with tomato production (*Solanum lycopersycum* L.) under Almería-type greenhouse. The installation of photovoltaic panels on the greenhouse roof occupied only 9.8% (of the cover). Two publications were made of this research. In the first publication, Ureña-Sánchez et al. (2012) concluded that tomato production (crop cycle 2009-10) was compatible with the use of flexible photovoltaic panels on the rooftop. In the second one, Pérez-Alonso et al. (2012) obtained an accumulated daily energy production of 5.63 kW h m^{-2} from October to June (crop cycle 2009–10). For the accumulated of the whole year it was 8.25 kW h m^{-2}. The efficiency in the conversion of solar electricity coming from the PV modules in useful AC electricity (performance ratio) was 0.81 ($\pm$ 0.06), and the overall system efficiency was 4.7%. None of these studies evaluated radiation, plant morphology, production, yield com-ponents, and fruit quality as a whole. For this reason, the aim of this study was to determine the effect of shading caused by placing flexible photovoltaic panels to generate energy (placed on the greenhouse roof) on tomato plant morphology, yield and quality.

2. Materials and methods

2.1. Plant material and crop conditions

This study was conducted during the 2010-11 and 2011-12 growing seasons in an asymmetric 'ridge and furrow' Almeria greenhouse (see Fig. 1 in Ureña-Sanchez et al., 2012) located in the experimental plot of the University of Almeria, south-eastern Spain (36°52' N, 2°17' W, 98 m.a.s.l.).

The greenhouse has a total area of 1024 m^2. The structure consists of galvanised steel tubes and wire. The cover is made of three-layer co-extruded polyethylene (200 μm thickness, with 80% light transmission between 400–800 nm under laboratory conditions). Ventilation is passive, formed by extendable side windows and zenithal windows with automated functioning that depends on the temperature and relative humidity inside the greenhouse. The total area of ventilation is 12.50%. All ventilation surfaces are equipped with insect screens.

The soil used for cultivation comprised several substrate layers forming a 'sandwich' with 20–30 cm of fertile soil, a layer of manure of 1–3 cm at the top, and a layer of silica sand approximately 8–12 cm deep (see Fig. 1 in Ureña-Sanchez et al., 2012). This system is com-monly used in south-eastern Spain.

The study was conducted using a crop of tomato (*Solanum lycopersicum* L.) cv. Daniela. The Daniela cultivar is one of the most cultivated phenotypes in the world (Andaluz et al., 2016). Its plants are very vigorous, it adapts to different types of soils and climates, and has high productivity when grown in a greenhouse. This type of tomato has a strong presence in European markets because it has a long shelf life and high quality (Resh, 2016; Saenz et al., 2013).

Plant transplanting and the end of the crop cycles were, for the first, from 13 September 2010 to 24 March 2011 and, for the second, from 1 September 2011 to 28 March 2012. In both cases, the planting frame measured 1.5 $\times$ 0.5 m, and fertilisation was performed by drip irrigation. All crop tasks performed in cultivation were usual in south-eastern Spain for the correct development of greenhouse planting (irrigation, fertilisation, tutoring, phytosanitary treatments, pruning, pollination, thinning of leaves and fruits, harvesting, etc.; López-Aragón et al., 2018).

In the 2011-12 season, lime was applied on the greenhouse roof on 5 March 2012 to reduce the radiation incident on the structure. The application of a solution of lime and water (known as 'Spanish White') to the greenhouse coating is a widespread practice in south-eastern Spain, aiming to reflect some solar radiation otherwise reaching the plants (Callejón-Ferre et al., 2009). Transmissivity levels under these conditions are approximately 30% of the total outside radiation (Morales et al., 1998). In the 2010-11 season, no lime was applied to the greenhouse roof because in the months of April and May, no crop was in the greenhouse.

2.2. Experimental design, photovoltaic panels, and shading treatments

The cultivation surface was divided by vertical polyethylene walls into three areas, where the treatments to be compared were placed. Fig. 1 shows the location of the two photovoltaic panel arrays (T1 and T2), with a surface area of 192 m^2 each, and the control without external shading (T0), with a surface area of 544 m^2. Each treatment comprised four replicates (R1, R2, R3 and R4) distributed equidistantly. The area of each replicate in treatments T1 and T2 was 25 m^2 with 50 plants, and 35 m^2 with 70 plants in the control.

Each treatment was defined according to the type of shading caused by the flexible solar panels mounted on the greenhouse roof. The panel used in the study was a thin-film amorphous-silicon FUJI FPV 1092 solar module (Fuji Electric Systems Co., Ltd., Japan) of 1.567 m^2 (Table 1). In T1, 12 modules formed by simple photovoltaic panels (PV1) were mounted. In T2, six modules were mounted, formed by two photovoltaic panels (PV2) joined together. The shaded surface on the roof of T1 and T2 was 18.8 m^2, which represents 9.8% of the surface of each treatment (Fig. 1).

The electrical conductivity and pH of the soil solution were determined by an EC-pH-SDT Hanna 9811 electrical conductivity and pH meter (Hanna Instruments SL, Eibar, Gipuzkoa, Spain) with a resolution of 0.01 dS m^{-1}. Soil solution extraction was performed periodically throughout the crop cycles with suction probes at a depth of 15 cm (see Fig. 1 in Ureña-Sanchez et al., 2012). Four probes were placed in T0 and two probes in T1 and T2. Fig. 1 shows the probe arrangement for each treatment.

2.3. Measurements of plant production, yield components, quality, and morphology

The control of total and marketable production was performed on the surface of each replicate of T0, T1 and T2 throughout each crop cycle. For the measurement, an EKS Premium digital scale (EKS, Beijing, China) with a resolution of 10 g was used. In total production, all fruits harvested were considered. In marketable production, fruits damaged by pests or diseases, and those that were immature, cracked, etc., were discarded.

Fruit weight (g) and diameter (mm) were evaluated in each harvest on a sample of 300 marketable fruits (3 treatments $\times$ 4 replicates $\times$ 25 fruits·replicate^{-1}). Fruit weight was measured with a BEC Engineering

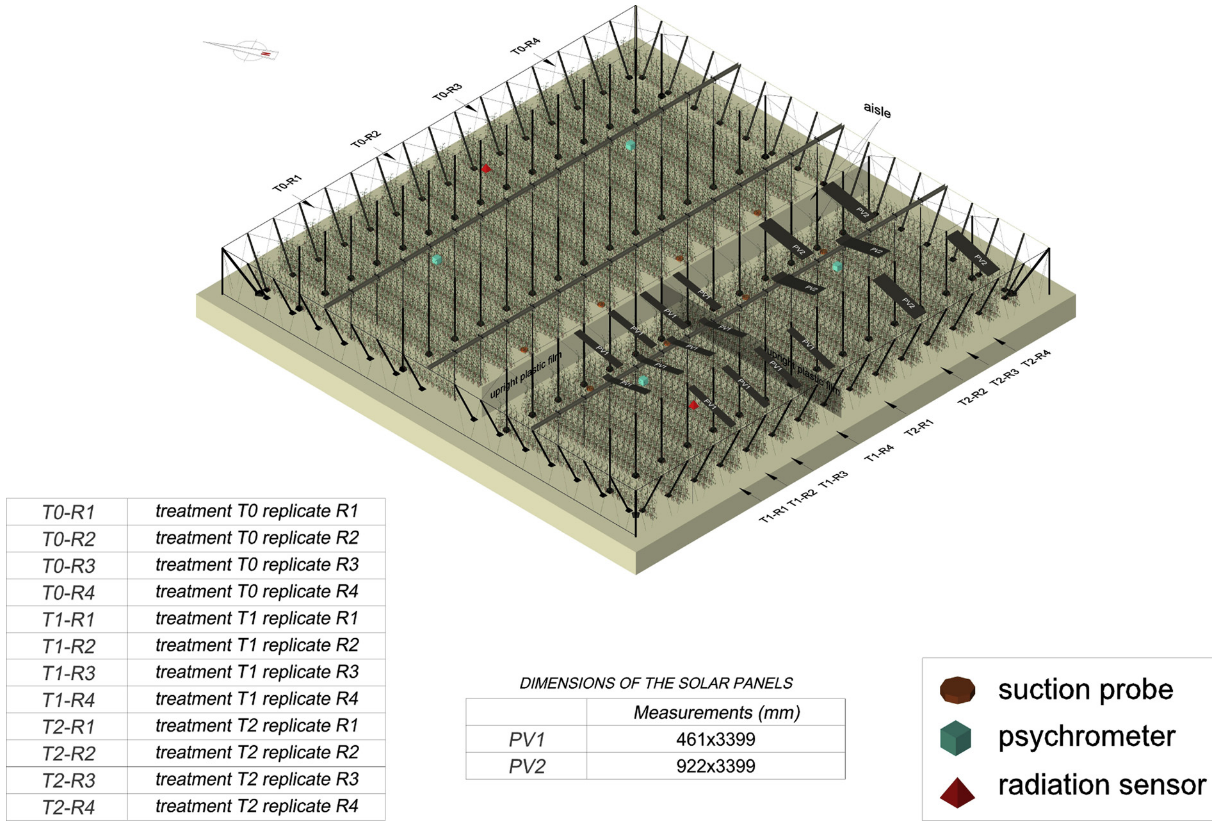

Fig. 1. Flexible solar panel arrays on the rooftop of a greenhouse.

Table 1
Technical specifications of the solar panels and the DC/AC converter (Ureña-Sánchez et al., 2012).

SOLAR PANELS		AC/DC CONVERTER	
Name	FUJI TPV 1096	Name	SMA SB 2500
Type	a-Si Thin film	AC Power(max)	2300 W
Open Circuit Voltage	429 V	AC Voltage	220–240 VAC
Short circuit Current	0.390 A	Frequency	50–60 Hz
Nominal* Voltage	319 V		
Nominal Current	0.288 A		
Nominal Power	92 W		
Area	1.567 m^2		
Weight	1.4 kg		

electronic scale with a resolution of 1 g. Maximum fruit diameter was determined using two callipers with an expandable loop, one for fruits with diameters between 30 and 95 mm and another for fruits with a diameter from 65 to 135 mm.

Fruit firmness, colour, total soluble solids (TSS) and pH were determined in some of the production harvests. In the 2010-11 season, the days evaluated were 157, 165, 172, 179 and 185 days after transplanting (DAT); whereas for the 2011-12 season, the days were 102, 109, 123, 130, 137, 144, 157, 172, 185 and 193 DAT. On each of these dates, quality parameters were determined on 100 fruits in each treatment (4 replicates × 25 fruits·replicate^{-1}).

Fruit firmness was determined with two types of measurements. One was through an AGROSTA 100 digital durometer (Durofel DFT 100, Serqueux, France) specific for measuring fruit and vegetables. This equipment has a head of 2.54 mm in length coupled to a precision mechanism. Three measurements were made per fruit in the equatorial zone and separated by the same distance. During the measurement, the head is pressed on the fruit surface, introducing it deeper as more resistance is offered by the measured material. The measurement range goes from 0 to 100. The measurement of 0 corresponds to the sensor completely outside, the measurement of 100 to the sensor fully in-serted. The resolution of the equipment is 1 graduation, and the accu-racy is ± 1 graduation. The other measurement of firmness was per-formed with a PCE-PTR 200 digital penetrometer (PCE Iberica SL, Tobarra, Albacete, Spain) equipped with a penetration strut of 11.3 mm in diameter (1.0 cm^2 surface) and operating at a slow and uniform penetration speed of 2 s to reach the notch marked on the strut itself. This penetrometer can measure pressures between 0 and 13 kg·cm^{-2}, with a resolution of 0.01 kg. Three perforations of the pulp were made in each equatorial zone, with an equidistant separation. In each of the points measured, the exocarp of the fruit of a size somewhat larger than the diameter of the one used (2 cm^2, approximately) was removed.

TSS (ºBrix) were determined individually for each fruit using an ATAGO PR-101 digital refractometer (Atago Co., Ltd., Tokyo, Japan) with a resolution of 0.1. Fruit acidity was determined using a CRISON MM 40 pH meter (Crison Instruments SA, Alella, Barcelona, Spain), with a resolution of 0.01 units. Fruit colour was measured on a graded colour scale (1–10) ranging from 1, when the fruit is green, to 10, when the colour is an intense red.

Photosynthetically active radiation (PAR, 400–700 nm) inside the greenhouse was determined by an external sensor and 23 internal sensors, of the 'LI-190SA Quantum Sensor' type (LI-COR Corporate Offices-US, Lincoln, Nebraska USA) with ‘Sensitivity: Typical 5 μA per 1000 μmol s^{-1} m^{-2}’ and Absolute Calibration of ± 5% traceable to the National Institute of Standards and Technology (NIST). The 23 sensors were distributed among T0, T1 and T2 (Fig. 1).

Plant morphology was determined with a random sample constituted by a total of 168 plants (3 treatments × 4 replicates × 14 plants·replicate^{-1}) in each crop cycle. The morphological parameters of each plant were measured every 14 days according to Fig. 2.

The studied plant morphology variables were as follows:

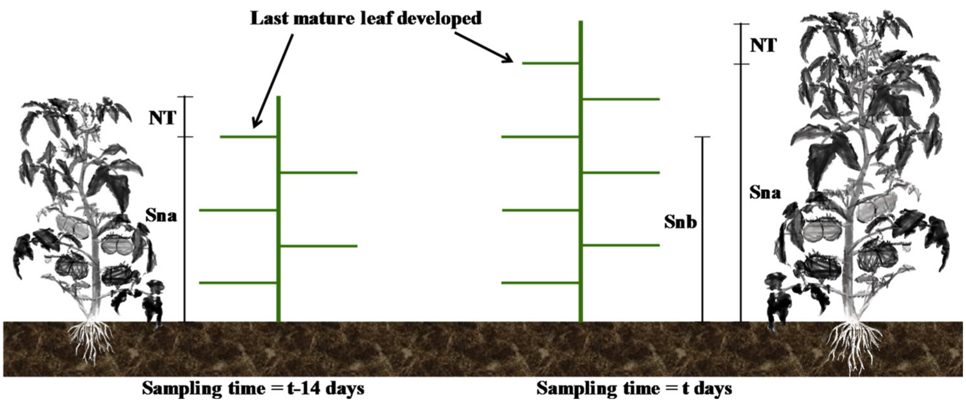

Fig. 2. Morphological measurements performed on each plant. List of measured parameters (in a 14-day interval). Sna (cm): distance of the last internode to the ground, considering as the last internode the one presenting the last leaf having reached physiological maturity. NT (cm): distance from the last internode to the apical meristem of the plant. Snb (cm): corresponds to Sna in the measurement made at t-14, where t is the current day of measurement.

- PL (cm): total plant length. Calculated according to the expression PL = Sna + NT. Length measurements were measured with a measuring tape;
- Number of internodes per plant;
- Mean internode (cm): mean internode length. Calculated according to the expression M.I. = Sna/Total leaves or total nodes;
- Total leaves: number of mature leaves accumulated throughout the crop cycle; and
- Stem diameter (mm): diameter measured by a digital calliper in the central zone of each plant internode.

The number of total flowers and the number of total fruits per branch were measured in the same plants used to study plant morphology.

2.4. Statistical analysis

Statgraphics Centurion XVII-X64 software was used. The normality and homogeneity of variances were verified prior to the data analysis. All data on production, quality and plant morphology were subjected to analysis of variance (ANOVA). The data on plant morphology, yield and fruit quality were analysed according to the linear model $Y_{ijk} = \mu + \alpha_i + \beta j + (\alpha\beta)_{ij} + \varepsilon_{ij}$, where Y_{ij} is the observation ij-th, μ is the global mean, α_i is the effect of the ith treatment (T0, T1, and T2), βj is the effect of the j-th crop cycle (2010-11 and 2011-12), $(\alpha\beta)_{ij}$ is the effect of the interaction between treatment and crop cycle, and ε_{ijk} is the experimental error (McIntosh, 1983; Montgomery, 1991; Gómez and Gómez, 1984).

The comparison between the means of each treatment was made by Bonferroni multiple range correction (Freund et al., 2010). Bonferroni correction considers that, if a null hypothesis is true (for example, if the comparison of TSS between two agricultural seasons does not differ statistically), a significant difference will be observed ($P < 0.05$). This is the type I or alpha (α) error. When three independent tests are performed (for example, unrelated treatments T0, T1 and T2) and the null hypothesis is valid for the three comparisons, the probability that at least one test is significant is no longer 0.05, but 0.143. Eq. (1) shows the error rate for three separate tests (Armstrong, 2014).

$$1 - (1 - \alpha)^n \quad (1)$$

where n is the number of tests performed (three in our case).

Bonferroni adjustment reduces the α applied to each comparison such that the study-wide error is 0.05. The modification of the Bonferroni procedure can be improved by the Dunn-Sidak procedure, which slightly improves the power for each comparison (Quinn and Keough, 2002). The adjusted significance value is shown in Eq. (2).

$$\alpha' = 1 - (1 - \alpha)^{1/n} \quad (2)$$

2.5. Photovoltaic energy production and installation efficiency

The cumulative daily production of PV energy, the yearly cumulative, the overall conversion efficiency to injected electric current to the grid 'PR' (Perfomance Ratio) and the overall system efficiency (PV efficiency) will be evaluated.

2.6. Technical-economic comparison of the installation of PV panels on the greenhouse roofs in Almería between 2012 and 2018

Based on the data of nominal power, installation cost, energy cost, energy production, operating self-consumption and support for the installation of PV modules on the greenhouse roofs reported by Ureña-Sánchez et al. (2012) and Pérez-Alonso et al. (2012), will be updated for the same experimental greenhouse of 1000 m^2 and a PV installation of the same characteristics but with better performance according to Carreño-Ortega et al. (2017).

2.7. Study limitations

The main limitation of this research is that it should have been conducted simultaneously in several greenhouses, whose random distribution of shading produced by the treatments with photovoltaic panels was different, thus avoiding the associated effect on crop development caused by the layout of the plants in the north or south zones.

Another limitation is that the study was conducted in a newly built greenhouse and therefore on soil where organic matter had recently been incorporated and on which only one previous crop had been grown. This could affect early crop growth in the first cycle studied. Also, due to the physical-chemical characteristics of the soil (pH, EC, etc.).

The time elapsed from data collection to the presentation of the results for publication; however, this has been the case when working with more than 35,000 data points.

3. Results

3.1. Shading effect of photovoltaic panels on PAR

Fig. 3 shows the monthly average daily photosynthetically active radiation (PAR) for the months associated with the study period in the 2010-11 and 2011-12 seasons. The results are from October to May and include the radiation outside the greenhouse and the radiation with shading treatments of 9.8% by photovoltaic panels on the roof (T1 and T2) and the control without photovoltaic panels (T0).

The lowest radiation occurred in December in the two crop cycles studied (2010-11 and 2011-12). The highest outside radiation occurred in April and May in the studied crop cycles. In contrast, in April and May of the 2010-11 season, the radiation inside the greenhouse was

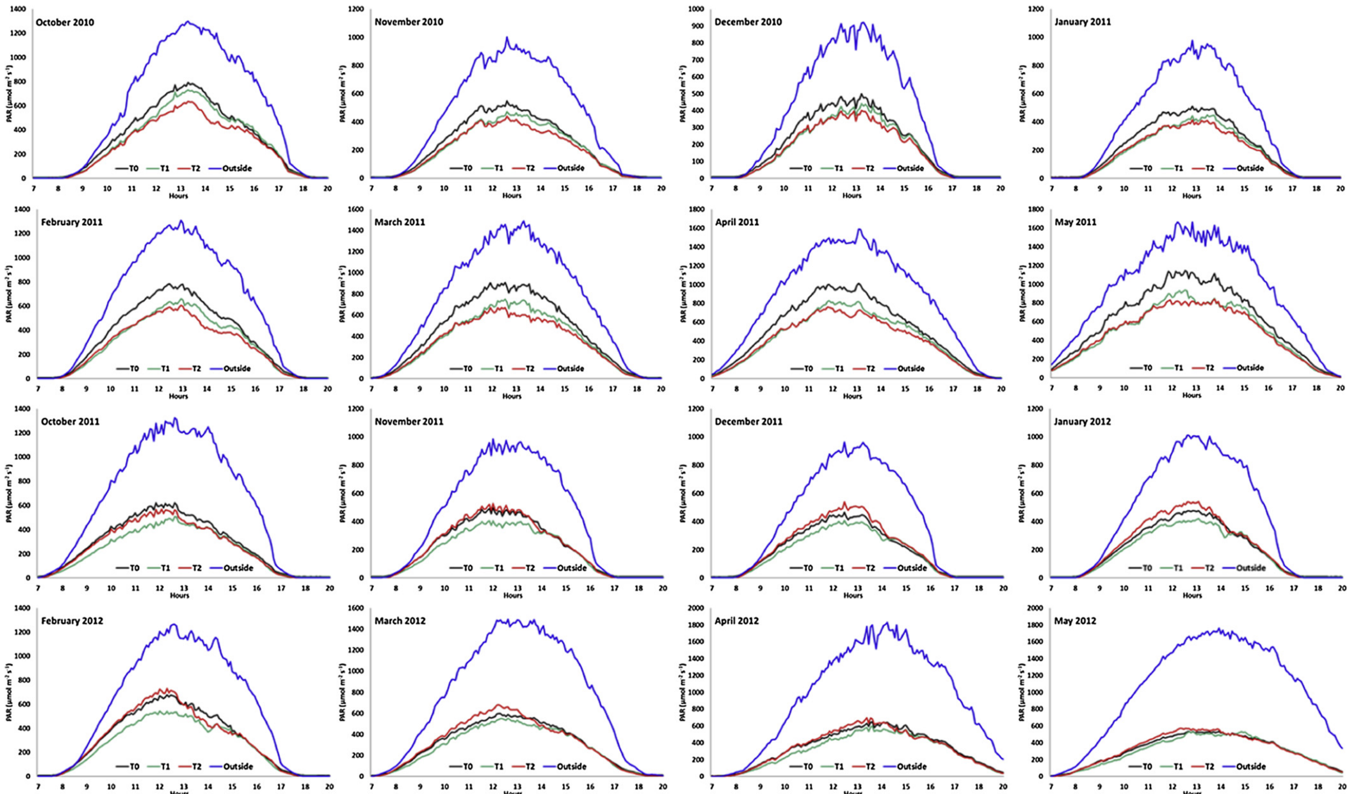

Fig. 3. Monthly daily average evolution of photosynthetically active radiation (PAR) for each month in the study period, as well as outside radiation.

Table 2
Average daily values of photosynthetically active radiation (PAR) for each month in the study period (μmol m^{-2} s^{-1}).

2010-11	October	November	December	January	February	March	April	May
Outside	691	499	486	516	698	775	870	956
T0	390	269	258	282	399	471	531	626
T1	357	233	222	236	326	377	433	500
T2	314	218	211	227	306	351	409	484
2011-12	**October**	**November**	**December**	**January**	**February**	**March**	**April**	**May**
Outside	710	532	523	561	679	764	990	1055
T0	318	263	244	259	352	303	355	317
T1	256	226	219	234	294	275	314	300
T2	288	268	267	282	350	315	355	325

The values correspond to the average radiation from sunrise to sunset.

Table 3
Maximum values of monthly daily average photosynthetically active radiation (PAR) (μmol m^{-2} s^{-1}).

2010-11	October	November	December	January	February	March	April	May
Outside	1300	1003	922	977	1308	1490	1593	1665
T0	794	550	499	511	784	911	1013	1145
T1	732	474	442	450	660	753	830	938
T2	637	440	401	415	606	672	760	844
2011-12	**October**	**November**	**December**	**January**	**February**	**March**	**April**	**May**
Outside	1325	987	963	1014	1264	1493	1832	1762
T0	623	498	467	478	680	599	646	537
T1	509	407	409	422	544	553	598	532
T2	571	529	540	542	732	680	698	573

The values correspond to the maximum radiation obtained from the average of the sensors for each treatment.

Table 4
Average values of pH and electrical conductivity (EC) of the soil solution ($dS\,m^{-1}$) in association with the treatments studied during the 2010-11 and 2011-12 seasons.

	2010-11 EC ($dS\,m^{-1}$)	pH	2011-12 EC ($dS\,m^{-1}$)	pH
T0	4.03a	7.64	2.87c	9.56a
T1	3.49b	7.64	5.75a	8.88b
T2	3.17c	7.57	3.36b	9.61a
Significance	*	n.s.	***	*

Analysis of variance according to the model $Yi = \mu + \alpha i + \varepsilon i$, where Yi is the i-th observation, μ is the global mean, αi is the effect of the i-th treatment (T0, T1 and T2), and εi is the experimental error. ns, *, **, and *** indicate no significance or significance for $P \leq 0.05$, 0.01 and 0.001, respectively. Numerical values for each column followed by a different letter denote significant differences for $P < 0.05$ according to the Bonferroni test.

much higher than that of the 2011-12 season for this same period (Table 2, Fig. 3). If this same calculation is made for the point value of the maximum daily radiation, the reduction produced in April 2010-11 (without lime) in T0 relative to the outside was 36.4%, and for April 2011-12 (with lime), it was 64.7%; therefore, the shading reduction associated with lime application was 28.3% (Table 3). As for the treatments studied in 2010-11, the highest radiation occurred in T0, followed by T1 and T2. In the case of 2011-12, the highest indoor PAR occurred in T2, followed by T0 and T1 (Table 2, Table 3, Fig. 3).

3.2. *Electrical conductivity (EC) and pH of the soil solution*

The EC of the soil solution showed significant differences between the treatments studied. In addition, the EC behaviour was different in the two crop cycles studied. In 2010-11, the highest average EC for the crop cycle occurred in T0 with 4.03 $dS\,m^{-1}$, whereas the lowest average EC occurred in T2 with 3.17 $dS\,m^{-1}$. In contrast, in 2011-12, the highest average EC of the soil solution occurred in T1 (5.75 $dS\,m^{-1}$) and the lowest in T0 (2.87 $dS\,m^{-1}$). Relative to the average pH of the soil solution, these findings were only significant in the 2011-12 season, showing significant differences in T1 compared to the other treatments (Table 4). The evolution of pH and EC of the soil solution changed over the two crop periods, as shown in Fig. 4.

3.3. *Shading effect of photovoltaic panels on plant morphology*

Plant length, internode length, number of leaves and number of internodes were not affected by shading by photovoltaic panels (no significant differences between T0, T1 and T2). The average values varied from 310.3 cm of plant length in T1 to 310.8 cm in T0. In contrast, between crop cycles, significant differences appeared because 2011–2012 was the season producing the greatest length and number of leaves and internodes. Internode length was similar between the two seasons. In addition, the behaviour of plant length and the number of leaves and internodes for T0, T1 and T2 was different between the two crop cycles, a fact demonstrated by interaction between the factors 'Treatments × Cycle' (Table 5; Fig. 5).

Stem diameter was similar in the treatments with photovoltaic panels and the control. In 2011-12, plants with thicker stems than those from the previous crop cycle were produced (2010-11). In addition, the behaviour of treatments T0, T1 and T2 was different between seasons, as deduced from the presence of factor interaction (Table 5).

The number of flowers per branch did not show significant differences between T0, T1 and T2, oscillating their average values between 7.2 and 7.5 flowers·branch^{-1}. In contrast, the number of fruits produced was higher in T2 than in the other treatments. The number of fruits·branch^{-1} ranged from 6.2 in T0 to 6.6 in T2. As for crop cycles, the number of flowers·branch^{-1} and fruits·branch^{-1} in 2010-11 were significantly higher than in 2011-12. In addition, T0, T1 and T2 showed similar behaviour in both seasons, as verified by the absence of factor interaction (Table 5; Fig. 5).

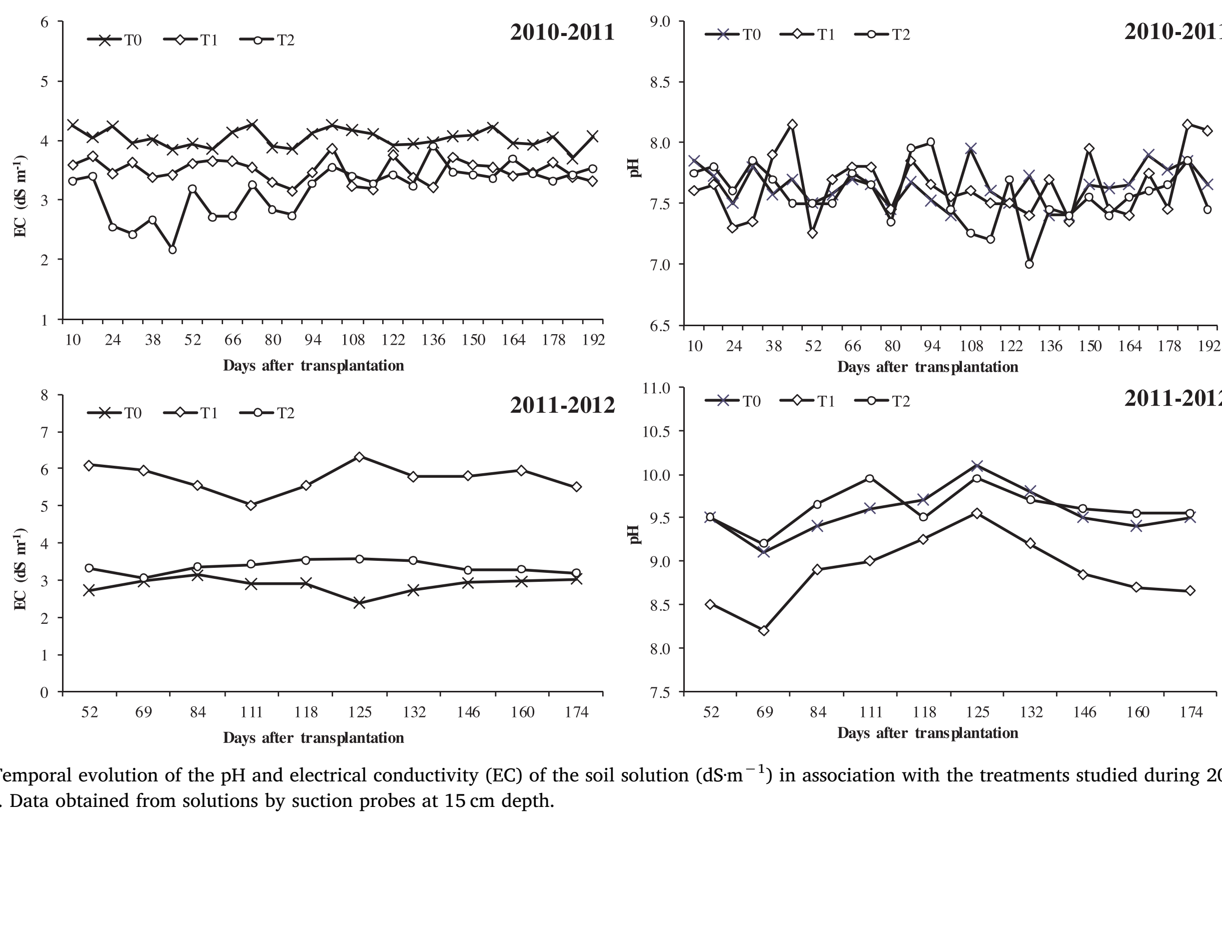

Fig. 4. Temporal evolution of the pH and electrical conductivity (EC) of the soil solution (dS·m^{-1}) in association with the treatments studied during 2010-11 and 2011-12. Data obtained from solutions by suction probes at 15 cm depth.

Table 5
Effect of shading by photovoltaic panels on plant morphology.

	Plant length (cm)	Leaves· plant^{-1}	Internodes· plant^{-1}	Internode length (cm)	Stem diameter (mm)	Flowers· branch^{-1}	Fruits· branch^{-1}
A: Treatments							
T0	317.8	41.1	37.6	8.45	12.49	7.2	6.2b
T1	310.3	40.8	37.6	8.25	11.99	7.2	6.3b
T2	315.9	41.7	38.2	8.27	12.03	7.5	6.6a
Significance	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
B: Cycle							
2010 - 11	288.1	38.7	34.8	8.27	11.87	7.7	6.6
2011 - 12	335.6	43.8	40.0	8.39	12.47	7.0	6.2
Significance	***	***	***	n.s.	***	***	***
A × B	**	**	**	n.s.	***	n.s.	n.s.

Analysis of variance according to the model $Y_{ijk} = \mu + \alpha_i + \beta j + (\alpha\beta)_{ij} + \varepsilon_{ij}$. ns, *, **, and *** indicate no significance or significance for $P \le 0.05$, 0.01 and 0.001, respectively. Numerical values for each column followed by different letters denote significant differences for $P < 0.05$ according to the Bonferroni test.

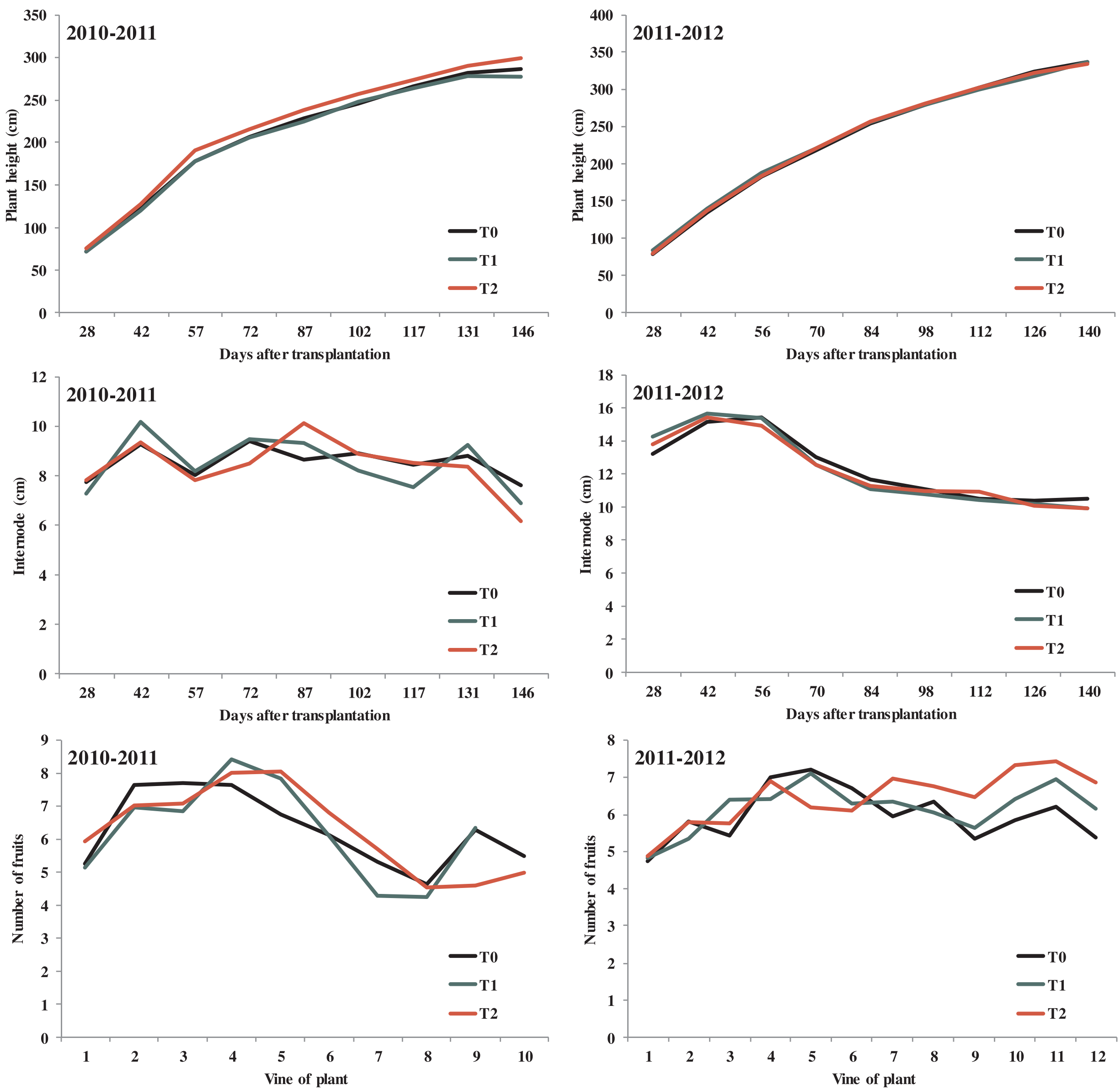

Fig. 5. Evolution of plant height (cm), internode length (cm) and number of fruits per branch related to the shading produced by the treatments with photovoltaic panels in the 2010-11 and 2011-12 growing seasons.

Table 6
Effect of shading by photovoltaic panels on total cumulative yield (kg m^{-2}) of tomato.

	Days after transplant							
	130	150	157	165	172	179	185	193
A: Treatments								
T0	1.94b	3.85b	4.91	6.07	7.55	8.62	10.40	11.73
T1	2.49a	4.10ab	5.13	6.23	7.49	8.49	9.99	11.02
T2	2.42a	4.49a	5.49	6.63	7.98	9.03	10.50	11.66
Significance	***	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
B: Cycle								
2010 - 11	1.41	3.26	4.63	6.49	8.59	9.35	11.08	12.27
2011 - 12	3.06	5.03	5.73	6.13	6.76	8.07	9.51	10.67
Significance	***	***	***	*	***	***	***	***
A × B	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Analysis of variance according to the model $Yijk = \mu + \alpha i + \beta j + (\alpha\beta)\ ij + \varepsilon ij$. n.s., *, ** and *** indicate no significance or significance for $P \leq 0.05$, 0.01 and 0.001, respectively. Numerical values for each column followed by a different letter denote significant differences for $P < 0.05$ according to the Bonferroni test.

3.4. Shading effect of photovoltaic panels on production and yield components

Shading caused by the two photovoltaic panel arrays (T1 and T2) did not significantly affect the control (T0) in the cumulative market-able yield for the period from 157 DAT to the end of the crop (193 DAT). In the 2011-12 season, a significant increase in yield of 15% was observed compared to that of 2010-11.

Regarding the early yield, the control showed a lower early yield than shading treatments with significant differences at 130 and 150 DAT. The second crop cycle (2011-12) produced more than double the early yield at 130 DAT than the first (2010-11). In addition, at 130 DAT, a significant interaction was observed in the yield between the factors 'Treatment × Cycle', which shows that the behaviour of T0, T1 and T2 differed in the two crop cycles studied (Table 6).

Marketable production meant a total yield reduction of 19.7%, 18.2% and 17.1% for T0, T1 and T2, respectively. The effect associated with shading caused using photovoltaic panels on marketable production showed a behaviour similar to that of total yield. Shading did not affect the cumulative marketable yield of the tomato crop. In contrast, no significant differences were observed between crop cycles. In addition, no interaction effect was observed between the factors 'Treatment and Cycle' at the end of the crop (Fig. 6).

3.5. Shading effect of photovoltaic panels on fruit weight, size and quality

Average fruit weight and size were higher in the control than under shading by photovoltaic panels. However, these differences were only significant between T1 and the control (T0). Fruit size was also significantly higher in 2010-11 than in 2011-12. In addition, an interaction existed between shading treatments and the crop cycle. This shows that the response of the fruit size in T0, T1 and T2 does not behave in the same way in the crop cycles studied (Table 7 and Fig. 7).

Fruit colour did not show significant differences between shading treatments. In contrast, in the first crop cycle, the colour was significantly more intense than in the second season. In addition, the colour of T0, T1 and T2 showed similar behaviour (not a significant interaction) in the crop cycles (Table 7). Fruit firmness was similar in the treatments and during the two seasons studied. The values were approximately 91% for hardness and 2.6 kg·cm^{-2} for penetration resistance (Table 7 and Fig. 7).

The TSS were equal between treatments, which were statistically superior to the control. In both growing seasons, the TSS increased throughout the DAT, being an average of 9% higher in 2010-11 than in 2011-12. In addition, an interaction was observed between the treatments and the crop cycle, so that the TSS between treatments had a different behaviour between seasons (Table 7 and Fig. 7). Fruit pH did not show significant differences between treatments nor between crop cycles; no interaction was observed between the factors studied (Table 7).

3.6. Photovoltaic energy production and installation efficiency

Daily energy productions indicate an accumulated value during the 2010-11 crop cycle of 4.96 kW h m^{-2} (September 2010 to June 2011) and for the yearly accumulated of 6.40 kW h m^{-2}. For the 2011-12 season (September 2011 to June 2012) of 4.42 and 5.70 kW h m^{-2}, respectively. Likewise, the overall conversion efficiency to injected electric current to the grid (performance ratio) in the 2010-11 crop cycle was 0.84 (± 0.06), and for the 2011-12 season 0.74 (± 0.04). The overall system efficiency (PV efficiency) was 4.18 (± 0.30) for the 2010-11 season and 3.67 (± 0.20) for the 2011-12 season.

3.7. Technical-economic comparison of the installation of PV panels on the greenhouse roofs in Almería between 2012 and 2018

Table 8 shows, in a comparative way, technical and economic parameters of the experimental installation used in the present study (Ureña-Sánchez et al., 2012; Pérez-Alonso et al., 2012), and a new installation of PV modules with thin crystalline silicon film more modern and with greater performance described by Carreño-Ortega et al.(2017).

4. Discussion

The lowest PAR occurred in November and January, and the highest radiation occurred in May, as described by Ureña-Sánchez et al. (2012). Likewise, the highest inside radiation of the greenhouse occurred in T0 during 2010-11, agreeing with those same authors. In contrast, this did not happen in 2011-12, where T2 showed the highest PAR, followed closely by T0. These differences could be due to the uneven accumulation of dirt on the plastic exterior during the second season. The in-side radiation of the greenhouse in April and May of the 2010-11 season was much higher than the inside radiation of that same period for the 2011-12 season. This was because in the second season, lime was applied on the greenhouse roof on 5 March 2012. In contrast, in the previous cycle (2010-11) lime was not applied. Radiation transmissivity

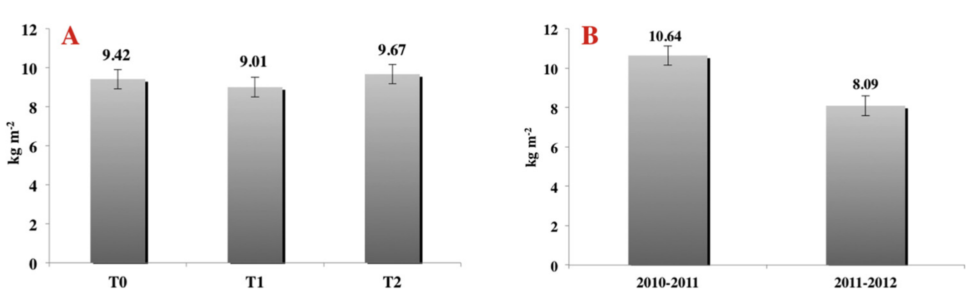

Fig. 6. Effect of shading by photovoltaic panels on cumulative marketable yield (kg m^{-2}) of tomato. The results come from the analysis of variance according to the model $Y_{ijk} = \mu + \alpha_i + \beta j + (\alpha\beta)_{ij} + \varepsilon_{ij}$. (A) shows the average of treatments T0, T1 and T2 for the two crop cycles. (B) shows the average of 2010-11 and 2011-12. The error bars correspond to the values of minimum significant differences according to the Bonferroni test.

Table 7
Effect of shading by photovoltaic panels on fruit weight, diameter and quality.

	AFW (g)	Diameter (mm)	Colour (1–0)	Hardness (%)	Firmness (kg cm^{-2})	TSS (ºBrix)	pH
A: Treatments							
T0	188.3a	74.5a	7	91.42	2.58	4.4b	3.9
T1	181.7b	73.4b	7	91.02	2.61	4.7a	3.9
T2	185.6ab	74.0ab	7	91.44	2.57	4.7a	3.9
Significance	**	***	n.s.	n.s.	n.s.	***	n.s.
B: Cycle							
2010 – 11	192.0	75.5	8	91.08	2.79	4.9	4.0
2011 – 12	181.9	73.2	6	91.42	2.49	4.5	3.8
Significance	***	***	***	n.s.	n.s.	***	n.s.
A × B	***	***	n.s.	n.s.	n.s.	**	n.s.

AFW: average fruit weight. TSS: total soluble solids. Analysis of variance according to the model $Y_{ijk}=\mu+\alpha_i+\beta_j+(\alpha\beta)_{ij}+\varepsilon_{ij}$. ns, *, ** and *** indicate no significance or significance for $P \le 0.05$, 0.01 and 0.001, respectively. Numerical values for each column followed by a different letter denote significant differences for $P < 0.05$ according to the Bonferroni test.

associated with lime application in the present study was like that described by Morales et al. (1998), which showed that this practice reduces outside radiation by 30%. For example, in the present study, lime application reduced the average daily radiation in the inside of the greenhouse by 25.2% in T0 for the month of April 2011-12 (with lime application), compared to T0 of 2010-11 (without time application).

Excessive solar reduction caused by high shading rates can decrease the total and marketable yield of tomato grown in a greenhouse (Cockshull et al., 1992; Challa and Bakker, 1998; Lorenzo et al., 2006). In contrast, light to moderate shading does not affect total and marketable yield (Gent, 2007; Ureña-Sánchez et al., 2012; Ezzaeri et al., 2018), and can even improve production under warm growing conditions and high solar radiation (Lorenzo et al., 2006; Ahemd et al., 2016). In the present study, no differences were found in the total or cumulative marketable yield associated with the use of shading of 9.8% by photovoltaic panels, as described by Ureña-Sánchez et al. (2012) and Ezzaeri et al. (2018). The main cause of the non-marketable production were fruits damaged by pests (especially by *Tuta absoluta*) and small, immature, and deformed fruits.

In the second season studied (2011-12), the yield increased by 15% compared to the first (2010-11). In addition, no significant interaction occurred in the cumulative yield from 150 DAT between the factors 'Treatment × Cycle'. This shows treatments behaved similarly in the two crop cycles studied.

Some studies show how early crop growth can be affected by an excessive reduction of light. Cockshull et al. (1992), in their study of

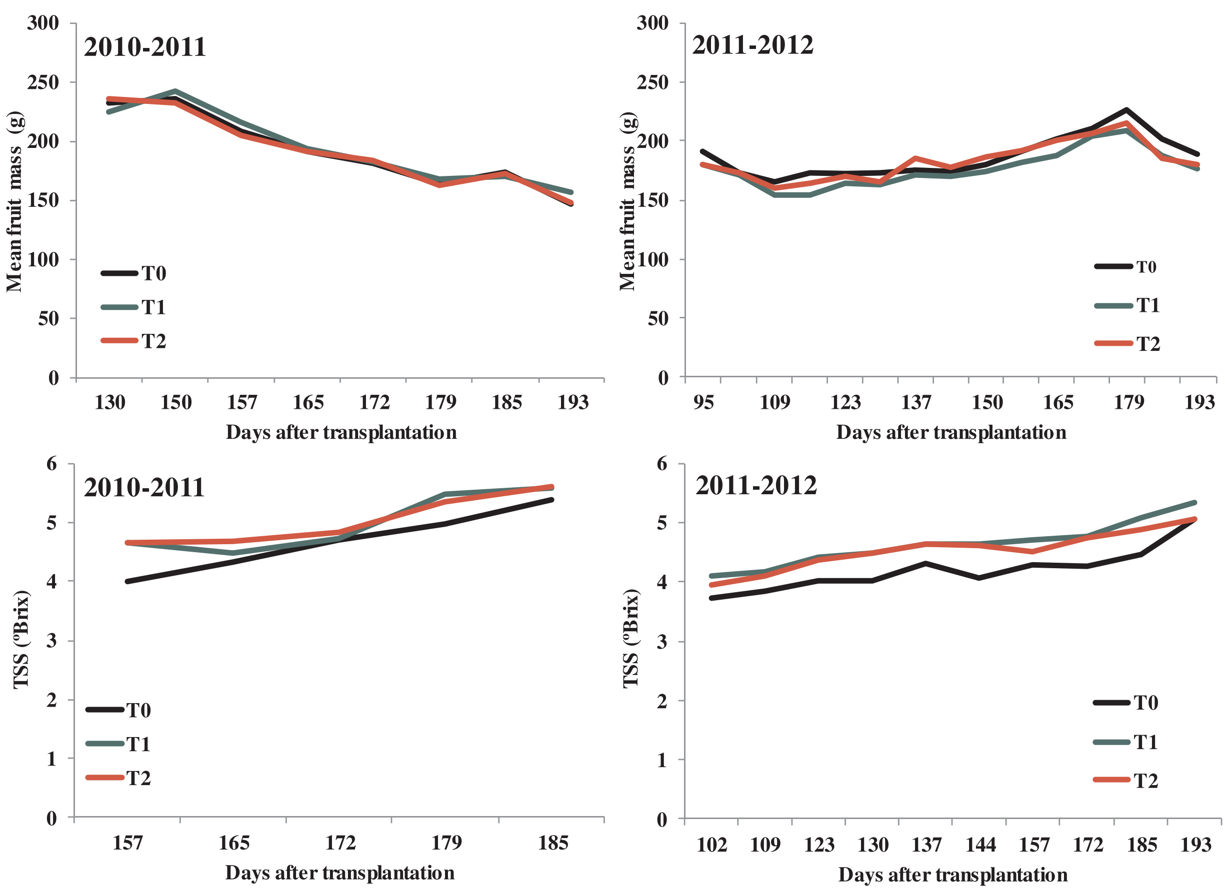

Fig. 7. Evolution of average fruit weight (AFW), total soluble solids (TSS) and fruit firmness related to shading treatments by photovoltaic panels in the 2010-11 and 2011-12 crop cycles.

Table 8
Technical and economic parameters of the two PV installations compared.

Parameter	Ureña-Sánchez et al. (2012) and Pérez-Alonso et al. (2012)	Present	Variation (%)
Year	2012	2018	
Modules power PV (Wp)	92	240	+160.87
PV module area (m^2)	1.567	1.66	+5.93
Number of modules per ha	625	590	−5.60
Installed power (kWp) per ha	57.50	141.60	+146.26
Energy (kWh) produced per ha and year	82,672.35	203,589.65	+146.26
Self-consumption of energy (kWh) per ha and year	10,240.00	10,240.00	0.00
Energy cost (€ $kW^{-1\,h^{-1}}$)	0.125	0.144	+15.20
PV installation cost (€ $Wp^{-1)}$	6.36	1.70	−73.27
Panels cost (€·$Wp^{-1)}$	3.96	0.70	−82.32
Subsidy to the PV energy production (€ $kW^{-1\,h^{-1)}}$	0.32	0.00	−100.00
Subsidy to the installation cost (%)	0.00	$\leq$ 50%	+50.00
Installation cost (€ ha^{-1})	365,700.00	240,720.00	−34.17
Subsidy for installation (€ ha^{-1})	0.00	120,360.00*	+100
Subsidy for energy production (€ $ha^{-1año^{-1}}$)	23,178.35	0.00	−100

* Value that is within the limit of the maximum subsidy of 120,000 € (BOJA, 2018).

fixed black shading screens in Great Britain, observed a decrease in the early marketable yield in the first harvest of 10.2% and 28% for the light treatment (6.2% shading) and dense treatment (16.5% shading), compared to the control (0% shading). In contrast, the results of the present study suggest a low shading rate (9.8%) did not affect early crop growth. The lower early production obtained in the control could be due to the higher EC of the soil solution in the initial phase of the crop (Fig. 4), as described by other authors (Awanng et al., 1993; Petersen et al., 1998; Lorenzo et al., 2006; Callejón-Ferre et al., 2009), indicating that high EC values of the soil solution can reduce crop yield and fruit size, increasing the firmness and flavour of tomato fruits.

Shading decreases tomato fruit size (Cockshull et al., 1992; Gent, 2007; Ureña-Sánchez et al., 2012; Bénard et al., 2015). In the present study, the average weight and size were significantly lower in T1, compared to the control. The absence of differences between T2 and the control shows that light shading of 9.8% in T1 and T2 can cause different effects according to the panel arrangement in these treatments (Fig. 1). This could also be produced by the higher EC in T1 produced during 2011-12 (Table 4), as described by other authors (Awanng et al., 1993; Petersen et al., 1998; Lorenzo et al., 2006; Callejón-Ferre et al., 2009).

Tomato cultivation requires high solar radiation (Castilla, 2005). There are other crops that do not need so much sunlight for proper growth. Examples of this, and their interaction with semitransparent PV solar panels on the greenhouse roofs, have been described by Buttaro et al. (2016) in arugula cultivation (*Diplotaxis tenuifolia* L.). In addition, Blando et al. (2018), in strawberries and raspberries cultivation, concluded that the parameters of fruit quality (sugars, anthocyanins, phenols, organic acids, etc.) are not affected by the shading of solar panels on the greenhouse roof. Also, tests with PV panels on the greenhouse roof (20%) in California pepper cultivation have been described by Kavga et al. (2019). These authors concluded that the quality of the pepper fruit is not affected.

Both, the crop type and the PV solar panel type (opaque, transparent or semitransparent) can contribute to a higher percentage of use of the roof surface. Perhaps, new tests should be carried out with other crops and other types of solar panels in the study area (Almería-Spain). This would determine the optimal cover shading percentages compatible with each greenhouse crop.

Fruit colour and firmness were not affected when the plants were grown under light shading (9.8%) from photovoltaic panels. This coincides with what was described by Ureña-Sánchez et al. (2012).

The TSS of the tomato fruit decrease when plants are exposed to high shading (60%). In contrast, these differences disappear under moderate shading (40–50%) (Callejón-Ferre et al., 2009; Klaring and Krumbein, 2013); however, in the present study, 9.8% shading by photovoltaic panels mounted on the greenhouse roof produced significantly more TSS than did the control without photovoltaic panels, coinciding with that indicated by Lorenzo et al. (2006) and Ahemd et al. (2016), affirming that shading can improve fruit quality. In ad-dition, this could also be influenced by the higher EC of T1 and T2 during the 2011-12 season, as described by other studies (Awanng et al., 1993; Petersen et al., 1998; Lorenzo et al., 2006; Callejón-Ferre et al., 2009).

Fruit pH is affected by shading above 40% (Callejón-Ferre et al., 2009). In contrast, light to moderate shading, approximately 10%, does not affect it (Ureña-Sánchez et al., 2012). In the present study, the use of photovoltaic panels resulted in a fruit pH like that of the control, as described by Ureña-Sánchez et al. (2012).

Moderate shading by photovoltaic panels placed on the greenhouse roof did not alter the plant height, stem diameter, internode length or number of leaves and internodes. This coincides with what was described by other authors (Cockshull et al., 1992; Abdel-Mawgoud et al., 1996; Ezzaeri et al., 2018), affirming that light to moderate shading does not affect plant architecture. Cockshull et al. (1992) obtained si-milar plant lengths under shading below 24%. In the present study, the plant length was similar in the control and under shading of 9.8%. Abdel-Mawgoud et al. (1996) showed that 30% of the shading did not increase the number of leaves; in the present study, the number of leaves and internodes was not affected by less shading. In the present study, the stem diameter was similar with both photovoltaic panel ar-rays and the control. This coincides with what was described by Ezzaeri et al. (2018), who did not find differences in the stem diameter under 10% shading by photovoltaic panels. Relative to the crop cycles, the 2011–12 season produced greater length and a greater number of leaves and internodes compared to the previous season. In contrast, the in-ternode length was similar in 2010–11 and 2011–12, showing the greatest length obtained in the second cycle was due to the higher number of internodes.

Regarding the number of flowers per branch, no differences existed between shading treatments and the control. In addition, the number of fruits per branch between T1 and the control did not show significant differences. This may agree with what was reported by Sandri et al. (2003), who stated that the number of fruits per square metre does not differ between shaded (52%) and unshaded tomato plantations. In our case, the T2 shading treatment produced more fruits per branch than the T1 and the control.

In general, 9.8% shading produced more fruits (Table 5) of smaller size (Table 7 and Fig. 7), so it did not affect crop yield (Table 6 and Fig. 6).

With 9.8% shading, production and morphology data (plant growth) are similar in all treatments (T0, T1 y T2). Dry biomass has not been analyzed and according Li et al. (2018) it would be very interesting to know the relationship of solar energy use for the plant biomass production with the electricity production.

In order to design PV greenhouses, it is necessary to know the relationship between the solar radiation available for the crop and the design parameters (PV cover ratio, arrangement pattern, height and orientation of the greenhouse) (Yano et al., 2010; Fatnassi et al., 2015; Cossu et al., 2018). Yano et al. (2010) demonstrated that for an orientation of the E-W greenhouse with modules on the cover in checkerboard, the radiation was more homogeneous that the straight-line arrangement. Fatnassi et al. (2015) obtained the same results. In this investigation, the PV greenhouse had the E-W orientation with quasi (of the modules) arrangement on checkerboard for the two treatments studied (T1 and T2; Fig. 1). No significant differences have been observed between both treatments.

In the production of photovoltaic energy there has been a decrease in the performance ratio (0.74) in the last crop cycle (2011-12) com-pared to 2010-11 (0.84); However, the latter value is higher than the one described by Ureña-Sánchez et al. (2012) in the 2009-10 cycle (0.81). Likewise, both the daily accumulated energy production during the year and the overall system efficiency (PV efficiency) had their highest values in the 2009-10 cycle (Ureña-Sánchez et al., 2012). These values were gradually decreasing in the next two cycles (2010-11 y 2011-12). This could be due to the deposition of dust in the panels, in summary an inadequate maintenance.

Yano et al. (2010) showed similar results to those obtained by Pérez-Alonso et al. (2012), for a place of latitude quite similar to Al-mería, of 8 kW h m^{-2} of daily accumulated energy production during the year, with modules of a slightly higher nominal efficiency, of 7%. Moretti and Marucci (2019) describe a maximum PV energy efficiency of 4.9% for June 21 with clear skies. This value is lower than that obtained by Pérez-Alonso et al. (2012) which was 5.5% for the entire month of June.

New materials and new manufacturing techniques have allowed to improve the efficiency of the PV systems used for years (Yano and Cossu, 2019). In our study, the nominal power of the PV modules (Wp) has improved by 160.87% compared to 2009 with only a 5.93% in-crease in the size of the PV modules (Table 8). For this reason, in a hectare of greenhouse where the PV modules occupy 9.8% of its cover, the installed power (kWp·ha^{-1}) would be 146.26% higher, generating 2.46 times more electrical energy (kWh) per ha and year. This value coincides with the one described by Cengiz and Mamis (2015) and Carreño-Ortega et al. (2017).

Translucent organic photovoltaic cells (OPV) can be installed on greenhouse roofs using different wavelength ranges of solar irradiance, not only for photosynthesis of crops but also, for the generation of electricity independently (Emmott et al., 2015; Chang et al., 2018). Emmott et al. (2015) describe that organic photovoltaic energy is an emerging solar energy technology that incorporates properties such as transparency, flexibility and rapid roll-to-roll manufacturing. After a technical analysis carried out by the authors, they conclude that semitransparent OPV devices may have difficulties in obtaining better results than opaque crystalline silicon with partial coverage. However, OPV devices that use PMDPP3T low band material, as well as a high efficiency intermediate band PCDTBT polymer, can generate improved efficiency compared to opaque and flexible thin film modules (CIGS type). Chang et al. (2018) analyze the recent developments of high-performance photovoltaic polymers (including infrared-absorbing materials and devices) that could achieve superior visible transparency and improved energy conversion efficiency. It would be interesting to develop studies that implies the use of these polymers in greenhouses. Also, dye sensitized solar cells (DSSC) are interesting for use in greenhouse applications (Yano and Cossu, 2019; Roslan et al., 2018).

The cost of electrical energy paid by the farmer has increased by 15.2%. However, the cost of the PV installation expressed in € Wp^{-1} has decreased by 73.27%. In our study, the decrease in the cost of PV panels was 82.32%, a value that coincides with the one described by Cengiz y Mamis (2015) and Carreño-Ortega et al. (2017).

Nowadays, the electric energy self-consumption in Spain is allowed and the electricity production supplied to the grid is not subsidized (BOE, 2019). However, the Government subsidizes up to 50% of the installation cost with a limit of 120,000 € (BOJA, 2018).

In 2018 the population of Almería province was 709,340 inhabitants and the greenhouses area was 30,230 ha (Cabrera-Sánchez et al., 2016). Approximately, 50% of this area is dedicated to tomato cultivation. With 9.8% of the area occupied by the PV panels (15,115 ha), the electrical energy demanded by the entire province of Almería in one year would be supplied. This data improves what was described by Pérez-Alonso et al. (2012) due to the higher efficiency of the new PV panels and a slight increase in the greenhouses area.

5. Conclusions

In the greenhouse interior, more PAR was absorbed in the control than under the 9.8% shading by photovoltaic panels on the greenhouse roof. In contrast, these differences did not affect the total and marketable yield; plant architecture; number of flowers per branch; or fruit colour, firmness, and pH.

Shading of 9.8% by photovoltaic panels reduced the tomato fruit size, but this did not affect the yield because more fruits of smaller size were produced; differences were not observed between the panel arrays (T1 and T2).

The shading treatments studied showed similar behaviour regarding fruit TSS, and both were superior to the reference control.

The interaction observed between some parameters of plant morphology, crop yield and fruit quality in the study highlights the need to consider several crop cycles to determine the relative effects the photovoltaic panels have on greenhouse crops.

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