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Micrometeorological environment in traditional and photovoltaic greenhouses and effects on growth and quality of tomato (*Solanum lycopersicum* L.)

*Roberta Bulgari, Gabriele Cola, Antonio Ferrante, Giulia Franzoni, Luigi Mariani, Livia Martinetti**

Abstract: *In recent years there was a large spread of photovoltaic (PV) greenhouses, in spite of some agronomic problems caused by micrometeorological limitations for the underlying crops during cold season. To evaluate the effects of PV panels situated on the roof of a greenhouse, Air Temperature (AT) and Global Solar Radiation (GSR) were monitored in a PV greenhouse and a traditional one and their effects on quali-quantitative features of tomato berries were analysed. In the PV greenhouse a relevant reduction of temperature (about -2°C in march-may) and global solar radiation (less than a half of the traditional one in the same period) was observed and tomato yield was lower, with a poor content of lycopene, β-carotene, sucrose, reducing sugars and total sugars in the fruits. On the contrary, chlorophyll concentration in the leaves and use efficiency of solar radiation were higher and the compensation point lower in comparison to the plants grown in the traditional greenhouse.*
Keywords: *photovoltaic (PV) greenhouses, tomato, solar radiation, energy saving, solar energy.*

Riassunto: *Negli ultimi anni si è avuta una grande diffusione delle serre coperte con pannelli fotovoltaici, ma dal punto di vista agronomico persistono delle problematiche conseguenti alle limitazioni micrometeorologiche che si osservano in esse durante la stagione fredda. Per verificare gli effetti di tali limitazioni è stato condotto un lavoro di monitoraggio della radiazione solare globale e della temperatura dell'aria in serre coperte o meno da pannelli fotovoltaici e sono state valutate le caratteristiche quanti-qualitative di una coltura di pomodoro in esse coltivata. Nella serra fotovoltaica si è assistito ad un sensibile calo della radiazione solare globale (meno della metà rispetto alla serra tradizionale nello stesso periodo) e della temperatura dell'aria (circa -2°C nel trimestre marzo-maggio), nonché a una riduzione della resa del pomodoro, con minore contenuto di licopene, β-carotene, saccarosio, zuccheri riducenti e totali nelle bacche. In questa serra le piante hanno presentato una maggiore concentrazione di clorofilla, maggiore efficienza nell'uso della radiazione solare e punto di compensazione minore rispetto alla serra tradizionale.*
Parole chiave: *serra fotovoltaica, pomodoro, radiazione solare, risparmio energetico, energia solare.*

1. INTRODUCTION

Advanced societies are expressing a growing attention to alternative energies from renewable sources. In this context solar energy is a possible candidate, because it is abundant, especially at mean and low latitudes. On the other hand it is a discontinuous source due to the typical daily and seasonal astronomic cycle of sun, and so it needs suitable storage systems, expensive and not always efficient (Stanghellini, 2010). Many researches are ongoing on this topic, and some good perspectives could derive from the application of new nanocomposites (Chang and Wu, 2013).

PV panels are long lasting (about 30 years) and recyclable devices and in rural environments they have been initially installed directly in farm fields, subtracting agricultural areas to crop production (Poncet *et al.*, 2012). In order to limit this problem two solutions were proposed: (a) agrivoltaic systems which associate solar panels and crops at the same time and on the same land area (Dupraz *et al.*, 2010) and (b) photovoltaic greenhouses where panels are installed on the roof (Marucci *et al.*, 2013; Carlini *et al.*, 2012).

The aim of both these solutions is to exploit the summer excess of global solar radiation for energy production. Nevertheless, since PV panels are generally fixed, they can create a shortage in GSR with possible repercussions on the whole set of micrometeorological variables (AT, GSR, relative humidity RH, air circulation, and so on) and on crop production (Abdel-Ghany and Al-Helal, 2011; Medrano *et al.*, 2005; Kadowaki *et al.*, 2012).

In agrivoltaic systems some experiments pointed out that mean daily AT and RH were similar to the full sun treatments and also the growth rate of some crops, as lettuce and cucumber in summer were not significantly different (Marrou *et al.*, 2013a). Moreover, considering two shade levels equal to

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* Corresponding author's e-mail: livia.martinetti@unimi.it

[1] Department of Agricultural and Environmental Sciences, Università degli Studi di Milano, Milano, Italy.

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50% and 70% of the incoming radiation in summer, lettuce yield was maintained similar through an improved radiation interception efficiency with the higher shading, even if some different varietal responses were observed. In particular, in the shade number of leaves decreased, whereas foliar area increased (Marrou *et al*., 2013b).

PV greenhouses showed a widespread diffusion in Italy, mainly as the consequence of the high government incentives. The main advantages are the energy production and the energy saving for air conditioning.

A quantitative evaluation of these advantages can be obtained considering that the yearly average power electrical requirement for a traditional Mediterranean greenhouse ranges from 20000 $kWh_{el}.ha^{-1}$ to 90000 $kWh_{el}.ha^{-1}$ in relation to the technological level (Campiotti *et al*., 2008). A significant part of these consumptions is realized in the periods of the year in which the solar radiation is excessive, and usually greenhouses are cooled by passive or dynamic means of protection or, in the warmer sites, the agricultural activity is even suspended (Marucci *et al*., 2013).

An optimally inclined south oriented PV panel in South Italy receives on average 2000 $kWh \cdot m^{-2}$, that can produce yearly 200 $kWh_{el}.ha^{-2}$ considering an efficiency of 10% (Šúri *et al*., 2007). In a PV Mediterranean greenhouse we can obtain on average an energy reduction of 30% for summer cooling and 11% for winter heating in comparison with a traditional greenhouse; in autumn and spring these savings are much greater (Carlini *et al*., 2012). In northern countries energy savings of about 35% for the winter heating can be obtained by storage of excess solar energy during summer (Bot *et al*., 2005).

Nevertheless, these greenhouses present some agronomic problems, since the usual silicon-based PV panels intercept the photosynthetically active radiation with depleting effects on crop yield, relevant especially in winter (Stanghellini, 2010; Carlini *et al*., 2012; Kozai *et al*., 1999).

The roof coverage area is important in determining the shading degree: some authors have observed that 10-13% of roof area coverage could be excessive for the crop production (Kadowaki *et al*., 2012; Yano *et al*., 2010).

Some experiments have shown the negative effect of the silicon PV panels on the growth of the plants when they are placed continuously on one pitch of the greenhouse roof; on the contrary, a solar radiation reduction up to 50% can be well tolerated by many species (lettuce, basil, strawberry, zucchini, tomato) if the shadow cones produced by the PV panels are small and fast moving, as with some specific models (Minuto *et al*., 2010). In particular, good results were obtained with panels with spaced silicon cells, or made of different materials as copper and indium diselenide (CIS) and copper, indium and gallium diselenide (CISG), that transmit some sunlight wavelength bands and reduce by only 3% the photosynthetically active radiation (PAR) in comparison with the traditional greenhouse. The problem is that such materials are still too expensive to be commonly used (Minuto *et al*., 2011). Some interesting perspectives derive from the use of organic/nanocrystal composites with an infrared sensitivity (800-2000 nm), that can give a good photovoltaic response even with low solar radiation (McDonald *et al*., 2005).

Flexible and semi-transparent PV panels represent the ideal solution, because they ensure a suitable rate of radiation for the crops (Huang *et al*., 2008; Marucci *et al*., 2013; Stanghellini, 2010; Tanaka *et al*., 2009). Unfortunately, at the moment their conversion efficiency of solar energy into electricity is too low (5-8%).

Shading and plant growth are also affected by geometrical arrangements of PV arrays: the straight-line arrangement of PV modules casts shadows continuously on a specific area for more than four months, whereas a checkerboard arrangement casts shadows intermittently during the crop growth and consequently the inhibitory effect of shading on growth is reduced (Kadowaki *et al*., 2012; Yano *et al*., 2010).

In order to limit the surface area of PV modules and have a reasonable amount of energy output without reduce excessively the PAR, new types of greenhouses applying solar concentrator technology have been recently proposed. These greenhouses combine reflection of near infrared radiation (NIR) with electrical power generation using PV cell/thermal collector modules (Sonneveld *et al*., 2010a; Sonneveld *et al*., 2010b).

In addition to the reduction of yield, other possible negative effects of shading on crops are (a) the increase of fungal diseases, that are stimulated by increased air humidity and reduced air circulation (Jacob *et al*., 2008; Marrou *et al*., 2013a; Minuto *et al*., 2009) and (b) the nitrate accumulation in leafy vegetables in presence of low GSR (Santamaria, 2006).

In the light of the abovementioned advantages and limitations, the economic evaluation of the performances of PV greenhouses should be made comparing the lower income from agricultural production with the lower costs for air conditioning and the proceeds from the sale of electricity (Marucci *et al.*, 2013).

The aim of this study was the monitoring of meteorological parameters, namely solar radiation and temperature, in a PV greenhouse compared with a traditional one, and the evaluation of quality and yield of tomato grown under the two different types of greenhouses situated in Lombardy. This study will be referred to operational greenhouses, currently used for crop production.

2. MATERIALS AND METHODS

Tomato plants (*Solanum lycopersicum* L. cv 'Caramba') were grown hydroponically on coconut fiber in two different greenhouses, traditional and photovoltaic, at the farm San Maurizio located in Merlino (LO). The PV modules were made of spaced monocrystalline silicon cells and mounted inside the south roof of an east-west oriented glasshouse, covering the 50% of the total roof area. Plants were transplanted in February 2013 at the density of 3 plants m^{-2} and the sampling occurred from May to September.

Since June the roof of the traditional greenhouse was painted with white shade paint to reduce the excess of radiation input. The paint was subsequently removed at the end of September.

During the experiment, both meteorological and agronomical data were recorded.

2.1. Meteorological monitoring

The two selected greenhouses were provided with two weather stations, each endowed with two pyranometers for GSR measurements (one used as backup) and one thermometer located in a suitable radiation shield for AT measurements. All sensors were placed at 2 m height. Stations were located in the central part of the greenhouses to minimize edge effects of the walls. Data were collected with a 5 minutes time step and averaged hourly and daily data were calculated and analyzed.

Reference hourly data of the synoptic weather station of Rodano (MI – Italy), 7.5 km far from Merlino, were provided by the regional environmental agency ARPA Lombardia. The two greenhouses were monitored from January 1st to December 31st 2013.

2.2. Thermal relations

Hourly air temperature was translated in the tomato thermal resources - Normal Heat Hours (Mariani *et al.*, 2012) - by means of a suitable response curve (Fig. 1), weighting each hourly value in terms of optimality for growth of the tomato. The curve is parameterized with 10, 24, 30 and 34°C respectively, representing minimum cardinal (C_{min}), lower optimal (L_{opt}), upper optimal (U_{opt}) and maximum cardinal (C_{max}). So one hour weighs 0 if spent at temperatures below C_{min} and above C_{max}, 1 if spent at temperatures between L_{opt} and U_{opt}, and a value changing linearly from 0 to 1 and from 1 to 0 for temperatures that change respectively from C_{min} to L_{opt} and from U_{opt} to C_{max}.

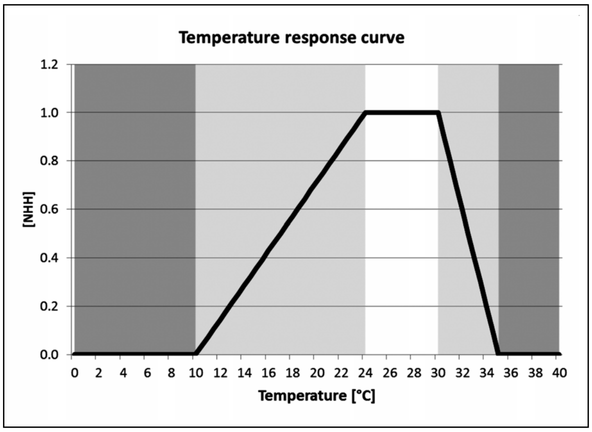

Fig. 1 - Response curve weighting air temperature (as normal heat hours) in order to obtain tomato thermal resources for growth.

Fig. 1 - Curva di risposta alla temperatura dell'aria (espressa come ore normali di caldo) per ricavare le esigenze termiche per la crescita del pomodoro.

2.3. Growth and quality determination

During the sampling period (May 8th - September 13th) the height of tomato plants, number of flowers and fruit number and yield were measured (10 plants for each greenhouse were chosen for the measurements).

For the destructive analysis for the determination of lycopene and β-carotene and sugars content (sucrose, reducing and total sugars, soluble solids content) some tomato fruits were hand harvested at maturity stage, placed in plastic bags and immediately frozen at -20°C until analysis.

2.3.1. Lycopene and β-carotene

Three tomato fruits for each greenhouse were singularly weighed and homogenized in a mixer. Then 0.1-0.2 g of the homogenized sample were weighed into a plastic tube covered with aluminum foil to exclude light, and lycopene and β-carotene were extracted using the method of Sadler *et al.* (1990). In brief, 8 mL of HEA (hexane–acetone–ethanol) (2:1:1, v:v:v) were added to the samples. The samples were vortexed and, after 10 min, 1 mL of distilled water was added. The solution was then left to separate into distinct polar and non-polar layers, and the absorbance of the hexane layer was measured at 444 nm (β-carotene) and 503 nm (lycopene) on a spectrophotometer.

2.3.2. Sugars determination

To separate the insoluble material, homogenized samples were centrifuged at 10000 rpm for 5 minutes (min) at room temperature. For sucrose determination, 0.1 mL of extract were added to 0.1 mL NaOH 2N and incubated at 100 °C for 10 min; then 0.75 mL of resorcinol were added and incubated at 80 °C for 10 min. A resorcinol solution was prepared by adding 35 mg of resorcinol and 90 mg of thiourea in 250 mL HCl 30%, mixed with 25 mL of acetic acid and 10 mL of distilled water. Samples were cooled at room temperature and spectrophotometer readings were performed at 500 nm. A calibration curve was built with sucrose standards at 0, 0.5, 1, 1.5, 2 mM.

Reducing sugars assay was performed using 0.2 mL of crude extract that were added to 0.2 mL of dinitrosalicylic acid (DNS). The reaction mixture was heated at 100°C for 5 min, then 1.5 mL of distilled water was added and absorbance readings were taken at 530 nm. Reducing sugars were expressed as glucose equivalent using a glucose standard curve (0, 1, 2, 3 and 4 mM).

Total sugars concentration was determined following the anthrone method (Yemm and Willis, 1954). 0.2 g of anthrone were melted in 100 mL of H_2SO_4 and shacked for 30-40 min. 1 mL of tomato extract was added to 5 mL of anthrone solution, cooled in ice for 5 min and mixed thoroughly. Samples were incubated at 95°C for 5 min and then cooled on ice. Absorbance readings were measured at 620 nm and a calibration curve was built with glucose standards at 0, 1, 2, 3 and 4 mM.

Soluble solids content (°Brix) of tomato juice was determined using a portable digital refractometer (Turoni, Forlì, Italy).

2.3.3. Chlorophyll determination and chlorophyll a fluorescence

Chlorophyll content was measured by chlorophyll meter (CL-01, Hansatech, UK), that provides an indicator of green color of leaves. This device determines relative chlorophyll content *in vivo* using dual wavelength optical absorbance (620 and 940 nm wavelength) measurement.

Chlorophyll *a* fluorescence was measured with a portable Handy Plant Efficiency Analyser (PEA, Hansatech, UK). Leaves were dark-adapted for 30 min. Using a leaf clip (4 mm diameter), a rapid pulse of high intensity light of 3000 µmol $m^{-2} s^{-1}$ (600 W m^{-2}) was absorbed by the leaf inducing fluorescence, which was measured by the sensor. The fluorescence parameters were calculated automatically. JIP analysis was performed to determine in particular the Performance Index (PI).

2.3.4. Leaf gas exchange

A CIRAS-1 portable infrared gas analyzer (PP Systems, Hertfordshire, UK) was used to determine light saturation curves using light intensity from 1600 to 0 µmol m^{-2} s^{-1}. The readings were taken between 9:30 A.M. and 11:30 A.M. from fully expanded leaves of three plants.

2.3.5. Statistical analysis

Data were subjected to two-way analysis of variance (ANOVA) and differences among means were determined using Bonferroni's post-test.

3. RESULTS

3.1. Meteorological monitoring

The ten days averages of GSR are presented in Fig. 2. The effects of the shade paint applied to the traditional greenhouse in summer are clearly visible. The PV greenhouse is characterized by the lowest values of incoming solar radiation. For instance, with reference to daily data (not shown), it is interesting to highlight that the daily value over 5 MJ m^{-2} was reached for the first time on February 6th by the Rodano station, on February 16th by the traditional greenhouse and only on May 2nd by PV greenhouse. Similarly the threshold of 10 MJ m^{-2} was reached for the first time on March 15th by the Rodano station and the traditional greenhouse, but was never reached by

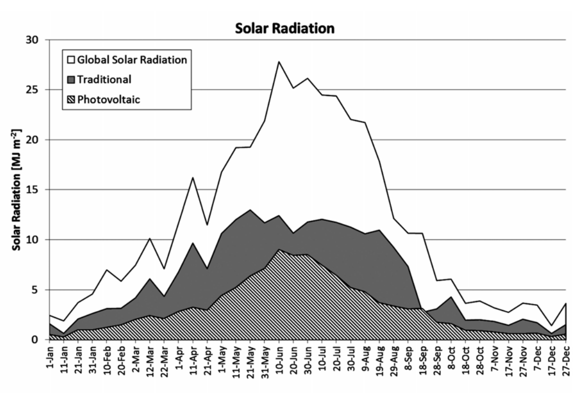

Fig. 2 - Yearly solar radiation course represented as ten days averages [MJ m^{-2}].

Fig. 2 - Andamento della radiazione solare rappresentata come medie di decadi [MJ m^{-2}].

PV greenhouse. This threshold was overcome by traditional greenhouse during 1/3 of the season. Considering the percentage of incoming solar radiation collected by the two systems, the PV greenhouse constantly got values under 35%, while traditional greenhouse was always higher than 50%, even during summer when its roof was painted with white shade paint. Finally, Fig. 3 shows the GSR accumulation since January 1st to December 31st for traditional and PV greenhouse. It is interesting to observe that the final accumulation of the PV greenhouse is one third of the available radiation against the half of the traditional greenhouse.

3.2. Thermal resources

With reference to thermal course, it is important to remember that this research was performed in operational greenhouses and for this reason the management of air conditioning was carried out by the farmer and the relative data are not available. Hence, temperature course can not be entirely explained in terms of effects of the PV covering. The accumulation of thermal resources (normal heat hours, NHH) is presented in Fig. 4. Both the greenhouses show higher resources than the reference station, but higher values are observed for the traditional one due to the higher level of incoming solar radiation, causing higher heating.

3.3. Plant growth

The height of tomato plants was similar in both growing conditions, traditional greenhouse and PV one, with some differences in July and September. The final plant height recorded in September was 5.8 m in the traditional and 5.25 m in the photovoltaic greenhouse (Fig. 5). The number of flowers was generally higher in the traditional greenhouse, only in the second detection of May it was lower than in the PV greenhouse (Fig. 6). The yield showed the same trend of fruit number (data not shown), since the weight of fruits was similar. During the cultivation period the plants grown under solar panels had lower productivity, except at the beginning of July, when the yield was 6 kg m^{-2} in both the greenhouses (Fig. 7).

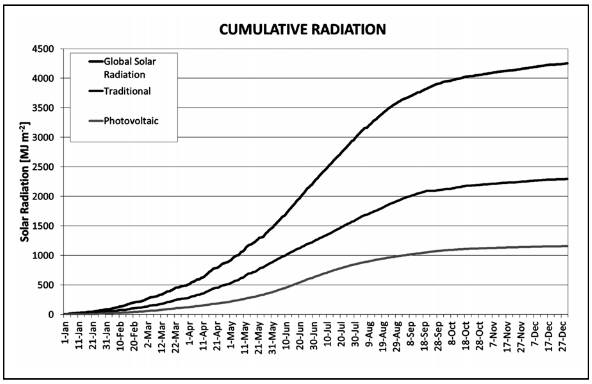

Fig. 3 - Radiation accumulation from January 1st to December 31st. Comparison among global solar radiation, traditional greenhouse and PV greenhouse.
Fig. 3 - Accumulo di radiazione dall'1 Gennaio al 31 Dicembre. Confronto tra la radiazione solare globale esterna e quelle nella serra tradizionale ed in quella fotovoltaica.

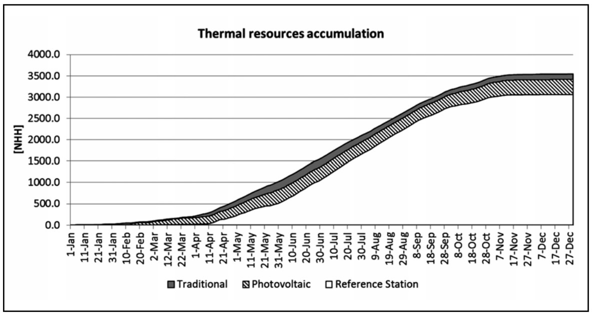

Fig. 4 - Thermal resources accumulation (NHH) from January 1st to December 31st. Comparison among reference station, traditional greenhouse and PV greenhouse.
Fig. 4 - Accumulo di risorse termiche (NHH) dall'1 Gennaio al 31 Dicembre. Confronto tra la stazione di riferimento, la serra tradizionale e quella fotovoltaica.

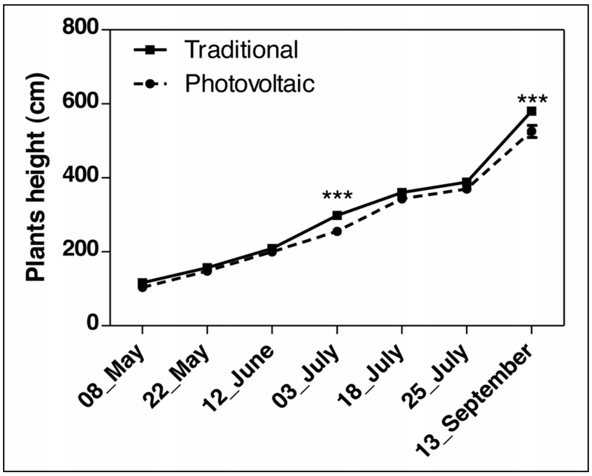

Fig. 5 - Tomato plants growth in traditional and PV greenhouses. Values are means with standard errors (n=10). Data were subjected to two-way ANOVA analysis and differences among means were determined using Bonferroni's post-test. Asterisks indicate statistical differences between means, ***P<0.001.
*Fig. 5 - Crescita delle piante di pomodoro nella serra tradizionale ed in quella fotovoltaica. I valori sono medie con errore standard (n=10). I dati sono stati sottoposti all'analisi della varianza e le differenze tra le medie sono state determinate usando il test di Bonferroni. Gli asterischi indicano differenze significative tra le medie per ***P<0,001.*

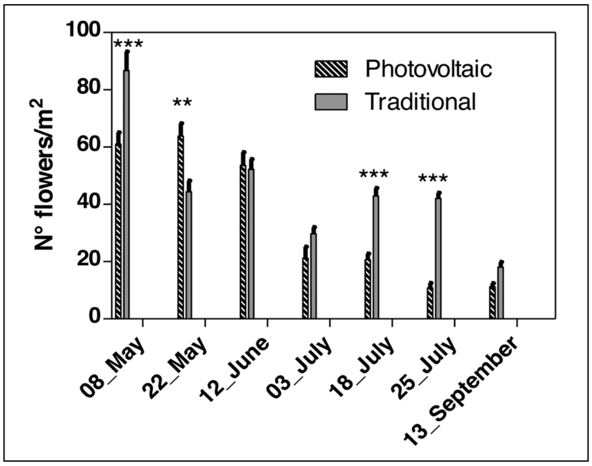

Fig. 6 - Flowers number for each sampling date. Values are means with standard errors (*n=10*). Data were subjected to two-way ANOVA analysis and differences among means were determined using Bonferroni's post-test. Asterisks indicate statistical differences between means, **P<0.01, ***P<0.001.

*Fig. 6 - Numero di fiori per ogni data di campionamento. I valori sono medie con errore standard (*n=10*). I dati sono stati sottoposti all'analisi della varianza e le differenze tra le medie sono state determinate usando il test di Bonferroni. Gli asterischi indicano differenze significative tra le medie per **P<0,01, ***P<0,001.*

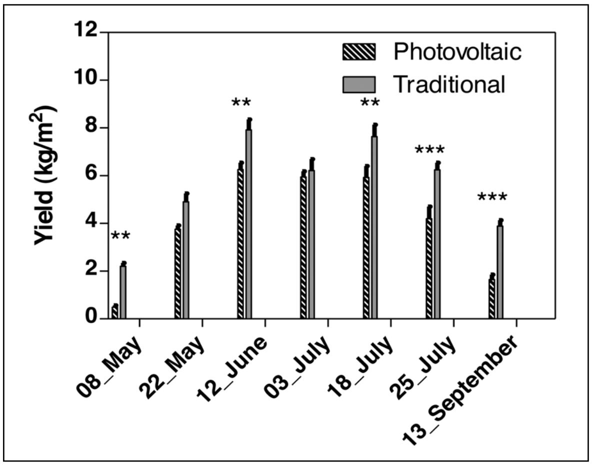

Fig. 7 - Yield of tomato plants grown in traditional and PV greenhouse. Values are means with standard error (*n*=10). Data were subjected to two-way ANOVA analysis and differences among means were determined using Bonferroni's post-test. Asterisks indicate statistical differences between means, **P<0.01, ***P<0.001.

*Fig. 7 - Produzione di frutti per m^2 in serra tradizionale e in quella fotovoltaica. I valori sono medie con errore standard (n=10). I dati sono stati sottoposti all'analisi della varianza e le differenze tra le medie sono state determinate usando il test di Bonferroni. Gli asterischi indicano differenze significative tra le medie per **P<0,01, ***P<0,001.*

3.4. Lycopene and β-carotene content

Tomatoes cultivated in traditional greenhouse had significantly higher lycopene content than fruits harvested in the PV one. In the traditional greenhouse the lycopene content was 82.8 mg/kg FW, while in the PV greenhouse the average was 41.7 (Tab. 1). Similar trend was observed for β-carotene content. In average it was 8.4 mg/kg FW in photovoltaic greenhouse and almost double values were found in the traditional one.

3.5. Sugars content

Tomatoes harvested in traditional greenhouse had a general higher sugar content than in PV greenhouse (Tab. 2). The sucrose was 7.59 mg/kg FW on average in the traditional greenhouse and 5.85 mg/kg FW in the PV one. The reducing sugars were 230.34 mg/kg in the traditional greenhouse and 151.49 mg/kg in fruits harvested from plants grown under PV panels. The total sugars in fruits grown in the traditional greenhouse were 643.81 mg/kg FW, while 508.46 mg/kg in the PV greenhouse. The total solids soluble content showed the same differences.

3.6. Photochemistry of plants grown in traditional and PV greenhouses

The maximum quantum efficiency of photosystem II (Fv/Fm) was not statistically different among the two growing conditions, except in October when higher values were measured in plants grown under photovoltaic greenhouse (Fig. 8 A). Since the

Greenhouse type	Lycopene (mg/kg FW)	β-carotene (mg/kg FW)
Traditional	82.80±4.541a	15.98±0.726a
Photovoltaic	41.69±3.220b	8.44±0.631b

Tab. 1 - Lycopene and β-carotene content (mg/kg FW) of tomato fruits in both greenhouses. Values are means with standard error (n=3). Data were subjected to one-way ANOVA and differences between means were determined using Bonferroni's post-test. Different letters indicate statistical differences for P<0.05.

Tab. 1 - Contenuto di licopene e β-carotene (mg/kg peso fresco) nei frutti di pomodoro in entrambe le serre. I valori sono medie con errore standard (n=3). I dati sono stati sottoposti all'analisi della varianza e le differenze tra le medie sono state determinate usando il test di Bonferroni. Lettere diverse indicano differenze significative per P<0,05.

Greenhouse	Sucrose (mg/g FW)	Reducing sugars (mg/g FW)	Total sugars (mg/g FW)	Soluble solids content (°Brix)
Traditional	7.59 ± 0.319a	230.34 ± 17.901a	643.81 ± 44.421a	2.566a
Photovoltaic	5.85 ± 0.412b	151.49 ± 22.825b	508.46 ± 15.818b	1.866b

Tab. 2 - Sugars content (mg/g FW) of tomato fruits. Values are means with standard error (n=3). Data were subjected to one-way ANOVA and differences between means were determined using Bonferroni's post-test. Different letters indicate statistical differences for P<0.05.

Tab. 2 - Contenuto in zuccheri (mg/g peso fresco) dei frutti di pomodoro. I valori sono medie con errore standard (n=3). I dati sono stati sottoposti all'analisi della varianza e le differenze tra le medie sono state determinate usando il test di Bonferroni. Lettere diverse indicano differenze significative per P<0,05.

threshold of stress for herbaceous plants is 0.83, the data recorded indicated that plants were slightly stressed in September and October, especially for the traditional greenhouse. However, the lower values of Fv/Fm in this period may indicate a senescence initiation process.

The performance index (PI) indicated that the overall leaf efficiency in the primary photochemistry was higher in plants grown under PV greenhouse at the beginning of tomato cultivation and statistical differences were observed on May 8th (Fig. 8 B). The number of active reaction centers at Fo (RC/CSo) was not different in plants grown in both the greenhouses

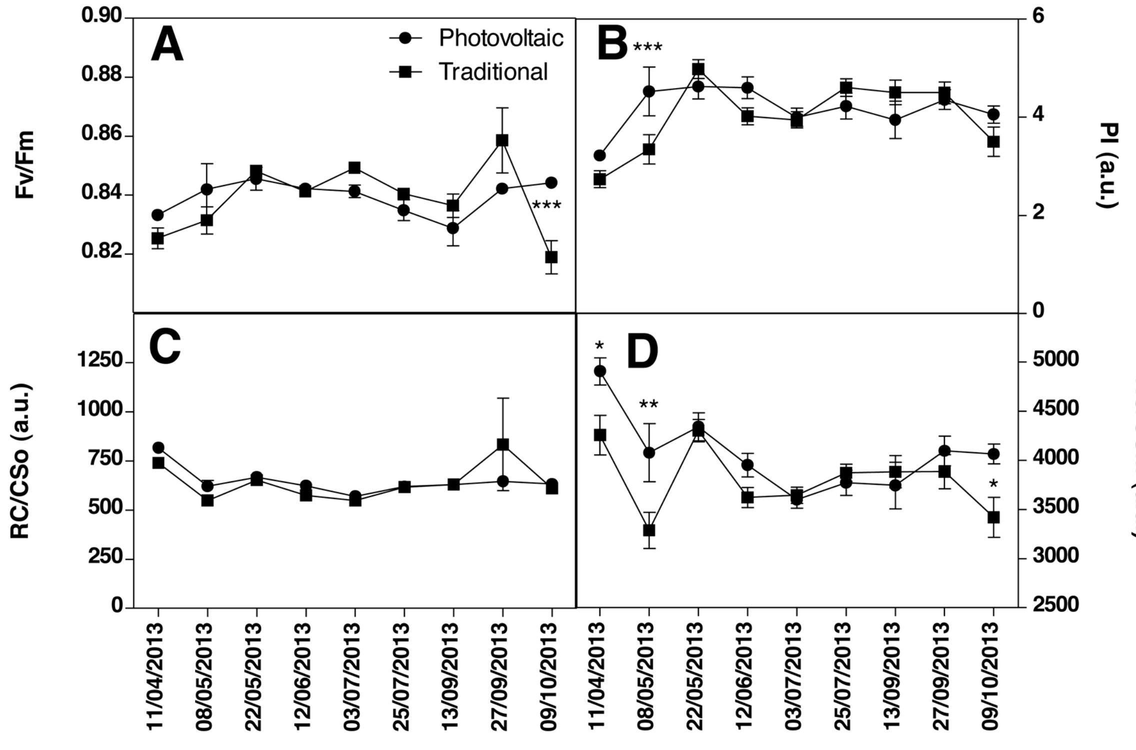

Fig. 8 - Fv/Fm ratio, maximum quantum efficiency of photosystem II (A), performance index (B), active reaction centres at Fo (C) and active reaction centres at Fm (D) measured from tomato leaves grown under traditional and PV greenhouse. The values are means with standard errors (n=18). Data were subjected to two-way ANOVA analysis and differences among means were determined using Bonferroni's post-test. Asterisks indicate statistical differences between means, *P<0.05, **P<0.01, ***P<0.001.

*Fig. 8 - Rapporto Fv/Fm, efficienza quantica massima del fotosistema II (A), indice di vitalità dell'attività fotosintetica (B), centri attivi di reazione a Fo (C) e a Fm (D) misurati in foglie di pomodoro cresciute in serra tradizionale e fotovoltaica. I valori sono medie con errori standard (n=18). I dati sono stati sottoposti all'analisi della varianza e le differenze tra le medie sono state determinate usando il test di Bonferroni. Gli asterischi indicano differenze significative tra le medie per *P<0,05, **P<0,01, ***P<0,001.*

(Fig. 8 C). On the contrary, the number of active reaction centers measured at Fm (RC/CSm) was higher in tomato plants grown under photovoltaic panels during the first two months and in October (Fig. 8 D).

The effective leaf functionality was evaluated by measuring the chlorophyll *a* fluorescence under environmental light. The exact light intensity and temperature during the measurement as well as the main chlorophyll *a* parameters in light adapted leaves are reported in Fig. 9.

The steady state fluorescence (Fs) and the maximal fluorescence level from leaves adapted to the light (Fm') showed the same trend with higher values in the traditional greenhouse. The highest values of these indexes were observed in July, then values progressively decline (Fig. 9 C and D). The efficiency of the photosystem II

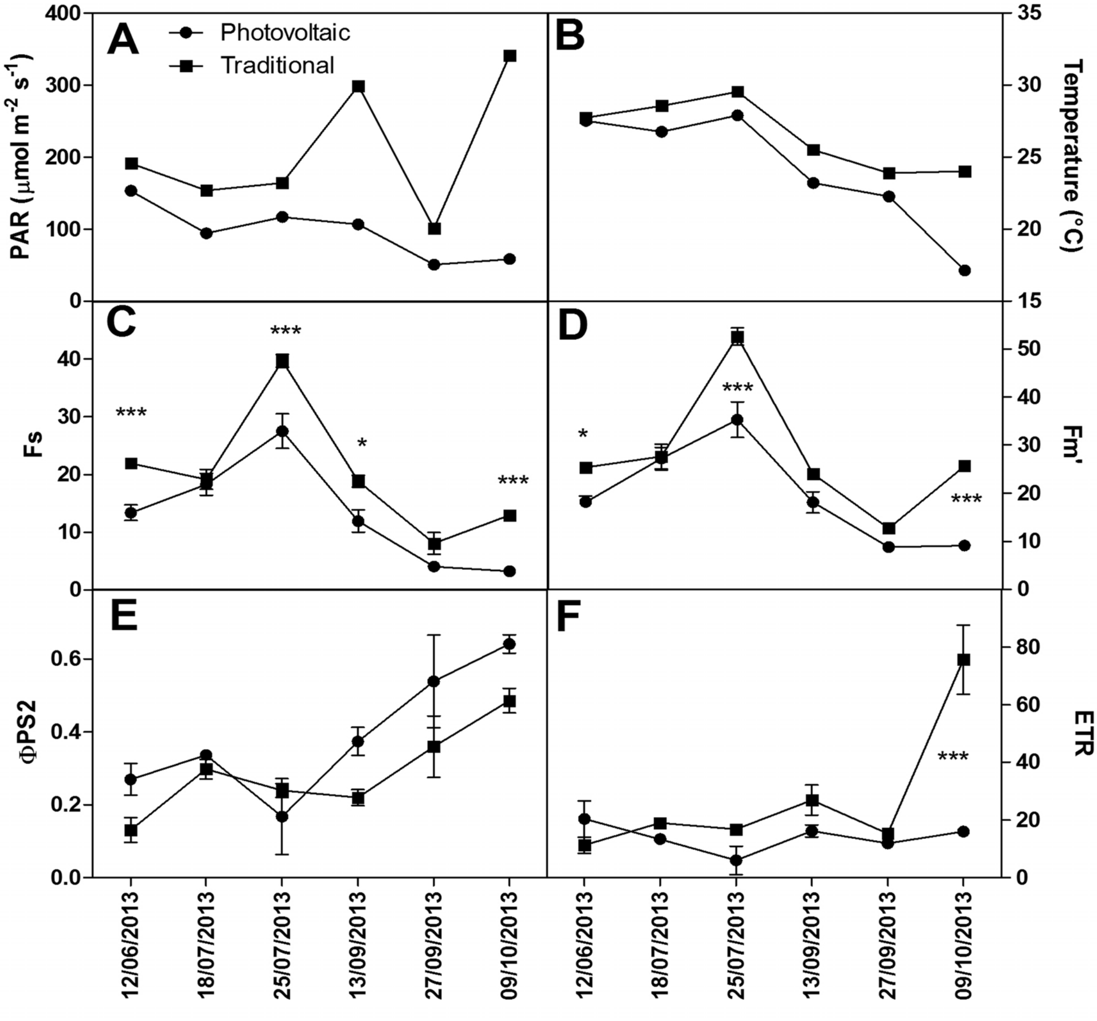

Fig. 9 - PAR intensity (A), leaf temperature (B) during chlorophyll *a* fluorescence measurement, steady state of chlorophyll fluorescence (C), maximum chlorophyll *a* fluorescence in light adapted leaves (D), effective quantum yield of photosystem II (E), electron transport rate in the PSII (F). Values are means with standard errors (*n*=5). Data were subjected to two-way ANOVA analysis and differences among means were determined using Bonferroni's post-test. Asterisks indicate statistical differences between means, *P<0.05, **P<0.01, ***P<0.001.

Fig. 9 - Intensità di luce PAR (A), temperatura della foglia (B) durante la misurazione della fluorescenza della clorofilla a, *stato stazionario della fluorescenza della clorofilla (C), fluorescenza massima della clorofilla* a *in foglie adattate alla luce (D), resa quantica effettiva del fotosistema II (E) e tasso del trasporto elettronico nel PSII (F). I valori sono medie con i relativi errori standard (n=5). I dati sono stati sottoposti all'analisi della varianza e le differenze tra le medie sono state determinate usando il test di Bonferroni. Gli asterischi indicano differenze significative tra le medie per *P<0,05, **P<0,01, ***P<0,001.*

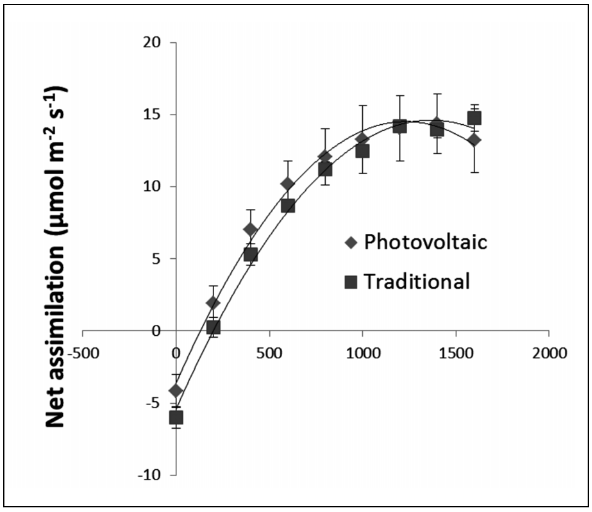

Fig. 10 - Light saturation curve of tomato plants grown under PV or traditional greenhouse. Values are means with standard errors (n=3). Data were subjected to two-way ANOVA analysis and no significant differences were observed between the two growing conditions.

Fig. 10 - Curva di saturazione alla luce in piante di pomodoro cresciute in serra tradizionale o fotovoltaica. I valori sono medie con errori standard (n=3). I dati sono stati sottoposti all'analisi della varianza e nessuna differenza è stata trovata tra le medie.

under light (FPS2) was not statistically different between the two growing conditions. (Fig. 9 E). The electron transfer rate (ETR) was slightly higher in plants cultivated in the traditional greenhouse, with exception in June and at the end of September (Fig. 9 F). Although, statistical differences were observed only at the last sampling point.

The tomato plants grown in both the greenhouses showed similar saturation light curve. Differences were found in the light compensation points. In plants cultivated in PV greenhouse the light compensation point was at 143 μmol m^{-2} s^{-1}, while in the traditional greenhouse was at 205 μmol m^{-2} s^{-1} (Fig. 10).

4. DISCUSSION

Protected crops undergo to relevant changes in the whole set of micrometeorological variables, giving rise to consistent modifications in environmental resources and limitations for crop. This is particularly relevant in PV greenhouses, where photovoltaic panels cause a reduction of incoming solar radiation, imprinting the whole terms of greenhouses energy balance.

The micrometeorological monitoring and the analysis methods applied in this work were aimed to quantify the availability of such resources for tomato growth.

The relevant reduction of temperature and global solar radiation observed in the PV greenhouse in comparison to the traditional greenhouse is in agreement with many other reports (Stanghellini, 2010; Minuto *et al.*, 2010; Kozai *et al.*, 1999).

The plant growth and productivity are directly correlated with the light intensity and environment temperature, which affect two important physiological processes: photosynthesis and respiration. The photosynthesis depends from both light intensity and temperature, while respiration only from temperature. Therefore, the sugar content and yield depend by the trend of these two physiological processes.

It is well known that light reduction reduces the photosynthesis and yield. These results have been proven in tomato plants grown under different levels of light intensity simulating the photovoltaic greenhouse (Kläring and Krumbein, 2013). The light availability also affects the leaf and fruit pigments; some of them are also antioxidant compounds with nutraceutical properties such as lycopene and β-carotene. Lycopene is responsible for the characteristic deep-red color of ripe tomato fruits (Shi *et al.*, 1999) and represents about 83% of the total pigments in the fruits (Gould, 1992). Nutrients in tomato are affected by several factors such as cultivar, agronomical practices, soil and light. Considering that in this study tomato plants were grown with the same agronomical techniques, the different lycopene and β-carotene content can be explained by the different environmental conditions in the two greenhouses. Moreover, carotenoid content is directly proportional to the light received by plants (Biswall, 1995), so higher values in the traditional greenhouse are due to a higher solar radiation. This result is in agreement with other experiments reported in the literature (Kläring and Krumbein, 2013).

Sugars content is an important quality parameter considering that the amount of sugars and acids and their interactions are highly related to flavor quality in tomatoes (Stevens *et al.*, 1979). This parameter is highly affected by the environment (Hartl, 2011), including solar radiation, temperature, day-length, water availability, soil mineral content, irrigation, fertilization (Dorais *et al.*, 2008). The higher sugar content of tomatoes grown in the traditional greenhouse is probably due to the higher availability of solar radiation. Tomato plants grown under high solar radiation produce fruit with high sugars level (Winsor and Adams, 1976).

The plant photochemistry behavior continuously changes during the plant growth in order to face stressful conditions. During the first weeks of cultivation the plants showed higher light use efficiency as demonstrated by the different chlorophyll *a* fluorescence parameters measured and calculated (PI and RC/CSm).

It means that plants tried to capture and efficiently use as much as possible the light received. However, the ETR is lower in plants grown under low light conditions at the end of the growing period. Since this parameter is directly correlated with photosynthesis (Fryer *et al.*, 1998), it explains the lower yield of plants in the photovoltaic greenhouse.

The differences in light saturation curves are in agreement with literature results. In low light conditions tomato plants lowered the respiration and the saturation point was reached faster than those adapted to higher light conditions. Therefore, the light compensation point was lowered as plant strategy to enhance the net photosynthesis by reducing the respiration rate (Loach, 1970; Pons and Poorter, 2014).

5. CONCLUSIONS

In this preliminary study the 50% greenhouse roof coverage with photovoltaic modules resulted in a significant lower solar radiation compared to traditional greenhouse, with quantitative and qualitative reduction of tomato production. Greenhouses with such PV percentage coverage, made in the recent past driven by attractive financial incentives for electricity production, have no longer reason to be realized. The eventual use of solar energy to meet the energy requirements of the greenhouses needs the finding of alternative solutions, efficient and low expensive, with a percentage of roof area coverage with photovoltaic modules compatible with crop production. The ideal solution could be the creation of innovative PV modules transparent to wavelength used by the crops, or retractable or removable when the solar radiation is defective. Some important progress has been made through the use of new materials, but further studies are needed.

Moreover, new efficient and cost effective ways of solar energy storage have to be developed. Finally, suitable species and appropriate technique of cultivation must be defined, in order to counterbalance the radiation reduction under a photovoltaic greenhouse.

In conclusion, this preliminary work, even if carried out in sub-optimal conditions, could be useful for the final goal, that is the calibration and validation of some mathematical models describing the energy fluxes and crop yield under PV or traditional greenhouses, in order to optimise the production of electricity and food.

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