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Smart greenhouse covers: a look into the future

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Abstract

In a greenhouse, the cover is the main element determining the amount and quality of entering and outgoing radiation, both short and longwave. The cover properties are therefore essential in determining inside climate and the amount of external resources (such as heating and water) required to maintain the greenhouse climate within the boundaries required for crop production. There is not a single "ideal" greenhouse cover for the entire world. Growers use different systems like different shading techniques and/or different types of thermal screens to optimize the radiative fluxes in the greenhouse on each season, but no system is optimum. Therefore, the development of new "smart" covering materials that would allow for the instantaneous modification of the radiometric properties of the cover, could potentially serve a large market worldwide. Some of these materials already exist in the market, such as the electrochromic glass or polymer dispersed liquid crystals, but they have not technically and economically been optimized for their use as greenhouse covers. So, companies operating in this sector have a need to identify which properties are useful in various conditions and to quantify the advantage of (some of) them being switchable. A number of theoretical covering materials with filters transmitting selectively certain ranges of wavelength (PAR, NIR, TIR) for which the effect on greenhouse microclimate and crop growth can be simulated, have been considered for analysis. The present work uses existing simulation models to quantify the benefit (in terms of production and reduced resource requirement) of improving the optical properties of the cover and the added value of making some of them switchable, for greenhouses typical of a mild winter region, represented by Agadir (Morocco), and a very popular crop, tomato. Results indicate an interesting potential for improvement of greenhouse microclimate and tomato yield, for the individual simulated switchable optical filters. However, the simulated yield increases are comparable to those obtained with existing technology, such as shading mobile screens in these regions, as reported in the literature. Therefore, newly developed smart covers will have to be competitive in price with the price of these types of screens to be competitive in these regions or they must lead to other benefits for crop production not simulated with the models (e.g., fruit quality, less risk of diseases).

Keywords: radiation, wind, screen, netting, crop water use

INTRODUCTION

Greenhouses are essentially solar collectors. Sunlight is collected through the transparent cover to drive photosynthesis and crop environment is warmed up by solar energy. Furthermore, greenhouses protect the crop against rain, hail, snow or wind and/or deterrence of birds and pests. The temperature within the confined environment of a greenhouse results from the balance of all energy fluxes entering and leaving it. As most fluxes (by far) are through the greenhouse cover, its properties are essential in determining inside climate and the amount of external resources (such as heating, cooling or water consumption) required to maintain it within the boundaries required for crop production.

If we question a grower what are the desired properties in a greenhouse cover, there are some clear answers to be expected:

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1. High light transmission (τ_{PAR}), which determines the amount of light for crop photosynthesis entering the greenhouse;
2. Optimum solar transmission (τ_{sun}), which determines greenhouse inside temperature through the amount of energy for crop growth and development entering the greenhouse;
3. Optimum light spectrum. In principle, represented by the ratio of the ratio of transmittance in the photosynthetic active range (τ_{PAR}) to the transmittance in the near infrared (τ_{NIR}), which determines how much of this energy is useful for photosynthesis;
4. Minimising heat losses. Defined by the insulation factor of the cover (U value), which is both affected by the transmissivity of the cover for thermal/far infrared radiation (τ_{TIR}) and by the thermal conductance;
5. Other parameters like condensation behavior, mechanical resistance, low sensitivity to aging, price, fabrication sizes, etc.

The first four properties can be all included in a group that we can name “radiometric properties of the cover”, which are, as we can see, essential in the selection by a grower. Unfortunately, there is not a set of “ideal” optical properties: properties that are useful in Holland may not be in Mexico, or properties being ideal for tomato and *Anthurium* sp. may differ when both crops are grown in the same location.

The external climate is continuously changing, and with it, the amount of sunlight and external temperatures, the properties of the greenhouse cover needed may be variable both in time and space. Table 1 gives an overview of the problems faced by greenhouse growers in the Mediterranean/sub-tropical region (in which the largest amount of greenhouses in the world are concentrated), what are the mitigating actions usually undertaken and what are the consequences. We also list which properties would be useful in the cover, and the techniques presently applied.

Table 1. Main factors limiting productivity of local greenhouses in regions with a Mediterranean/sub-tropical climate; what can be done (remedies) to mitigate climate within a greenhouse there, and what are the consequences.

Challenging season	**Mediterranean sub-tropic**	
	Winter	**Summer**
Limiting factor	Marginal light & temperature	High temperature
Corrective measures applied	Thermic foil Temporary of fixed double cover	Whitewash
Consequence	Poor production	No production
Required mitigating property of the cover	High TIR reflection (σ_{TIR}) Insulation High PAR transmission (τ_{PAR})	Reduced sunlight transmission (τ_{NIR} τ_{sun}) High TIR transmission (τ_{TIR})
Competing existing technologies	Internal mobile thermal screen	Good ventilation Whitewash Internal mobile shading screen

DEALING WITH LOW WINTER TEMPERATURES

In mild winter climate regions, the large majority of greenhouses are passive, they do not use any kind of artificial heating system. There are clear economic reasons for this (Bartzanas et al., 2005; López et al., 2008). Since winter production is the valuable cropping season, growers try to mitigate low temperatures to prevent frost or, more often, to slightly rise values which ensure the survival of the crop, but which still slow down growth and development. As a matter of fact, in clear nights, thermal inversion frequently occurs, resulting in lower inside greenhouse compared to outside temperature (Montero et al., 1985, 2013).

Thermic foil

Thermic foils are widely used in the Mediterranean region as they include some additives which are partially opaque to thermal infrared (TIR) radiation (specially between 7 and 14 µm). To be considered thermic, the material must have a transmission to thermal radiation lower than 20% (Hoffmann and Waaijenberg, 2002). As a matter of fact, these additives absorb, rather than reflect, thermal radiation. The consequence is that the cover warms up, and part of the heat is delivered to the outside and part to the inside. Different research works have proved that these covers have positive effects on the crop during the winter season: inducing a greater vegetative development, earlier harvests of greater quality and more abundance (Espí et al., 2006). The mineral fillers used nowadays have some important limitations: they accelerate the photodegradation of the film, diminish the light transmission, or they are really expensive. However, new additives that overcome these limitations have also been proposed (Espí et al., 2006). It must also be reminded that the presence of condensation on the internal side of a PE film modifying the thermal losses in passive greenhouses. In any case, the increase in temperature that can be achieved with thermic films is limited. For instance, Semida et al. (2013) reported a maximum increase of 2°C in a passive greenhouse tunnel with a lettuce crop. In Almeria, average increases of 1.5°C were observed for a thermal film in relation to a non-thermal film, with maximum increases of 3.5°C (Castilla and Bretones, 1979).

Double skins and screens

The use of double skins is also extended in the Mediterranean region to fight low winter temperatures. The double skins usually consist of two layers of permanent plastic films, with an inflated air layer in between. These types of covers were firstly developed in the USA in the 1960s (Roberts and Mears, 1969), with the aim of saving energy and limiting condensation, but also improving mechanical resistance of the greenhouse structure. In the Mediterranean region double inflated PE greenhouses are not so popular as in the USA, where they represent 65% of the greenhouse area, according to Fang et al. (2002). In double skin passive greenhouses, night time temperature increases of 2-3°C can be expected in relation to a single PE film greenhouse (Baytorun et al., 1993), but a decrease of at least 10% on perpendicular PAR transmission and even higher on hemispherical light transmission can be expected as well (Giacomelli and Roberts, 1993), which has a direct consequence on dry matter production which may or may be not compensated by the higher minimum temperatures.

As an even cheaper alternative, many Mediterranean growers use temporary low-cost, fixed, water-impermeable plastic screens (thickness 37.5 µm; normal light transmission 97%; 7% haze) installed inside the greenhouse during winter cycles. They are used to prevent rain and condensation from the roof falling on the crop and to slightly increase the greenhouse air temperature. There is very little scientific literature on the effects of these simple screens. Hernández et al. (2017) found air temperature differences of up to 1.5°C between screened and unscreened greenhouses in tests developed on Almeria during the winter season, decreasing the risk of thermal inversion. Also, observed canopy temperature was increased, decreasing the risk on condensation on the crop and thus, potential incidence of fungal diseases. On the other hand, these screens reduce the greenhouse transmission of shortwave radiation, which usually limits crop production in winter (Soriano et al., 2004) and intensifying the daytime CO_2 depletion (Sánchez-Guerrero et al., 2005), as the greenhouse air exchange with the outside is decreased.

A more expensive option, and therefore, less utilized by growers in Mediterranean passive greenhouses are the internal mobile aluminized screens, which were studied in detail by Baille et al. (1985), who concluded that aluminised screens outperform impermeable semi-transparent PE screens since they are more TIR reflective, thus minimising TIR losses. Little is known about the effect of such screens in unheated greenhouses. Even aluminized shading screens can also be effective in reducing the risk of frost damage and eliminating the problem of thermal inversion.

DEALING WITH HIGH TEMPERATURES

In mild winter climate regions, greenhouses are often located close to the sea where air humidity and temperature are normally near optimum for growing most vegetable crops and greenhouse climate can be acceptable during most of the growing season provided that enough natural ventilation capacity is available. Unfortunately, this is hardly the case in these areas, represented by the Mediterranean region (Montero et al., 1985; De Pascale and Stanghellini, 2011; Fernández et al., 2018). This leads growers to use shading to try to lower these high temperatures. Shading is done in the form of temporary whitewash and internal or external temporary fixed shading nets and mobile shading screens, they decrease light transmission substantially.

Whitewash

Whitewash is probably the most used shading technique in the Mediterranean region. It is usually executed by spraying the roof with a simple solution of calcium carbonate or calcium oxide diluted in water (Baille et al., 2001), although newer temporary coating products with more durability (resistance to washing by rainfall) and even with selective transmission to NIR radiation are available in the market. The reason for the popularity of this shading technique is its low cost and that it does not interfere with the air exchange through the greenhouse vents. On the other hand, whitewash induces a less uniform light distribution in the greenhouse than a shading screen, can be washed out by rain and on a daily basis, it shades the crop also during moments where shading is not required, during the early morning and later afternoon, because neither temperature nor radiation are high enough in the greenhouse (Garcia et al., 2011).

Whitewash can greatly decrease the canopy to air temperature difference in relation to a non-whitewashed greenhouse, decreasing transpiration and improving water use efficiency (Baille et al., 2001; Mashonjowa et al., 2010; Gazquez et al., 2006). Total yield can be affected due to the decrease in intercepted PAR by the crop (De Pascale and Stanghellini, 2011) under Mediterranean summer conditions. However, marketable yield can benefit from shading (Gazquez et al., 2006) due to lower incidence of fruit physiological problems (e.g., BER or cracking) and higher fruit homogeneity (Briassoulis et al., 2007).

Screening

Fixed shading nets are sometimes used as an alternative to whitewash and are placed outside or inside the cover during the high radiation season. In principle they provide a more uniform light transmission than the whitewash and rain episodes will not wash them away, which is an advantage in relation to most common types of whitewash products. A general rule is that highly reflective nets are preferred over dark colored nets, because the latter will absorb a large part of the incoming solar radiation, warming up the cover and therefore, the internal air by convection (Willits, 2001).

The other possibility is to use mobile screens, which can be placed internally or externally. Mobile screens should be preferably installed outside the greenhouse as they interfere much less with natural ventilation. External shading screens have shown excellent results in Mediterranean climate (Medrano et al., 2004; Garcia et al., 2011), improving the performance of non-shaded and permanently shaded references, respectively. However, external shading screens are more expensive and cannot be adapted to simple artisan greenhouse structures (e.g., parral type greenhouse). Their use is not recommended on very windy days as well.

If the screens are located inside, we find in literature that microclimate and yield are improved compared to unshaded references (Perdigones et al., 2008; Chen et al., 2011). Preferably, screens should be white and highly diffusive instead of aluminized, as the latter may induce high internal air temperatures. Screens should have a porosity that ensures enough air exchange. When compared to whitewash references, some authors have measured higher maximum air temperature (García-Balaguer et al., 2017), even in small and very efficiently ventilated greenhouses. Thus, internal shading should be carefully analyzed before installation in poorly ventilated greenhouses.

SWITCHABLE OPTICAL PROPERTIES?

It is obvious from the previous sections that none of the techniques used nowadays to modify the quantity, quality and geometrical distribution of the solar radiation reaching the crop during the growing cycle is optimal. Therefore, the development of new "smart" or "adaptable" covering materials that would allow for an (almost) instantaneous modification of the optical properties of the cover, could potentially have advantages.

The vision is that future greenhouse production systems will utilize sunlight in a very efficient way since they will be covered with these smart/adaptable materials. Solar light at any climate zone in the world will be converted in a form required by the crop to produce fresh products with high yield, good taste and high healthy components.

Some of these "adaptable" filters already exist in the market, such as the electrochromic glass, but they have not been optimized for their use as greenhouse covers, but for other high end uses such as architecture (e.g., privacy glasses) or in airplane industry (e.g., the windows in the Dreamliner model from Boeing). Casini (2018) has made a review of the most relevant technologies available nowadays that can be implemented in smart windows. The technologies which are potentially interesting to be further developed and implemented in greenhouse covers can be summarized as follows: 1) passive dynamic control, such as thermochromic and photochromic materials; 2) active dynamic control, such as polarized particles, mechanochromic, electrochromic, chemochromic and mechanically activated materials.

In active dynamically controlled materials, such as electrochromic glasses, an electric voltage is applied to change the optical properties (light transmission, diffusion). In passive synamically controlled materials, such as thermochromic plastics, optical properties are changed when they reach a certain temperature, they revert to initial properties when temperature drops again below the threshold value. This latter is the type of technology could potentially be more promising for low and mid tech greenhouses, which are majority in mild winter climate regions.

Companies operating in this sector have a need to identify which properties are useful in various conditions and to quantify the advantage of (some of) them being switchable. It is therefore interesting to quantify the benefit of improving the properties of the cover in terms of production and reduced resource requirement and to identify the added value of making some of the properties switchable, for the typical greenhouses of mild winter climate regions. Given the complexity of the greenhouse-crop system, and the many interactions among variables, this can be done by running scenario's through a dynamic greenhouse climate-crop model.

MODELING THE POTENTIAL OF SMART COVERS IN MILD WINTER CLIMATE REGIONS

The model and set up of the simulations

In the past, there have already been some attempts of evaluating the potential benefits of modifying the optical properties of the greenhouse shell through the growing cycle of the crop. In the CAGIM project inverse modeling was used to analyze the energy saving potential in glasshouses in The Netherlands by modifying the properties of the cover, such as outside emissivity and insulation, on a monthly basis (Lee et al., 2018).

For the present work we have used dynamic greenhouse climate, energy and crop models, earlier developed by Wageningen University and Research to analyze the potential use of smart covers in a mild winter climate region, represented by Agadir (Morocco). For the sake of simplicity we have limited this study to the following optical properties: τ_{sun}, τ_{PAR}, τ_{NIR} and τ_{TIR}.

The study has been carried out with a dynamic integral climate model KASPRO (De Zwart, 1996) and the crop growth model of Vanthoor (2011). KASPRO is able to dynamically simulate a full-scale virtual greenhouse based on the input of construction elements, greenhouse equipment, different covering materials and their main optical properties (transmission τ, reflection ρ and absorption α), set points for inside climate and the outside climate of a given location. Output are several climate parameters, such as air temperature, relative humidity, carbon dioxide (CO_2) concentration and resource consumption (i.e., water and energy). For the purpose of this paper the KASPRO model has been modified to allow for some of the optical properties of the greenhouse roof to be modified during the simulation by a trigger value. We have chosen internal greenhouse air temperature to be the trigger parameter in this study. Basically, when a certain greenhouse temperature threshold is achieved, the transmission of PAR, NIR or TIR wavelength bands is decreased by a factor input by the user. The amount of radiation which is not transmitted is considered to be reflected, thus, absorption remains unaffected in order to avoid interference with the increase in cover temperature (and thermal radiation) that would result from absorption.

The estimation of the potential tomato dry matter production has been done by coupling the microclimate (temperature, light, and CO_2 concentration) simulated by KASPRO with the tomato yield model of Vanthoor (2011) which is based on the photosynthesis model of Goudriaan and Van Laar (1994). The advantage of this yield model in relation to others is that it accounts for the effect supra and sub-optimal temperatures on photosynthesis and on production.

The climate of Agadir has been taken as representative for the sub-tropical/ Mediterranean region, and the traditional Canarian type greenhouse (Table 2) with a temporary whitewash (shading factor of 60%) as the reference scenario, a value typically used in the Mediterranean region. The date of application of whitewash (March 29) in the reference scenario was selected as the day after which (unshaded) greenhouse temperature would consistently (not just for one day) exceed 30°C for more than 5 h day^{-1}. Removal (October 1) was selected similarly, when duration of temperature exceeding 30°C would drop to less than 5 h day^{-1}. In addition, since such greenhouses have typically a limited ventilation capacity, interaction of ventilation rate and greenhouse cover properties has been studied. For Agadir, also a “reference” scenario with a controllable ventilation and higher air exchange capacity by natural ventilation, a narrow multi-span with double zenithal ventilation openings, has been calculated (Table 2). The period of whitewash application (determined as above) was shorter: April 26 to September 23, which follows from the higher ventilation capacity. Several filters that could be expected to increase productivity were simulated, the switchable ones with activation air temperatures of both 28 and 30°C, for the non-selective and NIR selective filters, respectively. Tomato transplant date was August 15 and end of crop cycle on June 15 the next year (the typical cycle of this region).

Table 2. Main geometrical parameters of the simulated greenhouses and main optical properties of the roof.

Parameter	Unit	Canarian	Multispan
Area	m^2	10000	10000
Ridge orientation	deg	0 (North-South)	0 (North-South)
Central path width	m	3	3
Gutter height	m	5	6
Roof slope	deg	6	22
Span width	m	10	9.6
Distance between pillars	m	5	5
Ratio windows to floor area	%	3	25
Hemispherical light transmission	%	77	81
Shortwave absorption	%	8	11
TIR transmission	%	35	35
Emissivity	-	0.6	0.6

The optical properties of the roof (plastic cover and greenhouse structural elements) when the filters are not active are included in Table 2. Basically, three types of permanent and switchable filters have been simulated (Table 3): non selective filters which are increasing reflection both in the PAR and NIR, NIR selective filters and TIR filters. The first two types of filters have been simulated for both the Canarian and the Multispan type, whereas the latter, only in the Multispan type. In Table 3, the percentage numbers represent the equivalent increase in reflection (and equivalent decrease in transmission) in the affected band, when the filter is active.

Table 3. Summary of filter type simulated and filter activation set points.

Filter type	**Filter activation set point**
Reference	Seasonal whitewash (%PAR + NIR, no TIR)
Non-selective filter PAR + NIR	
Switchable filter 60%	28°C/30°C
Selective NIR filter	
Permanent NIR filter 100%	Permanent
Switchable NIR 100%	28°C/30°C
Switchable NIR 100%, PAR reduction=10%	28°C/30°C
Switchable NIR 50%	28°C/30°C
TIR filter	
Permanent TIR filter 100%	Permanent
Switchable TIR 100%	22°C
Switchable TIR 100%	22°C

RESULTS AND DISCUSSION

The scenarios calculated are summarized together with the results in Tables 4 and 5. We have included some of the most relevant output parameters from the model to quantify the effect of the simulated filters: the potential predicted final tomato yield (kg m^{-2}), the total amount of hours that the greenhouse air temperature is above and below two thresholds for negatively affected dry matter production (Table 4) and the PAR integral (mol m^{-2}) in the growing cycle (Table 5).

Table 4. The scenarios calculated for Agadir, Morocco, and the expected potential tomato yield, the number of hours that greenhouse air temperature was above 28°C and below 12°C (the upper and lower physiological thresholds for penalized crop growth, respectively).

		Yield (kg m^{-2} y^{-1})		**Hours T>28°C**		**Hours T<12°C**	
		Canarian	**Multispan**	**Canarian**	**Multispan**	**Canarian**	**Multispan**
Reference	Whitewash	22.9	29.5	1068	43	748	1018
PAR+NIR	Switchable filter 60%	26.4	33.0	1595	571	454	1005
NIR	Permanent	26.2	30.5	719	478	1371	1130
	Switchable NIR 100%	28.0	33.1	1491	575	476	796
	Switchable NIR 100% (PAR reduction = 10%)	27.8	33.0	1476	573	476	796
	Switchable NIR 50%	27.5	33.1	1568	582	457	794
TIR	Permanent	21.5	32.0	1790	573	33	135
	Switchable TIR 100%	23.0	31.2	1202	511	51	187
	Switchable TIR 0%	23.0	30.4	1097	506	323	673

The simulation of both, the non-selective PAR+NIR and the NIR selective both permanent and switchable filters, shows a clear increase in potential yield in relation to the reference scenarios (whitewash) (Table 4). Indeed, these filters allow for a higher amount of PAR to be available for the crop than the simulated permanent seasonal whitewash (Table 5). This is of course achieved at the expense of a larger number of hours at supra-optimal temperatures, which in the case of the Canarian greenhouse is compensated by a decrease of hours at infra-optimal temperatures thanks to the higher amount of energy stored in the greenhouse soil. The switchable selective NIR filters perform only marginally better in terms of potential yield than the non-selective filters, proving that the larger availability of PAR under the NIR filters is not fully utilized by the crop, probably because there is another limiting factor acting, such as CO_2 concentration.

Table 5. The scenarios calculated for Agadir, Morocco, and the final PAR integral (mol m^{-2}).

		PAR integral (mol m^{-2})	
		Canarian	Multispan
Reference	Whitewash	4116	4473
PAR+NIR	Switchable filter 60%	4630	5769
NIR	Permanent	6161	6198
	Switchable NIR 100%	6161	6198
	Switchable NIR 100% (PAR reduction = 10%)	5812	5923
	Switchable NIR 50%	6161	6198

The switchable filters allow for a decrease in the peak temperatures in relation to the reference, when the whitewash was removed in the Canarian greenhouse (Figure 1), which agrees with the observations of other authors for different types of NIR reflecting films in hot climate conditions (Verlodt and Verschaeren, 2000; López-Marín et al., 2008). However, a permanent NIR filter decreases peak temperatures even more.

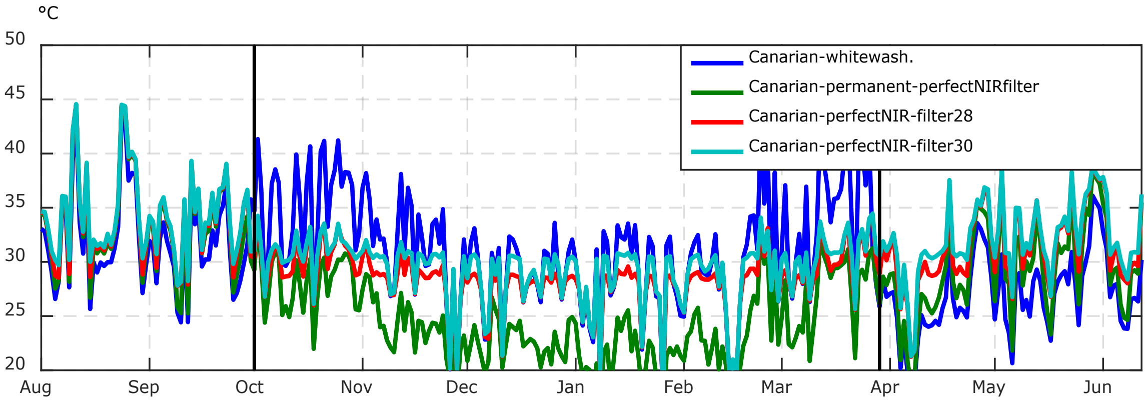

Figure 1. Evolution of maximum daily temperatures under the reference Canarian greenhouse and in the simulated selective NIR filters. The vertical black lines mark the moments of removal/application of whitewash (from left to right, respectively), the blue line represents the reference with whitewash application, the green line represents a permanent NIR filter applied, the red and petrol line a NIR filter activated at 28 and 30°C, respectively.

Results also indicate that a permanent selective NIR filter does not perform better than the switchable filters for mild winter climate regions if the growing cycle develops through the winter (which is usually the case) in passive greenhouses, because it decreases the amount of energy that can be stored in the greenhouse soil, penalizing the night time temperatures (Figure 2).

This result is in agreement with what already pointed out by Stanghellini et al. (2011), who advised against the potential use of NIR reflection in these regions in a permanent cover, but as a temporary coating or as a movable screen, to prevent their harmful effect during the winter months. If the growing cycle does not occur during the winter, permanent NIR filters in the cover can provide a good performance, as shown by López-Marín et al. (2008) and Garcia-Alonso et al. (2006) for a sweet pepper grown in south east of Spain.

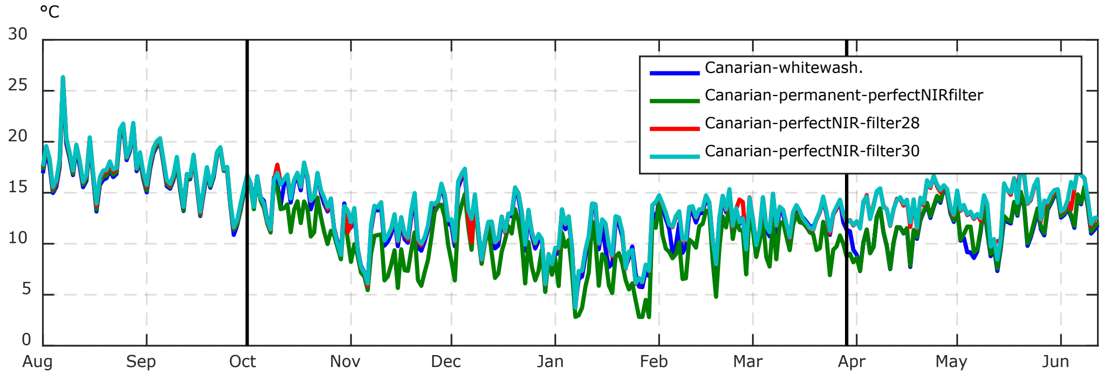

Figure 2. Evolution of minimum daily temperatures under the reference Canarian greenhouse and in the simulated selective NIR filters. The vertical black lines mark the moments of removal/application of whitewash (from left to right, respectively), the blue line represents the reference with whitewash application, the green line represents a permanent NIR filter applied, the red and petrol line a NIR filter activated at 28 and 30°C, respectively.

The higher ventilation capacity of the Multispan greenhouse equalized peak temperatures under all evaluated scenarios. Indeed, results in Table 4 highlight the importance of having a large ventilation capacity in the greenhouse under warm climates. The reference scenario already has an enormous reduction in the total number of hours that the greenhouse air temperatures are too high for optimum tomato production, caused by an improved ventilation capacity and management. We can therefore derive the conclusion that improving natural ventilation capacity might be prioritized over the use of a cover with switchable solar filters, as the benefits associated to a higher ventilation capacity extend beyond the control of high temperatures (humidity management, CO_2 supply from external air being the most obvious). We can also observe that the final PAR sum is larger under the better ventilated greenhouse when switchable filters are used, and that is caused again by the higher cooling capacity by natural ventilation, which allows for a later activation of the filters during the course of a daytime. This explains the larger percentage increase caused by the switchable filters in the better ventilated greenhouse (multispan) than in the Canarian type. Besides, the filters allow for the same temperatures to be achieved with less ventilation requirements, which would potentially allow for a more efficient use if CO_2 enrichment would be used.

Finally, one might argue that the higher integral of PAR radiation available for the crop obtained thanks to the switchable filters in relation to the whitewash could also be obtained by using mobile shading screens. This can be true depending on where the screen is located, inside or outside the greenhouse, as is explained in previous sections. Therefore, we could state that switchable non-selective filter (both PAR and NIR) seems a better option than both whitewash and a mobile shading screen for large commercial greenhouses with limited ventilation capacity, whereas it will have to be competitive in price with an interal mobile shading screen in better ventilated greenhouses.

In the simulations with the TIR reflecting filters we see differences between the two simulated types of greenhouse, Canarian and Multispan. For instance, the permanent TIR filter shows a decrease in potential yield in the Canarian greenhouse in relation to the reference material. Although, thermal radiation exchange is relatively less important at daytime, if the greenhouse is not efficiently ventilated (such as the Canarian), the limited radiative cooling causes an increase in the number of hours at supra-optimal temperatures which is more detrimental for dry matter production than the benefit obtained by the observed decrease in the number of hours at infra-optimal temperatures. In the better ventilated greenhouse, the large cooling capacity by ventilation minimizes the problem of lower radiative cooling, and therefore, the permanent filter has a better performance than the reference. However, in both cases, a 100% TIR switchable filter, that can be de-activated during daytime hours to allow for efficient radiative cooling, decreases substantially the amount of supra-optimal temperatures during day. The 100% TIR filter performs slightly better than the 50% TIR filter during the coldest months and during part of the spring. In any case, we can clearly state that TIR reflection is a much better option to maintain night time temperature higher in passive greenhouses than cover TIR absorption, in agreement with Piscia (2012) and Hoffmann and Waaijenberg (2002). The simulated TIR filters also induce and increase earliness (i.e., 30% higher early yield, at 120 dat, for the permanent TIR filer in the better ventilated greenhouse) is also very valuable, since crop prices in the period November-February are the highest for greenhouse-grown products in locations like Agadir, thanks to export to Europe. Finally, it could be argued that a movable aluminized thermal screen could be an alternative, instead of the TIR switchable filters in the cover. For a better industrial greenhouse structure, which are still a minority in these regions, the price of a hypothetical smart cover with permanent TIR reflection should be competitive in price with that of a movable energy saving screen in order to compete in the market.

CONCLUSIONS

There is no ideal greenhouse cover for any climate region in the world. Along the growing cycle, both crop productivity and quality and the resource efficiency benefit by modifications in the properties of the cover. These modifications are achieved nowadays in different ways: temporary coatings/screens, mobile screens, etc. However, none of these techniques are optimal, due to different reasons.

In recent years, smart semi-transparent materials are being developed in which optical properties of the material can be changed (almost) instantaneously. At the moment, the cost of these solutions is high and their use restricted to high value applications. However, this could change if we could quantify their advantages for horticultural usage in different climates, their potential benefit being used as smart greenhouse covers, and prove that there is a potentially large market. A possible approach is to make use of well validated greenhouse simulation and crop growth models to analyze and quantify the effect of instantaneously changing the optical properties in several greenhouse regions and with different levels of technology. In the present work, we have done this for a mild winter climate region (represented by Agadir, Morocco) and using a modified version of KASPRO (De Zwart, 1996) coupled to the tomato crop growth model of Vanthoor (2011). The results of the simulation indicate:

- There is perspective for non-selective but switchable reflection of PAR and NIR, which might be easier to achieve than a high selective NIR reflection;
- Good results are also obtained with switchable selective NIR reflection, also in addition to the effect of an improved ventilation capacity;
- Permanent NIR reflection decreases winter production (the worthy one) and has little effect after improved ventilation capacity;
- There is good perspective for plastic films with (non-switchable) improved TIR properties.

In the future it will be interesting to carry out simulations combining more than one filter in the same material, to verify if the filters can be used together without being detrimental to each other. In any case, the potential increases in yield simulated are similar to those obtained with already existing technologies in these regions, such as mobile shading screens, as reported in the literature. Thus, new developed smart covers will have to be price competitive to compete in the market.

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