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Evaluation of global, photosynthetically active radiation and diffuse radiation transmission of agricultural screens

M. Romero-Gámez*, E. M. Suárez-Rey, N. Castilla and T. Soriano
IFAPA-Centro Camino de Purchil. Apartado 2027, 18080 Granada. Spain

Abstract

Transmittance of a material depends on the type of radiation impinging on the material (direct or diffuse), the angle of incidence of the sun's rays (in direct radiation conditions) and the structure and characteristics of the material itself. The aim of this study was to evaluate the performance of nine agricultural screens of different densities, colours, thread diameters and porosities. A simple metal frame was used to quantify global, diffuse and photosynthetically active radiation (PAR) transmission to determine their transmittance values (as a function of the incidence angle of solar rays in direct radiation conditions) for global radiation and PAR, as well as the diffuse radiation transmitted characteristics of the screens (ratio of diffuse radiation to global radiation transmitted by screens). Non-coloured (translucent) screens contributed to a higher and more efficient proportion of diffuse radiation ($D_i/G_i \approx 90\%$). The green screen behaved similarly to the non-coloured 20 × 10 type as far as global radiation was concerned, although the PAR transmittance values were lower (up to 12.4% at 15°). Variation in transmission according to diameter and density of the threads was greatest in the black screens. The non-coloured-thread screens may be the best option for maximising the transmission of diffuse radiation and the 6 × 6 green screen for vegetables cultivation during the summer in inland areas with latitudes close to 36° N.

Additional key words: covering materials; incidence angle; porosity; screenhouse; transmittance.

Resumen

Evaluación de la transmisividad a radiación global, fotosintéticamente activa y difusa en mallas de uso agrícola

La transmisividad de un material depende del tipo de radiación (directa o difusa) incidente en el material, del ángulo de incidencia de los rayos solares (en condiciones de radiación directa) y de la estructura y características del material. El objetivo de este estudio fue evaluar el comportamiento de nueve mallas de uso agrícola de diferente densidad, color, diámetro del hilo y porosidad. Para ello, se determinaron los valores de transmisividad a radiación solar global y PAR y la radiación solar difusa transmitida bajo malla para ángulos de incidencia diferentes, empleando un bastidor diseñado para tal efecto. Las mallas no coloreadas (translúcidas) consiguieron un enriquecimiento de la radiación difusa bajo ellas ($D_i/G_i \approx 90\%$). La malla verde tuvo un comportamiento transmisivo similar al de la malla no coloreada 20 × 10 para la radiación global mientras que en el caso de la radiación PAR sus valores de transmisividad fueron menores (hasta 12,4% para 15°). La variación de transmisividad con el grosor y la densidad de los hilos fue mayor en las mallas negras. Las mallas no coloreadas podrían ser la mejor opción para maximizar la transmisividad a radiación difusa y la malla verde 6 × 6 para el cultivo de hortícolas durante la época estival en zonas de interior de latitudes cercanas a 36° N.

Palabras clave adicionales: ángulo de incidencia; invernadero de malla; materiales de cubierta; porosidad; transmitancia.

Introduction

During recent years growing in screenhouses vegetable crops has taken on considerable socio-economic importance especially for small-growers in semiarid and arid countries. In southern Spain, these systems are complementing the growing and marketing calendars of the plastic greenhouses production in the coastal areas.

Transmittance of a material depends not only upon the type of radiation impinging on the material (direct or diffuse) and the angle of incidence of the sun's rays

*Corresponding author: mercedes.romero.gamez@juntadeandalucia.es
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(in direct radiation conditions), but also upon the structure and characteristics of the material itself (composition, porosity, colour and shape and diameter of the thread) (Soni *et al.*, 2005; Soriano *et al.*, 2006; Sica & Picuno, 2008) and the absorbance and reflectance properties of the screen. As far as direct radiation is concerned, the more perpendicular the incidence of the sunlight (lower incidence angle), the more radiation will be transmitted through the screen, whilst at greater angles of incidence transmission will decrease.

Screens are characterized by their porosity, which influences their shading effect, and it is determined by the diameter and physical characteristics of the thread and the density of the screen (number of threads per centimetre), which in turns, affects its durability, global weight, strength, elasticity and insect exclusion (Castellano *et al.*, 2006).

Screens with black threads are the most common coverings used for shading structures, even though the use of non-coloured and coloured threads screens is increasing because of their capacity to modify solar radiation quality characteristics, their more favourable aesthetic impact upon the countryside (Castellano *et al.*, 2008b) and their ability to improve the microclimate providing the physical protection required (Shahak *et al.*, 2002). Various studies have demonstrated that when crops are grown beneath coloured screening, there is a notable increase in production, reduction of stresses and a general improvement in the vitality of the plant canopy, ripening, fruit colour, size and quality, together with a reduction in sunburnt. Studies on the transmittance properties of screens reveal that the colour of the screen influences the spectral distribution of the light that passes through it by absorbing its complementary colours (Castellano *et al.*, 2008a).

Crops such as fruit vegetables with a high plant canopy utilize diffuse radiation better than direct radiation, as diffuse radiation penetrates the middle layers of a high-grown crop and results in a better horizontal radiation distribution in the greenhouse (Hemmig *et al.*, 2008). For this reason, as stated by Cabrera *et al.* (2009), since the pioneering work of Deltour & Nisen (1970), laboratory studies aimed at characterizing the diffusive properties of greenhouse cladding materials have become of paramount interest (Pearson *et al.,* 1995; Wang & Deltour, 1999; Montero *et al.*, 2001; Pollet *et al.*, 2005). Diffuse radiation represents a significant fraction of the total solar radiation that enters a greenhouse (Baille & Tchamitchian, 1993), although few detailed studies have been undertaken to characterize diffuse radiation under greenhouse conditions (Basiaux *et al.*, 1973; Burek *et al.*, 1989) and little information is available about this component and its proportion compared to direct radiation (Baille & Tchamitchian, 1993; Hanan, 1998). Most of the studies carried out *in situ* have compared outdoors and under protection global radiation to estimate the material transmission to global radiation, but this offers little information about the diffusive properties of the covering material. Abdel-Ghany & Al-Helal (2010) measured diffuse radiation under different screens with incident angles of solar beam varying from 0° to 5°.

Diffuse radiation within a plastic greenhouse can be estimated on the basis of the radiation outside and two parameters: the coefficient of enrichment of diffuse radiation (D_i/D_o) and the factor ($\tau_{b\text{-}d}$) for converting direct radiation into diffuse radiation (Baille *et al.*, 2003). Knowledge of the coefficient of diffuse radiation enrichment (D_i/D_o) is of prime importance in crop models studies (Spitters, 1986), especially in those aimed at assessing the advantages and efficiency of a determined greenhouse cladding material. As mentioned by Cabrera *et al.* (2009), the principle challenge in the future will be that of maximizing the beneficial effects of diffuse radiation upon the homogeneity of interception of radiation by the plant canopy and upon factors affecting crop yield.

A common commercial parameter defining a screen is the shading factor, which describes the ability of a screen to absorb and reflect the visible range (380-760 nm) of the sun radiation (Castellano *et al.*, 2008b). But the commercial shading degree does not take into account diffuse radiation, which is an important component of global sunlight (above all on cloudy days, when it is the major fraction).

There is no European norm to define the spectroradiometric properties that screens for agricultural use should comply with (Sica & Picuno, 2008) or certify the quality of the screen to guarantee its homogeneity (Soler *et al.*, 2007). Worldwide, there is just one national norm in Italy (10335/94; UNI, 1994) that regulates the methodology for assessing screens used for shading. Other national standards deal partly with agricultural films such as the French standard NF EN 13206 (NF, 2002) and the Italian standards UNI 9738 (UNI, 1990) and UNI 9298 (UNI, 1988) (Castellano *et al.,* 2008c).

The aim of this study was an experimental evaluation of the performance of nine of the most commonly used in Spain screening materials of different densities,

colours, thread diameters and porosities to: i) document the global and PAR transmittance values, ii) evaluate the screen transmission for diffuse solar radiation as well as the alterations of the radiation diffuse component when passing through the screens. These measurements were performed on eleven different angles of incidence (from 15° up to 65°) using a simple frame structure.

Material and methods

A metal framework® (Soriano *et al.*, 2008) was used to measure the solar radiation transmission of different plastic screens in various conditions and to determine the solar radiation transmittance values of shading screens. To quantify solar radiation transmittance at various angles of incidence of direct sunlight upon the surface of the materials, the panel where the screens were located was movable.

The framework (Fig. 1) was a black metal structure made of hollow, square, metal bars (4 × 4 cm^2) with a square base of 3 × 3 m^2. Each corner of the structure supported a 3 m high metal bar (4 × 4 cm^2). The arms supporting the material being tested were inserted into the top of two rear metal supports in such a way as to be able to swivel up and down at different known angles to the horizontal. The framework was also fitted with wheels to allow it to be directed towards the sun at all times according to the azimuth angle. The base of the framework had a horizontal platform to incorporate the measuring radiation sensors.

The study was conducted at the "IFAPA Camino de Purchil" Centre of Granada, located in the agricultural plain of Granada (37°10'21" N, 3°38'10" W; 600 m asl). Radiation measurements were made on fully sunny days during February, March and April 2009 between 8.00 and 12.00 a.m. solar time and on fully cloudy days in January to obtain $\tau_{b\text{-}d}$ (direct to diffuse radiation conversion factor, Baille *et al.,* 2003):

$$\tau_{b\text{-}d} = D^*/I_o = (D_i - \tau_d D_o)/I_o \quad [1]$$

where D* = direct solar radiation converted into diffuse radiation under the cladding material (W m^{-2}); I_o = outside direct solar radiation (W m^{-2}); D_i = diffuse solar radiation under the cladding material (W m^{-2}); τ_d = transmission of diffuse solar radiation (equivalent to global radiation transmission on completely cloudy days); and D_o = outside diffuse solar radiation (W m^{-2}).

To characterize the transmission of solar radiation in the screens, we used global radiation sensors (CM6B, Kipp & Zonen), PAR sensors (SKP215/S, Sky Instruments) and shadow rings (CM121B, Kipp & Zonen) for the diffuse radiation. Thus, three sensors were installed on the chassis of the framework beneath the screens and three more on a flat platform just outside the frame. All the sensors were previously calibrated. A correction factor (S) is given by the manufacturer of the ring of shade and was applied in the

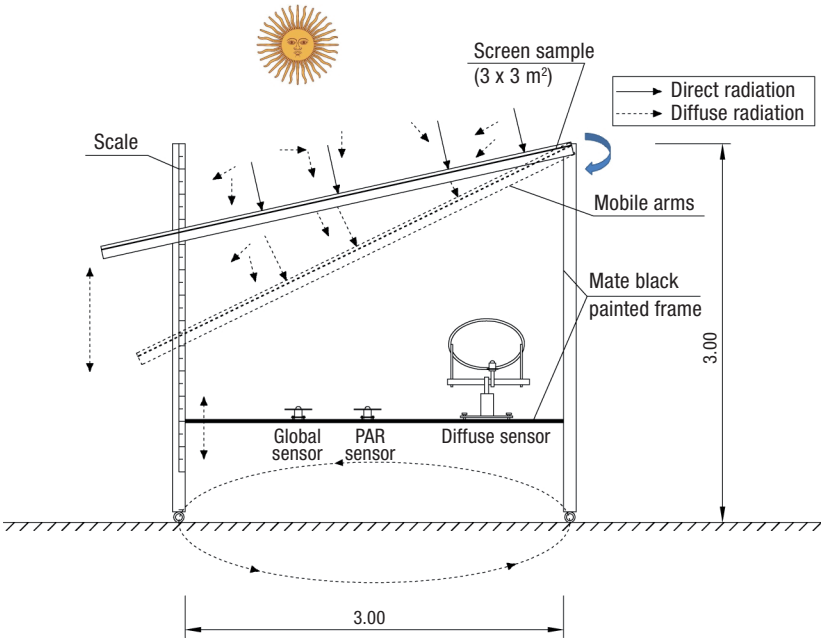

Figure 1. Framework to measure the transmission of solar radiation of plastic netting.

calculation of the diffuse radiation to compensate for the reduction in diffuse radiation in the resulting band of shade (Kipp & Zonen BV, Holland).

All sensors were connected to a CR10X datalogger (Campbell), programmed to simultaneously measure every 2 min and record mean values every 10 min (five repetitions). The transmission of the screens was calculated using the ratio of the radiation values measured by the sensors beneath the screens and outside the framework.

Nine different kinds of screens were tested. These screens are commonly found for shading in commercial screenhouses of inland areas in southern Spain. They were composed of a weave of high-density polyethylene threads of different diameter, colour and density: both black and non-coloured (white) screens with 20 × 10, 16 × 10, 9 × 6 y 6 × 6 threads cm^{-2}, and a green screen with 6 × 6 threads cm^{-2}, all of which were manufactured by Condepols. The geometric characterization was determined for the nine screens, counting the number of threads, measuring their diameter (Digital Caliper 0-150 nm), and calculating the number of holes and the size of the hole and, finally, the porosity of the screen (Table 1). The recorded angles of incidence varied from 15° up to 65° in a 5° step.

Results and discussion

Transmittance values of the screens for global radiation and PAR

The global radiation and PAR transmittance values of the tested screens are shown in Fig. 2. The global radiation and PAR behaviour of the various screens depending on the angle of incidence, was similar: an increase in the angle of incidence resulted in a reduction in radiation transmittance in all the samples. These results agree with those of Montero *et al.* (2001) for global radiation. At equal porosity, the non-coloured screens were the most transmissive to global radiation and PAR, followed by the green screen and finally the black screens. Similar results were also obtained for global radiation by Soriano *et al.* (2006). The threads of the black screens absorbed all the radiation wavelengths, contributing to a relevant reduction in transmittance as compared with the green or the non-coloured threads. Non-coloured and in a lower level, the green screen, were partially translucent contributing to increasing global and PAR transmittance relative to the black screens. Möller *et al.* (2010) also found that non-coloured and clear screens scattered radiation significantly.

The highest global and PAR transmittance values were reached with the 6 × 6 non-coloured screens, which attained values of 88% for global radiation transmittance and close to 86% for PAR transmittance at the lowest angle of incidence studied (15°). On the other hand, the highest values for black screens were close to 66% and 61% for global radiation and PAR respectively, the least dense weave of 6 × 6 being once more the most transmissive (Fig. 2).

The green screen behaved more closely to the non-coloured types in terms of transmittance to global radiation although as far as PAR was concerned, their transmittance values were quite low which could be attributed to the fact that the green threads reflect a considerable amount of radiation in the green wavelength (500 to 600 nm). Castellano *et al.* (2008a) measured transmittance under field conditions. They found out that PAR transmittance under the green screen behaved very closely to the non-coloured one within the range of 500-550 nm. According to these authors,

Table 1. Main characteristics of the plastic screens studied

Density (threads cm^{-2})	Colour	Thread diameter (mm)	Weight (g m^{-2})	Hole size (mm^2)	Porosity (%)
20 × 10	Black	0.23	150	0.18	31.00
	Non-coloured	0.25		0.15	25.00
16 × 10	Black	0.23	122	0.30	40.20
	Non-coloured	0.25		0.26	35.00
9 × 6	Black	0.28	95	1.45	58.00
	Non-coloured				
6 × 6	Black	0.28	75	2.57	66.40
	Non-coloured				
	Green				

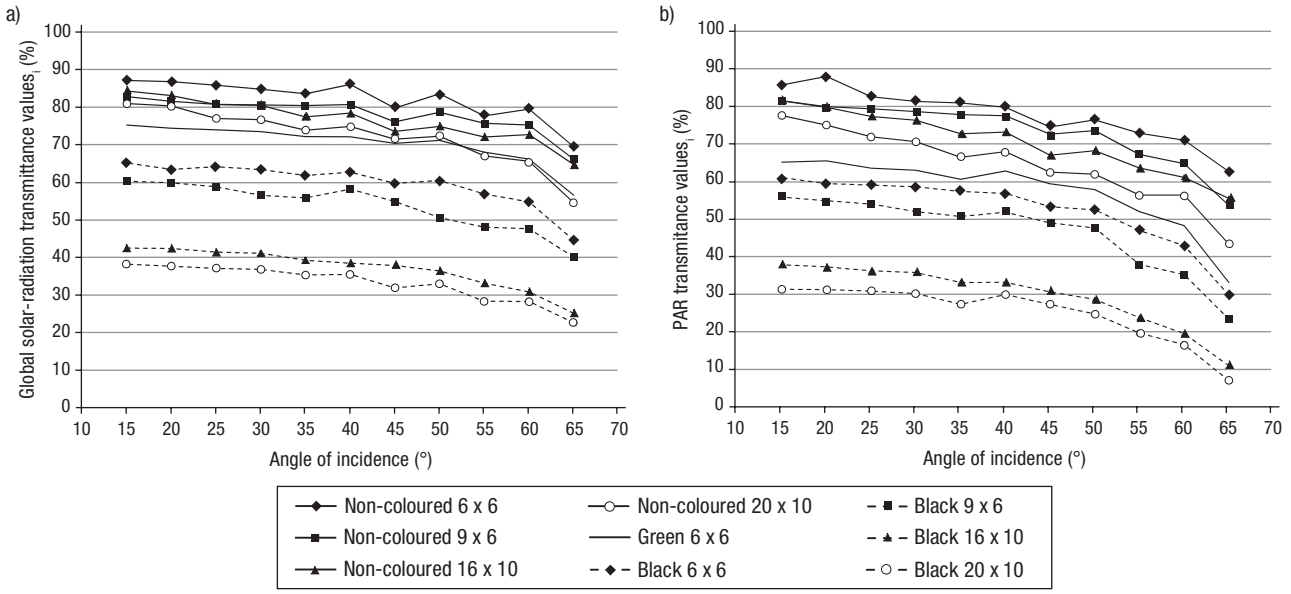

Figure 2. a) Global radiation transmittance values (%) and b) PAR transmittance values (%) *versus* angles of incidence (15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60° and 65°) for 20 × 10, 16 × 10, 9 × 6 and 6 × 6 thread cm^{-2} both black and non-coloured screens, and a 6 × 6 threads cm^{-2} green screen.

the difference in PAR transmittance between these two screens was greater in the 550-600 nm range, with a maximum difference of 6% at 600 nm.

Fig. 2 shows that the global and PAR radiation transmittance of the lower porosity non-coloured screen (20 × 10) was lower than that of the higher porosity green screen (6 × 6) at high angles of incidence. The maximum global and PAR transmittance values for the green screen (76% and 65% respectively) were close to those obtained with the densest non-coloured screen (20 × 10). Variation in transmittance according to the diameter and density of the threads was greatest in the black screens.

Diffuse component of solar radiation transmitted by screens (D_i/G_i)

Diffuse radiation on a sunny day is very low as compared with the direct radiation in our conditions. Daily average of 10.7% (JD 71) was registered for diffuse solar radiation, while the remaining 89.3% was direct global radiation. These values were similar to those recorded by the group of the Applied Physic Department at the University of Granada (12.6% diffuse-87.4% direct solar radiation; Tovar *et al.*, 2001).

Transmitted diffuse radiation with respect to transmitted global radiation (D_i/G_i in %) for the different screens tested and the various angles of incidence are displayed in Fig. 3. As can be observed, the densest non-coloured screens greatly enriched diffuse radiation at all angles of incidence, followed by the more open weave non-coloured screens and for the green screen. In particular,

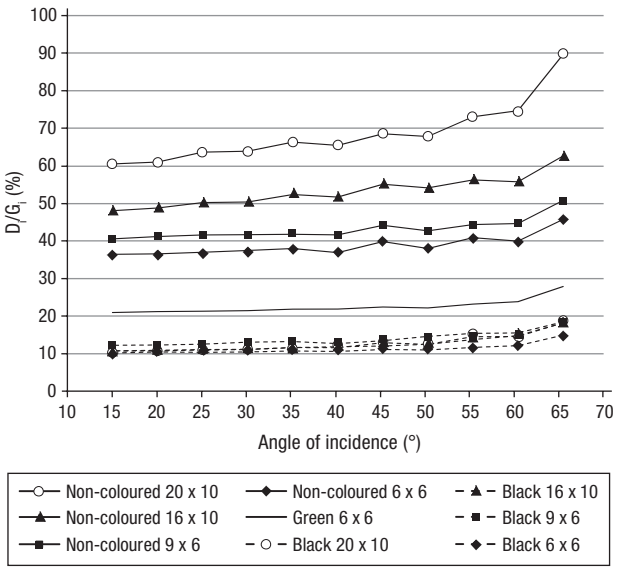

Figure 3. Diffuse component of solar radiation transmitted (D_i/G_i) *versus* the angles of incidence (15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60° and 65°) for both 20 × 10, 16 × 10, 9 × 6 and 6 × 6 thread cm^{-2} black and non-coloured screens, and a 6 × 6 threads cm^{-2} green screen.

at the highest angle of incidence, $D_i/G_i \approx 90\%$ for the 20 × 10 non-coloured screen, 62.4% for the 16 × 10 non-coloured screen followed by the more open weave non-coloured screens (50.7% for the 9 × 6 and 45.6% for the 6 × 6 at 65°) and for the green screen (≈ 28% at 65°). This effect is mainly due to the reflective and diffusive properties of the non-coloured and the green screen. Möller *et al.* (2010) found a further enrichment in diffuse radiation because of the higher scattering in the densest screens (largest for the 50 mesh screens than for the 25 mesh screens). Screening made of non-coloured threads maximized the transmission of diffuse radiation and the conversion of direct into diffuse radiation (Castellano *et al.*, 2008a) because these threads were translucent and thus allow part of the solar radiation through them in the same way as a light-diffusing plastic film. The higher the thread density, the higher proportion of diffuse radiation could be found in the transmitted radiation in these screens. The indicated values of the ratio (D_i/G_i) for non-coloured screens, especially in the lower porosity types (up to ≈ 90%) (Fig. 3), were higher than those of light-diffusing polyethylene covering films reported by Cabrera *et al.* (2009). Möller *et al.* (2010) found that diffuse radiation below a non-black screen was much larger than that above the screens because of the contribution of scattered direct radiation in comparison to the diffuse radiation below the screens.

At high angles of incidence, we may expect that the translucent characteristics of the threads contribute to scatter the transmitted radiation, the whole screen acting similarly to a plastic film.

As far as black screens are concerned, however, transmitted diffuse radiation was considerably lower than the non-coloured screens, showing maximum values for D_i/G_i of 18.6% at the highest angles of incidence. Black threads are opaque and solar radiation is not modified by the screen (Castellano *et al.*, 2008b) because the threads absorb all wavelengths of light and no radiation scattering is produced. The lowest reductions in transmission with black screening were found in the 6 × 6 screen at all angles of incidence, with very similar values for the 20 × 10, 16 × 10 and 6 × 6 screens at low angles.

The percentage of diffuse radiation transmitted by screens changed from 60.3% for the 20 × 10 non-coloured screen and 21.1% for the green screen to 10.4% for the 20 × 10 black screen, at an incident angle of 15°. Other authors found values from 170% for the dark-green screen to 17% for the black screen with incident angles of solar beam varying from 0° to 5° (Abdel-Ghany & Al-Helal, 2010).

These results agree with those of other authors, who have determined that the diffusion of the covering material varies greatly according to differences in its structure (Deltour & Nisen, 1970; Basiaux *et al.*, 1973; Raviv & Allingham, 1983; Pearson *et al.*, 1995; Abdel-Ghany & Al-Helal, 2010).

Therefore, relative to diffuse radiation, three effects could be highlighted: i) the densest non-coloured screens enriched diffuse radiation more than the less dense types because of the light scattering effect caused by their higher number of threads; ii) the black screens reduced diffuse transmitted radiation because their threads are opaque to solar radiation and the impinging diffuse radiation (coming from all sky directions) was therefore, only partially transmitted; iii) the angle of incidence showed higher influence on diffuse radiation transmission for the high density non-coloured screens than for the lower density ones.

Transmission of diffuse solar radiation (τ_d), measured in completely cloudy conditions, was highest in the densest non-coloured screens, with values around 70%. In the lowest density (6 × 6) types, the non-coloured screen, τ_d was 64%, higher than the green (58%) and black (54%) types.

The higher value of direct to diffuse radiation conversion factor ($\tau_{b\text{-}d}$) calculated from Equation [1], was reached for the 20 × 10 non-coloured screen (0.81). In the black screens, the proportion of direct solar radiation falling on the screen that is converted into diffuse radiation was much lower, with values between 0.01 and 0.05.

Within this context, when choosing screens it is also useful also to bear in mind criteria such as ventilation and visual and environmental impact, besides the insect exclusion criteria (when appropriate) because less dense screens reach a degree of shading similar to denser ones of clearer colours. For instance, a 6 × 6 green screen, as compared with a 20 × 10 non-coloured one, will presumably allow more ventilation (Teitel *et al.*, 2007; 2009) and because of its colour, might improve the aesthetic environmental impact upon the rural landscape generating a similar shading (Castellano *et al.*, 2008b), besides using less plastic material (for the threads) in its fabrication process and contributing to limit the global impact upon the environment.

The non-coloured translucent screens showed the highest levels of transmittance to global radiation and PAR, followed by the green types and finally the black screens for the same threads density and porosity. The

green screen had similar transmittance values for global radiation as the non-coloured translucent screens, whereas for PAR radiation it had somewhat lower transmittance levels because of the effect of the green wavelength reflection.

The relative behaviour of the different screens regarding global radiation and PAR transmittance depending on the angle of incidence was similar: transmittance values fall concomitantly with an increase in the angle of incidence. Variation in transmittance according to the diameter and density of the threads was greatest in the black screens.

The amounts of transmitted diffuse radiation were higher in the non-coloured and the green screens than in the black ones. This effect was particularly notable in the densest non-coloured screens (20 × 10 and 16 × 10), where diffuse radiation forms a substantial fraction of the transmitted global radiation, especially at high angles of incidence.

Therefore, the non-coloured-thread screens may be the best option for maximising the transmission of diffuse radiation. This enrichment of diffuse radiation is very important for climbing plants because it enables the crop to catch more radiation, increasing the potential photosynthetic surface effectively and thus, the total production.

In this context, choosing the most appropriate screen will depend mainly on the crop growing season and the climatic conditions (*e.g.,* frequency of cloudy days and/or wind). The green screen 6 × 6 may be the best option for vegetables cultivation during the summer in inland areas with latitudes close to 36°N, where radiation is not a limiting factor, due to its lower environmental and visual impact. In contrast, the higher density and non-coloured screens pose an interesting option in regions with strong winds.

Greenhouse crops grown during autum-winter cycles have shown a positive response on the use of diffuse radiation by the plants, but this effect is unknown in summer conditions. Therefore, it would be interesting to investigate the response of these crops under different colored screens in future studies.

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