Smart materials: crop experiment with electrochromic glass

First experiment with the potted plant Anthurium

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Report WPR-912

Abstract
Some high-value ornamental crops, such as Anthurium sp. and Phalenopsis sp., are shade loving crops which are grown under relatively low sunlight levels. In summer, these are achieved by different shading techniques such as shading screens, temporary coatings and combinations of both. However, these options are not optimal because screens do not allow to regulate light smoothly (slow reaction to changing light conditions) and coatings take also light in days with low radiation. Glass in which the transmission can be modulated (i.e. electrochromic glasses) could overcome these problems bringing a more stable climate in the greenhouse and possibly a higher light sum. This could all lead to improved and faster growth of these crops. A small-scale experiment was conducted with the shade plant pot-anthurium as crop example for a first evaluation of the possibilities of EC Glass to be used as greenhouse cover. The questions we wanted to answer were if it controls light intensity as programmed, and if it improves crop growth and time to market. Five shading treatments were compared: 1. Float glass (no shade); 2. EC Glass managed at a fixed level; 3. EC glass managed as a screen; 4. Coating; 5. Diffuse glass (no shade). The light levels were well controlled under both EC glass panes, but damage was induced to plants on very hot days due to overheating of the glass panes in dark state and consequent overheating of ambient air. There was a trend to shorter plants and smaller leaves & flowers compared to the reference in a greenhouse. More research is required to evaluate the potential of smart glasses to become greenhouse covers for these high value crops.

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Disclaimer

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Summary

A small-scale experiment has been conducted during the summer of 2019 with the aim to explore the performance and benefits of Electrochromic glass (EC Glass) as greenhouse cover. The shade plant Anthurium in 14 cm pots was used as an example of shade loving plant. The experiment is part of the project "Smart materials", a Public Private Partnership in which fundamental material development is combined with applied crop physiological experiments to create new smart materials that can be applied in greenhouse horticulture. Because EC Glass is able to change the light transmission smoothly reacting on an electric switch, it is a promising material to use as a greenhouse cover to regulate the light intensity for the plants better than with the traditional shading systems: more constant, smoother and faster. Potentially this leads to benefits for the plant, such as a more stable climate inside the greenhouse due to less variation in solar energy entering, being able to allow higher light intensities with a lower risk for stomatal closure, stress and leaf burns, with a shorter crop cycle as potential result.
The performance of two sheets of Electrochromic glass was compared to that of traditional shading techniques and no shading in a "greenhouse in greenhouse" construction. In total, five cubicles were created with glass panes on a metal construction and sidewalls made of dark tissue. Each cubicle becoming one of the following shading treatments: Float glass (transparent, no shade), diffuse glass (no shade, better scattering of the light); coated Glass (white wash), EC Glass regulating at a fixed value and EC Glass managed as a screen. The plants growing under the five treatments were compared with plants of the same varieties, age and history that were growing in a commercially comparable environment in a reference greenhouse.

The experiment with plants lasted 11 weeks. During this period, the light level below the electrochromic glass has been well controlled at the set point of 270 $\mu mol/m^2s$. The EC glass in dark condition not only reduced the light intensity, but also shifted the light spectrum under the glass (with relatively more green and yellow and less red and far red). Because of the light absorption by the material, the surface temperature of the EC glass panes increased up to 58°C during very hot days in the month of July, leading to overheating of the air between the glass and the plants and to high leaf temperatures, which resulted in some plants with leaf burning spots, at a degree similar to that of the Coating treatment. Under the unshaded treatments the plant temperatures increased above lethal values and leading to severe burning of most of the plants.

The plants under the EC Glass were for most parameters comparable to the ones under the glass with coating (white wash). However, compared to the reference plants in a "normal" greenhouse, plants in all the treatments in the experiment were smaller (smaller leaves & flowers and a lower fresh weight per plant). This effect was probably caused by the trial set up where the cloth creating sidewalls in the cubicle hampered air circulation and exchange with the rest of the greenhouse for cooler and more humid air. The trial setup needs to be improved for conducting future research.

1 Introduction

High light intensities and the associated heat can lead to serious damage of the foliage of tropical ornamental plants, especially those plants that originate from the shaded layers in the tropical forests. For the successful commercial production of such plants in greenhouses, shading is needed to maintain the light intensity below damage thresholds.
Traditional systems used in The Netherlands to reduce the light intensity in greenhouses are:

- To apply a coating (white wash) on the greenhouse glass cover and sidewalls, that reflects part of the incident light, reducing also the associated heat inside the greenhouse. As the coating reduces light intensity, it is generally applied in spring -as soon as April- and removed again in autumn (October), to avoid too low light intensities in the greenhouses by which the plants would stop growing and or flowering. White washing is an effective way to reduce both light intensity and heat from the greenhouses. However, the coating remains on the cover permanently so at dark, cloudy days the plants can receive too little light. If this happens for several days, it reduces the growth rate of the plants and delays their time to market.
- To install and use shading screens. Screens are available in different materials and different light transmission, and they can be mounted inside or outside the greenhouse. Growers can choose the material with the desired level of light transmission. The screens are connected to the climate computer and can be programmed to unfold or fold depending on the outside light intensity at every moment, so they keep folded on dark and clouded days, and unfolded when it is too sunny outside. The drawback of screens can be sometimes too late/ too slow in days with variable clouds. This forces growers to choose a conservative screening strategy or combine them with a fixed shading percentage like the above mentioned white washing of the cover. Another drawback of screens is that they can have a negative interaction with ventilation, and lead to increase instead of decrease of temperature.

Within the project “PPS Smart materials” different research groups and companies work on the development of new smart materials for application in greenhouse horticulture. As well fundamental material development as applied crop physiological experiments are part of the project. Development focusses on the instantaneous control of the light intensity, diffusion and spectrum through these materials. “Switchable glasses” reacting on an electric impulse able to control light intensity (from transparent to dark), light scattering (from transparent to diffuse/opaque) and light colour are of special interest.
If such materials could be used as greenhouse cover materials, they might provide an interesting possibility to regulate the light level in the greenhouse better than the traditional systems, leading to certain (expected) benefits:

- Possibility to regulate light smoothly
- Use instead of regular screen → disadvantage regular screen: always too late/too slow, growers choose conservative screening strategy, fixed shading percentage, has negative interaction with ventilation
- More stable climate inside the greenhouse due to less variation in solar energy entering
- Possibly less screening (up to 50%) needed due to more stable light intensity, no safety needed compared to a traditional screen (shading percentage screening strategy) → higher light sum possible, faster/higher production → pot plants (tropical), cut flowers (such as roses)
- less risk on leaf burn in shade loving crops such as Anthurium, Bromelia, Hortensia, Calathea Spathyphillum and many others
- Possibly a growth advantage –less stomatal closure and stress- for the mentioned crops at the same light sum due to more stable light intensity
- Possibility to use them as black-out screen without the associated heating-up effect of greenhouse in afternoon with the black-out screens in (facultative) short-day crops such as (pot)chrysanthemum, kalanchoe, poinsettia, gerbera, begonia
- Possibility to use as light emission screen during night-time for all crops with assimilation light during the night like for instance roses, gerbera, lysianthus, chrysanthemum and others.

A small-scale experiment was designed to explore the performance and benefits of switchable glass as greenhouse cover with potted Anthurium plants. Two sheets of Electrochromic glass (Light intensity switchable glass being switchable on an electric impulse at a given light intensity: from highly transparent to dark) were supplied and in a “greenhouse in a greenhouse” approach, compared with coated (white wash), transparent glass (no shade) and diffuse glass (no shade, better scattering of the light) during the summer of 2019.

1.1 Objectives

The main objective of this experiment was to perform a first evaluation of the opportunities and constraints of electrochromic glass (EC Glass) to be used as greenhouse cover with the shade plant potanthurium as crop example. What is the EC Glass performance in greenhouse conditions compared to traditional shading techniques? Besides, we would like to find out

- If the EC-glass controls the light intensity as programmed.
- How EC-glass affects crop development and growth (time to the market).
- How EC-glass affects the quality of the crop (size, colour, leaf quality, etc.).

2 Material and methods

Hemispherical transmission measurements were performed with two Electrochromic glass sheets (size 0.84m*1.35m) in the LightLab of WUR Greenhouse Horticulture in Wageningen, in order to calculate the level of shading achieved by the tint level of the glass.

These previous measurements will help calculate the tint level that is needed to get the transmission of the EC glass to reach the desired light level below the EC-glass.

2.1 Hemispherical transmission measurements

Figure 1 shows the tint level of the EC glass plotted against the hemispherical transmission.

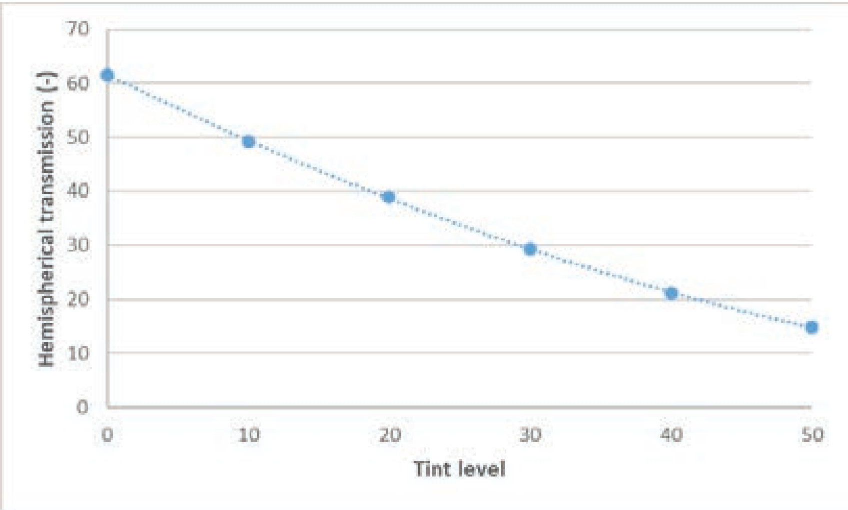


Figure 1 *Hemispherical transmission of the glass depending on the tint level.*

With the above graph, the tint level can be calculated which is needed to set the transmission of the EC glass to reach the desired light level below the EC-glass.

2.2 Setup Greenhouse experiment

Due to the limited availability of the material, and in order to see the effect of EC-glass on potanthurium a small-scale experiment was performed with a "greenhouse in a greenhouse" approach.

Figure 2 *The greenhouse compartment where the experiment took place.*

2.2.1 The greenhouse compartment

The experiment took place in a 144 m^2 greenhouse compartment equipped with 14 cultivation tables of 4 m x 1.78 m (7.12 m^2) each, specially meant for the cultivation of potted plants (Figure 2).

The greenhouse compartment is equipped with a roof shading screen as well as lateral screens, as it can be appreciated in Figure 2. However, for the duration of this experiment they remained folded in order to allow as much light as possible on top of the Electrochromic glass panes.

The RH of the air can be increased whenever it drops below a certain threshold, in our case below 70%, by means of a high pressure misting system, and CO_2 was supplied to maintain a concentration in the air of 650 ppm during daytime.

2.2.2 The “greenhouses in the greenhouse”

The EC-glasses (size 0.84m*1.35m) were placed horizontally on metal racks at a small distance from the tables (65 cm) to reduce as much as possible unfiltered incident light from the sides. However, still too much light came from the sides even with the side screens closed all day; therefore, the sides of the racks where covered with opaque tissue to create a ‘cubicle’ in order to avoid light from the sides (Figure 4). Two fans per cubicle were installed to force some ventilation between the air in the cubicles and the greenhouse air, which was kept at a RH of 75% with the aid of the above-mentioned fogging system.

2.2.3 Plants

Anthurium potted plants of the variety Royal Champion (Anthura) rooted in 14 cm pots in potting soil were placed at a density of 30 plants per m^2 on the tables on the 21st of June. At that moment, the plants entered phase 2 in terms of cultivation density (see Figure 5).
Although we planned to follow these plants until the end of the experiment, part of the plants were replaced after 5 weeks by plants of the variety Amalia Elegance (Dümmen Orange).
The 14 tables in the greenhouse were filled with plants, in order to create a realistic growing environment (in growers’ terms: to maintain the “climate”).

Outside the “cubicles”, there was a higher light intensity than in the cubicles because we kept the shading screens permanently open. Therefore, the plants outside the cubicles were protected from excess light by means of a double layer of a white non-woven sheet above the plants on metal racks. As these plants were under suboptimal conditions, we used plants of the same age but grown in a separate greenhouse under more ‘commercially comparable’ growing conditions as reference for plant growth measurements.

2.2.4 Irrigation and nutrients

Plants were irrigated by means of an ‘ebb and flood’ system (the table fills with water during a few minutes and the plants get water from below the pot) once every three to five days (as it is normal practice in commercial cultivation in summer) with a nutrient solution with the composition given in Table 1 (Straver *et al.* 1999).

Table 1 Composition of the nutrient solution

		Main elements (mmol/l)							Trace elements (µmol/l)					
EC	pH	NH_4	K	Ca	Mg	NO_3	SO_4	P	Fe	Mn	Zn	B	Cu	Mo
1.5	5.2	1.25	6	3.25	0.8	11.5	1.1	1.6	20	5	3	10	0.8	0.5

2.2.5 Shading treatments

In total 5 different shading treatments were set up:
- Float glass (no shade).
- Diffuse glass with 2-sided anti-reflection coating (no shade).
- EC Regel (EC Glass darkens to maintain a PAR level in the cubicle of 270 µmol/m^{2}s at all times).
- EC Screen (EC Glass darkens as a screen, at a PAR threshold of 270 µmol/m^{2}s in the cubicle).
- Coating (a float glass pane coated with white wash –Redusol- 1:4).

Below every glass pane a PAR-sensor was placed. The EC Regel pane and EC Screen were controlled based on this PAR-sensor. The EC Regel controls every 30 seconds the light level. The EC Screen mimics a shading screen, so it becomes dark/transparent if the average light intensity of the last 20 minutes was higher/lower than 270 µmol/m^{2}s.

Maintaining the light level at 270 µmol/m^{2}s or letting the glass become dark with this level as threshold is rather conservative for potanthurium. Although recent research (Van Noort *et al.* 2013) has shown that these plants can handle high light intensities up to 400 µmol/m^{2}s and short light pulses up to 500 µmol/m^{2}s of provided air humidity and leaf temperature are well controlled. We foresee difficulties controlling these parameters due to the closed environment of the cubicle. Therefore, we chose to maintain a conservative light intensity.

Plants grown in a separate greenhouse under ‘commercially comparable’ growing conditions were used as a reference for plant growth measurements.

Figure 3 *The "cubicles" or small "greenhouses in the greenhouse" on the cultivation tables.*

2.2.6 Sensors and measurements

In the greenhouse climate parameters such as temperature, relative humidity, CO_2 concentration, PAR level, position of windows and screens, etc., are monitored continuously and recorded at 5-minute intervals. In each cubicle, besides the above-mentioned PAR sensor that was needed for controlling the light intensity below the Electrochromic glass, an air temperature and relative humidity sensor were installed.

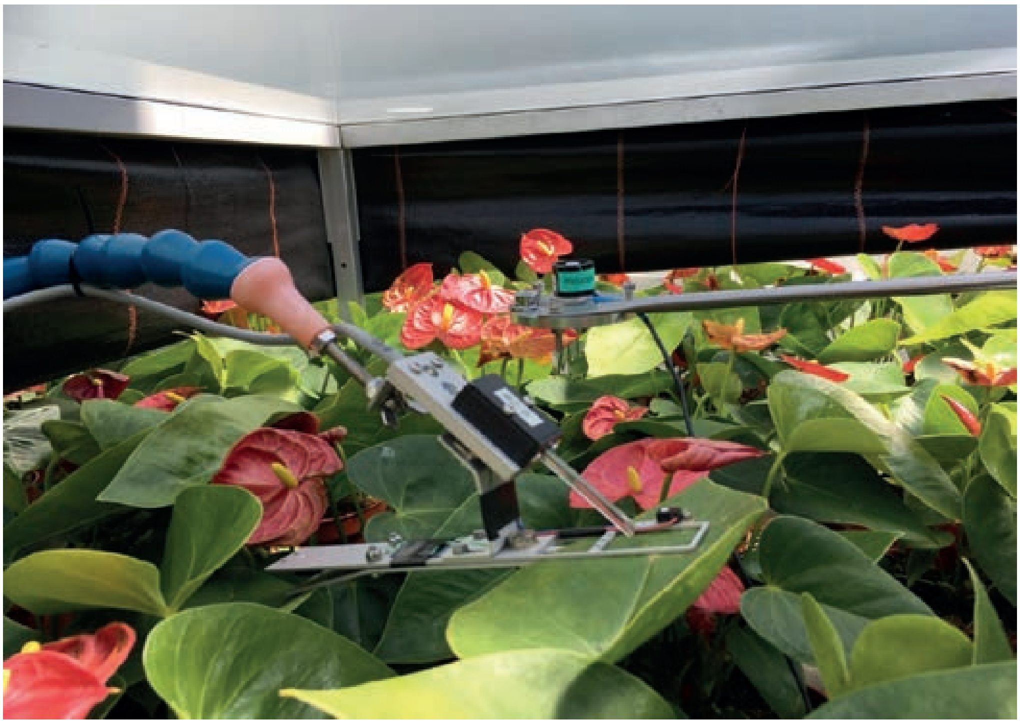


Figure 4 *The inside of a cubicle where the Hex-PAM sensor and the PAR sensor are visible.*

The conditions at the plant level were monitored inside each cubicle with the aid of a Hex-PAM (Pulse-Amplitude-Modulation") sensor which clipped to a mature leaf, can measure the leaf temperature, humidity, PAR and photosynthesis activity. This latter parameter is measured by the electron transport speed (ETR), which is the first step in the photosynthesis cycle, based on chlorophyll fluorescence quantum yield. With the help of the "Saturation Pulse Method", the quantum yield of photosynthetic energy conversion is derived.
The measuring leaf and plant is changed once every 7 days.

Besides these measurements, incidental measurements of the temperature of the glass surface were done under different weather conditions by means of an infrared handheld thermometer that was directed to a small piece of non-reflecting adhesive ribbon (Testo emission sticker).

The light spectrum in each cubicle was measured below the shading treatments with a JETI Spectrophotometer and the spectrum of the Electrochromic glass in both the state of maximum transparency and the state of maximal shading / darkest tint colour.

Plant growth measurements (number of leaves and flowers, plant size, leaf and flower size, leaf surface, dry matter content), were performed destructively on 10 Royal Champion plants after 5 weeks of cultivation and on 10 Amalia Elegance plants at the end of the experiment (again after 5 weeks of cultivation).

2.2.7 Timeline

The cultivation of potanthurium in 14 cm pots, from the moment the plants are supplied by the propagator until the moment they are "ready for the market" requires under Dutch greenhouse conditions approximately 30 weeks.
The plants are cultivated in three growth "phases", each phase lasting approximately 10 weeks and separated from the previous by a spacing episode (see Figure 6) in which the plant density decreases to allow enough growing space for the plants without competing with one another.

The Royal Champion (Anthura) plants were supplied in week 14, cultivated during phase 1 in a separate compartment (Demo 2030 greenhouse, WUR Bleiswijk), then transferred in week 24 to the compartment where the experiment with electrochromic glass was about to take place. The intention was to cultivate them in this experimental compartment during phase 2, from week 24, that means till the next growing- spacing phase or approximately until week 34.

However, after 5 weeks (august 9th) too many plants in the unshaded cubicles were totally burned and on the 13th of august replaced by new plants of the second variety, Amalia Elegance (Dümmen Orange).

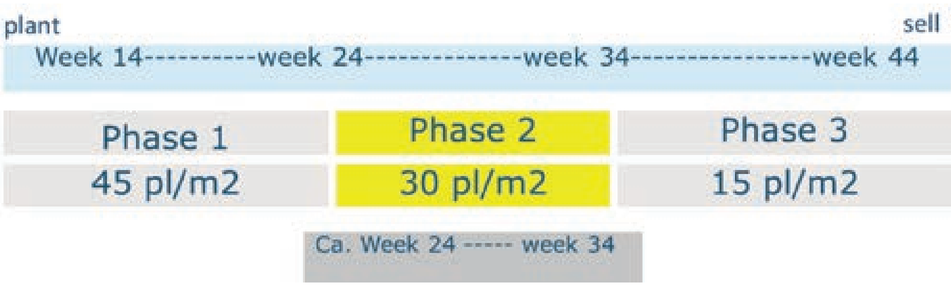


Figure 5 *Schematic representation of the three phases of this pot anthurium cultivation. The yellow rectangles indicate the duration and phase of our experiment.*

3 Results and discussion

3.1 Spectrum measurements

At the moment of measuring the spectrum of the light entering the cubicles, the light intensity outside the main greenhouse was about 1000 μmol/m²s. Inside the cubicles, the total PAR light intensity (400-700 nm) varied between 6 μmol/m²s (the cubicle covered by the EC glass at maximum darkness) and 766 μmol/m²s (the cubicle covered with diffuse glass).

For the wavelengths between 300 and 800 nm, the measured intensity expressed as photon flux density is shown in Figure 6. In this graph, it is to see that the spectrum of the treatments does not differ much, only the intensity.

When the EC Glass is at the lightest condition (yellow line) it transmits slightly less blue and UV. The rest of the spectrum is very similar to the coated (whites washed) glass and the float glass.

When the EC Glass is at its darkest, it absorbs a great part of the light (the flat light blue line close to the x-axis).

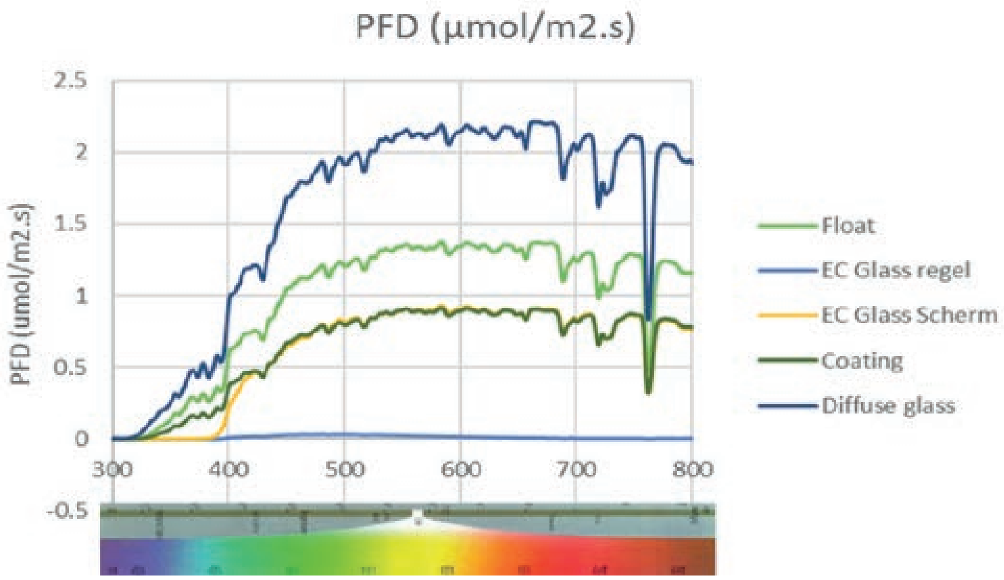


Figure 6 *Light spectrum inside the cubicles (absolute values). The EC Glass regel line shows the spectrum of the EC glass at its darkest tint. The EC Glass Scherm shows the spectrum of the EC Glass at its most transparent condition.*

To appreciate if and how the EC Glass modifies the spectrum, Figure 7 shows the spectrum at a relative intensity (the spectrum of the darkest tinted EC Glass is magnified).
The light spectrum below the glass shifts to wavelengths with more energy. The EC Glass modifies not only the intensity, but also the spectrum of the light for the plants (relatively more green and yellow pass through the glass, and less red and far red).

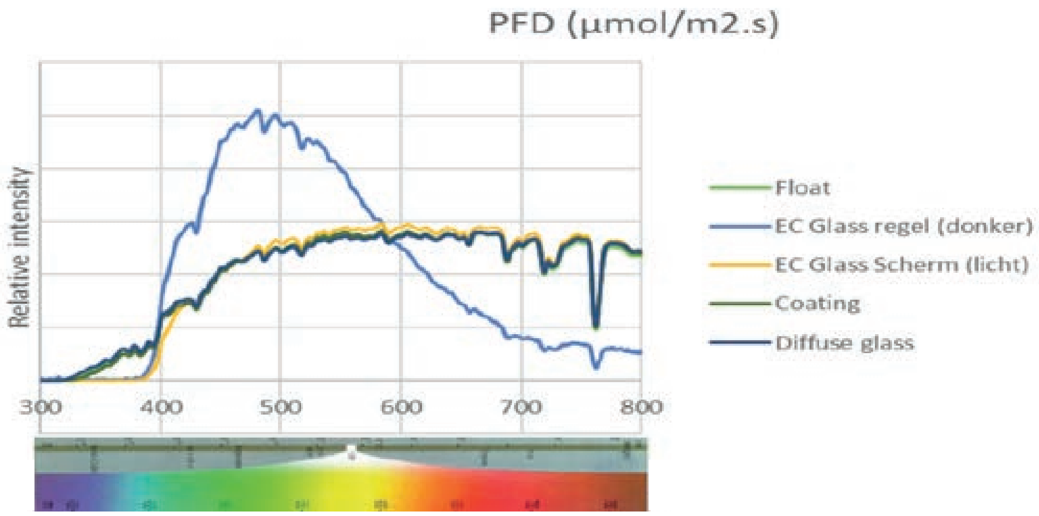


Figure 7 *Light spectrum inside the cubicles (relative values, the EC glass Regel –darkest- is magnified).*

3.2 Light levels in all shading treatments

The measurements of all the PAR meters from the 30th of July (one in each of the 5 shading treatments and one in the greenhouse) are displayed in Figure 8 as an example of a sunny day.
It is very clear that the light level below the diffuse and the float plate is always too high. The light level below the coated plate (purple line) exceeds in the middle of the day (between 10:30 and 15:00) frequently the 270 µmol/m²s. Therefore, screening and whitewash are often combined in practice.
During a large part of the day, the light level below the EC Regel (red line) is kept very close to the control level of 270 µmol/m²s and never exceeds 400 µmol/m²s.
The light level below the EC Screen (yellow line) is well below the threshold value most of the hours of the day. However, the EC Screen shows a delay when 'opening', which can be seen by the light peak just after 10AM, and a delay when 'closing' that causes some light dips –close to 100 µmol/m²s- as the ones between 10:30 and 11:00 and between 13:00 and 14:00.

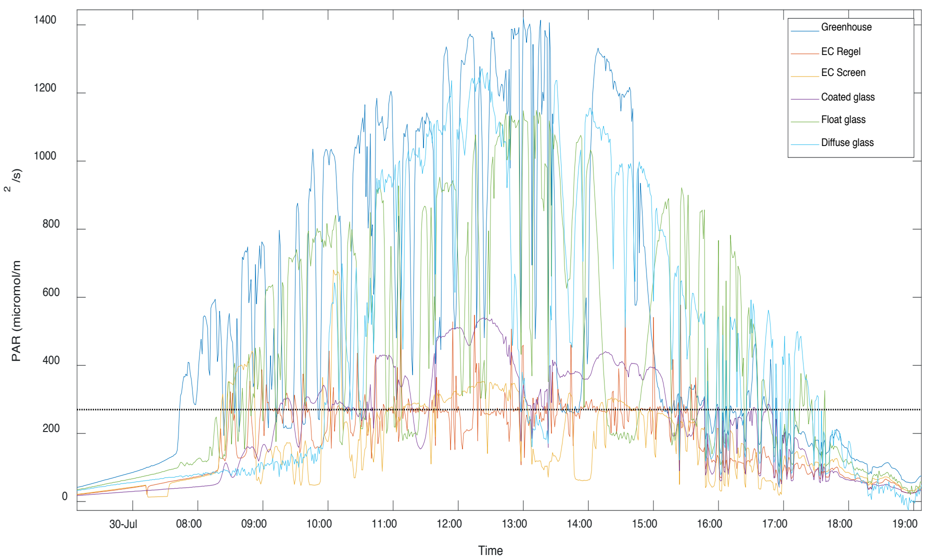


Figure 8 *The light intensity for each treatment during a sunny day. The dotted back line represents a light intensity of 270 µmol/m²s.*

Figure 9 shows the average light intensity of the three shading treatments (EC Regel, EC Screen and coating) per day. The average is calculated only over the time that the light level in the greenhouse exceeds 443 μmol/m²s, as this is the value in which the EC Glass starts to control the light (443 * 0.6 = 270 below the EC Glass). The three shading treatments achieved very similar average day values, were the EC Screen had the highest values at certain days and being the least constant of the treatments.

The light level on the 23rd of July was too high due to a failure of the network connection.

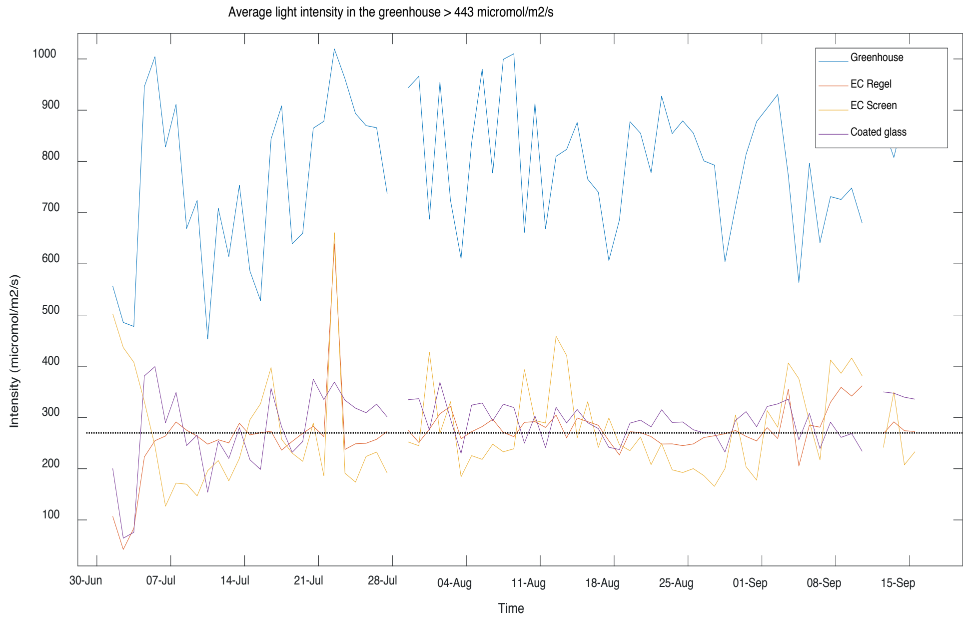


Figure 9 *Average light intensitity per day in the greenhouse and in the cubicles with the treatments EC glass regel, EC glass screen and coated glass.*

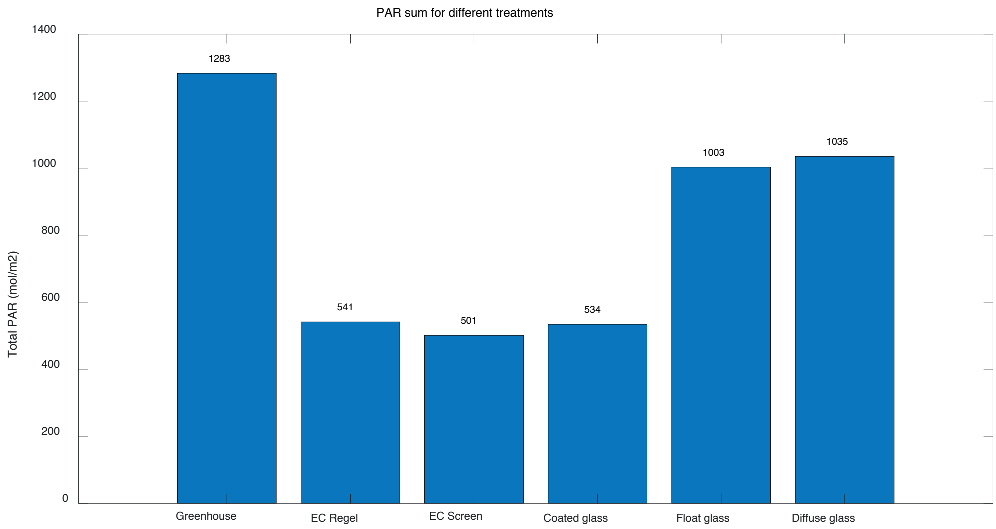


Figure 10 *Total PAR light sum in the greenhouse and in all the cubicles.*

Despite the instantaneous differences between the different shade treatments, the total light sum over the 11 weeks of the experiment, see Figure 10, was very similar for the EC Regel, EC Screen and the coated glass treatments.

The average daylight sum was 6.5 mol/day for the treatment under the EC Screen and 7 mol/day for the coated glass and EC Regel. Although in the past (before 2013) growers used to keep the plants at daily sums of around 5 mol PAR/day, potanthurium can handle light sums up to 10 mol PAR/day. This provided: 1- leaf temperature does not exceed 32°C, 2- instantaneous intensity does not or only briefly and incidentally exceed 400 μmol/m²s, and: 3- relative humidity keeps at around 80% (Van Noort *et al.* 2013). The unshaded treatments reached daily light sums of 13 mol PAR/day and 13.5 mol PAR/day. That is in all conditions excessive for these plants.

3.3 Temperatures

Air temperatures were measured at 5-minutes intervals in each cubicle. The temperature of the glass surface was measured at different moments with a hand-held IR meter. The HEX-PAM measured the leaf temperature at five-minute intervals.

3.3.1 Air temperature inside the cubicles

The temperature in all the cubicles rose under the influence of sunlight. In the very hot days, the temperature in most cubicles rose above 40°C. In Figure 11, the maximum day temperatures in the greenhouse and in all cubicles are shown. The maximum temperature in the greenhouse was easily 5°C lower than in the cubicles. The greenhouse could ventilate by opening the ventilation windows, while the air exchange between the greenhouses and the cubicles was limited, despite the added fans, by the tissue covering the sidewalls. In addition, the misting system that was activated to increase the RH in the greenhouse has an evaporative cooling effect that hardly reached the air in the cubicles.

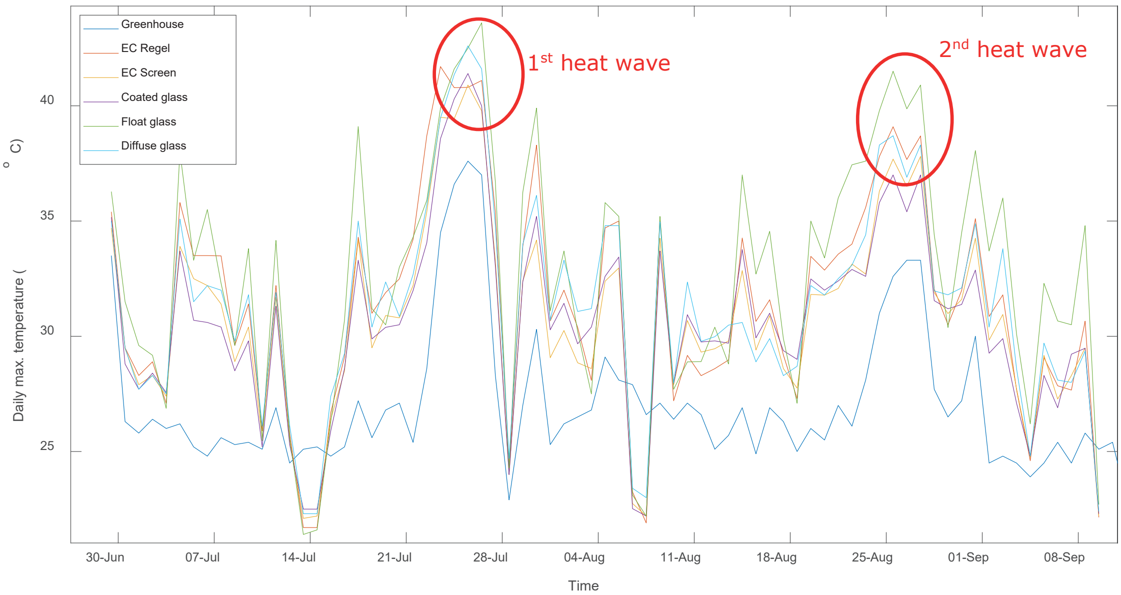


Figure 11 *The daily maximum temperatures measured for each treatment.*

Below the float glass the maximum temperature was always higher than below the diffuse glass pane. Under the Coated glass pane, the lowest air temperature was registered.
The two cubicles covered with the EC Glass panes showed different maximum temperatures: below the EC Regel, it is always warmer than below the EC Screen. A plausible explanation could be that the EC Regel controls the light level more frequently (every 30 seconds) compared to the EC Screen (every 30 minutes) which results in more heat production.

3.3.2 Temperature of the glass panes

Incidental temperature measurements of the glass surface (Table 1) showed that under the influence of high sun radiation, the EC Glass panes became very hot. The higher the incident radiation, the more frequent the glass needs to regulate, and the more light is absorbed by the glass, resulting in an increase of the surface temperature, with temperatures as high as 59.5°C measured on a very sunny day, 18.5°C higher than the coated glass.

Table 2

Temperatures (in °C) of the surface of the glass panes of all treatments at different moments and weather conditions

Day, time, conditions Treatment	28-06 13:00 shade screen in greenhouse unfolded	04-07 10:00 sunny	05-07 14:00 sunny	05-07 15:00 sunny	19-07 13:00 partially clouded	23-07 13:00 very sunny	23-07 14:00 very sunny
Float	30	34	27.5	30	29.5	39.5	45
EC Glass regel	31.3	40	48	58	34.5	48	55
EC Glass screen	33.5	37	47	57	36	52	59.5
Coating	32	30	35	33.5	26	37.5	41
Diffuse Glass	29.3	34	32	35.5	25	36.5	41.5

The coated glass had most of the times a cooler surface temperature, probably because it reflected the light instead of absorbing it like the EC glass does.

3.3.3 Leaf Temperature

The Hex-PAM equipment monitors several photosynthesis related parameters at leaf level. One of the key parameters is the leaf temperature.
Ideally, Anthurium leaf temperature should be maintained below 32°C. Above this temperature in combination with RH below 50%, stomata closure occurs and the plant cannot cool itself anymore by evaporating water.
As a result, the leaf temperature increases and the humidity in the air around the leaf decreases further. Leaf temperature increase indicates stomata closure, which costs growth, as no CO_2 can enter the leaves for the photosynthesis. Moreover, damage to the photosystem II at leaf temperatures above 44°C will make the leaf unable to perform any photosynthesis, also when the temperatures become lower (see 3.4). At higher temperatures, leaf burn due to overheating which is visible as necrotic spots, whole leaves drying out and becoming necrotic, and subsequently the flowers will burn/ dry out (Figure 16).

The measurements with the PAM sensors showed that leaf temperatures rose up to 54.7°C in the unshaded cubicles at moments with high radiation and very low RH (Figure 12). As a result, plants showed very quickly clearly visible burning symptoms (Figure 15). All shading treatments led to a reduction of the leaf temperature compared to the unshaded ones. The maximum leaf temperature registered under the EC Glass was 41.8°C (EC Regel, Figure 13) and 42.4°C (EC Screen). Under the coating pane, the maximum leaf temperature was 39.2°C (Figure 14). So, in terms of leaf temperature, the coated glass plate performed slightly better than the EC Glass panes. Some plants in the cubicles, especially the ones closer to the eastern wall, showed some leaf burning. Please note that the high leaf temperatures generally occur at low RH levels below 40%. In Table 2 the occurrence of leaf burning, the highest registered temperature, and the lowest measured RH are summarized.

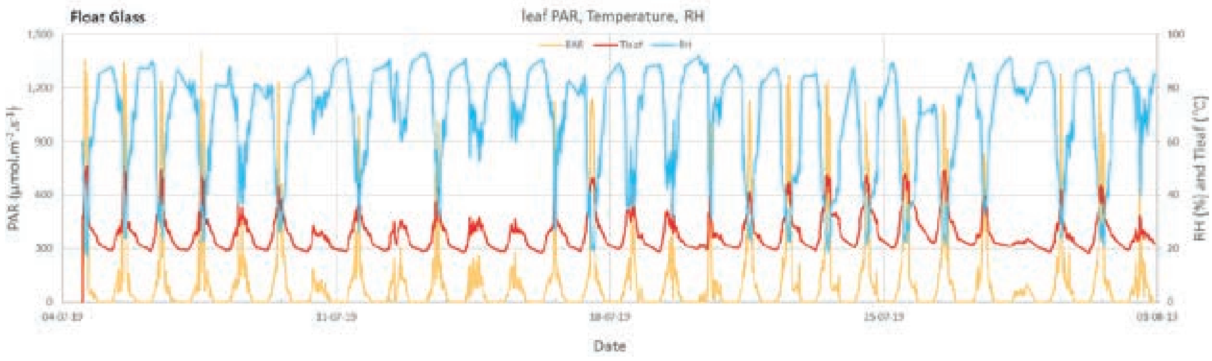


Figure 12 *Leaf PAR, leaf Temperature and RH as measured with the PAM in the month of July in one of the 2 cubicles with no shadow (float glass).*

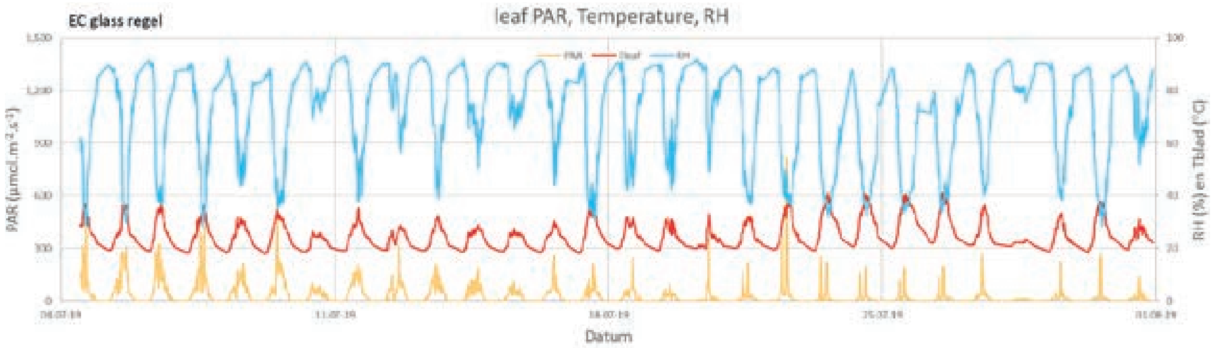


Figure 13 *Leaf PAR, leaf Temperature and RH as measured with the PAM in the month of July in one of the two cubicles with EC glass.*

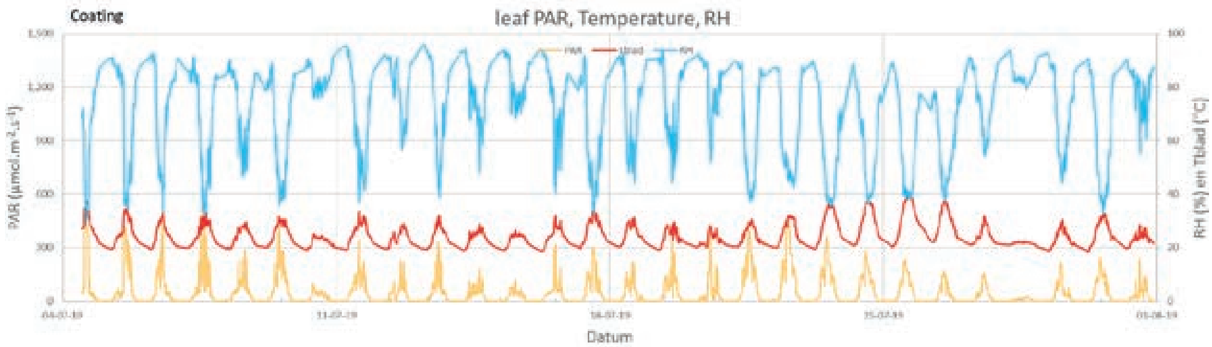


Figure 14 *Leaf PAR, leaf Temperature and RH as measured with the PAM in the month of July in the cubicle with coated glass.*

In accordance with previous research (Van Noort *et al.* 2013) we presume that the temperatures of the foliage would have been lower, with less or even no leaf burning as result, if we would have been able to control better the RH in the shaded cubicles by misting or fogging.

Table 3

Summary of highest measured leaf temperatures and PAR per treatment, as well as the lowest RH, the number of plants with burning symptoms and if in those plants damage to the photosystem was observed with the fluorescence measurement.

Treatment	Max. Leaf T	Min. RH leaf	Max. PAR	# plants with leaf burn (2/08)	Damage to PS2
Float glass	50.8°C	17.5 %	1404 µmol/m²/s	21	Yes
EC Regel	40.4°C	28.5 %	356 µmol/m²/s	5	No
EC Screen	42.4°C	27.1 %	578 µmol/m²/s	5	No
Coating	39.2°C	32.1 %	424 µmol/m²/s	3	No
Diffuse glass	54.7°C	22.8 %	1446 µmol/m²/s	18	Yes


Figure 15 *Left: first burning symptoms EC glass regel, after the failure on the 23rd of July; right: aspect of the totally burned plants under the diffuse glass pane (no shade).*

3.4 Photosynthesis (Chlorophyll fluorescence)

With the PAM, it is possible to monitor the course of the photosynthesis during a certain period, as affected by the PAR light conditions, CO_2 concentration, temperature, RH and the stomata regulation.
The following graphs show the measurements of the month of July, where we had the hottest week of this year (first heat wave with outside temperatures above 40°C), and where the differences among the treatments are most evident. The measurements of the month of September, with very little days of critical weather, are shown in Annex 1.

In the graphs, we show the calculated efficiency of the photosystem 2 (PS2) based on the fluorescence measurements in the different treatments. We also show the Fv/Fm value, or the maximum photosynthetic efficiency of the dark-adapted leaf.
(For the calculation of Fv/Fm, Fo (minimum) and Fm (maximum fluorescence of dark-adapted leaf) are needed. Fo and Fm are measured once a day in the dark (one hour before sunrise). That is why there is only one Fv/Fm value per day. If there is no light damage, the value of FV/Fm is every day the same. Values lower than the day before indicate that there is damage caused by light stress to the PS2.
Figure 16 shows the damage caused to the PS2 of a leaf in one of the unshaded cubicles (the diffuse glass): A small decrease after the 18th of July, followed by a new leaf on the 19th of July; a serious decrease to nearly zero after the first heat wave period in July 23 to 27th of July.
A similar plot was obtained with the plants under the other unshaded treatment.
The same graph but from the plants in two of the shaded treatments (Figure 17 and Figure 18) shows a better situation for the PS2: there was some damage to the PS2 causing a small decrease followed by stabilisation.

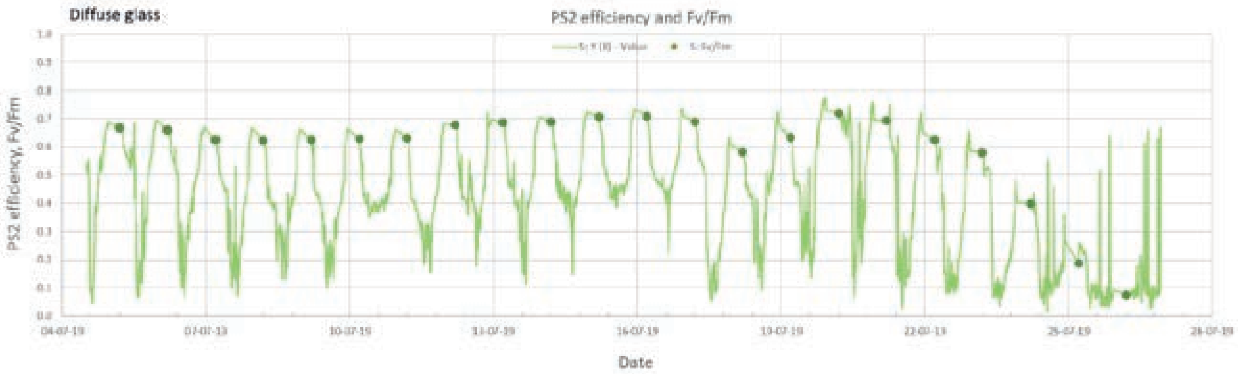


Figure 16 *PS2 efficiency of plants in the Diffuse glass treatment.*

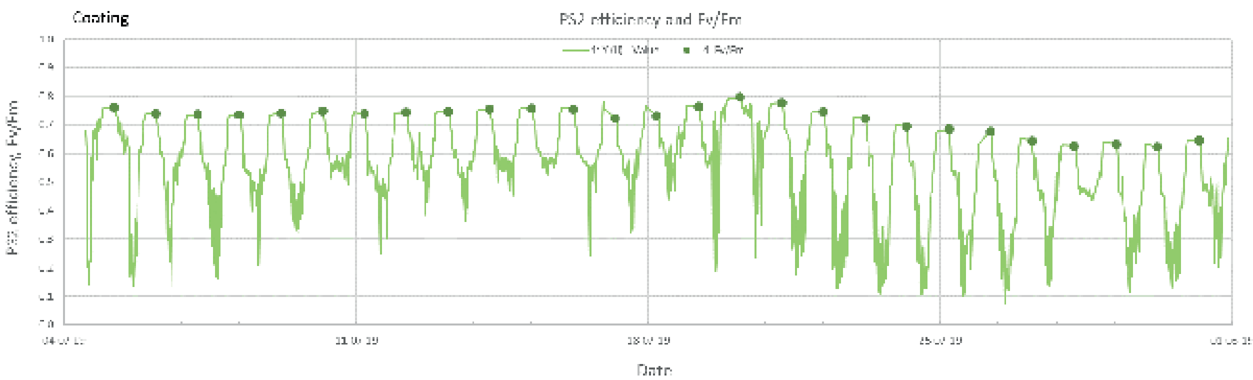


Figure 17 *PS2 efficiency of plants in the coated glass treatment.*

Figure 18 *PS2 efficiency of plants in the EC Screen treatment.*

The trend in the EC Regel is very similar to that of Figure 18; that of the float glass (no shade) very similar to that of Figure 16, and therefore, both are not shown.

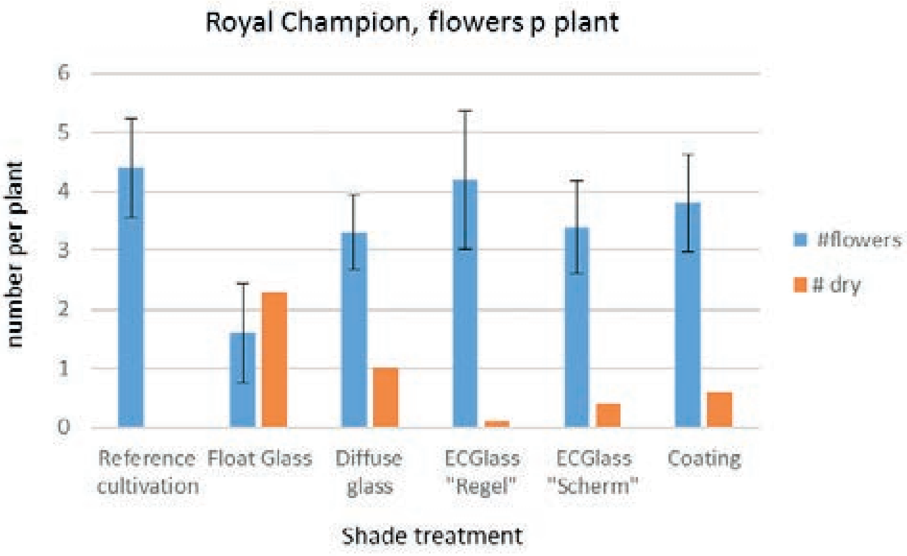
In terms of photosynthesis and light damage to the PS2, both EC glass treatments showed the same trend as the coating.

3.5 Plant growth and development

A selection of the results of the plant measurements are graphically shown below. Only 10 plants per treatment and variety were measured and there is quite some heterogeneity among the plants, which becomes evident in the sometimes big error bars (standard deviation).
Although we had 5 treatments in the experiment, in all graphs a sixth treatment is shown, that we have called "reference cultivation". These plants, of the same age and history, were taken from a different greenhouse, the one where the plants developed during phase I of the cultivation.

In Annex 2 and 3, pictures are shown where the aspect of the plants just before the measurements can be appreciated. The tables with the results of all measurements are shown in Annex 4.

In Figure 19, the number of flowers per variety is shown. Flower initiation happened already in the previous cultivation phase, so no big differences are to be expected. However, in both cultivars there is a trend for less flowers and more buds in the unshaded treatments (Float glass and Diffuse glass). If developed, the flowers show severe burning symptoms when unshaded. In the three shade treatments (EC Glass and Coating) there are less burned flowers but the number of flowers is as expected, not very different.



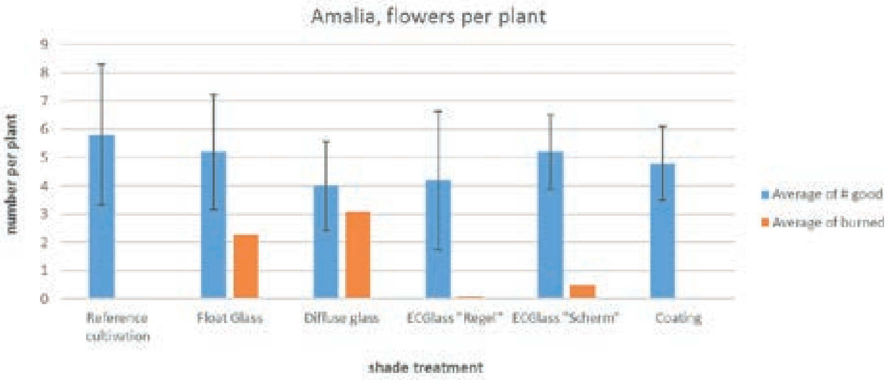


Figure 19 *The average number of flowers per plant and the average flowers dry or burned for both varieties (above Amalia Elegance, below Royal Champion).*

Compared with the plants from the reference cultivation, there was in both cultivars and in all the treatments in the experiment a trend for a lower plant fresh weight (Figure 20), for shorter plants (Figure 21) and for smaller leaves and flowers (Figure 23). This can be easily explained by the suboptimum conditions of temperature and RH in the cubicles, due to the lack of air circulation caused by the cloth covering the sidewalls.
Comparing within all the treatments in the experiment, the plants were smaller and lighter in the treatments with no shade (Float glass and Diffuse glass). However, because of burned /dried flowers and leaves, they had lost all their ornamental value.

The plants under the EC Glass treatments were comparable to the Coated glass treatment for most measured parameters.

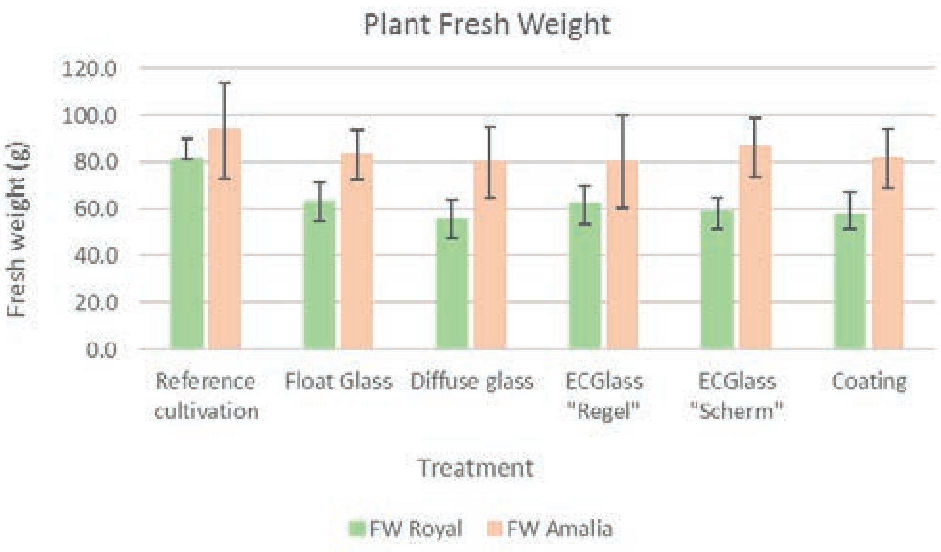
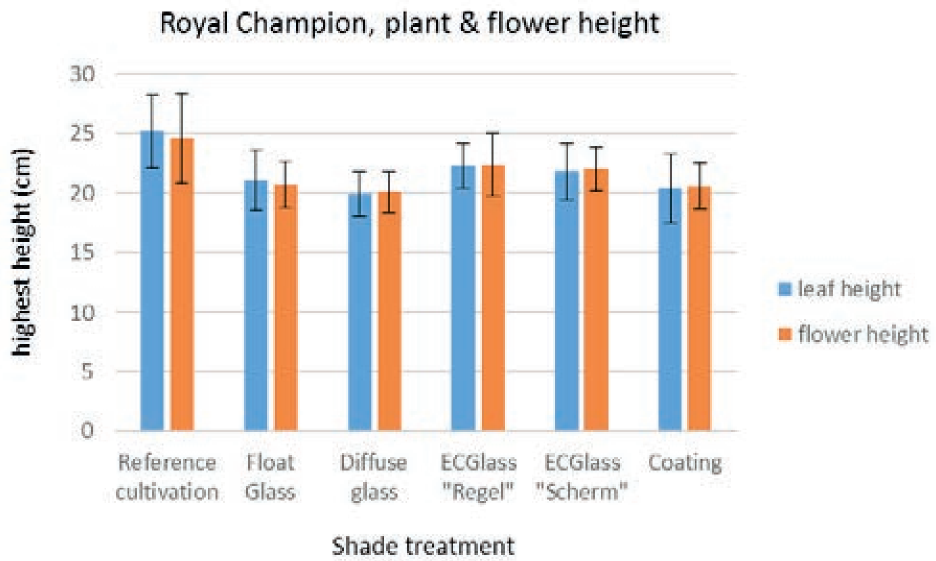


Figure 20 *Plant Fresh Weight for the different treatments.*



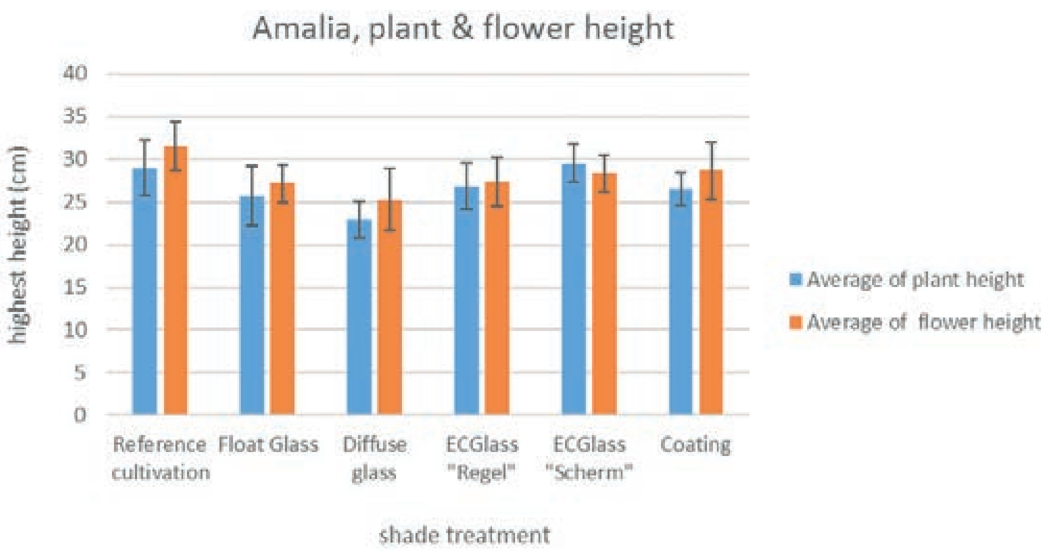
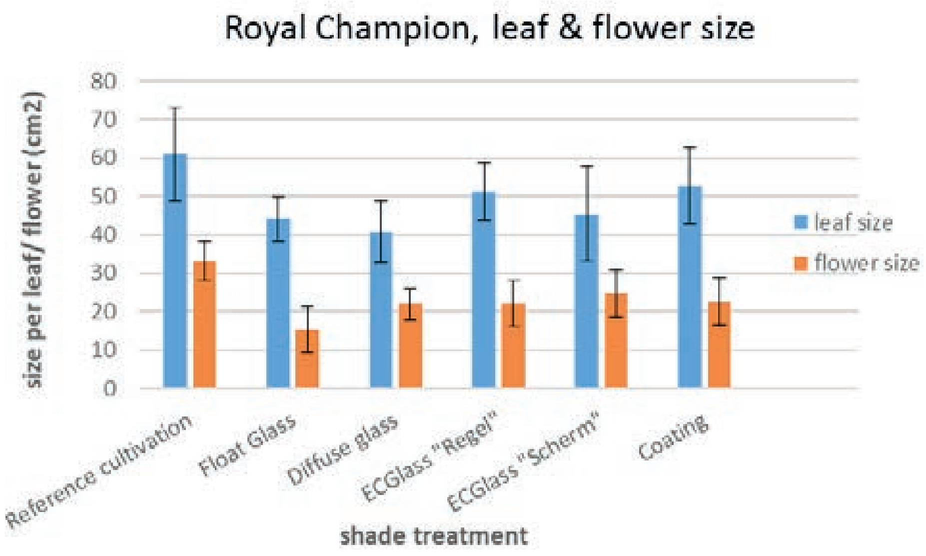


Figure 21 *The average height of the plant (highest leaf) and the highest flower for both varieties (above Royal Champion, below Amalia Elegance).*



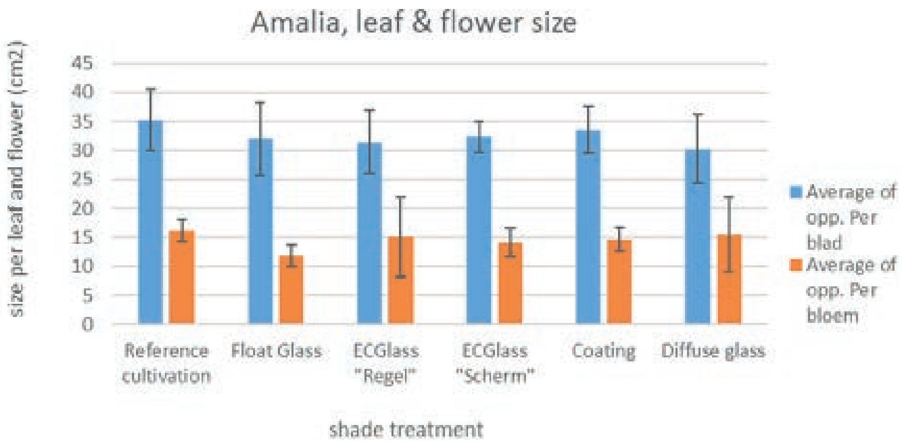


Figure 22 *The average surface of an individual leaf and flower for both varieties (above Royal Champion, below Amalia Elegance).*

Anthurium is a slow grower. As the experiment was conducted during only one third of the total duration of the cultivation, not very big differences in plant growth and development were to be expected. Moreover, because of the decision to replace the plants after 5 weeks of cultivation, we reduced even more the chance to observe great differences.

4 Conclusions

- The light level below the electrochromic glass has been well controlled at the set point of 270 μmol/m^{2}s.
- The surface temperature of the EC glass panes and the temperature below the EC glass pane were always higher at high light intensities compared to the other treatments.
- The EC glass in dark condition shifts the light spectrum under the glass to wavelengths with more energy with relatively more green and yellow and less red and far red.
- The plants below the float and diffuse panes were severely burnt during a heatwave (leaf temperatures reached 49°C), whereas only a few plants below the EC glass panes had burning spots.
- Before the heatwave, the crop below the EC panes and coated glass pane was in good condition, even though the control of the EC glasses failed which allowed light intensities up to 1000 μmol/m^{2}s.
- All plants in the experiment were smaller (smaller leaves & flowers and a lower fresh weight per plant) than the reference plants in a "normal" greenhouse. This effect was probably caused by the trial set up where the cloth creating sidewalls in the cubicle hampered air circulation and exchange with the rest of the greenhouse for cooler and more humid air. For a future experiment, the trial setup needs to be improved.
- The plants under the EC Glass were for most parameters comparable to the ones under the glass with coating (white wash).
- More research is required to evaluate the potential of EC glasses to become greenhouse covers for these high value crops.

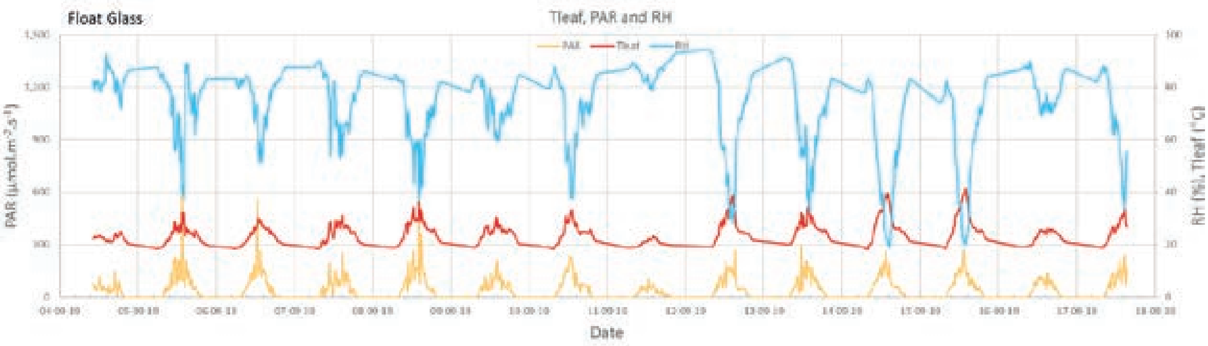
References

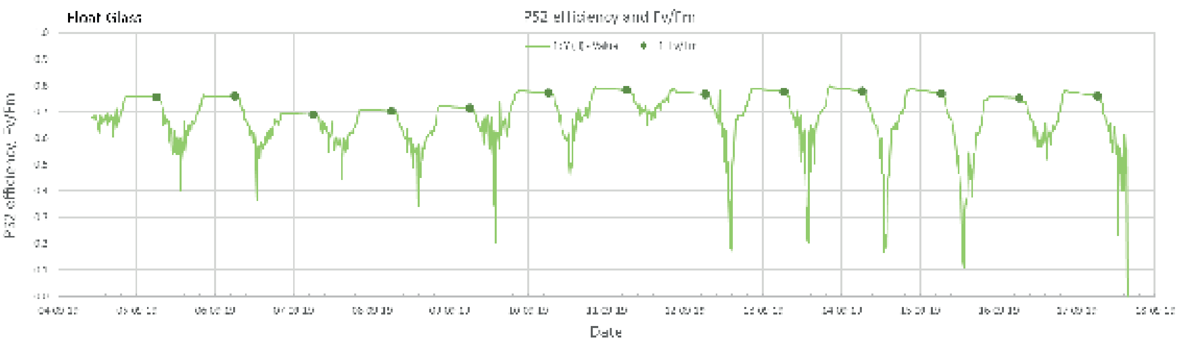
Straver, N.; De Kreij, C. en Verberkt, H., 1999.
Bemestingsadviesbasis potplanten, PBG publicatie.

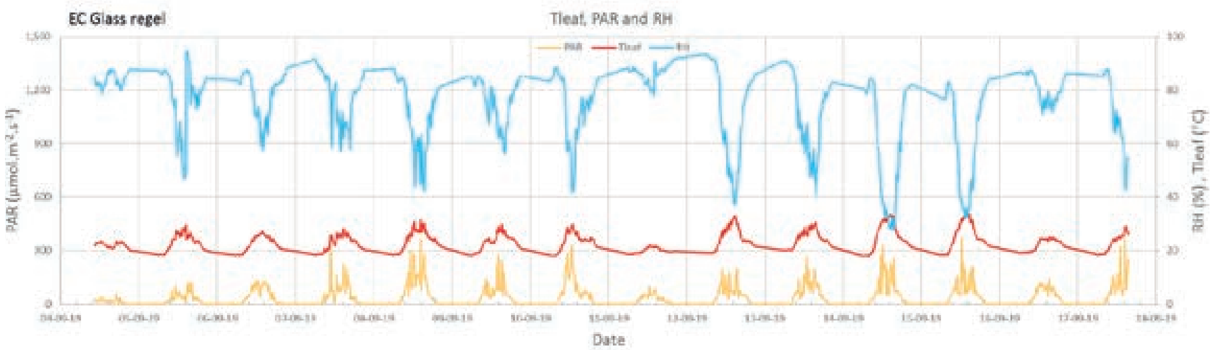
Van Noort, F.; Kromwijk, W.; Snel, J.; Warmenhoven, M.; Meinen E.; Li, T.; Kempkes, F. en Marcelis, L., 2013.
Grip op licht bij potanthurium en bromelia. Meer energie besparing bij Het Nieuwe Telen Potplanten met meer natuurlijk, diffuus licht en verbeterde monitoring. Rapport GTB-1287, Wageningen UR Glastuinbouw.

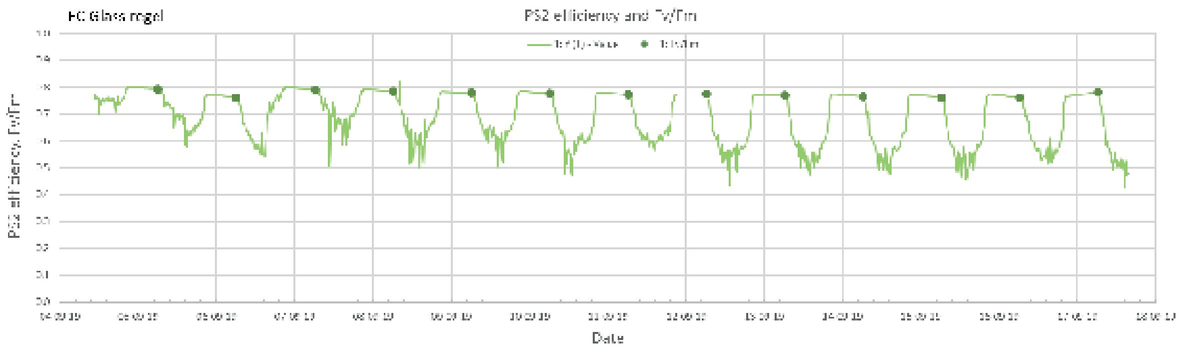
Annex 1 PAM measurements September

Results of the PAM measurements during the last weeks of the experiment (September)

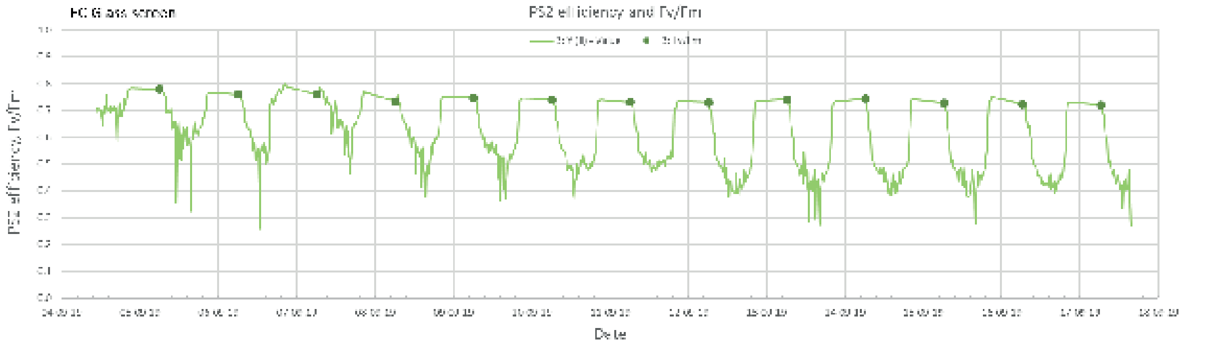


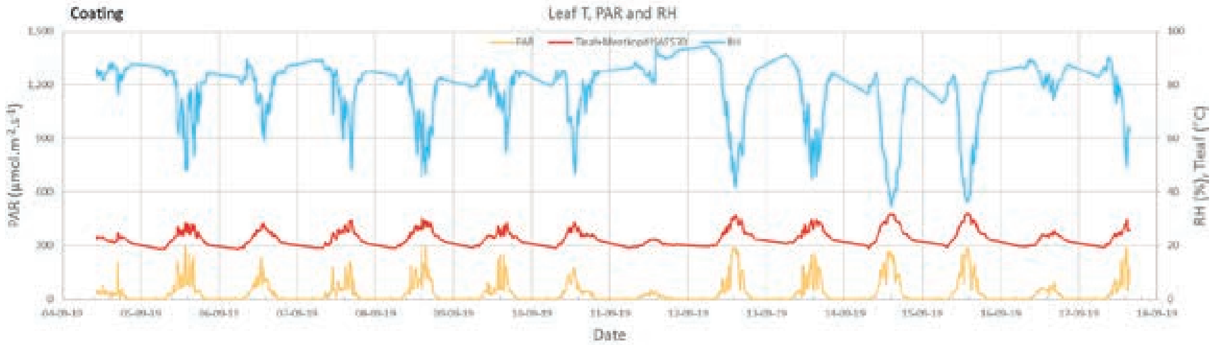


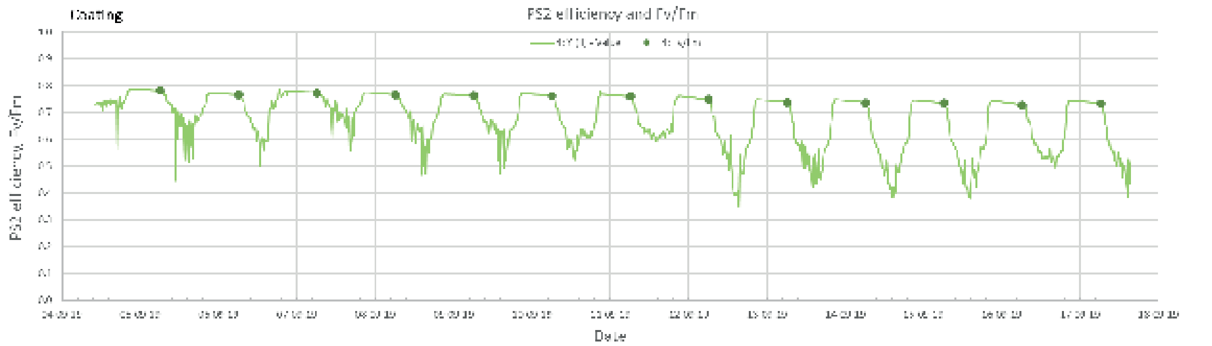


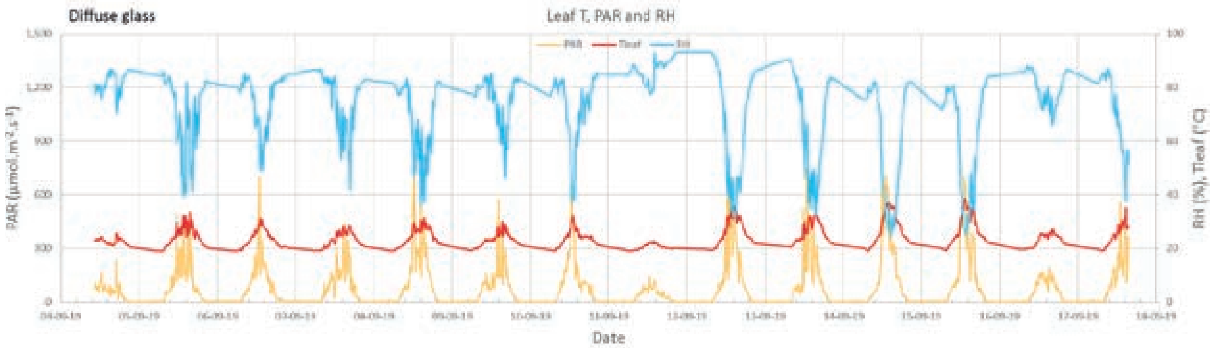


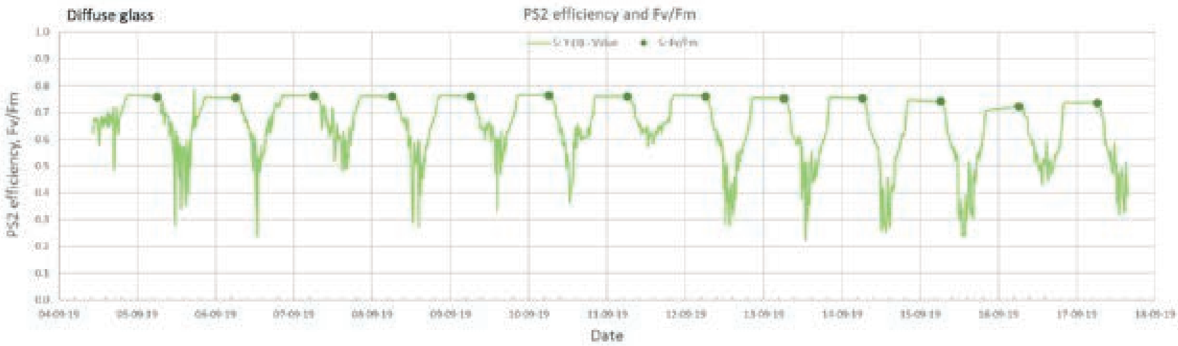

EC Glass screen
Tleaf, PAR and RH
PAR
Tleaf
RH
PAR (µmol.m-2.s-1)
RH (%), Tleaf (°C)
Date


EC Glass screen
PS2 efficiency and Fv/Fm
PS2 efficiency, Fv/Fm
Date


Coating
Leaf T, PAR and RH
PAR
RH
PAR (µmol.m-2.s-1)
RH (%), Tleaf (°C)
Date


Coating
PS2 efficiency and Fv/Fm
PS2 efficiency, Fv/Fm
Date


Diffuse glass
Leaf T, PAR and RH
PAR
Tleaf
RH
PAR (µmol.m-2.s-1)
RH (%), Tleaf (°C)
Date



Diffuse glass
PS2 efficiency and Fv/Fm
PS2 efficiency, Fv/Fm
Date

Annex 2 Pictures Royal Champion

Pictures of the Royal Champion variety at the moment of the destructive plant measurements


ELECTROCHROMIC GLASS,
CONSTANT LIGHT LEVEL

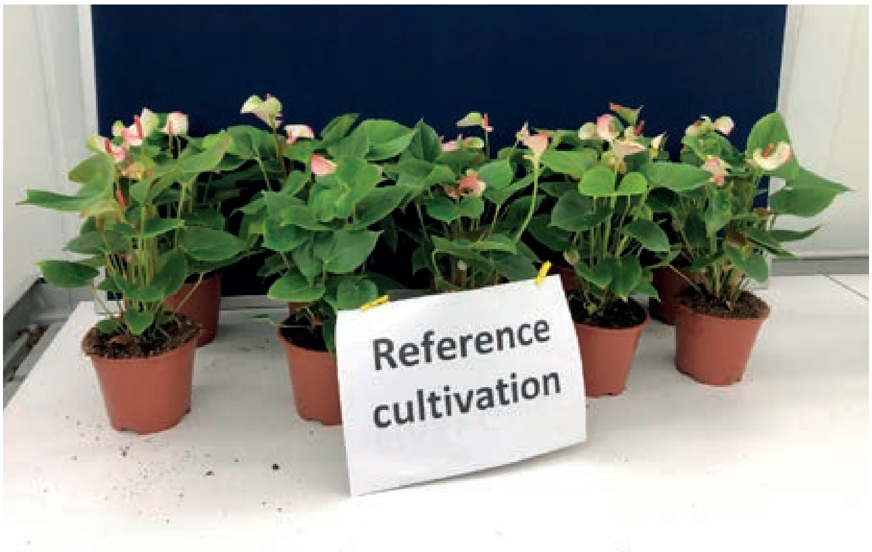

WHITE WASHED FLOAT GLASS
("COATING")


FLOAT GLASS


DIFFUSE GLASS

Annex 3 Pictures Amalia Elegance

Pictures of the Amalia Elegance variety at the moment of the destructive plant measurements




Diffuse
glass

Annex 4 Plant parameters

The tables below show the results of the plant measurements for both varieties. Values are means of ten plants. Different letters indicate significant differences between treatments (ANOVA, l.s.d. level 5%).

Royal Champion

Treatment	# buds (lsd 0.79)	# flowers (lsd 0.74)	# f.burned (lsd 0.61)	# leaves (lsd 2.63)	# l.burned (lsd 0.88)
Float	3.4 .b	1.7 ..c	2.3 ..c	17.4 .b	1.5 ..c
EC Glass regel	1.4 a	4.2 a	0.1 a	14.4 a	0.1 a
EC Glass screen	1.5 a	3.4 .b	0.4 a	15.9 ab	0.1 a
Coating	1.8 a	3.8 ab	0.6 a	14.1 a	0.9 .b
Diffuse Glass	1.2 a	3.3 .b	1.0 .b	16.9 .b	2.2 ..c
Reference Cultivation	1.3 a	4.4 a	0.0 a	14.6 a	0.0 a

Treatment	FW (g) (lsd 7.69)	Leaf height (cm) (lsd 2.26)	Flower height (cm) (lsd 2.29)	Sm width (cm) (lsd 3.25)	Wd width (cm) (lsd 3.70)
Float	63.3 .b	21.1 .b	20.7 .b	27.2 .b	29.6 .b
EC Glass regel	62.5 .b	22.3 .b	24.4 a	28.5 ab	32.2 ab
EC Glass screen	58.7 .b	21.8 .b	22.0 .b	29.2 ab	29.2 .b
Coating	57.8 .b	20.4 .b	20.6 .b	27.7 .b	31.1 ab
Diffuse Glass	55.6 .bc	19.9 .b	20.1 .b	25.0 .b	28.8 .b
Reference Cultivation	81.3 a	25.2 a	24.6 a	31.6 a	34.7 a

Treatment	Leaf surface p plant (cm^2) (lsd 94.6)	Leaf surface p leaf (cm^2) (lsd 9.17)	Flower surface p plant (cm^2) (lsd 23.2)	Flower surface p fl (cm^2) (lsd 4.71)
Float	760 .b	44.2 .b	60.0 ..c	14.7 ..c
EC Glass regel	731 .b	51.2 .b	92.7 .b	22.1 .b
EC Glass screen	709 .b	45.5 .b	81.2 .bc	24.8 .b
Coating	711 .b	52.1 ab	84.0 .b	22.6 .b
Diffuse Glass	673 .b	41.0 .b	72.0 .bc	22.0 .b
Reference Cultivation	869 a	60.9 a	144.0 a	33.2 a

Amalia Elegance

Treatment	# buds (lsd 0.71)	# flowers (lsd 1.70)	# f.burned (lsd 0.70)	# leaves (lsd 5.58)
Float	1.2 a	5.2 ab	2.3 .b	26.4 a
EC Glass regel	0.8 a	4.2 ab	0.1 a	24.0 a
EC Glass screen	0.9 a	5.2 ab	0.5 a	26.7 a
Coating	0.9 a	4.8 ab	0.0 a	24.3 a
Diffuse Glass	0.7 a	4.0 .b	3.1 ..c	26.3 a
Reference Cultivation	0.9 a	5.8 a	0.0 a	25.1 a

Treatment	FW (g) (lsd 12.5)	Leaf height (cm) (lsd 2.49)	Flower height (cm) (lsd 2.48)	Sm width (cm) (lsd 2.85)	Wd width (cm) (lsd 3.70)
Float	83.1 ab	25.7 .b	27.2 .bc	28.6 a	33.1 ab
EC Glass regel	80.2 .b	26.8 ab	27.4 .bc	29.4 a	35.3 a
EC Glass screen	86.4 .b	29.6 a	28.4 .b	29.2 a	34.6 .b
Coating	81.6 .b	26.5 .b	28.6 .bc	27.8 a	31.4 .b
Diffuse Glass	79.9 .b	22.9 ..c	25.3 ..c	27.7 a	31.3 .b
Reference Cultivation	93.8 a	29.0 a	31.5 a	30.4 a	35.3 a

Treatment	Leaf surface p plant (cm^2) (lsd 119)	Leaf surface p leaf (cm^2) (lsd 4.2)	Flower surface p plant (cm^2) (lsd 29.5)	Flower surface p fl (cm^2) (lsd 3.8)
Float	817 a	32.0 ab	60.8 .b	11.9 .b
EC Glass regel	870 a	31.5 ab	59.3 .b	15.4 ab
EC Glass screen	858 a	32.4 ab	72.2 ab	14.1 ab
Coating	799 a	33.6 ab	70.0 ab	14.6 ab
Diffuse Glass	779 a	30.3 .b	65.6 .b	15.5 ab
Reference Cultivation	875 a	35.3 a	95.9 a	16.2 a

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