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Review

Compatibility between Crops and Solar Panels: An Overview from Shading Systems

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Abstract: The use of alternative energy in agricultural production is desired by many researchers, especially for protected crops that are grown in greenhouses with photovoltaic panels on the roofs. These panels allow for the passage of varying levels of sunlight according to the needs of each type of crop. In this way, sustainable and more economic energy can be generated than that offered by fossil fuels. The objective of this work is to review the literature regarding the applications of selective shading systems with crops, highlighting the use of photovoltaic panels. In this work, shading systems have been classified as bleaching, mesh, screens, and photovoltaic modules. The search was conducted using Web of Science Core Collection and Scopus until February 2018. In total, 113 articles from scientific journals and related conferences were selected. The most important authors of this topic are "Yano A" and "Abdel-Ghany AM", and regarding the number of documents cited, the most important journal is Biosystems Engineering. The year 2017 had the most publications, with a total of 20, followed by 2015 with 14. The use of shading systems, especially of photovoltaic panels, requires more crop-specific research to determine the optimum percentage of panels that does not reduce agricultural production.

Keywords: sunlight; shading; greenhouse; solar panels; renewable energy

1. Introduction

Depending on the latitude, the weather conditions (temperature, humidity, and CO_2) often are not optimal for crops. For this reason, crops are usually protected by structures (greenhouses). Even so, climate control becomes necessary—in winter/fall due to low temperatures during the night and in spring/summer due to high temperatures during the day (Callejón-Ferre et al. [1]; Castilla [2]). A clear example of this situation occurs in Mediterranean countries.

To correct high and low temperatures, several shading systems in greenhouses are available: bleaching, mesh, screens, and photovoltaic panels (Figure 1).

Bleaching is the simplest and most economical technique that is used as a shading system. It consists of applying a solution of water and calcium carbonate to the roof of the greenhouse [1]. The other systems that were used (mesh and screens) can be used inside or outside of the greenhouse, and can be permanent (fixed) or mobile (displaceable; Figure 1).

Recently, photovoltaic panels have been used on the roofs of the greenhouses. These can be opaque, semi-transparent, or transparent, allowing for less solar radiation to pass through, which can intentionally affect or not affect the crop development. This situation, supposedly, would allow for the compatible generation of electrical energy and agricultural production (Ureña-Sánchez et al. [3]).

The integration of semi-transparent photovoltaic panels can decrease the solar irradiation and the internal air temperatures, as well as generate electric energy for environmental control systems (Hassanien et al. [4]).

Some concern remains about the impact that solar panels could have on crop yield and fruit quality, as a direct relation exists between the solar radiation that is received by the plants and decreased crop yields (kg·m^{-2}) and smaller fruit sizes [5].

The objective of this work is to review the literature for applications of selective shading systems on crops, highlighting the use of photovoltaic panels.

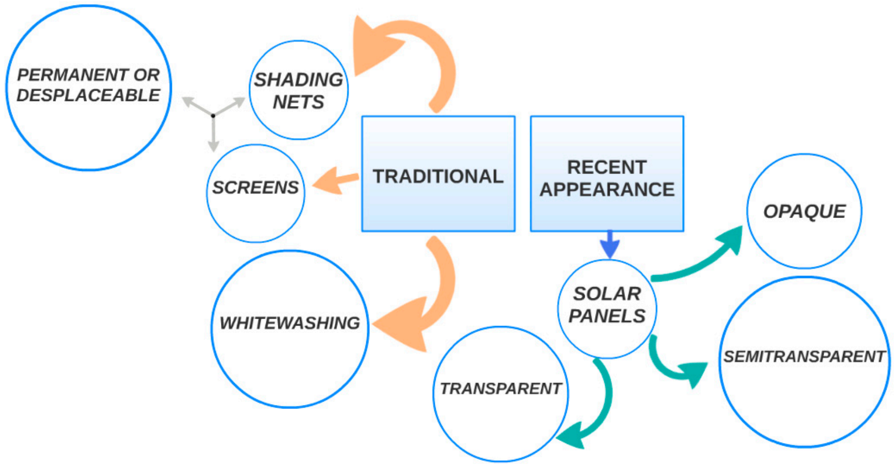

Figure 1. Shading systems in greenhouses typical of Mediterranean countries.

2. Material and Methods

The analysed articles were obtained electronically from the Library of the University of Almeria with a license from the Spanish Foundation for Science and Technology (FECYT) of Web of Science Core Collection (Wos) provided by Clarivate Analytics [6] and Scopus [7]. Through the 'Advanced search' option, terms such as 'greenhouse', 'solar', 'roof', 'energy', 'covering material', and 'shading' were used. A total of 113 articles (articles from scientific journals and conferences) that were directly or indirectly related to the previous terms have been analysed in the period from January 1990 to February 2018.

Only two databases have been used, which could limit the number of bibliographic citations obtained. Likewise, because only articles and congresses were considered, information from books, book chapters, and other similar formats is excluded.

3. Shading, Mesh, Screens and Others

Shading produced by different systems and used in greenhouses has been investigated by numerous authors, mainly from the 1990s to the present (Table 1).

Table 1. Studies related to shading in greenhouses.

Authors	Location	Observations
Cockshull et al. (1992) [5]	United Kingdom	Shading nets and whitewashing on tomato
Abdel-Mawgoud et al. (1996) [8]	Egypt	Effects of shading
Papadopoulos y Pararajasingham (1997) [9]	Canada	Plant spacing
Klaring (1998) [10]	Germany	Shading on broccoli
Kittas et al. (1999) [11]	Greece	Shading on the spectral distribution of light
Araki et al. (1999) [12]	Belgium	Shading nets on spinach
Abreu y Meneses (2000) [13]	Portugal	Effects of whitewashing on tomato
Kittas et al. (2003a) [14]	Greece	Aluminized thermal shading screen on roses

Table 1. *Cont.*

Authors	Location	Observations
Kittas et al. (2003b) [15]	Greece	Aluminized thermal shading screen on roses
Sandri et al. (2003) [16]	Brazil	Effects of shading screen on tomato
Medrano et al. (2004) [17]	Spain	Mobile shading on tomato
Bartzanas y Kittas (2005) [18]	Greece	Shading and evaporative cooling system
Lorenzo et al. (2006) [19]	Spain	Mobile shading on tomato
Rosales et al. (2006) [20]	Spain	Temperature and solar radiation
Gent (2007) [21]	United States	Reflective-aluminized shading screen on tomato
Callejón-Ferre et al. (2009) [1]	Spain	Reflective-aluminized shading screen on tomato
Abdel-Ghany y Al-Helal (2010) [22]	Saudi Arabia	Shading nets
Sato et al. (2010) [23]	Japan	Effects of shading
Aberkani et al. (2010) [24]	Canada	Shading using a retractable liquid foam on tomato and pepper
Abdel-Ghany y Al-Helal (2011) [25]	Saudi Arabia	Shading nets
Al-Helal y Abdel-Ghany (2011) [26]	Saudi Arabia	Shading nets
Chen et al. (2011) [27]	Taiwan	Shading nets
García et al. (2011) [28]	Spain	Mobile shading and fog system
Abdel-Ghany y Al-Helal (2012) [29]	Saudi Arabia	Shading nets
Holcman y Sentlhas (2012) [30]	Brazil	Shading screens of different colors
Ilic et al. (2012) [31]	Serbia	Shading nets
Abdel-Ghany et al. (2015) [32]	Saudi Arabia	Shading nets
Hernández et al. (2015) [33]	Spain	Shading and increased N doses
Ahmed et al. (2016) [34]	Saudi Arabia	Shading nets and whitewashing on tomato and pepper
Nagy et al. (2017) [35]	Hungary	Shading nets on pepper
Murakami et al. (2017) [36]	Japan	Shading nets on melon
Yasin et al. (2017) [37]	Denmark	Shading nets on Grass Weeds
Costa et al. (2017) [38]	Brazil	Reflective-aluminized shading screen on tomato
Holcman et al. (2017) [39]	Brazil	Thermo-reflective shading screen on tomato
Priarone et al. (2017) [40]	Italy	Benefits of shading

3.1. Mesh

Cockshull et al. [5] explain that shading can reduce the average tomato size, but in turn favours a more homogeneous ripening in summer.

Araki et al. [12], in a plantation of spinach, observed that shading of 45% is optimal for growth in the months of June, August, and September, but 60% is optimal for the month of July.

Abdel-Ghanyand Al-Helal [22] claim that the diffusion of solar radiation occurring with shading mesh is related to the colour, texture, and porosity of the mesh; however, they caution that the methods used to measure the porosity of shading mesh may have an estimated error of 14% to 38% [25]. In addition, they revealed that shading mesh behaves like translucent materials, and the colour and solidity of the mesh influence heat transfer [26]. Later, they confirmed that the temperature and porosity of the mesh are more relevant parameters than texture and colour when radiative transmission and reflection are measured [29].

Chen et al. [27] developed a model to evaluate the performance of shading mesh and to predict air temperature in greenhouses.

In Serbia, Ilic et al. [31] observed that shading with coloured mesh in a tomato plantation reduced the amount of fruit with cracked skin and increased the commercial production by 35%, although the fruits had a lower beta-carotene content.

Abdel-Ghany et al. [32] compared upper exterior shading of the greenhouse with interior shading, finding that interior shading increases the thermal radiation by 147% and daytime air temperatures, whereas this increase is not seen with exterior shading.

Ahmed et al. [34] claim that shading methods reduce energy and water consumption, and increase fruit productivity and quality.

Nagy et al. [35] conducted a study of the production of pepper plants grown in a greenhouse under white, red and green shading and determined that the content of ascorbic acid increased even more in the fruits of plants grown with white shading.

Murakami et al. [36] state that the use of mesh in a melon crop reduced the leaf temperature of greenhouse plants by approximately 5 °C, and the size of the fruit was not affected, although the sugar accumulation in the fruit did increase.

3.2. Screens

In rose cultivations in glass greenhouses in Greece, Kittas et al. [14,15] reported that the aluminized thermal screens achieved a more homogeneous microclimate and increased the winter air temperature, thus achieving energy savings of approximately 15%.

Sandri et al. [16] verified that the number of fruits per square metre did not differ in shaded tomato plantations (52%) when compared with those that were unshaded.

Medrano et al. [17] found that the use of external mobile shading reduced the transpiration rate in tomato plants.

Lorenzo et al. [19] explained that, in hot climates with sparse water sources, mobile shading can improve tomato quality and water-use efficiency.

In the north-eastern United States, Gent [21] achieved 9% more commercial tomato production with a 50% shade based on aluminized cloth; the shade only reduced the size of the fruits one of the five years that were studied; in addition, the amount of tomatoes with cracked skin was reduced by 10%.

Callejón-Ferre et al. [1] found that tomatoes have less °Brix when aluminized screens with 60% shading are used instead of traditional bleaching, but no difference was observed with a lower percentage shading.

García et al. [28] explain that mobile shading and misting are equally efficient in reducing high air temperatures.

Yasin et al. [37] studied how the use of greenhouse climate screens affected the growth and development of three common weeds; shade substantially reduced the height of the plant, the number of leaves, and the index of foliar chlorophyll content.

Costa et al. [38] evaluated the growth parameters of the tray seedlings, as well as the growth and production of plants in pepper pots in greenhouses with three different types of shading—transparent low-density polyethylene and reflective aluminized screen under the film, black filament with 50% shade, and aluminized screen—with better yields being obtained with the first method.

Holcman et al. [30] comment that in cherry tomato crops, a greater yield of the plant and greater average weight of the fruits are obtained with a diffusive plastic than with the use of a thermoreflective shading screen.

3.3. Others

Klaring [10] found that broccoli yield is reduced by 1% for every 1% reduction in irradiation by shading.

Abdel-Mawgoud et al. [8] found that, in tomatoes with 30% shade, the yield was not reduced, although the total dry matter did decrease; the shade can serve to improve the commercial quality of the fruit by reducing burns.

Rosales et al. [20] comment that the increase in temperature and solar radiation in the cherry tomato during May in Spain diminishes the nutritional quality of the fruits.

Sato et al. [23] claim that as the shading level increases, the dry weights of tomato plants decrease, but no differences occur in the distribution of the organic dry matter.

Hernández et al. [33] state that in tomatoes with 50% of the sunlight attenuated by shading, a higher yield, as well as a higher concentration of lycopene, was obtained with lower doses of irrigated nitrogen (7 mM of N), regardless of the doses of N to tomatoes without shade.

Papadopoulos and Pararajasingham [9] explored the consequences of spacing between plants and light penetration for tomato productivity.

Kittas et al. [11] evaluated the quality of light that is received by plants by comparing three types of shading: bleaching, external mesh, and internal aluminized screens. Their results indicate the need to better control the characteristics of the light that is caused by the shading system used.

Abreu and Meneses [13] assert that roof bleaching reduces radiation transmission by 50%, which in turn reduces periods with temperatures above 30 °C.

Bartzanas and Kittas [18] took different measurements in a partially shaded greenhouse with a cooling system, finding that in the shaded part, greater transpiration occurred.

Aberkani et al. [24] comment that differences in air temperature of up to 6 °C, a humidity increase of 10% and reduction in the need for ventilation are possible when polyethylene liquid foam is used in greenhouse ceilings.

Holcman and Sentelhas [39] maintain that the lowest transmission of solar radiation is achieved with black polyethylene sheets ascompared with the use of red or blue sheets or with thermo-reflective sheets; the highest temperatures are reached with blue sheets.

Priarone et al. [40] investigated the selection of the most favourable solutions for ventilation, heating, cooling and thermo-hygrometric control of a greenhouse, and they propose, as optimal, the shading of the glazed surfaces, the natural ventilation and the forced convection of the external air.

4. Photovoltaic Modules in Greenhouses

The application of photovoltaic modules (PM) to agricultural environments has been analysed by a large number of authors (Table 2).

Table 2. Studies related to photovoltaic modules in agriculture.

Authors	Location	Observations
Kozai et al. (1999) [41]	Japan	Electricity generated using photovoltaic cells
Yano et al. (2007) [42]	Japan	Applications of photovoltaic power systems
Campiotti et al. (2008) [43]	Italy	Prototype of photovoltaic greenhouse
Yano et al. (2009) [44]	Japan	Photovoltaic modules mounted inside the roof
Minuto et al. (2009) [45]	Italy	Semi-transparent photovoltaic systems
Yano et al. (2010) [46]	Japan	Configuration of photovoltaic modules
Qoaider y Steinbrecht (2010) [47]	Germany	The economic feasibility of photovoltaic technology
Carlini et al. (2010) [48]	Italy	Performance analysis of greenhouses with PV
Sonneveld et al. (2010) [49]	Netherlands	Hybrid system with PV and thermal energy
Dupraz et al. (2011) [50]	France	Agrivoltaic system
Campiotti et al. (2011) [51]	Italy	Photovoltaic system on tomato
Pérez-Alonso et al. (2011)[52]	Spain	Flexible solar panels and shading
Ganguly et al. (2011) [53]	India	Floriculture greenhouse by solar photovoltaic
Carlini et al. (2012) [54]	Italy	Photovoltaic system on tomato
Kadowaki et al. (2012) [55]	Japan	Configuration of photovoltaic modules on onions
Marucci et al. (2012) [56]	Italy	Semi-transparent photovoltaic systems
Pérez-Alonso et al. (2012)[57]	Spain	Evaluation of a photovoltaic system
Poncet et al. (2012) [58]	France	Agrivoltaic system
Klaring y Krumbein (2013) [59]	Germany	PM and permanent shading
Marrou et al. (2013) [60]	France	Agrivoltaic system
Castellano (2014) [61]	Italy	Configuration of photovoltaic modules
Juang y Kacira (2014) [62]	South Corea	PM in an arid environment
Cossu et al. (2014) [63]	Italy	PM and shading
Tani et al. (2014) [64]	Japan	PM and light diffusion on lettuce
Pérez-Alonso et al. (2014) [65]	Spain	PM and shading on tomato
Pérez-García et al. (2014) [66]	Spain	Evaluation of a photovoltaic system
Serrano et al. (2014) [67]	Spain	PM and shading
Yano et al. (2014) [68]	Japan	Semi-transparent photovoltaic systems
Fatnassi et al. (2015) [69]	France	Configuration of photovoltaic modules
Marucci et al. (2015) [70]	Italy	Prototype of dynamics photovoltaic greenhouse
Bulgari et al. (2015) [71]	Italy	PM and shading on tomato
Yang et al. (2015) [72]	China	Transparent photovoltaic systems
Castellano y Tsirogiannis (2015) [73]	Italy	Configuration of photovoltaic modules
Cossu et al. (2016) [74]	Japan	Semi-transparent photovoltaic systems
Marucci y Capuccini (2016a) [75]	Italy	PM and energy efficiency

Table 2. *Cont.*

Authors	Location	Observations
Marucci y Capuccini (2016b) [76]	Italy	PM and energy efficiency
Hassanien et al. (2016) [77]	Egypt	The challenges for photovoltaic systems
Buttaro et al. (2016) [78]	Italy	Semi-transparent photovoltaic systems
Castellano et al. (2016a) [79]	Italy	PM and photosynthetic photon flux
Castellano et al. (2016b) [80]	Italy	PM and shading
Cuce et al. (2016) [81]	United Kingdom	PM and energy consumption
Saifultah et al. (2016) [82]	South Corea	Semi-transparent photovoltaic systems
Dinesh y Pearce (2016) [83]	United States	Agrivoltaic system
Cossu et al. (2017) [84]	Japan	PM and radiation
Cossu et al. (2017) [85]	Japan	Configuration of photovoltaic modules
Carreño-Ortega et al. (2017) [86]	Spain	Environmental and socioeconomic development
Marucci et al. (2017) [87]	Italy	Photovoltaic greenhouse tunnel
Valle et al. (2017) [88]	France	Agrivoltaic system
Trypanagnostopoulos et al. (2017) [89]	Greece	PM and shading
Loik et al. (2017) [90]	United States	PM and energy balance
Yildirim et al. (2017) [91]	Turkey	PM and economic and environmental evaluation
Trypanagnostopoulos et al. (2017) [92]	Greece	Electricity generated using photovoltaic cells
Kavga et al. (2017) [93]	Greece	PM and shading
Marucci et al. (2018) [94]	Italy	Photovoltaic greenhouse tunnel
Liu et al. (2018) [95]	China	PM and shading

Kozai et al. [41] explain that considerable amounts of electricity can be generated without significantly affecting the transmission of solar radiation if the number of photovoltaic modules and the orientation of the greenhouse are correctly chosen for the latitude and the time of year.

Yano et al. [42] made use of the energy that is generated by photovoltaic modules to operate an autonomous lateral ventilation system. Later, Yano et al. [44] verified that when photovoltaic modules are mounted on the interior surface of greenhouses in Japan, greater energy efficiency is obtained with inclination angles of 20 degrees than with angles of 28 degrees.

Campiotti et al. [43] describe a prototype photovoltaic greenhouse being built in southern Italy.

Yano et al. [46] and Fatnassi et al. [69] found that the arrangement of panels in the form of a chessboard compared to panels placed in other arrangements improves the distribution of sunlight within the greenhouses. Kadowaki et al. [55] found that the placement of photovoltaic modules in this arrangement is desired to reduce the effects of shading. Additionally, Cossu et al. [85] suggest new design criteria for PV greenhouses, concerning the decrease of the PV array coverage and different installation patterns of the PV panels on the roof.

Qoaider and Steinbrecht [47] demonstrated that providing power for entire farming populations is feasible with photovoltaic energy.

Carlini et al. [48] used TRNSYS 16 software to simulate temperatures and humidity in a greenhouse with photovoltaic modules in order to determine the performance of the greenhouse.

Sonneveld et al. [49] developed a hybrid system of photovoltaic and thermal panels together with the reflection of near infrared radiation to improve climate conditions in a greenhouse and avoid the use of fossil fuels.

Dupraz et al. [50] propose that an agrovoltaic system (using agricultural land for the generation of solar energy) may be the best solution in countries with few areas conducive to agriculture. One year later, Poncet et al. [58] stated that the main challenge for the agrovoltaic systems is to achieve higher productivity and quality, while reducing the environmental impact. However, Marrou et al. [60] note that moving from an open crop to an agrovoltaic system requires small modifications focused on the mitigation of shaded areas and the selection of plants adapted to fluctuating shadows. More recently, Dinesh and Pearce [83] affirmed that the value of electricity that is generated by solar energy and the production of shade-adapted crops creates an increase of more than 30% of the economic value of the lands that deploy an agrovoltaic system.

Campiotti et al. [51], in an experiment that was carried out in southern Italy with a greenhouse with rooftop photovoltaic panels, found that the energy requirements of 21 tomato plants for 120 days were 19.48 kW·h, and the modules produced a total of 333.6 kW·h from September to December. Later, Pérez-Alonso et al. [57] and Pérez-García et al. [66] conducted two experiments in south-eastern Spain, in which an annual energy yield of 8.25 kW·h·m^{-2} was achieved through 24 flexible modules.

Pérez-Alonso et al. [52] did not obtain significant differences between tomatoes shaded by flexible photovoltaic panels and non-shaded tomatoes; however, Klaring and Krumbein [59] maintain that restricting the intensity of solar radiation through permanent shading leads to a reduction in the growth and yield of the tomato plant but not the quality of the fruit.

Ganguly et al. [53] managed to maintain an optimum temperature for the cultivation of flowers in a greenhouse in India from energy provided by panels installed in the roof and a support system for critical hours, providing a clear example of agronomic compatibility.

Carlini et al. [54] proved that solar greenhouses with photovoltaic modules manage to save energy in both cooling and heating tasks.

Castellano [61] discusses different configurations for the placement of photovoltaic modules in greenhouses and analyses some parameters with Autodesk Ecotect Analysis software.

In South Korea, Juang and Kacira [62] propose adding integrated photovoltaic systems to the structure of greenhouses to alleviate the energy and food problems of certain populations that have difficulty accessing electricity, fertilizers, or good quality water.

Cossu et al. [63], in a greenhouse with 50% of the roof surface being occupied by photovoltaic modules, included supplementary lighting with the energy that was generated by the modules, but the plantation was too shaded and did not obtain benefits.

Tani et al. [64] claim that light diffusion films can be applied to improve productivity in crops shaded by photovoltaic panels.

Pérez-Alonso et al. [65] state that the commercial production of tomatoes is compatible with 9.8% shading that is produced by flexible photovoltaic modules. Tripanagnostopoulos et al. [92] propose that a PV system covering only 6.5% of the roof surface could be enough to completely cover the electricity needs for the auxiliary processes of a greenhouse. Liu et al. [95] have developed new types of photovoltaic sheets that shade on the field can be reduced.

Serrano et al. [67] made use of flexible panels to supply energy to autonomous systems and to replace the shading elements, thus achieving normal crop development.

Marucci et al. [70] used dynamic panels, which move along the longitudinal axis, in order to vary the degree of shading.

Bulgari et al. [71] reveal that the efficiency of the use of solar radiation by tomato plants is greater in greenhouses with solar panel shading, but the fruit tends to have lower lycopene, beta-carotene, sucrose, reducing sugars, and total sugar content.

Castellano and Tsirogiannis [73] performed an analysis of different photovoltaic configurations in the greenhouse to determine the effects of shading and energy efficiency.

Marucci and Capuccini [75] reported that it is possible to combine the production of electricity and agricultural production if the type of crop, the latitude, and the characteristics of the greenhouse are taken into account. That same year, Marucci and Capuccini [76] affirmed that the use of photovoltaic panels is a viable alternative both for shading greenhouses and for electricity production in warm areas.

Hassanien et al. [77] conducted a small discussion on photovoltaic technology and the challenges it faces in the agricultural environment.

Castellano et al. [79] used a model that predicts the density distribution of photosynthetic photons in photovoltaic greenhouses with an error of 19%. That same year, Castellano et al. [80] developed a model to predict the effect of shading within a photovoltaic greenhouse.

Cuce et al. [81] managed to save up to 80% in energy consumption in greenhouses by combining solar and thermal energy with new insulation materials.

Cossu et al. [84] developed an algorithm to estimate the global radiation that had accumulated within photovoltaic greenhouses to aid in the selection of the most suitable plant species according to their light needs.

Carreño-Ortega et al. [86] estimated that the use of photovoltaic modules in the agricultural environment can increase the profitability of the farms up to 52.78% and that environmental and economic improvements would also be obtained.

Marucci et al. [87,94] analysed the shading variation produced by the application of flexible and semi-transparent photovoltaic panels in a tunnel-type greenhouse, where the percentage of shading during the year never exceeded 40%.

Valle et al. [88] demonstrated that an agrivoltaic system achieved high productivity per unit of land area using solar trackers instead of stationary photovoltaic panels, whereas the production of lettuce biomass was maintained close to or even similar to that obtained under full sun conditions.

Trypanagnostopoulos et al. [89,93] explained that the use of photovoltaic panels in a lettuce crop produced a 20% shading of the greenhouse, and plant growth was the same as that of the reference greenhouse, without photovoltaic panels on the roof.

Loik et al. [90] reported that in a trial conducted on a tomato crop, the wavelength-selective photovoltaic systems produced a small decrease in water use, whereas minimal effects were observed on the number and fresh weight of the fruit for several commercial species.

Yildirim et al. [91] conducted an economic and environmental assessment for tomato, cucumber and lettuce crops using photovoltaic solar panels on the roof of the greenhouse and connected to the grid to support a heat pump and generate electricity.

Minuto et al. [45] conducted an experiment with semi-transparent photovoltaic panels on a glass greenhouse and did not find large differences in the behaviour of the tomato plants due to shade.

Marucci et al. [56] explored the possibility of using semi-transparent photovoltaic materials to avoid the loss of solar radiation by shading.

Yano et al. [68] revealed that the electrical energy produced by semi-transparent modules with a cell density of 39% is sufficient for regions with high demand in summer and low demand in winter.

Yang et al. [72] optimized the use of sunlight by manipulating the photonic crystals in transparent organic photovoltaic cells.

Buttaro et al. [78], in a greenhouse arugula plantation, found that semi-transparent modules can satisfy all of the required electricity demand and that the yield of the plantation decreases if traditional modules are used.

Cossu et al. [74] claim that semi-transparent photovoltaic technology with spherical microcells can be used to contribute to the sustainability of greenhouses.

Saifultah et al. [82] conducted a review of materials used for manufacturing semi-transparent modules.

5. Other Related Studies

Table 3 shows articles that are related to greenhouses, renewable energies and/or shading but do not fit into the categories described above.

Table 3. Other related studies.

Authors	Location	Observations
Bot et al. (2005) [96]	Netherlands	Energy saving
Marcelis et al. (2006) [97]	Netherlands	Effects of light quantity
Hemming et al. (2006) [98]	Netherlands	Effects of diffuse light
Suri et al. (2007) [99]	Italy	Solar energy in the European Union
Hemming et al. (2008) [100]	Netherlands	Effects of diffuse light
Sonneveld et al. (2010b) [101]	Netherlands	The feasibility of solar energy
Abdel-Ghany y Al-Helal (2011) [102]	Saudi Arabia	Thermal model

Table 3. *Cont.*

Authors	Location	Observations
Abdel-Ghany (2011) [103]	Saudi Arabia	Solar energy and heat
Bibi et al. (2012) [104]	Pakistan	Effects of diffuse light
Verheul (2012) [105]	Norway	Light Intensity
Schuch et al. (2014) [106]	Germany	Solar energy and heating
Klaring et al. (2015) [107]	Germany	Heating and carbon dioxide emissions
Bian et al. (2015) [108]	China	Effects of light quality
El-Maghlany et al. (2015) [109]	Egypt	Solar energy and heating cost savings
Cakir y Sahin (2015) [110]	Turkey	Analysis of types greenhouses
Attar y Farhat (2015) [111]	Tunisia	Heating and costs
Shyam et al. (2015) [112]	India	Greenhouse dryer
Elkhadraoui (2015) [113]	Tunisia	Greenhouse dryer
Reca et al. (2016) [114]	Spain	The profitability of photovoltaic systems
Ziapour y Hashtroudi (2017) [115]	Iran	Solar energy and saving energy process
Arabkooshar et al. (2017) [116]	Iran	Hybrid solar-geothermal heating system
Xue (2017) [117]	China	Solar energy and costs
Anifantis et al. (2017) [118]	Italy	Heating

Reca et al. [114] verified that the profitability and energy efficiency of a photovoltaic system for irrigation is relatively low, although it can be improved by using excess energy for other tasks.

Bot et al. [96] developed Dutch-type greenhouses that do not use fossil fuels, thus improving the insulation value of the roofs and capturing solar energy for storage.

Marcelis et al. [97] showed that light has a positive effect on the yield and quality of greenhouse crops, but this effect is more noticeable when the amount of light is lower.

Verheul [105] states that an increase in the intensity of the light increases the tomato yield, but not the quality.

In Holland, Hemming et al. [98] observed that covering greenhouses with light-diffusing materials led to increases in production in the summer months by 6%. Later, in Dutch greenhouses, Hemming et al. [100] and Bibi et al. [104] obtained great results in cucumbers, proving that diffuse light improves photosynthesis in the middle zones of plants.

Suri et al. [99] state that photovoltaic energy is already in a position to make a significant contribution to the European Union's energy landscape.

Sonneveld et al. [101] presented the possibility of taking advantage of excess solar energy in summer to convert it into high-grade electricity and use it for cooling or heating.

Abdel-Ghanyand Al-Helal [102] developed an improved thermal model for greenhouses.

Abdel-Ghany [103] states that at a density of plants corresponding to a leaf area index of 3, 54% of the solar radiation used by the greenhouse is converted into sensible heat and 46% into latent heat through evapotranspiration.

Schuch et al. [106] reduced the consumption of fossil fuels by 81% with a system to capture solar thermal energy in a tomato greenhouse.

Klaring et al. [107] reported that carbon dioxide emissions from tomato crops can be reduced by lowering the heating temperature without affecting the fruit, but harvest times are increased.

Bian et al. [108] discussed the advantages of LED technology to modify the accumulation of phytochemicals with light.

El-Maghlany et al. [109] performed an efficiency analysis of solar energy capture and energy savings according to the type of greenhouse.

Cakir and Sahin [110] analysed different greenhouse types and found the elliptical greenhouse to be the most appropriate for the cold climate and latitude of Bayburt, Turkey.

Attar and Farhat [111] explain that the cost of heating in a 1000-m^3 greenhouse can be reduced by 51.8% if a heated water system is integrated.

Shyam et al. [112] and Elkhadraoui et al. [113] developed greenhouses as biomass dryers with electricity that is supplied from solar panels.

Ziapour and Hashtroudi [115] modified the roof of a greenhouse to partially reflect sunlight in a collector, and thus save on energy expenditure.

Arabkooshar et al. [116] used thermal panels and geothermal wells for heating, thus reducing the diesel consumption in winter.

Xue [117] states that photovoltaic greenhouses that occupy a large area of land require large outlays, which are not available to farmers or even to large companies.

Anifantis et al. [118] analyses the performance of an independent renewable energy system for greenhouse heating by using photovoltaic panels that are connected to an electrolyser, which produces hydrogen by electrolysis during the day and stores it in a pressure tank.

6. Studies Related to Shading and Photovoltaic Panels in Greenhouses by Country

The country of the main author of each of the publications analysed has been used to create Figure 2.

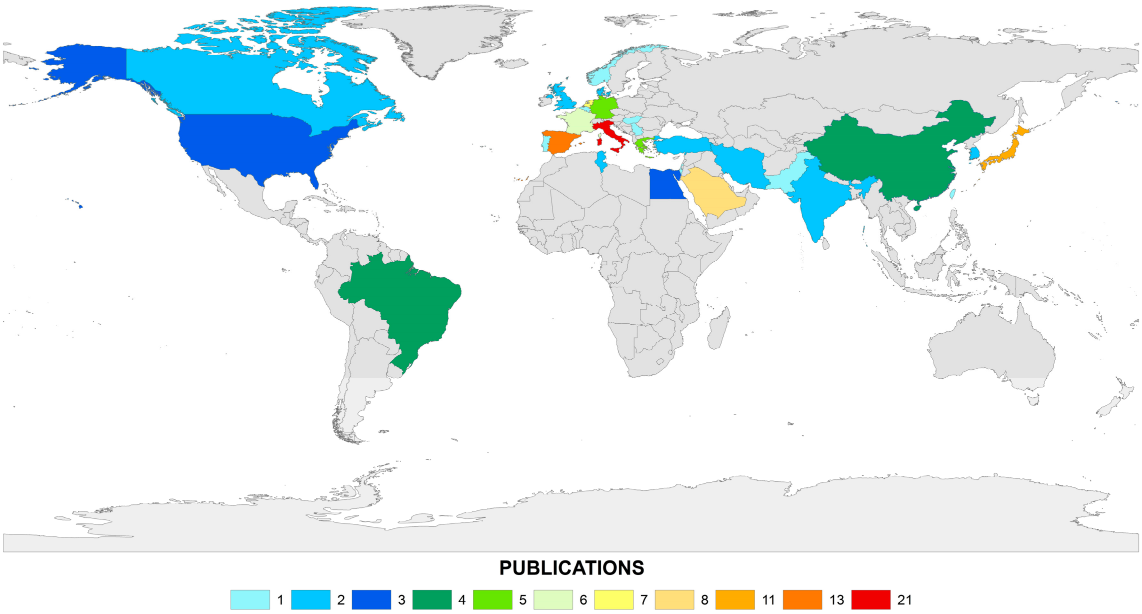

Figure 2. Publications by country.

The 113 publications analysed, which were related in some way to greenhouses, solar panels, tomato, and/or shade, represent 27 countries. If we look at the number of investigations in each country, the one with the most publications is Italy, with a total of 21, followed by Spain with 13; Japan with 12; Saudi Arabia with 8; Greece with 7; Holland with 6; France and Germany with 5; Brazil and China with 4; Egypt and the United States with 3; Canada, South Korea, India, Iran, United Kingdom, Tunisia, and Turkey with 2, and Belgium, Denmark, Hungary, Norway, Pakistan, Portugal, Serbia, and Taiwan with 1 (Figure 2).

In Figure 3, the research carried out in each section of the review by each country is indicated.

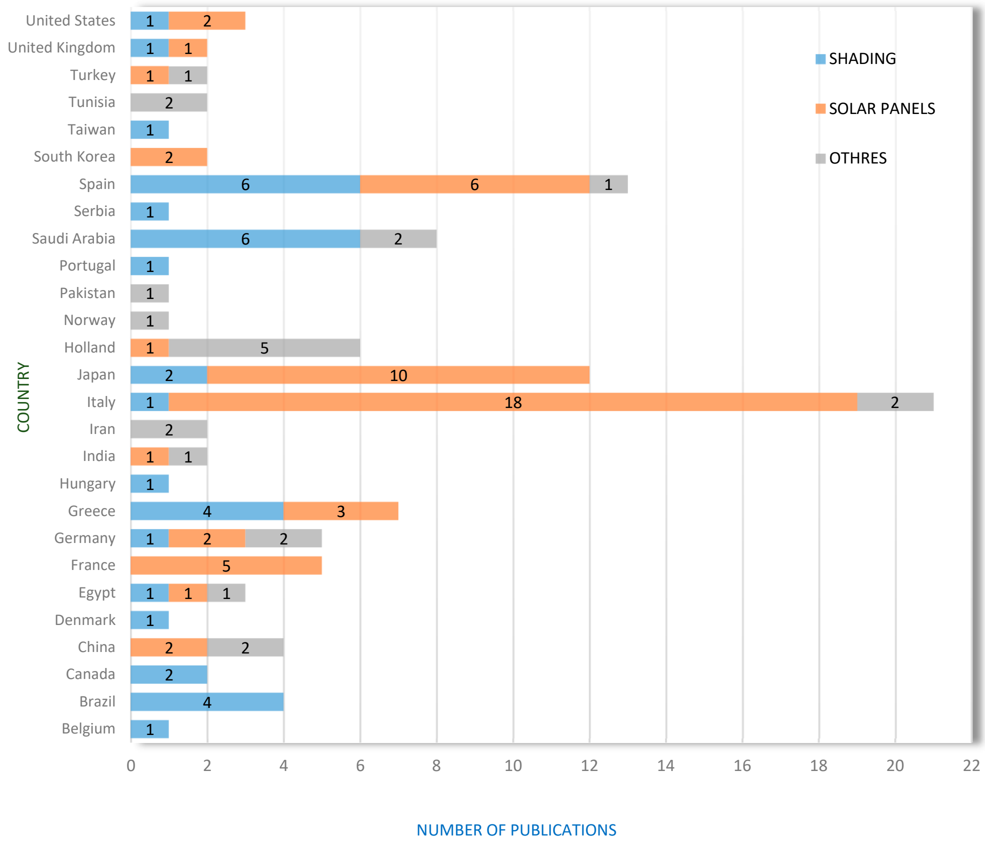

Figure 3. Number of publications in each field per country.

7. Studies Related to Shading and Photovoltaic Modules in Greenhouses by Year

Figure 4 shows the number of studies per year, as well as the fields studied.

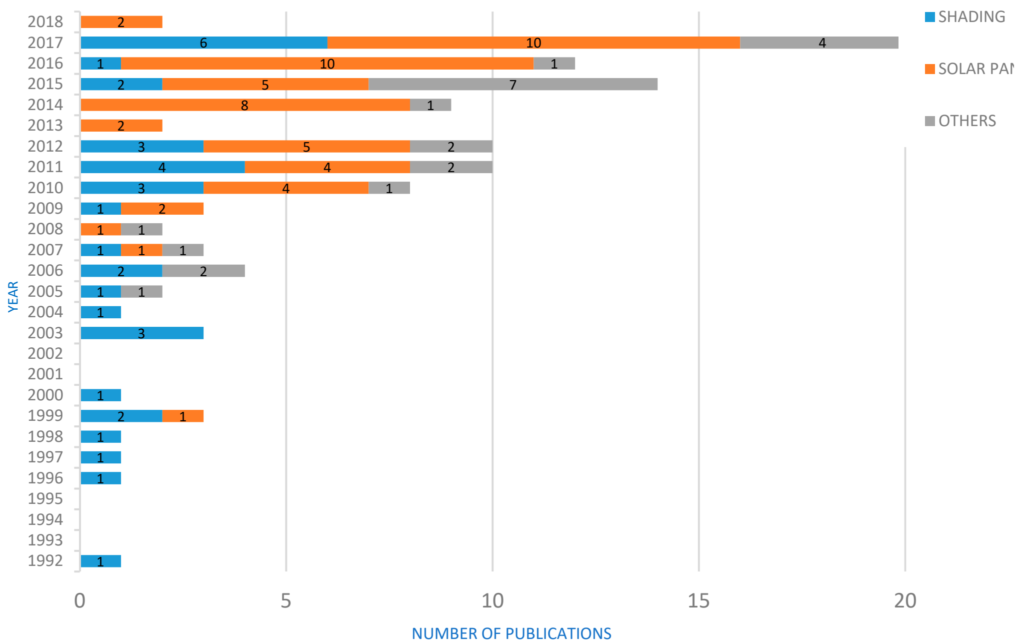

Figure 4. Number of publications in each field of knowledge per year.

A clear tendency to increase the number of publications can be observed. A notable difference is apparent in the number of studies that have carried out since 2010, with the exception of 2013, when only two studies that were related to the subject were analysed; however, 2017 had the most publications, with a total of 20, followed by 2015 with 14.

8. Studies Related to Authors and the Number of Citations

Table 4 shows the authors that appear in at least two citations.

Table 4. Authors and the number of documents.

Authors	Documents	Authors	Documents
Yano A	8	Onoe M	2
Abdel-Ghany AM	8	Cecchini M	2
Al-Helal IM	6	Trypanagnostopoulos G	2
Marucci A	6	Chessa F	2
Colantoni A	5	Deligios PA	2
Callejón-Ferre AJ	5	Marrou H	2
Kittas C	5	Murakami K	2
Pérez-Alonso J	5	Poncet C	2
Castellano S	4	Hiraki E	2
Monarca D	4	Caparrós I	2
Pérez-García M	4	Giménez M	2
Cossu M	4	Brun R	2
Serio F	3	Bibbiani C	2
Santamaria P	3	Incrocci L	2
Sánchez-Guerrero MC	3	Holcman E	2
García ML	3	Furue A	2
Pazzona A	3	Sentelhas PC	2
Sirigu A	3	Carlini M	2
Ledda L	3	Fatnassi H	2
Murgia L	3	Sonneveld PJ	2
Noda S	3	Alonzo G	2
Cappuccini A	3	Campiotti C	2
Klaring HP	3	Farhat A	2
Carreño-Ortega A	3	Krumbein A	2
Baille A	3	Dufour L	2
Katsoulas k	3	Swinkels GLAM	2
Ishizu F	3	Bot GPA	2
Medrano E	3	Cabrera FJ	2
Lorenzo P	3	Dueck T	2
Tripanagnostopoulos Y	3	Li M	2
Kadowaki M	3	Kavga A	2
Hemming S	3	Dondi F	2
Tanaka T	3	Capuccini A	2

If we observe the number of documents per each author, the ones with the most publications are "Yano A" and "Abdel-Ghany AM", with a total of 8, followed by "Al-Helal IM" and "Marucci A" with 6 (see Table 4).

9. Studies Related to Journals and the Number of Citations

Table 5 shows the journals that appear in at least two articles.

Table 5. Journals/Conferences and the number of documents.

Journals/Conferences	Documents
Acta Horticulturae	19
Biosystems Engineering	8
Renewable Energy	6
Solar Energy	5
Renewable & Sustainable Energy Reviews	5
Applied Energy	5
Journal of Agricultural Engineering	5
ScientiaHorticulturae	4
Energy Conversion and Management	3
Solar Energy Materials and Solar Cells	3
Energies	2
Agricultural and Forest Meteorology	2
Journal of Renewable and Sustainable Energy	2
Mathematical Problems in Engineering	2

The most important conference document is Acta Horticulturae with 19 documents. The most important journal is Biosystems Engineering, with a total of eight documents, followed by Renewable Energy with 6; Solar Energy, Renewable & Sustainable Energy Reviews, Applied Energy and Journal of Agricultural Engineering with five. It should be noted that Acta Horticulturae is not a journal in the true sense of the word.

10. Conclusions of the Review

The countries with the highest number of publications concerning solar panels and crops were Italy, with a total of 21; Spain with 13; and Japan with 12. During the past decade, the number of relevant publications has increased. These three countries are in the same latitude range, although the studies are very different depending on the type of crop selected and the type of greenhouse structure.

The most important authors of this topic are "Yano A" and "Abdel-Ghany AM", and regarding the number of documents that are cited, the most important journal is Biosystems Engineering.

Most of the studies justify the use of photovoltaic panels alongside agricultural production, although others cast general doubt on the economics of using these panels. Further technological development of photovoltaic panels with respect to transparency and energy efficiency could make their coexistence with greenhouse crops more economically viable. The trend of research on this subject is the search for the percentage of shading that makes the shading compatible for each type of crop.

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