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Photovoltaic Tiles for the Wavelength-Selective Greenhouse: Exploring Yellow and Green Dye-Sensitized Solar Cells in Outdoor Conditions

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Abstract: In response to two major global crises, Agriculture 4.0 proposes the use of the same land both for energy production and plant culture. The wavelength-selective greenhouse could be a promising agrivoltaic system if it can provide an optimal balance between the microclimate suitable for plants and increasing energy production, an ambitious future goal being an energy independent and combined fully automated arboretum. The dye-sensitized solar cell has recently been proposed as an ideal candidate due to its easy adaptation to the conditions imposed by the optimal operation of greenhouses. Using laboratory-sized yellow and green dye-sensitized solar cells, the photovoltaic tiles, as the main part of a wavelength-selective greenhouse, were constructed and tested under outdoor conditions on a hot summer day. The values of the temperature coefficient for the maximum power (γ), namely $-0.003\%/^{\circ}$C for the Si tile, $-0.0017\%/^{\circ}$C for the yellow tile, and $-0.0004\%/^{\circ}$C for the green tile have highlighted that the thermal stability of the green and yellow tiles is clearly higher than that of the Si tile. Furthermore, it was experimentally demonstrated that the DSSC based on DN-F15 green dye decreases in temperature by approximately 3 °C compared to the ambient temperature. Thus, in addition to the basic function of energy production, the photovoltaic tile based on green DSSCs is proposed as a smart solution to lower the temperature inside the greenhouse, a small step in the development of a strategy for adapting agriculture to advancing climate change. Therefore, the photovoltaic tile concept based on yellow and green DSSCs has been experimentally validated both from the energy production and greenhouse microclimate perspectives.

Keywords: dye-sensitized solar cell; outdoor conditions; wavelength-selective greenhouses; photovoltaic tile; temperature decrease

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1. Introduction

In recent years, two major problems facing the planet have been the energy crisis and the food crisis, due to the growth of the world's population by 30%, to almost 10 billion by 2050, up from 7.9 billion [1], thus leading to an increase in food demand, even in a modest economic growth scenario, by roughly 50% as compared to the 2013 agricultural output [2]. To solve the two major crises, both in the short and long term, Agriculture 4.0 [3] proposes the use of the same land both for solar cells and plant culture. This mixed-use approach has been called "agrivoltaics" or "solar farming" [4]. Agrivoltaic systems may alleviate land competition or other spatial constraints for solar power development, creating a significant opportunity for future energy sustainability.

In this context, greenhouse technology is relevant to the worldwide demand for increased production, as it provides the right microclimate for plants, thus facilitating optimal plant growth and high production at a better quality than other traditional methods [5].

Several studies have highlighted that the integration of photovoltaic panels (PV) in greenhouses has many advantages, such as the following: (i) diminishing the cost of production by partially or totally reducing the energy consumption of conventional sources [6]; (ii) partially decreasing irrigation water consumption by reducing the rate of evapotranspiration [7]; and (iii) optimally using land for food and energy production [8,9].

The global solar radiation that flows into the interior space of a greenhouse consists of ultraviolet (UV), photosynthetic active radiation (PAR), which is essential for the growth and photosynthesis of plants (400–700 nm), and near-infrared (NIR) [10]. Chlorophyll is the primary pigment used in photosynthesis, having two important absorption peaks corresponding to chlorophyll a and b located in the red and blue regions, especially from 625 nm to 675 nm and from 430 nm to 475 nm, respectively [11]. Therefore, it is extremely important to strike a balance between maximizing the flow of the PAR component into the greenhouse by reducing the shading effect of the PV panels [12] and further enhancing the production of energy, which increases along with the increase in size of the opaque surface of the panels [13]. Thus, the roof coverage using a crystalline silicon module was estimated not to exceed 30% [14,15], but for crops with a high economic value, such as tomatoes, or in cases where food yield is considered a priority, a value of <10% was indicated [8].

Due to the major disadvantages of conventional PV installations on greenhouses such as opacity, which prevents light transmission and hampers plant growth and crop productivity, dye-sensitized solar cells (DSSCs) have also been recently proposed as an ideal candidate for greenhouse application, due to their cost effectiveness, simple manufacturing process, scalability, efficient use of materials, and minimal light sensitivity, but mainly for their ability to vary in both colour and transparency [16–20].

From the perspective of greenhouse applications, DSSC cells are still in the research stage; the few studies available have focused only on the visible dye sensitization of the DSSC tiles [21]. N. Roslan et al. used visible dye-sensitized solar modules as a shading device for a mini greenhouse and found out that DSSC shading lowered the interior heat by 1.47 °C and increased the relative humidity by 10.91% compared with the unshaded greenhouse and under normal ventilation [22,23]. In another study, L. Lu et al., using the same mini greenhouse configuration and the same DSSC modules sensitized with visible absorption dye, concluded that the temperature at the bottom surface of the DSSC is higher than that at the upper surface of the DSSC [24]. The sensitizer D35 (DN-F04) was also used in module fabrication for greenhouse applications, but no information about the temperature difference was provided [25]. Even though solar modules sensitized with visible dyes are characterized by the highest photovoltaic efficiencies compared to UV and NIR absorbing dyes, they drastically reduce PAR inside the greenhouse with negative effects on plants.

But, no less important and still unexplored, the manipulation of the light spectrum by the dye could provide solutions for controlling greenhouse parameters, reducing harmful radiation, and potentially lowering plant disease risks. It is well known that the partial absorption of UV radiation prevents the cellular damage of the plants [26], and that IR radiation obturation leads to a reduction of the air temperature inside the greenhouse, which leads to an increase in crop production. Also, within the greenhouse, in addition to controlling parameters such as light, relative humidity, and the amount of CO_2, it is very important to have a control over the excessive temperature inside, especially during the summer months, which can have a negative effect on agricultural production [27]. Therefore, to reduce the temperatures inside the greenhouse close to the ambient temperature, a traditional method such as ventilation, black cloth net shading, or whitewash on the roof surface of the greenhouse can be used [8]. In the context of inherent global warming, the design and development of new methods for inside temperature control should be imperatively considered. Thus, in accordance with the Intergovernmental Panel on Climate

Change (IPCC)'s Sixth Assessment Report (AR6), published in 2021, in the lowest-emission scenario, the global mean surface temperature is expected to increase between 1.0 and 1.8 °C relative to the preindustrial period by 2100 and between 3.3 and 5.7 °C in the highest emissions scenario. An increase in the global average temperature above 2 °C is predicted to affect many plants and to change agriculture patterns.

In our previous studies, a DSSC based on UV dye with the requirements imposed by a greenhouse to have transparency over the entire PAR range, while having an efficiency of nearly 5% at an irradiance between 50 mW/cm^2 and 100 mW/cm^2, irradiance corresponding to maximum light intensity in all seasons, was demonstrated for the first time [28].

In this context, we started from the following premises: (i) the choice of affordable commercial dyes that absorb UV and NIR and are partially transparent to PAR, namely DN-F01 dye (Dyenamo Yellow, a broad absorption at around 355–470 nm) and DN-F15 (Dyenamo Transparent Green, two broad absorptions at around 337–480 nm and 580–742 nm) and (ii) a control over the excessive temperature inside of the greenhouse through the dyes.

In our study, photovoltaic tiles based on yellow and green DSSCs for a wavelength-selective greenhouse were first tested in outdoor conditions to monitor their behaviour in terms of temperature, light intensity, and photovoltaic parameters. Based on the promising results obtained, the concept of photovoltaic tiles based on yellow and green DSSCs has been experimentally validated for the next implementation in a wavelength-selective greenhouse.

2. Materials and Methods

2.1. Assembly of Cells and Production of Photovoltaic Tiles

The fabrication of DSSCs using brookite TiO_2 as a light scattering layer was carried out according to our previous work [28]. Thus, the photoanodes with 3.90 µm of the thickness are made up of three layers as follows: (i) the first layer consists of TiO_2 nanoparticles crystallized in anatase form, obtained by the hydrothermal method at 100 °C for 12 h and calcinated at 500 °C for 60 min with 1 °C/min; (ii) the second layer contains a brookite phase based on TiO_2 as a scattering layer calcinated at 500 °C for 60 min with 1 °C/min; and (iii) the third layer consists of a final 40 mM $TiCl_4$ treatment applied on the photoanode surface, and sintered at 450 °C for 1 h.

The photoanodes obtained were immersed for 5 h in a 0.5 mM solution of acetonitrile based Dyenamo Yellow dye (DN-F01) and a 0.1 mM solution of Dyenamo Transparent Green dye (DN-F15, Dyenamo, Stockholm, Sweden) in acetonitrile and tert-butanol (1:1) with 0.1 mM Chenodeoxycholic acid.

The photoanodes and platinized counter electrode (H_2PtCl_6 at 400 °C for 30 min) were encapsulated using a Meltonix 1170–60 thick spacer (DuPont, Wilmington, NC, USA). The electrolyte was injected into the space between the electrodes and consisted of a solution of 0.6 M 1-butyl-3-methyl-immidazolium iodide, 0.03 M I_2, 0.10 M guanidiniumthiocyanate, and 0.5 M 4 tert-butylpyridine in acetonitrile/valeronitrile (85/15) for DN-F01 and 0.6 M 1-butyl-3-methyl-immidazolium iodide, 0.05 M I_2, 0.1 M lithium iodide, and 0.4 M 4-tertbutylpyridine in acetonitrile for DN-F15.

The frame of the tiles was made from transparent Polylactic Acid (PLA) using a Raise 3D E2 3D printer and has 14 empty places which were filled with identical 5 cm × 3 cm (active surface of 4.5 cm × 2.5 cm) yellow DSSCs (further referred to as yellow tile) and green DSSCs (further referred to as green tile). The solar cells were connected in parallel to have the same voltage, and the current was collected from all 14 cells. A third tile was made based on 14 commercial silicon solar cells (DIY Solar Panel Mini Solar Charging Module Board (serial connection) for Research Projects 4.5 cm × 2.5 cm, manufacturer VBESTLIFE, Shenzhen, China, with an individual active surface of 2 cm × 2 cm) (further referred to as Si tile) in order to be compared with the yellow and green tiles in outdoor conditions. Since the efficiency of the 14 silicon solar cells is relatively high and connected in parallel, the short-circuit current exceeds 1 A when the irradiation is around 1000 W/m^2, it was chosen that these cells would connect to only 9 of them, to be able to have a relative efficiency equal to that of the DSSCs while preserving the effect of the air temperature on the entire tile.

2.2. The Measurement Setup for Outdoor Testing

The measurement setup was installed on the INCEMC building (on a platform at a height of 5 m from the ground). Photovoltaic tiles based on yellow and green DSSCs were tested on 29 June 2022 from 10:00 a.m. to 6:00 p.m. in the evening. This time interval was chosen to be able to observe their behaviour in conditions of maximum temperatures. The tilt angle of the cells was set to 30°, which is approximately the optimal angle for summer in Timisoara, Romania (45.4°N, 21.1°E) with the azimuth to the south.

On the experimental stand (Figure 1), the temperature sensors (type k thermocouple, referred to as PV thermocouples) were attached under each individual tile using Kapton tape and a thermal compound for better heat transfer. For the ambient environment, a temperature sensor (DHT22 Temperature Sensor) was also used and installed on the platform at a height of 1.5 m. The monitoring of the data from the temperature sensors was carried out using the SPER SCIENTIFIC 800025 device (Scottsdale, AZ, USA), which was connected to the computer interface. The measurement error of the temperature sensors was ±0.1%.

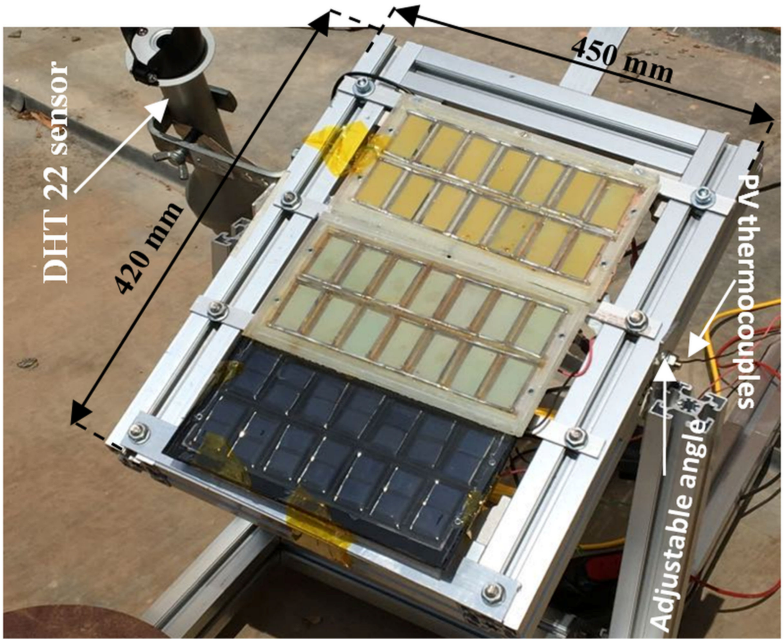

Figure 1. Photograph of assembled yellow, green and Si tiles on aluminum platform.

The SOLAR-4000 (Solar analyzer) and Wireless sensor (SOLAR-4000 SENSOR, Beha-Amprobe, Thalwil, Switzerland), were used to monitor and record the solar radiation that fell on the surface of the photovoltaic tiles. The irradiance sensor was positioned at the same tilt angle as the cells. The J-V curves of the three tiles and the meteorological parameters (temperature on each tile, outside temperature, and solar irradiance) were recorded every 15 min.

The photovoltaic tiles were mounted on an aluminum platform with an adjustable tilt angle. All cables were placed next to the experimental stand and connected to the measuring instruments and the computer where all the experimental data were recorded, these being placed inside so as not to be affected by the weather conditions during the measurements. It was taken into account that the wires needed to measure the electrical parameters had a resistance as low as possible so as not to influence the measurements.

To measure the performance of the photovoltaic tiles, a Keithley 2450 source meter (Cleveland, OH, USA) was used, and an Agilent 34970A (Santa Clara, CA, USA) was used as a multifunctional switching unit. Both instruments were controlled from a computer using the Python interface. The PV tiles were kept in open circuit during the test due to the automatic measurement limitations of the system. The P_{max} parameters were extracted from the J-V curves. The measurement time for each individual tile was approximately

20 s. The UV-visible-NIR analysis (transmission and reflection modes) of the samples was performed using a UV/Vis/NIR (Lambda 950 UV-Vis-NIR from Perkin Elmer, Waltham, CT, USA) spectrophotometer in the range of wavelengths of 300–1000 nm at ambient temperature. For collecting the diffuse reflectance spectra, a 150 mm integrating sphere was utilized.

3. Results and Discussion

Figure 2 shows the UV-Vis-NIR transmission and diffuse reflectance spectra of the solar cells used as the tile units. In contrast to Si cells that do not transmit light all over the entire domain (300–1000 nm), DSSCs are partially transparent, similar with those reported in the literature [29].

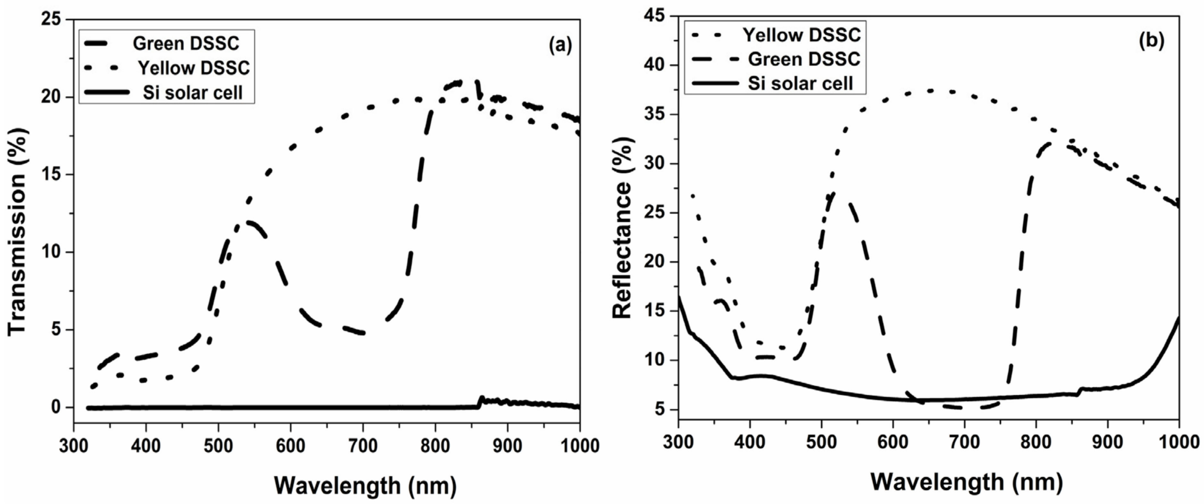

Figure 2. UV-Vis- Short Wave NIR (**a**) transmission and (**b**) diffuse reflectance spectra of the solar cells used as the tile units.

In the case of the DSSC, the absorption of light radiation being modelled by the photoactive component of the solar cell, namely the dye, the UVA, and the visible and short wave NIR (750–1000 nm) ranges were analysed. Thus, the yellow tile absorbs in the range 370–457 nm, at the same time reducing the intensity of the blue radiation needed by chlorophyll a. The green tile is characterized by two broad absorptions at approximately 375–467 nm and 544–775 nm, and it also partially reduces the light intensity required for chlorophyll a and b. However, unlike the Si solar cell, DSSCs allow more light to pass through, avoiding the efficiency losses seen in opaque systems. Transmitting 5% of red and blue light, the green DSSC can provide the light intensity required for low-light-demanding crop plants. Furthermore, the diffuse reflectance spectra have highlighted a similar evolution, the dye also modelling the reflectivity of the tile.

Before assembling into the tile and outdoor testing, all 14 DSSCs were characterized under a simulated solar radiation of AM1.5G and stored under dark conditions, open circuit, and at 22 °C. The J-V characteristics of the solar cells used in the construction of the tiles are presented in Figure 3 and are characterized by an efficiency of nearly 2.3% for the yellow DSSC, 1.89% for the green DSSC, and 11% for the commercial silicon solar cell. The climate of Timisoara, Romania is temperate continental with a monthly mean global solar irradiation in June of about 5.898 kWh/m^2/day [30].

Figure 4 shows the solar irradiation under study for one day on the DSSCs' surface. It was observed that solar irradiance increased from 721 W/m^2 at 10:00 a.m. to 1000 W/m^2 at 1:00 p.m. After 2:45 p.m., the solar irradiation decreased smoothly until 4:15 p.m. at a value of 794 W/m^2. From 4:30 p.m., solar irradiance decreased drastically until 6:00 p.m. at a value of 40 W/m^2.

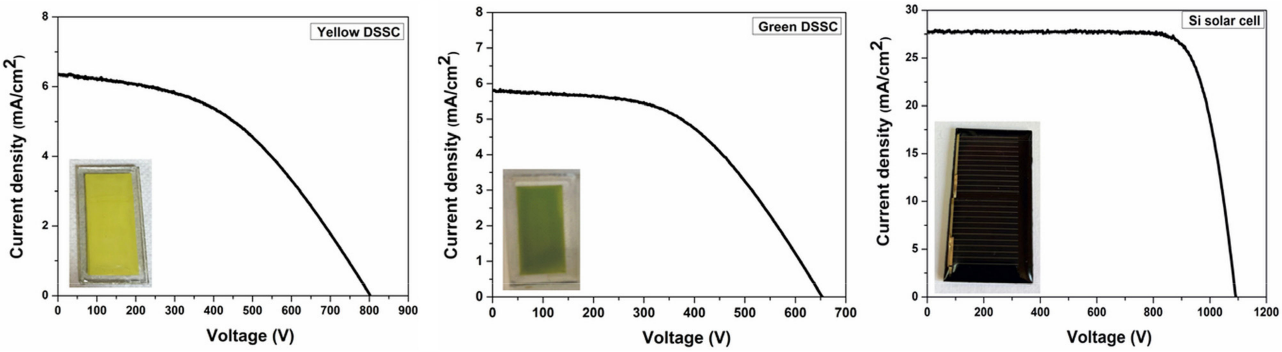

Figure 3. J-V characteristics of the solar cells used as the tile units.

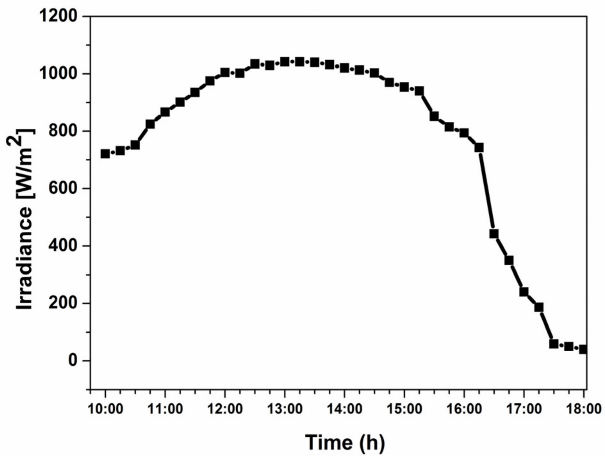

Figure 4. Daily solar irradiation incident on the solar cell surface.

Special attention was given to the maximum air temperature of 44.9 ± 0.9 °C recorded during the measurements between 2:00–3:00 p.m.

Figure 5 illustrates the evolution of the temperature transmitted through each tile. In the case of the Si tile, the transmitted temperature varies between 69.2 and 70.9 °C. The rise of 20 °C compared to the air temperature is caused by the increase in absorbance, especially of the infrared radiation. Thus, the heat accumulation in the Si tile is responsible for the increased cell surface temperature [31]. Due to the high and broad wavelength reflectivity, a more moderate heat transmitted by the yellow tile was measured, with the maximum temperature varying by only approximately 12 °C above the air temperature. Surprisingly, but also expectedly, the maximum temperature transmitted by the green tile was below the air temperature, namely 41.85 ± 1.05 °C. The average temperatures between 2:00 and 3:00 p.m. show a decrease in temperature of approximately 3 °C compared to the ambient temperature. Thus, as can be observed, the DSSC based on green dye acts as a filter, preventing heating through absorption of the near-infrared light in the range of 700–775 nm (Figure 2) and converting it into electrical energy along with significant reflectance after the wavelength of 775 nm.

In terms of diminishing the cost of crop production by reducing the energy consumption from conventional sources, the evolution of P_{max} for all three tiles were monitored during a hot summer day (Figure 6). In the case of the Si tile, P_{max} was 0.78 W at 10:00 a.m. and decreased to 0.70 W at 3:00 p.m. (at 70.9 °C), followed by a moderate drop to 0.68 W at 5:00 p.m. A similar evolution of P_{max} was also observed for the yellow tile, namely 0.40 W at 10:00 a.m., 0.374 W at 3:00 p.m. (at 59.8 °C), and 0.35 W at 5:00 p.m. Although the P_{max} provided by the green tile is smaller, with a value of 0.27 W at 10:00 a.m., the DSSCs based on green dye showed that it works much better at maximum air temperatures, increasing and remaining constant at the value of 0.31 W until 3:00 p.m. Moreover, the loss values of P_{max} within the hours 10:00 a.m. and 5:00 p.m., namely −0.10 W for the Si tile, −0.05 W for the yellow tile, and −0.06 W for the green tile, highlight that the tiles based on DSSCs can be efficient both at a lower light irradiance and in high temperature conditions.

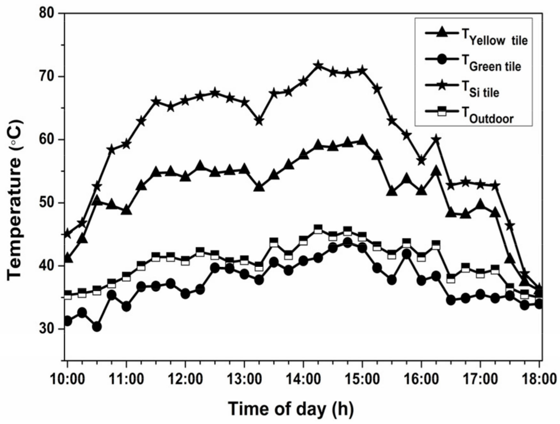

Figure 5. The temperature evolution of the tiles as a function of the time of day.

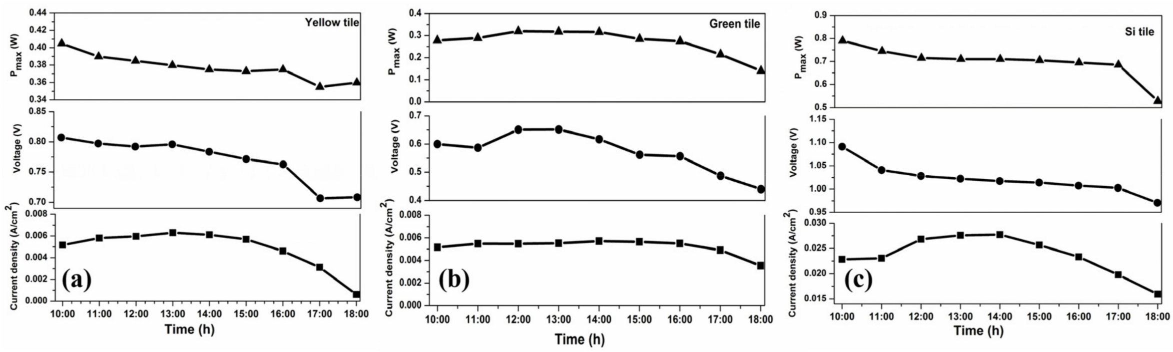

Figure 6. P_{max}, $V_{OC,}$ *and* J_{SC} vs. the time of day for the tiles based on (**a**) yellow DSSCs, (**b**) green DSSCs, and (**c**) Si solar cells.

Quantifying the impact of the temperature variation, the temperature coefficient considered in performance studies of photovoltaic cells, namely the temperature coefficient for the maximum power (γ), will be used in the following analysis of the variation of P_{max} as a function of temperature. The thermal stability under the maximum air temperature conditions is directly reflected in the values of γ, which were $-0.003\%/°C$ for the Si tile, $-0.0017\%/°C$ for the yellow tile, and $-0.0004\%/°C$ for the green tile. The thermal stability of the green and yellow tiles is clearly higher than that of the Si tile.

Furthermore, Figure 7 displays the evolution of P_{max} (W) vs. $\Delta_{Irradiance}$ (W/m^2) and temperature (°C) vs. $\Delta_{Irradiance}$ (W/m^2) for all three tiles based on the yellow DSSCs, the green DSSCs, and the Si solar cells. Each hour is marked with numbers from 10 to 18, starting at 10:00 a.m. and ending at 6:00 p.m.

For a deeper insight into the effect of air temperature on the photovoltaic performance of the tiles, the data corresponding to 3:30 p.m. was added, being characterized by a similar irradiance value (866 W/m^2) to that at 11:00 a.m. (noted with 11). Under the same illuminance, the temperature transmitted through each tile represents the main factor that limits the effective functioning of the photovoltaic tiles especially for the yellow and Si tiles. Moreover, it can be seen that even if the air temperature variations are significant, P_{max} changes undergo moderate variations in the case of DSSCs compared to Si solar cells. In the case of the green tile, P_{max} was mainly influenced by the light intensity, increasing in a first stage (10→11) and then remaining almost constant (11→12→13→14→15) even though the temperature continued to rise.

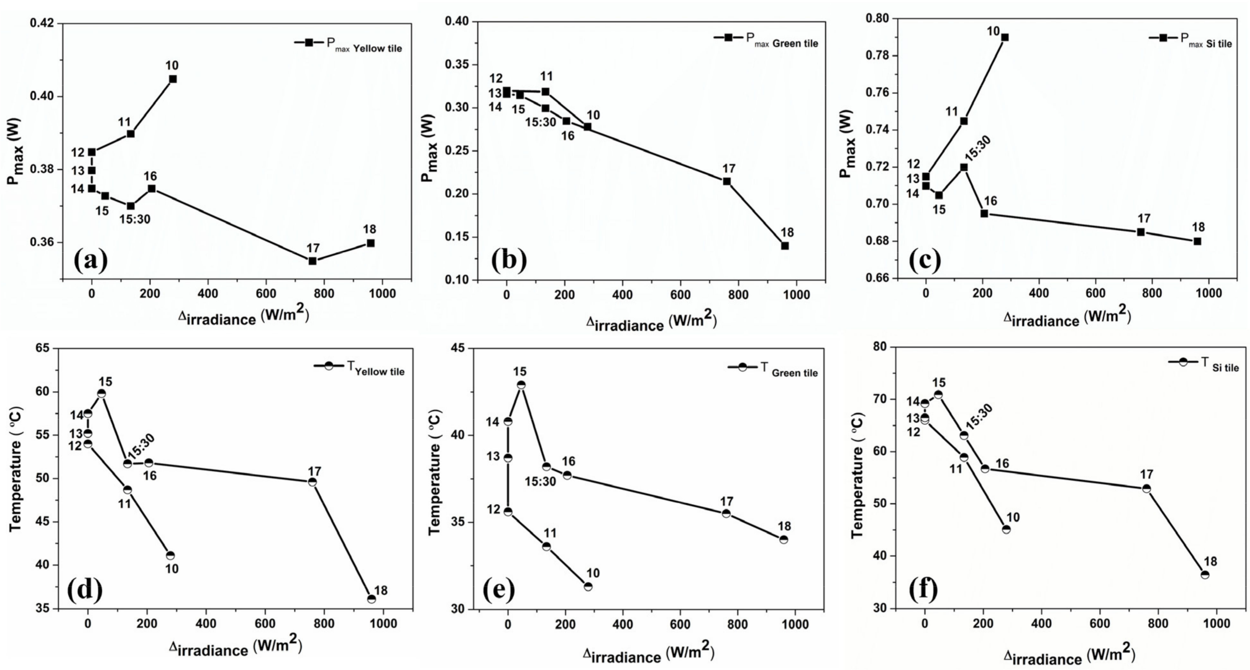

Figure 7. P_{max} vs. $\Delta_{Irradiance}$ and temperature vs. $\Delta_{Irradiance}$ for the tiles based on (**a**,**d**) yellow DSSCs; (**b**,**e**) green DSSCs; and (**c**,**f**) Si solar cells.

So far, the research for the development of the wavelength-selective greenhouse has focused on the visible dye sensitization of DSSC tiles. The main drawback of the implementation of DSSC tiles based on visible absorption dye is the absorption of the same range radiation as the photosynthetic active radiation (PAR), which is essential for the growth and photosynthesis of plants. Our study proposed a compromise solution for a wavelength-selective greenhouse, maximizing the accessibility of PAR radiation into the greenhouse and preserving the photovoltaic efficiency of the solar cells. Taking into consideration the preliminary results presented above, the concept of photovoltaic tiles based on yellow and green DSSCs has been experimentally validated both from the energy production and greenhouse microclimate perspectives.

4. Conclusions

Photovoltaic tiles based on yellow and green DSSCs for wavelength-selective greenhouses were first tested in outdoor conditions with a maximum air temperature of 44.9 ± 0.9 °C. Even if the yellow tile transmitted a maximum temperature that varied by only approximately 12 °C above the air temperature compared to 20 °C for the Si tile, the green tile surprisingly lowered the temperature by 3 °C. It was experimentally demonstrated that the DSSC based on green dye functioned as a filter to prevent heating, by the absorption of near-infrared light due to the green dye and its conversion into electrical energy. Moreover, even if the air temperature variations were significant, P_{max} underwent moderate variations in the case of DSSCs compared to Si solar cells. This result suggests that yellow and green tiles can contribute to the reduction of the cost of crop production by reducing the energy consumption of conventional sources. The photovoltaic tile based on green DSSCs could also be proposed as a smart solution to reduce the temperature inside the greenhouse, a small step in developing a strategy to adapt agriculture to advancing climate change. Furthermore, based on the values of γ, which were $-0.003\%/°C$ for the Si tile, $-0.0017\%/°C$ for the yellow tile, and $-0.0004\%/°C$ for the green tile, the thermal stability of the green and yellow tiles is clearly higher than that of the Si tile under the maximum air temperature conditions.

As a final conclusion, the photovoltaic tile concept based on yellow and green DSSCs has been experimentally validated, opening a new perspective for the development of a wavelength-selective greenhouse and, furthermore, a geodesic dome greenhouse, energy independent and combined fully automated arboretum, as a promising agrivoltaic system.

Future work will be focused on monitoring the microclimate of the mini greenhouses based on yellow and green tiles, respectively, as well as the plant response from the perspective of optimal plant growth and high production.

Author Contributions: Conceptualization, D.U. and M.M. (Marinela Miclau); software and formal analysis, E.I., R.R., M.M. (Magdalena Marinca) and S.B.; validation, M.M. (Marinela Miclau) and A.G.; investigation, M.V. and D.U.; writing—original draft preparation, D.U.; writing—review and editing, D.U., M.M. (Marinela Miclau) and M.V. All authors have read and agreed to the published version of the manuscript.

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

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