

Characterization of the Spectrum of Solar Irradiance under Different Crop Protection Coverings in Mediterranean Conditions and Effect on the Interception of Photosynthetically Active Radiation

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Abstract

Plants use visible light and part of adjacent ultraviolet and near infrared regions for photosynthesis. Crop protection coverings enable plant cultivation in areas or seasons not suitable open field. However, the use of covering materials is a detriment to solar irradiance, which may decrease the photosynthetic rate. Here, the effect of two different covering materials, tempered glass and white polyethylene mesh, on solar irradiance was compared to open field (control) under real farming conditions. Relative irradiance (RI) and photosynthetic photon flux density (PPFD) were recorded along 380-780 nm wavelength spectrums in the two conditions at 10:00 h and 13:00 h. Also the efficiency of *Capsicum* peppers in capturing solar irradiance was evaluated in leaves as the reflectance of both RI and PPFD under the mentioned growing conditions. Low differences in RI among the three conditions were found, and the lowest values corresponded to glasshouse conditions. Differences were more obvious in PPFD and, compared to open field, both mesh greenhouse and glasshouse conditions provoked remarkable decreases in all the spectral bands, 50-55% and 75-80% respectively. Covering materials also differed on the ratio of reflected PPFD and incident PPFD. Glasshouse plants displayed the highest reflectance at both 10:00 h and 13:00 h (0.05-0.20), followed by mesh greenhouse (0.05-0.10), suggesting that glasshouse conditions might decrease the photosynthesis rate due to both PPFD decrease and reflectance, although the effect of polyethylene mesh should not be disregarded as it also decreases considerably PPFD. Our results have important implications for the physiology and the productivity of crops under different covering materials.

Keywords: photon flux; photosynthesis; polyethylene mesh; tempered glass; visible light

Introduction

Solar irradiance which reaches Earth causes different phenomena essential for life formation and evolution in our planet. This is the main factor on the energy balance of Earth and consequently determines temperature, provokes air flows, and it is also involved in a range of physicochemical processes in the atmosphere and Earth's surface. Thus, there is a set of effects of solar irradiance on the development of living organisms (Norval *et al.*, 2011). In particular, light or visible spectrum is the most important factor in the physiological process of photosynthesis in plants (Ahmad *et al.*, 2015).

Plants use a wide spectral band of the visible light and adjacent regions in the conversion of light into chemical energy in photosynthesis. Such spectral range is called photosynthetically active radiation (PAR), which is comprised between 380 and 780 nm, and encompasses approximately 45% of the spectrum of solar irradiance (Escobedo *et al.*, 2011). Several plant pigments, mainly chlorophylls, have high photon interception efficiency, especially those from blue and red regions (Aliniaiefard *et al.*, 2016). Therefore, photosynthetic photon flux density (PPFD) is a suitable and common parameter in plants (Begón *et al.*, 1995; Ekmekci *et al.*, 2000). In this regard,

there are many studies on photobiology to assess the effect of different light sources on plant growth, development and composition (Smith, 1982; Bourget, 2008; Kosvancova *et al.*, 2009; Dueck *et al.*, 2012; Olle *et al.*, 2013; Nhut *et al.*, 2015; Bantis *et al.*, 2016; Snowden *et al.*, 2016). Although it is commonly accepted that plants have higher response to red light, followed by blue light (Dougher *et al.*, 2001), the increase of blue light may improve the growth of certain species (Snowden *et al.*, 2016; Dougher *et al.*, 2001). Others have reported that green light, under strong white light conditions, may provide higher photosynthesis rate than blue or red light (Yorio *et al.*, 2001; Terashima *et al.*, 2009).

In addition, many structures and covering materials have been developed to enable the cultivation of different species in areas or seasons where climate conditions are not suitable for open field (Ali, 2012). The main purpose of these greenhouses is to provide, in the most efficient way, a warm microclimate within the structure, enabling an optimal plant growth to increase yields and/or to widen growing seasons (Ureña-Sánchez *et al.*, 2012; Alsadon *et al.*, 2016). The first greenhouses were built in glass so that light could enter inside, while temperatures were considerably higher than outside. Later, during the second part of 20th century a range of plastic films, lighter and less expensive than glass, became more and more popular. By contrast, these covering materials may play a role as barrier against solar irradiance, modifying its quality and intensity, which is being mainly studied in the last years (Abdel-Ghany *et al.*, 2012).

In the Mediterranean east coast of Spain the most traditional growing conditions are: i) open field, and protected cultivation under ii) glasshouse and iii) an intermediate alternative which consists of greenhouses covered with plastic mesh. Comparatively glasshouses are more expensive to build and to maintain, but glass can stay for many years. By contrast, mesh greenhouses are cheaper and once the mesh degrades it is changed for a new one. One of the main objectives of mesh greenhouses is to prevent the entrance of pests (and disease vectors), as well as providing warm temperatures inside, although at a lower extent than glasshouses, but better air circulation (Serrano-Carriño, 2005; Castilla, 2013). Also these mesh greenhouses can be used commercially for a range of species, from vegetables to citrus and other fruit trees.

Considering the wide response of different species to light irradiance it is of paramount importance for plant growers and scientists to plan the best conditions for yield and quality of each crop or experiment, as well as to choose the most suitable covering materials to achieve the best spectral composition for different species (Hui-Zhi, 2018). Therefore, the aim of the present work is to characterize, both qualitatively and quantitatively, the spectral pattern of solar irradiance which reaches plants under three very different growing systems in the Mediterranean coast of Spain: i) glasshouse, ii) mesh greenhouse and iii) open field, as well as the efficiency of plants in capturing PPFD under each condition. To our knowledge, this is the first comparative assay between glasshouse and mesh greenhouse in terms of their effect on light transmittance based on natural Mediterranean sunlight conditions.

Materials and Methods

The research experimental conditions

All measurements and experiments were performed in facilities of the Universitat Politècnica of Valencia main Campus (Campus de Vera, Valencia, Spain). Three usual growing systems in the Mediterranean coast region were tested in the present experiment: open field, glasshouse, mesh greenhouse (Fig. 1).

Glasshouse. A sector of 6.9 × 20 × 4.8 m (width × length × maximum height) within a set of 13 Venlo-type modules and 4 mm-thick tempered glass as covering material, was chosen for the present experiment. These glasshouses were built in April 1997 following north/south orientation. Common maintenance practices have been done periodically to these glasshouses. The sector chosen (Nº.7) is located right in the middle of the modules.

Mesh greenhouse. A brand-new (built on December 2016) 25 × 25 × 4 m greenhouse using white mesh, polyethylene 20 × 10 threads cm², as covering material, was chosen for greenhouse conditions. The mesh greenhouse is located in an experimental field of UPV at 500 m from the glasshouses and also having north/south orientation.

Open field. An open field sector of the UPV experimental field above mentioned, close to the mesh greenhouse, was chosen for open field conditions (i.e. control or free sunlight exposure).



Fig. 1. Facilities used: Open field (control), close to the entrance to mesh greenhouse; mesh greenhouse and glasshouse

Studied parameters

An Asenstek handheld ALP-01 spectrometer (New Taipei City, Taiwan), covering a range of 380 to 780 nm wavelength spectrum, an illuminance range of 5 to 50,000 lux, reliable chromaticity from 50 to 50,000 lux, optical resolution of 8 nm, repeatability (2σ) for $x, y < 0.0005$, integration time from 6 ms to 16 s and temperature range from -10 to 45 °C. The spectrometer was calibrated at Asenstek labs (New Taipei City, Taiwan) providing a $\pm 3\%$ of uncertainty for measurements. The spectrometer provides records every nanometer along the spectrum. Within the PAR spectrum (380-780 nm), the spectrometer works considering the following main spectral regions according to the Commission Internationale de l'Éclairage (CIE, 2011): i) long wavelength UV (380-399 nm, UV-A), ii) blue (400-499 nm), iii) green (500-599 nm), iv) red (600-700 nm) and v) near infrared (701-780 nm, IR-A).

Relative irradiance (RI) was estimated on the basis of the sampled (measured) spectrum data compared to both the reference spectrum and the dark spectrum of the spectrometer.

Photosynthetic Photon Flux Density (PPFD) was estimated as a parameter directly related to photosynthetically active radiation or (PAR). PPFD was expressed as $\mu\text{mol m}^{-2} \text{s}^{-1}$ ($1 \mu\text{mol} = 6,023 \cdot 10^{17}$ photons).

In addition to the mentioned parameters, the following ratios were estimated on the basis of PPFD estimates from different spectral regions:

$$R/B = \frac{PPFD_R}{PPFD_B}; \quad R/IR-A = \frac{PPFD_R}{PPFD_{IR-A}}$$

where $PPFD_R$, $PPFD_B$, $PPFD_{IR-A}$ are PPFD estimates corresponding to the red, blue and near infrared spectral regions.

Finally, measurements of incident and reflected RI and PPFD along the 380-780 nm spectrum were recorded at both 10:00 h and 13:00 h on the leaves of a species grown at this season and high economic value in Mediterranean areas (Pereira-Dias *et al.*, 2017): common pepper (*Capsicum annuum* L.) California Wonder cv. 'Ferrari'. The study was performed to assess which regions of the spectrum were mostly intercepted by photosynthetic tissues at the time of our experiment and comparing the three conditions.

Measurements conditions

All measurements were recorded in March 2017 in the main Campus of UPV, in the city of Valencia (39° 28' N, 0° 22' W, sea level). Valencia city has a Mediterranean climate

with relatively low rainfall records (annual mean 445 mm). This climate is considered BSk according to Köppen-Geiger climate classification (Kottek *et al.*, 2006). The month of March was chosen: i) in order to avoid extreme sunlight and temperature conditions typical of winter or summer and ii) the commercial use of the three growing conditions evaluated (i.e. glasshouse, greenhouse and open field) overlap in this month and therefore this is the most suitable part of the year for real unbiased comparison among them, under the same solar irradiance conditions.

Measurements were recorded at 10 cm above ground level in the central period of March, i.e. from 8 Mar 2017 to 20 Mar 2017. Seven days ($n = 7$) were chosen for measurements within this period to ensure clear sky conditions (Table 1). Data were recorded twice per day: at 10:00 h and 13:00 h and from three different points of each facility (2 m distance between points). Spectrometer was positioned normal to the solar incidence angle. In the case measurements of reflectance in pepper leaves, the spectrometer was positioned normal to the surface of peppers leaves, at a distance of 1 cm between each leaf and the sensor. Measurements were always taken under sunny conditions, avoiding any shade within both glasshouse and greenhouse. Temperature, relative humidity and solar zenith angle are shown on Table 1.

Additional measurements

As a complement of the experiment described above, additional measurements of incident and reflected RI and PPFD were recorded at both 10:00 h and 13:00 h on the leaves of a species grown at this season: common pepper (*Capsicum annuum* L.) California Wonder cv. 'Ferrari'. The study was performed to assess which regions of the spectrum were mostly intercepted by photosynthetic tissues at the time of our experiment and comparing the three conditions. The spectrometer was positioned normal to the surface of leaves, at a distance of 1 cm between leaves and the sensor.

Results

Relative irradiance

The graphic representation of RI indicates the levels of irradiance corresponding to the different regions on the spectrum. Our measurements showed, for the three studied growing systems, RI distributions with the highest values (i.e. RI = 1.00) corresponded to the green region, followed by the long wavelength blue region and the red region.

Table 1. Temperature, relative humidity and solar zenith angle conditions of the experiment were visited daily in March 2017 in AVAMET, meteoxarxa of the Associació Valenciana de Meteorologia Josep Peinado (<http://www.avamet.org/mxo-mxo.php>)

| Date (d/m/y) | Mean temperature (min-max) (°C) | Relative humidity (%) | Solar zenith angle (°) | |
|--------------|------------------------------------|-----------------------|------------------------|---------|
| | | | 10:00 h | 13:00 h |
| 08/03/2017 | 21.5 (17.6-25.4) | 73 | 53.7 | 45.4 |
| 10/03/2017 | 17.8 (14.1-21.5) | 60 | 52.2 | 44.8 |
| 14/03/2017 | 14.8 (12.4-17.2) | 70 | 51.4 | 43.2 |
| 15/03/2017 | 13.2 (9.4-17.1) | 67 | 50.7 | 42.9 |
| 16/03/2017 | 13.3 (8.7-18.0) | 66 | 50.1 | 42.6 |
| 20/03/2017 | 15.7 (11.1-20.3) | 68 | 49.3 | 41.1 |
| 21/03/2017 | 13.8 (10.6-16.9) | 83 | 48.8 | 40.3 |

Finally, the lowest values were found in the border regions, i.e. $\lambda < 440$ nm, from short wavelength blue light to UV-A and the IR-A region. This means that the maximum levels of solar irradiance recorded, regardless growing conditions or time of the day, corresponded to the photons of green light and those with the highest wavelength of blue light.

Moreover, the decrease within the red and IR-A spectrum showed a peaks-and-valleys shape, while a stronger decrease was found within the short wavelength blue and UV-A spectrum. Furthermore, although the three growing systems displayed similar RI distributions, some differences were observed. Thus, RI values from open field and mesh greenhouse conditions were very close and higher to those from glasshouse conditions in most of the spectrum, particularly in the red region and, to a lesser extent, in the blue region (Fig. 2).

Also these differences were slightly higher at 13:00 h for the red spectrum, although lower for the blue spectrum. On the contrary, the graphs corresponding to the three conditions joined in the frame of the green spectrum, where they reached the maximum values. All these findings suggest that glasshouse conditions might decrease the level of irradiance of blue and particularly red light (in comparison to the reference of green light) to a slightly higher degree than mesh greenhouse.

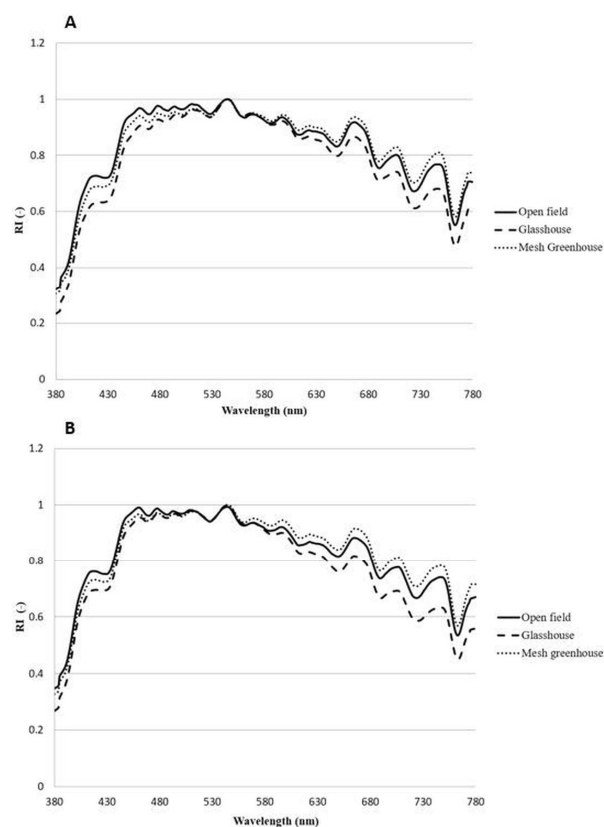


Fig. 2. Relative irradiance (0 to 1 scale) corresponding to open field (control), glasshouse and mesh greenhouse conditions at 10:00 h (A) and 13:00 h (B) along the wavelength spectrum

Photosynthetic Photon Flux Density

PPFD spectrums at both 10:00 h and 13:00 h records were quite similar, although some differences were also found. Thus, in both cases PPFD values from open field conditions ($PPFD_{OF}$) were considerably higher than $PPFD_{GH}$ and particularly $PPFD_{GL}$, including blue, green and red regions as well as total PPFD (Table 2, Fig. 3).

These results indicate that both mesh and, in particular, glass coverings provoke a remarkable decrease on the PAR in comparison to open field: 2-fold in mesh greenhouse and 4-5 fold in glasshouse (Table 2). Also, PPFD values increased from 10:00 h to 13:00 h in the three studied conditions (Table 2, Fig. 3), which is due to a higher level of total solar irradiance at noon. However, the magnitude of the increase corresponding to mesh greenhouse and glasshouse was slightly lower than open field conditions (Fig. 3). In this regard, it is known that solar global radiation is composed of a direct and a diffuse component, with the diffuse component coming from scattering due to atmospheric particles (Iqbal, 1983). It has been also reported that materials such as glass or polyethylene films have a filtering effect on direct radiation and, therefore, increase the diffuse component of solar radiation (Hemming *et al.*, 2008 and 2014).

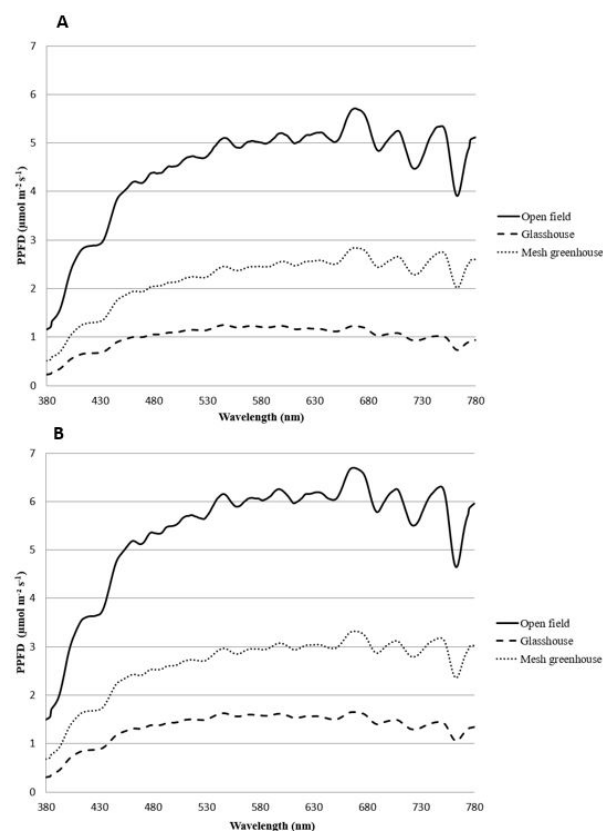


Fig. 3. Photosynthetic Photon Flux Density (PPFD, $\mu\text{mol m}^{-2} \text{s}^{-1}$) corresponding to open field (control), glasshouse and mesh greenhouse conditions at 10:00 h (A) and 13:00 h (B) along the wavelength spectrum

Table 2. Estimates of mean photosynthetic photon flux density (PPFD), corresponding to the total spectrum and the different regions long-wavelength UV (UV-A), blue (B), green (G), red (R) and near infrared (IR-A), and B/R and R/IR-A ratios

| | Open field | Glasshouse | Mesh greenhouse |
|---------------------------------------------------|--------------------|------------|-----------------|
| Time 10:00 h | | | |
| PPFD TOTAL ($\mu\text{mol}/\text{m}^2\text{s}$) | 1378c ¹ | 351a | 664b |
| PPFD UV-A ($\mu\text{mol}/\text{m}^2\text{s}$) | 31c | 8a | 14b |
| PPFD B ($\mu\text{mol}/\text{m}^2\text{s}$) | 366c | 83a | 168b |
| PPFD G ($\mu\text{mol}/\text{m}^2\text{s}$) | 491c | 111a | 237b |
| PPFD R ($\mu\text{mol}/\text{m}^2\text{s}$) | 521c | 117a | 259b |
| PPFD IR-A ($\mu\text{mol}/\text{m}^2\text{s}$) | 388c | 82a | 198b |
| B/R | 0.70b | 0.65a | 0.65a |
| R/IR-A | 1.35a | 1.43b | 1.31a |
| Time 13:00 h | | | |
| PPFD TOTAL ($\mu\text{mol}/\text{m}^2\text{s}$) | 1665c | 423a | 804b |
| PPFD UV-A ($\mu\text{mol}/\text{m}^2\text{s}$) | 39c | 9a | 18b |
| PPFD B ($\mu\text{mol}/\text{m}^2\text{s}$) | 453c | 113a | 212b |
| PPFD G ($\mu\text{mol}/\text{m}^2\text{s}$) | 593c | 156a | 286b |
| PPFD R ($\mu\text{mol}/\text{m}^2\text{s}$) | 620c | 154a | 306b |
| PPFD IR-A ($\mu\text{mol}/\text{m}^2\text{s}$) | 462c | 107a | 234b |
| B/R | 0.73b | 0.74b | 0.69a |
| R/IR-A | 1.34a | 1.47b | 1.31a |

¹Mean values within rows separated by different letters are significantly different ($p < 0.05$) according to the Newman-Keuls test.

Furthermore, at 10:00 h the diffuse component of solar radiation is higher than direct component, in both open field and under a glasshouse or a mesh greenhouse. However, at noon, while in open field there is a great increase in the direct component, in glasshouse or mesh greenhouse the filtering effect of such materials reduces the direct component (Zivanovic *et al.*, 2017). As a result, the difference between the solar global radiation measured at 10:00 h and at 13:00 h is higher in open field, than in a glasshouse or mesh greenhouse. In addition, compared to open field, decreases on PPFD mean values were very similar among the different spectral regions within each covering material. Thus, compared to open field values, PPFD decreases under mesh greenhouse were comprised between 49% and 55% respectively in IR-A and green region (at 10:00 h), while decreases for glasshouse ranged from 75% to 80% respectively in the green region (at 13:00 h) and red region (both at 10:00 h and 13:00 h) (Table 2).

B/R and R/IR-A ratios within PPFD

In all cases, B/R values were lower than the unit, which means that the PPFD received at the photosynthetic tissues of plants will have higher proportion of photons from the red region than from the blue region (Table 2). As a whole, open field conditions displayed the highest B/R values (≥ 0.70) among the three evaluated conditions, although differences were low. Additionally, B/R ratio from 10:00 h to 13:00 h increased slightly in the three studied conditions, with glasshouse showing the highest increase, which indicates that the contribution of the blue region to the PAR increases in comparison to the red region at higher irradiance levels (Table 2). Studies based on LED sources have reported that a moderate predominance of red light versus blue light results in higher growth and development of plants, although the optimal B/R ratio may differ among species and even growth parameters (Son *et al.*, 2013; Nhut *et al.*, 2015).

Nevertheless, the low differences found here (with the only exception of the increase on glasshouse from 10:00 h to 13:00 h), suggest that no effects on plants due to B/R ratio changes must be expected among growing systems.

Regarding the R/IR-A ratio, all values indicate that the red region predominates over the near infrared region in terms of PAR (Table 2), in agreement with the results observed in Fig. 3. Furthermore, this ratio was significantly higher under glasshouse conditions, suggesting that glass is more efficient in decreasing PPFD_{IR} than PPFD_R.

Study of the relationship between incident irradiance and reflected irradiance

a) Ratio of the reflected RI and the incident RI

Regarding the relationship between reflected and incident RI (RI_{refl}/RI_{inc} ratio) on Capsicum pepper leaves, similar trends were observed in both 10:00 h and 13:00 h measurements, although some differences were found among growing systems at the IR-A region. Thus, regardless growing conditions, reflected RI was lower than incident RI in most of the spectrum (ratio < 1), from UV-A to the red region, with the lowest values found on the red (ratio 0.20-0.35) and particularly blue (ratio 0.20) spectrums, while a peak and higher values appeared within the green spectrum (ratio close to 0.40 in most region) (Fig. 4). This must be attributed to photosynthetic plant tissues, which have a considerable capture ability of the whole visible spectrum, although higher in blue and red light, and less efficient (i.e. maximum reflectance) in the green region, the reason for which photosynthetically active tissues look green (Nishio, 2000; Terashima *et al.*, 2009). In addition, as it was said before, differences in RI_{refl}/RI_{inc} ratios were very low or even nil among open field, glasshouse or mesh greenhouse, and the same was found comparing 10:00 h and 13:00 h, which suggest that spectrum-specific absorbance efficiencies of photosynthetic tissues are not affected by covering materials or solar irradiance intensity.

The only exception was found in the IR-A region. A remarkable increase of RI_{refl}/RI_{inc} ratio, from 0.4 to 1.2-1.6, was detected within this region and even reflected IR-A was higher than incident IR-A (ratio >1) in most of its spectrum, particularly at 10:00 h under glasshouse conditions (Fig. 4).

b) Ratio of the reflected PPF and the incident PPF

On the whole, similar trends were found in the graphs of the relationship between reflected and incident PPF on Capsicum pepper leaves. Thus, with the only exception of IR-A region (> 700 nm), the amount of reflected PPF was very low along most of the wavelength spectrum ($PPFD_{refl}/PPFD_{inc}$ ratio < 0.20), with the green and red regions having the highest values (Fig. 5). By contrast, IR-A values had a remarkable increase.

These findings suggest that most PPF from visible light were captured by photosynthetic tissues on Capsicum leaves, while efficiency for IR-A is apparently lower. In addition, differences between growing systems and time of the day were considerably higher than those observed for RI. Thus, despite having similar trends, the $PPFD_{refl}/PPFD_{inc}$ ratios for glasshouse were always higher than those from open field and mesh greenhouse along the whole spectrum and at both 10:00 h and 13:00 h and particularly in the IR-A region (Fig. 5). However, apart from the IR-A region,

these ratios showed a decrease from 10:00 h and 13:00 h in most of the wavelength spectrum (i.e. UV-A and visible region, < 700 nm), especially in the glasshouse and at a lesser extent in the open field. As a consequence, differences between glasshouse and the other conditions decreased. This was probably due to the increase of temperatures from 10:00 h to 13:00 h, which usually increases the photosynthetic efficiency of photosynthetically active tissues (Hikosaka *et al.*, 2005), particularly within glasshouse and therefore decreased the $PPFD_{refl}/PPFD_{inc}$ ratios within the region comprised between 380 and 700 nm.

On the contrary, $PPFD_{refl}/PPFD_{inc}$ ratios corresponding to IR-A were considerably higher than those from the other regions, which as suggested for RI, can be explained by the lower efficiency of plants in capturing photon flux from IR-A and that leaves re-emit part of the energy as heat/infrared. Moreover, a remarkable increase on the RI_{refl}/RI_{inc} ratio was found in IR-A within glasshouse conditions, and at a lesser extent in mesh greenhouse, from 10:00 h to 13:00 h, showing both graphs very different to that of open field conditions (Fig. 5). The increase of both incident IR-A at 13:00 h (Table 2, Fig. 3) and diffuse IR within the glasshouse (i.e. greenhouse effect) are probably the reason for these results.

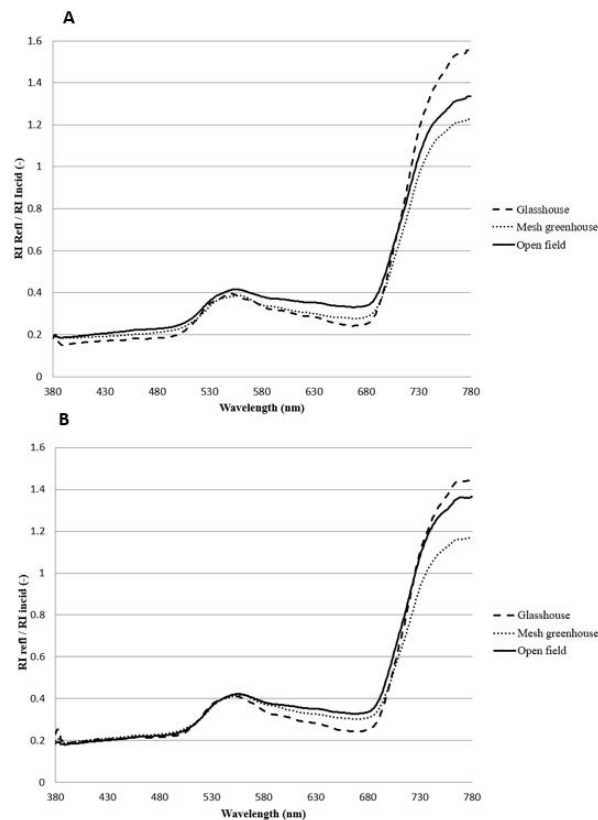


Fig. 4. Ratio of the reflected RI and the incident RI corresponding to open field (control), glasshouse and mesh greenhouse conditions at 10:00 h (A) and 13:00 h (B) along the wavelength spectrum

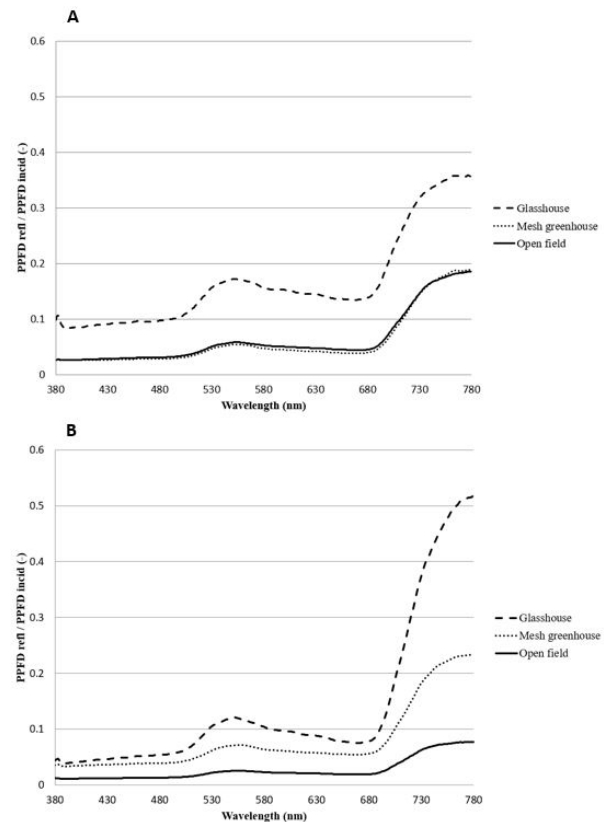


Fig. 5. Ratio of the reflected PPF and the incident PPF corresponding to open field (control), glasshouse and mesh greenhouse conditions at 10:00 h (A) and 13:00 h (B) along the wavelength spectrum

In comparison to open field conditions, the use of tempered glass as covering material in greenhouses decreased considerably the total amount and quality of solar irradiance indoors. Nevertheless, even white polyethylene mesh, despite its very thin thickness and high whole density, also caused remarkable decreases. The time of the day also had weakening effect but at much lower extent than covering materials. The effect was more obvious on PPFD than RI and, in general, within each covering material all the bands of the spectrum (visible light and adjacent UV-A and IR-A) were affected in similar proportion (50-55% and 75-80% PPFD decreases in mesh greenhouse and glasshouse respectively). Some differences were also found in terms of reflected/incident PPFD on plant leaves although, with the only exception of IR-A region, this ratio was <0.20 . Thus, as a measurement of light capture efficiency, glasshouse-grown plants showed the highest reflectance at both 10:00 h and 13:00 h, followed by mesh greenhouse at 13:00 h.

Discussion

Relative irradiance

Both phenomena on spectral irradiance curve may be due to a wavelength-selective interaction with elements such as ozone, contaminant particles, water vapor, or scattering, among others (Lagarrea *et al.*, 2010). Thus, when solar radiation passes through the atmosphere each particle weakens part of the energy from radiation and this decrease depends on the kind and number of particles that are in the path of solar beams.

Thus, while ozone mainly weakens UV, blue light is the visible region most affected by Rayleigh scattering, causing the blue colour of the sky and decreasing the amount of blue light (particularly short wavelengths) which arrives to earth's surface compared to other visible regions (Sneep *et al.*, 2005). Moreover, absorption and scattering may explain the results found at the red and particularly IR-A regions. Therefore, water vapour is the main absorbent component for global radiation, showing a remarkable absorption band at infrared. Also, according to scattering phenomena, both Rayleigh (small) and Mie (larger) particles in the path of solar radiation subtracts energy from incident radiation and reemits it everywhere (Stamnes, 1997; Bohren *et al.*, 2010). The combination of both wavelength-selective phenomena would explain the peak-and-valley shape observed in red-IR-A.

The results observed in the blue region and the UV-A adjacent region are probably due to the interaction of the electromagnetic radiation with electrons of Si-O bonds and glass structural defects, which usually provoke a strong absorption of the UV region and even, depending on glass composition, impurities and defects formed during manufacturing process, glass may have some effect on part of the nearest blue light region (Kajiara, 2007). On the other hand, silica glass is opaque for most IR spectrum and to a lesser extent the closest neighbour region of visible light (i.e. high wavelength red light) (Kitamura *et al.*, 2007).

Also, glass and most plastic films used for greenhouses are known for their relatively high transmission of visible light as well as thermal spectrum, although glass has been reported to provide similar or higher performance than polyester films (0.90 transmittance of visible light vs. 0.70-0.80) (Hanson, 1963; Baeza *et al.*, 2012; Al-Mahdouri *et al.*,

2013). Nevertheless, the contrary was found in our experiment. Probably our findings are due to the fact that our polyester covering has a mesh structure, whose pores allow higher transmittance of visible light compared to polyester films, and even higher performance than glass.

Photosynthetic Photon Flux Density

All these findings indicate significant and high differences between both covering materials in terms of transmittance for the spectral regions of PAR. By contrast, considering each covering material the weakening effect on PAR due to factors such as time of the day (10:00 h vs. 13:00 h) or spectral region (i.e. specific PAR region decrease) is very low or negligible. In this regard, photosynthesis and, consequently, plant growth and biomass production is highly correlated with the availability of PAR (Tardieu, 2013; Ahmad *et al.*, 2015) and, according to our findings, the use of glasshouse and, to a lesser extent, mesh greenhouse can limit these processes. In fact, other authors have reported higher biomass and development in plants grown in open field than those grown in glasshouses, which may increase internode length, weak stems and etiolation (Hanson, 1963; Baeza *et al.*, 2012). Furthermore, in a previous work, encompassing a collection of *Capsicum* peppers and using the same open field and glasshouse facilities of the present experiment, we reported higher levels of bioactive compounds (i.e. ascorbic acid, phenolics, carotenoids) in all accessions grown open field (Rodriguez *et al.*, 2009). That behaviour can be now explained by the remarkable differences between PPFD_{OF} and PPFD_{GL} found in the present experiment as these compounds usually accumulate in plant tissues in response to oxidative stress conditions (i.e. photo-oxidative stress) (Dumas *et al.*, 2003; Toor *et al.*, 2006; Kahlen *et al.*, 2011).

B/R and R/IR-A ratios within PPFD

This is probably due in part to the properties of glass (in our case) and other covering materials to provide the greenhouse effect. Thus, photons flux (mainly visible) can pass through these materials. Once the floor and other structures inside intercept this flow and re-emit at higher wavelength as IR (i.e. heat), these covering materials prevent this energy from leaving (Engindeniz *et al.*, 2006; Cabrera *et al.*, 2016). Our results indicate that glass allows the entrance of IR-A photon flux, but at a lower extent than those from other spectrums from the visible region due to its filtering effect on the whole IR. On the contrary, R/IR-A ratios from mesh greenhouse and open field were similar and, therefore, we can conclude that mesh screen does not provide significant changes in the relationship between the red and IR-A regions compared to glass panels. As observed also for other parameters, i.e. RI or PPFD, the very low thickness and considerable whole surface of mesh screen is probably the main reason for the lack of differences in R/IR-A ratio compared to open field conditions.

Ratio of the reflected RI and the incident RI

These results can be explained by: i) the low efficiency of plants in capturing energy from IR-A, which is reflected more than UV and visible light due to its longer wavelengths and ii) leaves, as any surface receiving solar irradiance, re-emit part of the energy as IR (21), and therefore providing the highest reflectance levels.

Ratio of the reflected PPFD and the incident PPFD

Despite glasshouse offers the warmest climate and it is an efficient barrier against pests, it may also decrease remarkably the photosynthetic rate because of PPFD decrease and reflectance, particularly obvious in Mediterranean climates according to our findings. However, growers and researchers must also consider that polyethylene mesh also decreases considerably PPFD. These results have important implications for selecting the covering materials in order to obtain an optimal efficiency in crop productivity under protected cultivation.

Conclusions

In comparison to open field conditions, the use of tempered glass as covering material in greenhouses decreased considerably the total amount and quality of solar irradiance indoors. Nevertheless, even white polyethylene mesh, despite its very thin thickness and high whole density, also caused remarkable decreases. The time of the day also had weakening effect but at much lower extent than covering materials. The effect was more obvious on PPFD than RI and, in general, within each covering material all the bands of the spectrum (visible light and adjacent UV-A and IR-A) were affected in similar proportion (50-55% and 75-80% PPFD decreases in mesh greenhouse and glasshouse respectively). Some differences were also found in terms of reflected/incident PPFD on plant leaves although, with the only exception of IR-A region, this ratio was <0.20. Thus, as a measurement of light capture efficiency, glasshouse-grown plants showed the highest reflectance at both 10h00 and 13h00, followed by mesh greenhouse at 13h00. In conclusion, despite glasshouse offers the warmest climate and it is an efficient barrier against pests, it may also decrease remarkably the photosynthetic rate because of PPFD decrease and reflectance. However, growers and researchers must also consider that polyethylene mesh also decreases considerably PPFD. These results have important implications for selecting the covering materials in order to obtain an optimal efficiency in crop productivity under protected cultivation.

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