Cultivation of the potted plants Schefflera and Anthurium under electrochromic glass

Smart Materials crop experiments

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Abstract
Anthurium and Schefflera are high-value ornamental crops requiring low sunlight levels, preferably of diffuse nature. This is achieved by shading screens, temporary coatings and combinations of both. Electrochromic glass able to regulate light transmission or diffusion could allow higher light sum than traditional shading without exceeding light damage thresholds, leading to improved crop growth. Two small-scale experiments were conducted simultaneously to evaluate the possibilities of EC Glass to be used as greenhouse cover for these crops. Two types of electrochromic glass where used: a darkening EC glass for anthurium; a diffusing EC glass for Schefflera. The EC Glasses were compared to a reference float glass with a temporary coating. Darkening EC Glass gave very good control of the light conditions: higher light sum by more constant light, less peaks on sunny days and more light on clouded days. However, this did not translate in faster growth, more flowers or better plant quality. The achieved light advantage by the glass was counteracted by high leaf temperatures that lead to stomata closure and lower photosynthesis efficiency during sunny periods. Diffusing EC Glass gave also good control of the light conditions as programmed: diffuse light whenever the set threshold was reached. The diffusive state lead to a slightly lower light sum than the reference coated glass. However, the changing diffusion conditions did not result in faster growth, nor better plant quality: the plants from the Diffusing Glass treatments remained shorter and had a lower leaf area than the constantly diffuse reference.

Referaat
Anthurium en Schefflera zijn hoogwaardige sierteeltgewassen die geteeld worden met laag, bij voorkeur diffuus licht. Dit wordt bereikt door schermdoeken, tijdelijke coatings en combinaties van beide. Met elektrochroom glas dat in staat is om de lichttransmissie of -diffusie te reguleren, kan een hogere lichtsom worden behaald dan met traditionele afscherming, zonder de drempels voor lichtschade te overschrijden. Dit kan teeltversnelling geven. Twee kleinschalige experimenten zijn simultaan uitgevoerd om de mogelijkheden van EC Glass als kasdek voor deze gewassen te evalueren. Twee soorten elektrochroom glas zijn gebruikt: tintbaar EC Glas voor anthurium; helder-diffuus EC glas voor Schefflera. De EC-glazen werden vergeleken met een referentie van floatglas met een tijdelijke coating. Tintbaar EC Glass gaf een zeer goede controle over de lichtomstandigheden: hogere lichtsom door constanter licht, minder pieken op zonnige dagen en meer licht op bewolkte dagen. Dit vertaalde zich echter niet in een snellere groei, meer bloemen of een betere plantkwaliteit. Het bereikte lichtvoordeel van het glas werd teniet gedaan door hoge bladtemperaturen die leidden tot huidmondjessluiting en een lagere fotosynthese-efficiëntie. Diffuus EC Glass gaf ook een goede licht controle zoals geprogrammeerd: diffuus licht wanneer de ingestelde drempel werd bereikt. De diffuse toestand leidt tot een iets lagere lichtsom dan het referentieglas. De veranderende diffusiecondities leidden echter niet tot snellere groei, noch tot betere plantkwaliteit: de planten uit de diffusieglasbehandelingen bleven korter en hadden een lager bladoppervlak dan de continu diffuse referentie.

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Summary

The project “Smart materials” is 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. Within the framework of this project, two small-scale experiments have been conducted during the summer of 2020. The aim of the experiments was to explore the performance of Electrochromic glass (EC Glass) as greenhouse cover and the possible benefits for plant growth and time to market of ornamental shade crops. Two glass type -crop combinations were compared with a different reference material (coated float glass).

1. Darkening Electrochromic Glass was tested as greenhouse cover for the flowering plant Anthurium. The glass can switch from clear state to progressively darker states when increasing voltages are applied. The material was already used with this crop in a first test in 2019 (García Victoria *et al.* 2020). As reference, float glass was used coated with a temporary coating at a dilution resulting in a shading factor that ensured that PAR values below the reference would be close to the desired PAR value during as many hours as possible, based on the analysis of historical PAR data from this compartment during the months that the trial would be held.
2. Diffusing electrochromic glass was tested as greenhouse cover for the green plant Schefflera. The glass can switch from clear state to highly diffusive state (from Hortiscatter 0 to Hortiscatter 80%, two possible states). As reference, float glass was used coated with a temporary coating at a dilution resulting in comparable shading as the diffusing glass in diffuse state.

The crops were cultivated in pots on elevated plant tables in a greenhouse compartment in Bleiswijk. The electrochromic glass as well as the reference glass was laid on metal frames at 50 cm above the tables. Plants grew below the glass cover on in total 4 tables per glass-crop combination. The set up was that of a “greenhouse in greenhouse” construction.

The hypothesis was that because EC Glass is able to change the light transmission / the light diffusion smoothly and fast 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 (in our reference, a coating on the greenhouse cover): 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

Darkening electrochromic glass
The experiment with plants (Anthurium) lasted 16 weeks. During this period, the light level below the darkening electrochromic glass has been perfectly controlled as programmed: to maintain a constant level of 300 μmol/m^2s. As a result of this smooth regulation, the plants under the darkening Electrochromic glass enjoyed more constant light, less peaks on very sunny days and more light on clouded days. This lead to a higher total PAR light sum than the coated glass reference, without exceeding the maximum light intensity threshold of 300 μmol/m^2s.

Despite the good performance of the glass in terms of light regulation, no advantages were observed in the speed by which plants grew and developed: the plants growing under the Electrochromic glass were not taller, nor wider, nor had a higher leaf area or fresh or dry weight, and did not have more flowers or buds than those growing under the coated reference. The explanation has been provided by the data collected by the PAM sensors . These monitor at plant level: leaf temperature, Relative humidity at the boundary layer and chlorophyll fluorescence, a measure of the efficiency of the Photosystem 2 (PS2) and thus photosynthesis capacity. The leaves under the Electrochromic glass showed in sunny days higher temperatures dan the leaves under the reference coated glass. Presumably, the high leaf temperatures induced closure of stomata, what caused the cease of transpiration, leading to dryer conditions at the boundary layer level. As a consequence, the efficiency of PS2 was lower.

The cause of the increase in leaf temperature is the increase in the temperature of the glass above the plants, due to both the electric power needed to regulate the light, and the absorption of light which is the essence of the light regulation by the material. The results confirm those obtained in a previous experiment.

In conclusion: the light advantage caused by the good light regulation of the electrochromic glass was counteracted by an increase of the leaf temperatures leading to stomata closure and less efficient photosynthesis compared to the reference.

Diffusing electrochromic glass
The experiment with plants (Schefflera) lasted 15 weeks. During this period, the light level below the diffusing electrochromic glass has been perfectly controlled as programmed: to switch from clear to diffuse at the set light intensity threshold (400 µmol/m^2s).
The diffusive state lead to a slightly lower light sum than the reference coated glass. The changing conditions did not result in faster crop growth, nor better plant quality. Instead, the plants from the diffusing electrochromic glass treatments were at the end of the experiment shorter, had less leaf area (projected and measured) and suffered more often a split apex, which stops the length growth of the stem and induced ramifications. There is not a ready explanation for this effect, but it could be that shade crops benefit from constant diffuse light rather than from a combination of direct light at low light levels and diffuse light at higher light levels. Maybe, because the reference coated glass provided conditions already around the optimum.

In conclusion: Despite the good light diffusion regulation by the glass, no beneficial effects have been found on the plants due to this type of light regulation compared to the reference conditions, which see, close to optimum values. Concerning changing light diffusion: there seems to be no benefit for shade loving plants of changing light conditions from clear to diffuse compared to permanently diffuse light

1 Introduction

Within the project "PPS Smart materials" different research groups and companies work on the development of new smart materials for application in greenhouse horticulture. Both fundamental material development and applied crop physiological experiments are part of the project. Development focusses on the instantaneous control of the light intensity, diffusion and spectrum through materials.

The present study concentrates within the framework of this project in two electrochromic glass types, "Switchable glasses". The glass reacts on an electric impulse allowing to control light intensity (from transparent to dark) or light scattering (from transparent to diffuse).

Limiting the light level up to a certain threshold is needed in order to cultivate shade plants. In practice, this is achieved by shading with screens above the crop, above the greenhouse roof, by white-washing the greenhouse cover, of by combinations of white wash and screen. This conservative method works well, but reacts slow and costs light in days with low radiation. Research has shown (Van Noort *et al.* 2013), that growth, quality and time to market of shade plants can be further improved when more light is allowed, provided the light is diffuse, and other conditions (relative humidity and leaf temperature) remain optimal. From this follows the interest for and expected benefit from greenhouse cover materials able to regulate the light level in the greenhouse faster, smother, better than the traditional systems: Higher light sum possible without exceeding light intensity thresholds, and therefore, faster growth and time to market.

During the summer of 2019, a small-scale experiment was conducted with one of these materials (darkening Electrochromic Glass), to explore the performance and benefits of switchable glass as greenhouse cover for the shade crop Anthurium in pots. The results showed that the material was promising because of the very smooth light regulation. However, an associated effect was found to that of the light regulation: the surface temperature of the EC glass could increase in very sunny and hot days up to 58°C leading to overheating of the air between the glass and the plants and to high leaf temperatures, which resulted in some plants in leaf burning. The plants under the EC Glass were for most parameters comparable to the ones under the glass with coating (white wash). It was concluded that the leaves probably heated up due to hampered air exchange between the space under the glass and the rest of the greenhouse for cooler and more humid air. This was attributed to the set-up, in which a semi-closed cubicle was created to avoid unregulated light coming from the sides, as glass was only available to cover the top of the cubicle.

The trial setup needed improvement for conducting future research. Although the best improvement would have been given by sufficient glass to cover a small greenhouse, which it is impossible at this stage, the experiment in the present report was conducted with a set-up which was considerably improved, considering the boundaries imposed by the limited availability of material.

1.1 Objectives

The objective is to perform a test in a greenhouse compartment in WUR Greenhouse Horticulture Research Centre in Bleiswijk to evaluate the effect on light availability and crop growth and quality on potted plants under two types of electrochromic glasses:

1. An electrochromic glass (ECG), which can switch from clear state to progressively darker states until it becomes completely opaque, when increasing voltages are applied. We have two glass panes (each one of 0.84 m * 1.35 m), which were already used in a first test in 2019.
2. An electrochromic glass (PVL), which can switch from clear state to highly diffusive state (from Hortiscatter 0 to Hortiscatter 80%). Therefore, unlike the first glass, there are only two possible states. We had two panes (each one of 2.57 m x 1 m) from this glass.

1.2 Research questions

1. Do switchable glasses improve crop growth (in potted plants expressed as time to market, size and good plant shape)?
2. Do they improve quality (leave burn, flower color) compared to the commercial way of cultivation with white wash or a diffusive coating on the glass cover (reference)?

1.3 Hypothesis

a. The higher light sum per unit time underneath the electrochromic glasses will increase crop growth per unit time.
b. The reduction of undesirable peaks of light intensity underneath the darkening ECG glass with continuous control will increase the growth (reduce the time to market), decrease risk of leaf burn and improve the quality of the plant.
c. The higher diffusion activated at high light intensities of the diffusing PVL glass will result in more homogeneous and lower leaf temperatures, which will result in less risk of leaf burn and improved quality of the plant, and a higher PAR sum than the reference, due to the slightly higher transmission of the PVL glass in clear state.

1.4 Approach

A crop cultivation experiment (15 weeks, week 15 - April 6 - till - week 31 – July 28) was conducted with two potted plant crops: Anthurium and Schefflera (one crop per EC glass type used). The electrochromic material available was limited and did not allow for covering a small greenhouse, so a “greenhouse in a greenhouse” approach was chosen meaning that eight “smaller greenhouses” were created inside one 144 m^2 greenhouse equipped with cultivation tables, by covering the crops with either the ECG Glass or the reference glasses on a heightened aluminum frame on the table.

2 Material and methods

2.1 Glass treatments

Two glass panes samples of each glass type were supplied. Following a previous experience in 2019 (García Victoria *et al.* 2020), a comparative experiment was designed (randomized block design). Per glass type one reference (coated material), in duplicate. The resulting treatments are shown in table 1.

Table 1
Treatments.

Treatment code	Glass type	Treatment	Crop
ECG 1	Darkening Glass	Glass pane managed to maintain an average light intensity of 300 μmol/m²s	Anthurium
ECG 2	Darkening Glass	Repetition of ECG 1	Anthurium
ECG Ref 1	Float glass coated (Redusol, 1:4), final average transmission 40%.	Reference	Anthurium
ECG Ref 2	Float glass coated (Redusol, 1:4), final average transmission 40%.	Repetition of reference	Anthurium
PVL 1	Diffusing Glass	Glass pane managed to go on diffuse state when a PAR intensity set point of 430 μmols/m²s is exceeded	Schefflera
PVL 2	Diffusing Glass	Repetition of PVL1	Schefflera
PVL Ref 1	Float glass coated (Redufuse, 1:4), final average transmission 68 %	Reference	Schefflera
PVL Ref 2	Float glass coated (Redufuse, 1:4), final average transmission 68 %	Repetition of reference	Schefflera

2.2 Setup Greenhouse experiment

Due to the limited availability of the material, a small-scale experiment was performed with a “greenhouse in a greenhouse” approach. One greenhouse compartment in Bleiswijk (9.04) (Figure 1) was used.

Figure 1 *The greenhouse compartment where teh 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, especially suited for the cultivation of potted plants (Figure 1).

The tables allow irrigation by means of ebb flood. Two different irrigation solutions are allowed, one for each crop (see section 2.1.4).

The greenhouse compartment is equipped with a roof shading screen as well as lateral screens, (Figure 1). However, for the duration of this experiment they remained folded (with some exceptions, see section 2.1.7) in order to allow as much light as possible on top of the tested glass panes.
The RH of the air could be increased whenever it dropped 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 a greenhouse” construction

All the glass panes (electrochromic glass and reference glass planes alike) were installed horizontally above the plants (as a flat second roof) supported by aluminum frames (Figure 2) placed on the center of the tables, in a similar way as in the experiment of 2019 (Garcia Victoria *et al.* 2020).

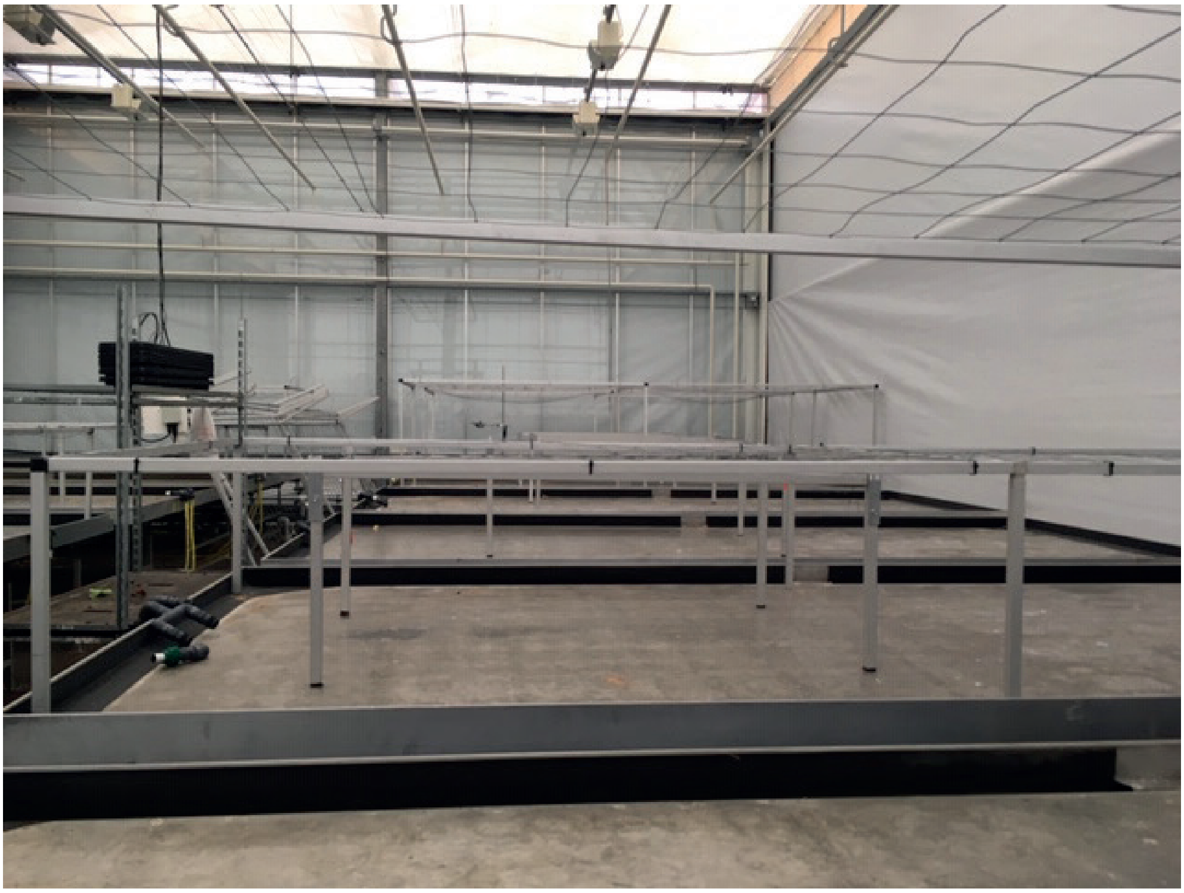


***Figure 2** Aluminium frames built to support the heavy Electrochromic Glass panes and the reference glass panes.*

The height of the supporting racks as well as the way to avoid lateral light as much as possible was pre-determined by means of Solar Ray Trace Simulations.

2.2.3 Ray Trace simulations for height and lateral light avoidance

Solar ray tracing simulations have been performed to:

1. Analyze the effect on horizontal light distribution of the distance between the glass panes and the plants.
2. Find solutions to minimize “pollution” from side radiation not crossing the test panes.

For the first question, the distance between the glass and the table, distances of 10 to 50 cm with steps of 10 cm were simulated. For the second question, how to minimize lateral light pollution, 7 solutions were proposed:

a. No curtain/cover.
b. Side vertical curtain on the sides with black material (same as last year, Figure 3).
c. Side vertical curtain with specular mirror.
d. Side vertical curtain with matt reflection film (some specular effect).
e. Side vertical curtain with Lambertian diffusor.
f. Horizontal foil with a shading factor of 70% and glass on fully clear state.
g. Horizontal foil with a shading factor of 30% and glass transmission of 0%.

Simulations were performed for each combination of height and solution.
The results are shown in 3.2 and have led to a final layout on the tables as represented by the scheme (Figure 3), and pictures below (Figure 4 and Figure 5) where the distance of 50 cm used last year was maintained.
To minimize the amount of light intercepted by plants that has not been transmitted through the glass, and in view of the results from the simulations, a horizontal shading screen, kindly supplied by L. Svensson at no cost, was installed around the glass. For each material, a different screen was used.

For Anthurium, around the darkening ECG glass and its reference (light reducing coated float glass) a Harmony 6020 O E FR screen, with transmissivity 40%, was used.
For Schefflera, around the diffusing PVL glass and its reference (diffuse coated float glass) a Harmony 3315 O FR screen, with a Transmissivity of 67%.

These screens placed horizontally around the glass offer a similar result as a side black vertical curtain but limits the increase in temperature compared to the close cubicle with the mentioned vertical curtain.

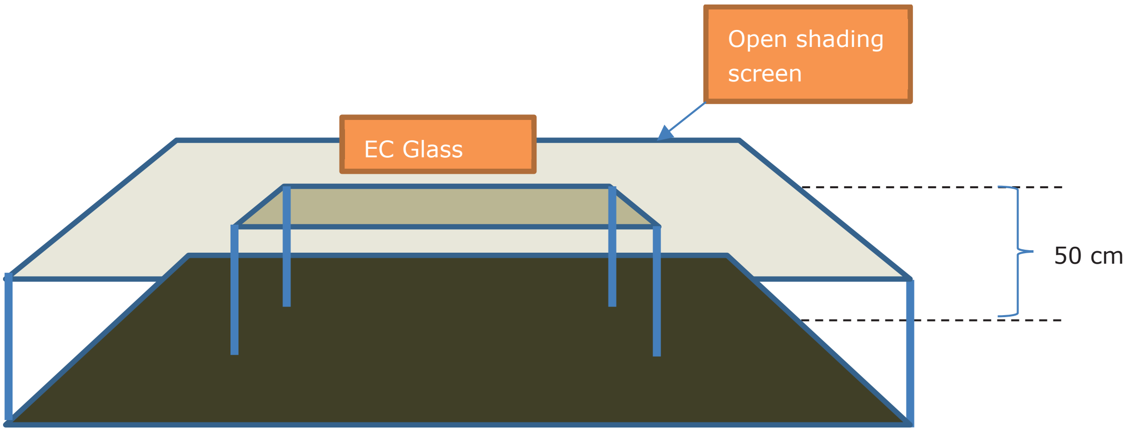


Figure 3 *Scheme of the construction on each table to support the glass and shading screen; down, the final set up with the screen around the glass.*

Figure 4 *The construction with aluminium frame to support the glass and the surrounding screen to avoid lateral radiation.*

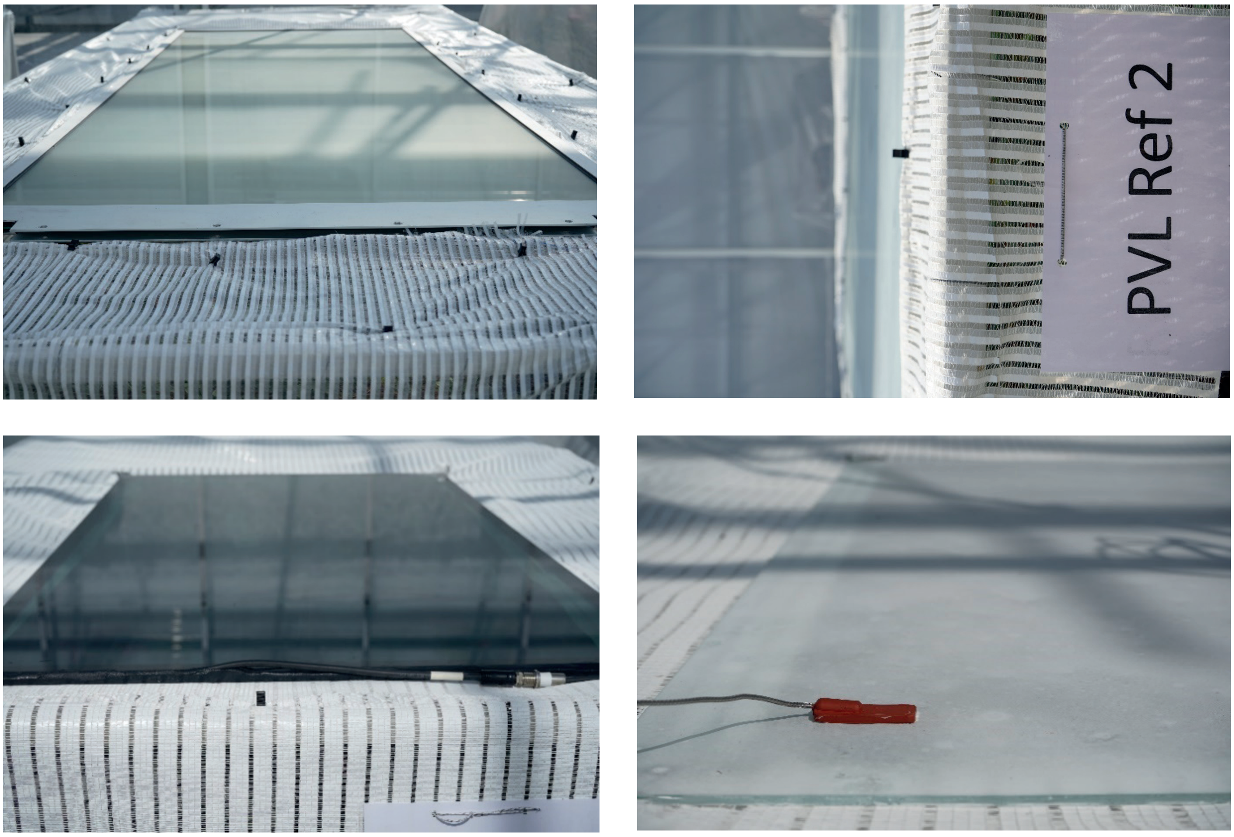


Figure 5 *Final set up: up left, the diffusing glass; up right, the reference for the diffusing glass; down left, the darkening glass; down right the reference for the darkening glass (Reduheat coated) with a surface temperature sensor.*

2.2.4 Plants

Each of the 14 tables in the greenhouse were filled with plants, 7 with each crop, in order to create a realistic growing environment (in growers' terms: to maintain the "climate"). However, only 8 tables were dedicated to the treatments. On the remaining 6 tables, plants from another compartment were placed temporarily (in the first weeks) and later replaced by plants from every spacing episode (see below).

2.2.4.1 Anthurium

For the experiment with the darkening electrochromic glass, small anthurium plants (cv. Royal Champion, Anthura), in pots of 12 cm were used, with a development stage that allows cultivation until nearly the "ready to market" stage.
Plants were supplied by a commercial grower on April 2, 2020 with an initial height (including the pot) of 16-18 cm before the flowering stage. The plants were placed directly after arrival on the tables at a density of 72 plants per m^2.

After 4 weeks, on the 4th of May, the plants were spaced for the first time, from 70 to 50 plants/m^2.
The plants were spaced a second time on the 10th of June to their final density of 33 plants/m^2.
The total number of plants to be placed in the greenhouse compartment for the tables with the four treatments was 3.192.

2.2.4.2 Schefflera

For the diffusing electrochromic glass, Schefflera, a tropical green plant, was selected as it can deal better than anthurium with the higher light levels under this glass type (PVL does not influence the light transmission but the light diffusion).

Schefflera cuttings (mostly one leaf) of one variety were supplied on the 8th of April 2020 by a commercial grower in 13 cm pots containing peat free potting soil. The pots were placed tight against each other (about 50 pl/m^2) at the start. The plants grow fast and after 4 weeks (7-5) spaced to a density of 33 pl/m^2. In four more weeks (4-06) plants were spaced for the second time to a final density of 21 pl/m^2 and wood sticks were used to keep them growing upright. At this stage, the faster plants would be 50 cm tall and ready to market in about 2-4 more weeks. However, the space below the glass was limiting, so, a measurement was performed (premature ending measurement).
In order to investigate the plant reactions when the conditions would become more challenging for the glass due to hotter weather in combination with even higher light intensities, it was decided to heighten the frames with the glass by 30 cm and allow the plants to keep growing beyond their commercial length, at a density of 18 pots/m^2.

2.2.5 Irrigation and fertilization

Fertilization took place with every irrigation by means of filling the cultivation table (ebb flood) with water containing a balanced nutrient solution.

2.2.5.1 Anthurium

The potting soil usually contains a slow release fertilizer mix; anthurium transpires very little; the plants are cultivated, according to commercial practice, rather dry, so they normally got only one irrigation per 5-7 days; this irrigation (by means of ebb flood.) consisted of a nutrient solution (see table 2) with EC 1.8 mS/cm (Straver *et al.* 1999). When plants of one treatment dried faster, they could have some extra water by a hose, or gave an extra water flood, as each treatment was placed in a different table.

Table 2
Composition of the nutrient solution anthurium.

		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

2.2.5.2 Schefflera

The potting soil is a peet free mixture of organic materials. Plants were irrigated once every 3-4 days by ebb flood. The composition of the nutrient solution is based on the nutrient solution from Bemestings Advies Basis potplanten for this crop, Straver *et al.* 1999, but adapted to the caracteristics of the growing substrate, and was modified every 3-4 weeks according to the changes that occur in the substrate. In Table 3 the start solution is given.

Table 3
Composition of the nutrient solution schefflera.

		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
2.9	5.4	0.7	6.1	7.0	2.5	19.8	2.6	0.8	8.5	9	9	30	9.8	1.5

2.2.6 Management of light modulation by the EC Glasses

Below every glass pane an Apogee PAR-sensor which monitored and recorded the PAR light at 5 minutes intervals was placed above the crop at about 5 –15 cm below the glass .

Figure 6 *A PAR sensor was placed under each glass treatment to monitor (reference treatments) and modulate (electrochromic glass) the light at plant level under the glass.*

2.2.6.1 Darkening glass

The ECG glass was controlled based on this PAR-sensor. The glass controls the light level once every 30 seconds, becoming from transparent to dark if the average light intensity of the last 30 seconds was higher or lower than the setpoint (300 μmol/m^2s),

This is a slightly higher threshold than the 2019 experiment (that was controlled at 270 μmol/m^2s). Research (Van Noort *et al.* 2013) has shown that anthurium plants can handle light intensities up to 400 μmol/m^2s and short light pulses up to 500 μmol/m^2s, provided air humidity and leaf temperature are well controlled. We foresee less difficulties controlling these parameters than in the previous experiment thanks to the partially open screen, so still being conservative, we felt it was safe to increase the threshold with 10% more light compared to the previous experiment.

2.2.6.2 Diffusing glass

The PAR sensor below the glass was also used to control the PVL glass switch: When the light level below the PVL was higher than 430 μmol/m^2s the glass switched to diffuse. At levels below this threshold, the glass was transparent.

2.2.6.3 Management during conditions of extreme weather

Despite the low transmission of the greenhouse, on sunny days there still might be too much radiation under the PVL glass, and too much heat development under the darkening ECG glass due to the proximity of the plants to the dark glass " roof" (as we learned in the 2019 experiment).

Figure 7, shows the results of simulating the PAR intensity below the PVL glass, with the actual climate data of April to August of the past year 2019. For the simulations, we assumed 40% hemispherical transmission for the compartment and 68% for the PVL glass. Although this would be very diffuse light, this could possibly affect the plant growth (risk for light damage and overheating, with leaf burning as a possible result).

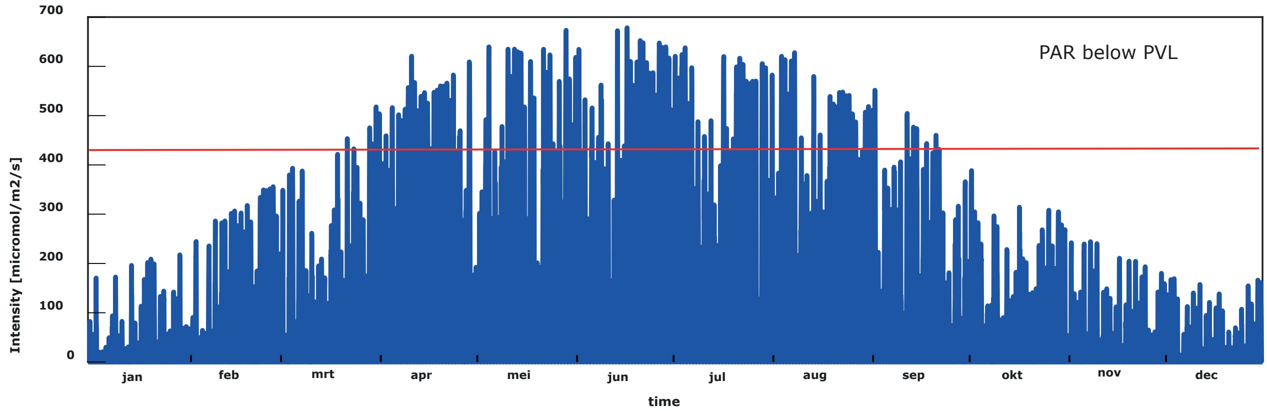


Figure 7 *Radiation under the PVL glass for year 2019 from April to August, PAR intensity below the PVL assuming an average 40% hemispherical transmission for the compartment and 68% for the PVL.*

As a protective measure, we concluded that the top screen might be used on days with an outside radiation above 750 W/m^2, (less than 11% of the daytime hours between April and August 2019), and in the event of a heatwave with days with outside temperatures above 35°C.

In view of the good performance of the glass and the plants, the "extreme wheather threshold" was increased to 850 W/m^2 on the 22nd of April and to 1000 W/m^2 on the 4th of May.

2.2.7 Sensors and climate 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 treatment, 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.

The conditions at the plant level (only for the Anthurium plants) were monitored during the period 28-05 to 28-07 with the aid of a Hex-PAM (Pulse-Amplitude-Modulation) sensor which, clipped to a mature leaf (Figure 8), 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.

Figure 8 *The PAM sensor monitoring at leaf level PAR, leaf temperature, RH and the electron transport speed (ETR) as a measure for the photosynthetic activity.*

The measuring leaf and plant is changed once every 7 days.

Two contact temperature sensors (pt100 patch surface sensor, RT) monitored the surface temperature of one of the two replicates of the darkening glass, as it was known from the 2019 experiment that it could become very hot, and of one of the coated references. The contact sensors (see Figure 5, down right) where attached to the glass by means of a heat transmitting adhesive tape.

The light spectrum was measured on the experiment of 2019 below the darkening Electrochromic glass treatments with a JETI Spectrophotometer in both the state of maximum transparency and the state of maximal shading / darkest tint colour (García Victoria *et al.* 2020).

2.2.8 Plant measurements

Plant measurements have been conducted at the start, at the spacing moments and at the end of the experiment.

For non-destructive measurements, an automatized WUR-developed device based on vision technique (WUR Plantalizer, Figure 9, Figure 10) was used. The WUR Plantalizer has one upper and one lateral camera and photographs each plant 12 times from above and from the side by turning the plant 360 degrees. The images are processed automatically and used for estimation of different measures.

2.2.8.1 Start measurement

At the beginning (when the plants were supplied just before the start of the experiments in the first week of April) both a non-destructive (with the WUR Plantalizer, PL) of 10 plants per treatment and a destructive (D) measurement of 10 plants was performed, in order to quantify

- Projected leaf area (PL)
- Plant height (PL)
- Number of flowers (PL, if present)
- Leaf angle (PL)
- Flower and leaf colour (PL)
- Number of leaves (D)
- Leaf area (D), with a leaf area meter (LI-3100C, Li-Cor inc., Lincoln, USA).
- Fresh and dry weight (D) of leaves including the stems will be determined, the latter after drying for at least 48 h at 80 °C in a ventilated oven.

The plants for the non-destructive measurement were randomly selected from the sampling area (center of the glass), and then labelled with a number so these plants would be followed during the progress and end measurements.

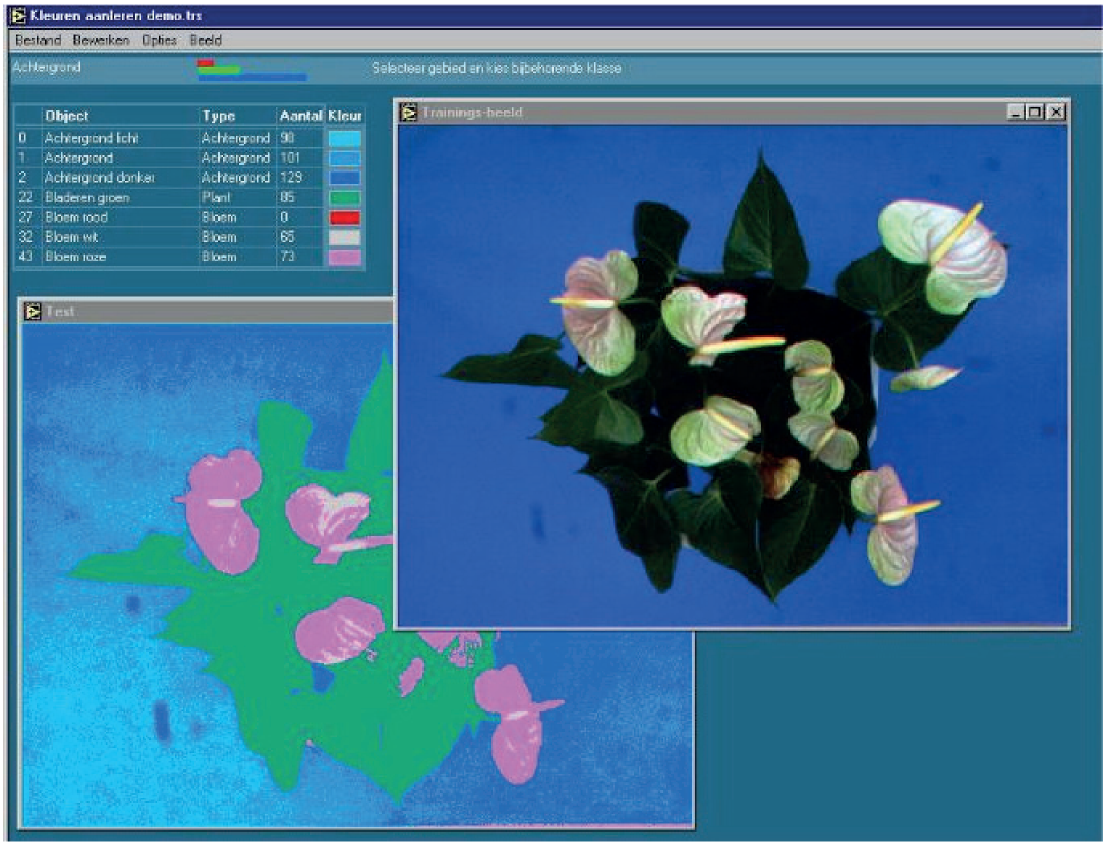


Figure 9 *An image of a plant as "seen" by the WUR Plantalizer, and the measurements it can produce.*

Figure 10 *The WUR Plantalizer is a Vision device that allows automated non-destructive measurements of plants. Left: the transporting band after the measurements; top right: plants passing through the vision chamber. Bottom right: the full equipment.*

2.2.8.2 Progress measurements

At each spacing episode (whenever plants were given more space by decreasing plant density), the labelled 10 plants per treatment were measured non- destructively again (with the WUR Plantalizer, PL).
The 10 plants per treatment were photographed individually by the WUR Plantalizer and as a group per treatment manually at the moment they were measured.

2.2.8.3 End measurements

At the end of the experiments (end of July 2020), again both destructive and non-destructive measurements were performed as described for the start measurements under 2.2.8.1.

3 Results and discussion

3.1 Transmission measurements

3.1.8.1 Darkening glass (ECG)

Hemispherical transmission measurements were performed in 2019 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 helped calculating the tint level needed to get the transmission of the EC glass to reach the desired light level below the EC-glass (García Victoria *et al.* 2020)

3.1.8.2 Diffusing glass (PVL)

Hemispherical transmission measurements were performed with two Electrochromic glass sheets (size 2.57 m x 1 m) in the LightLab of WUR Greenhouse Horticulture in Wageningen
The material can switch from clear state to highly diffusive state (from Hortiscatter 0% to Hortiscatter 80%). Unlike the darkening ECG glass, there are only two possible states. The material has a transmission of 73% in clear state and 68% at maximum diffuse state.

3.1.8.3 The Greenhouse Compartment

The light transmission of the compartment was measured on a cloudy day on multiple spots per table with the side screens closed to avoid light from the sides.
On average only 40% (see Figure 11) of the light is reaching the tables, and there are position differences; therefore, no treatments were laid on the tables closer to the greenhouse side walls.

meting	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	AVG
tafel 1	23%	24%	25%	26%	28%	29%	29%	30%	31%	32%	33%	33%	34%	35%	35%	35%			32.8%
	30%	31%	32%	33%	34%	34%	35%	36%	37%	37%	37%	38%	38%	39%	39%	39%			
tafel 2	33%	34%	36%	37%	38%	39%	40%	41%	42%	42%	43%	43%	44%	44%	44%	44%	44%	44%	40.1%
	33%	34%	35%	36%	37%	38%	39%	40%	40%	41%	41%	42%	42%	42%	43%	43%	43%	43%	
tafel 3	32%	33%	35%	36%	38%	39%	40%	41%	42%	43%	44%	44%	45%	45%	45%	45%	44%		41.1%
	35%	36%	37%	38%	39%	40%	41%	41%	42%	43%	43%	44%	44%	45%	45%	45%	45%	45%	
tafel 4	36%	36%	38%	39%	40%	41%	42%	43%	43%	44%	45%	46%	47%	48%	48%	48%			43.4%
	38%	38%	40%	41%	42%	44%	44%	45%	46%	46%	47%	47%	47%	48%	48%				
tafel 5	38%	40%	41%	42%	43%	44%	45%	45%	46%	46%	47%	48%	48%	49%	50%	50%			45.2%
	38%	39%	40%	42%	44%	45%	46%	47%	47%	48%	48%	48%	48%	49%					
tafel 6	39%	41%	42%	43%	45%	46%	48%	49%	49%	50%	50%	51%	51%						45.8%
	39%	40%	41%	42%	43%	45%	46%	47%	48%	48%	48%	48%	48%	48%					
tafel 7	35%	36%	37%	38%	40%	41%	42%	43%	44%	43%	44%	44%	44%						39.6%
	34%	34%	34%	36%	38%	39%	40%	41%	41%	42%	41%	40%	40%						

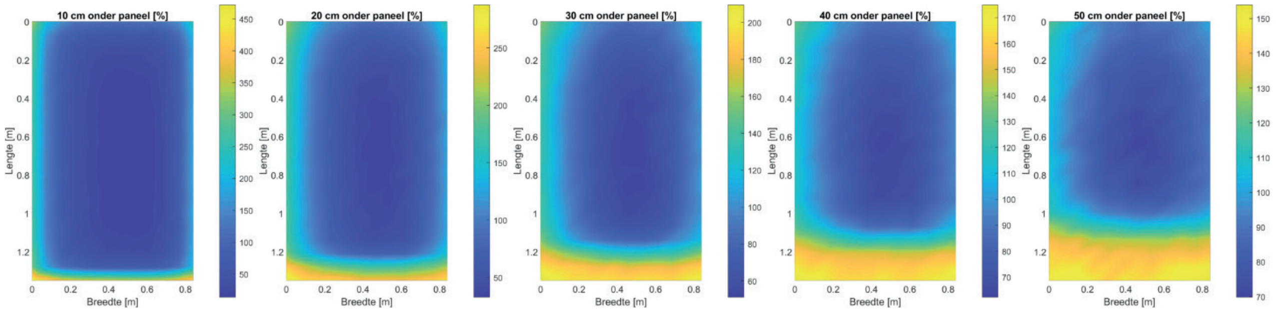
AVG	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	meting
29.8%					32%	32%	32%	31%	30%	30%	29%	29%	28%	26%	24%	23%	23%	22%	tafel 8
						36%	36%	36%	35%	34%	33%	31%	30%	30%	29%	28%	27%	26%	
35.8%								37%	37%	37%	36%	36%	36%	34%	33%	31%	31%	30%	tafel 9
							43%	42%	42%	41%	39%	38%	37%	35%	34%	32%	31%	29%	
40.4%						45%	45%	44%	44%	43%	42%	40%	39%	37%	35%	33%	32%	32%	tafel 10
						48%	47%	47%	47%	46%	44%	42%	41%	39%	38%	36%	34%	33%	
42.4%								48%	47%	47%	46%	45%	43%	42%	40%	38%	36%	36%	tafel 11
				48%	48%	47%	47%	46%	45%	44%	43%	42%	40%	39%	38%	37%	35%	34%	
42.6%							49%	48%	48%	46%	45%	44%	42%	41%	39%	37%	36%	35%	tafel 12
							48%	47%	47%	47%	46%	45%	43%	42%	40%	38%	35%	34%	
40.0%								47%	46%	46%	44%	43%	42%	40%	38%	36%	35%	35%	tafel 13
								44%	44%	43%	43%	41%	40%	39%	37%	34%	33%	31%	
33.4%							41%	40%	40%	40%	39%	38%	37%	35%	34%	32%	30%	30%	tafel 14
						34%	34%	34%	33%	32%	32%	31%	31%	30%	28%	27%	26%	27%	

pad · deur · 39.5%

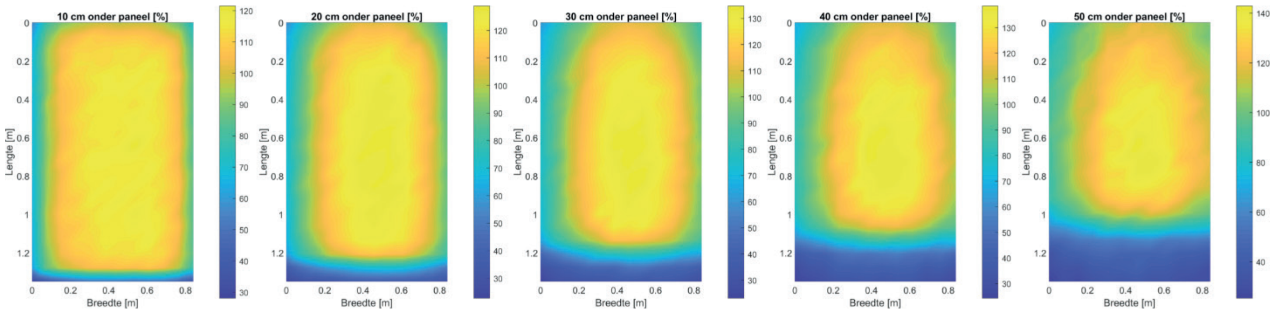
Figure 11 *Transmission of the greenhouse per table when measured with the side screens closed. The color scale indicates maximum transmission (green) to minimum transmission (red).*

3.2 Solar ray tracing simulations

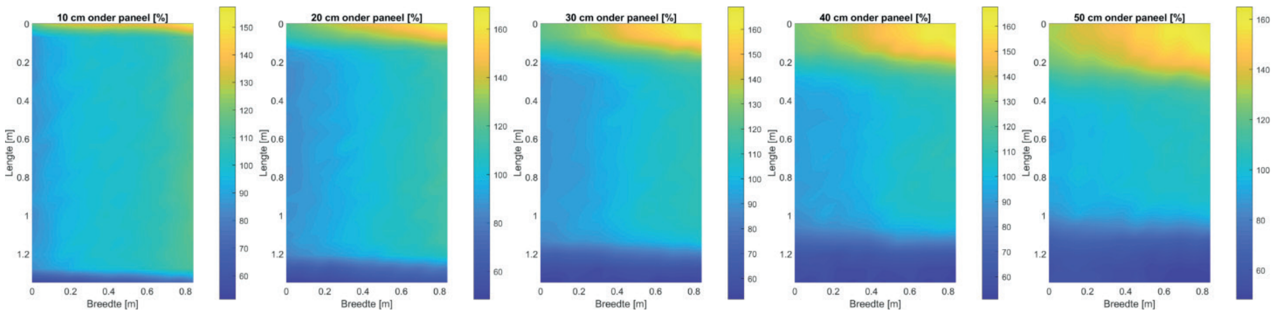
Simulations were performed with 7 solutions to minimize light pollution from the sides under the glass placed horizontally at different heights above the crop.
The results of the simulations are shown graphically in Figure 12. The plots show the light sum of the whole experimental period (based on actual meteo of Bleiswijk 2018 (diffuse and direct)) expressed as a distribution under the glass surface in percentage of the light relative to the mean sum of the whole surface



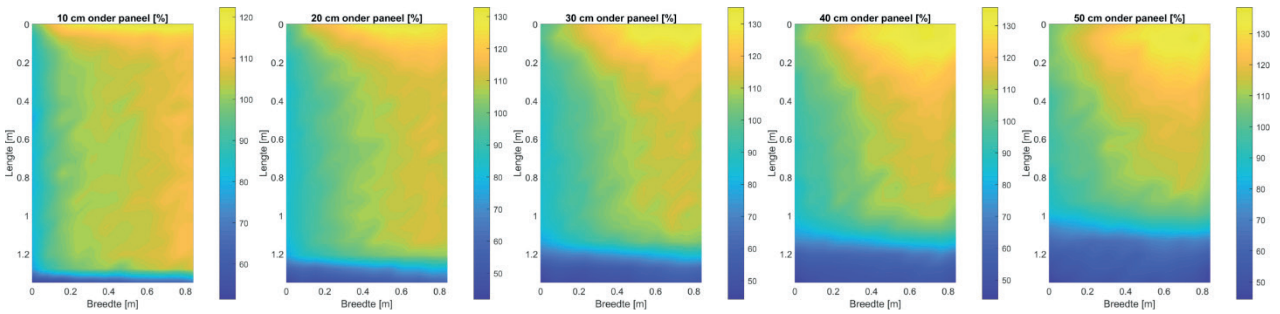
a. Open on the sides



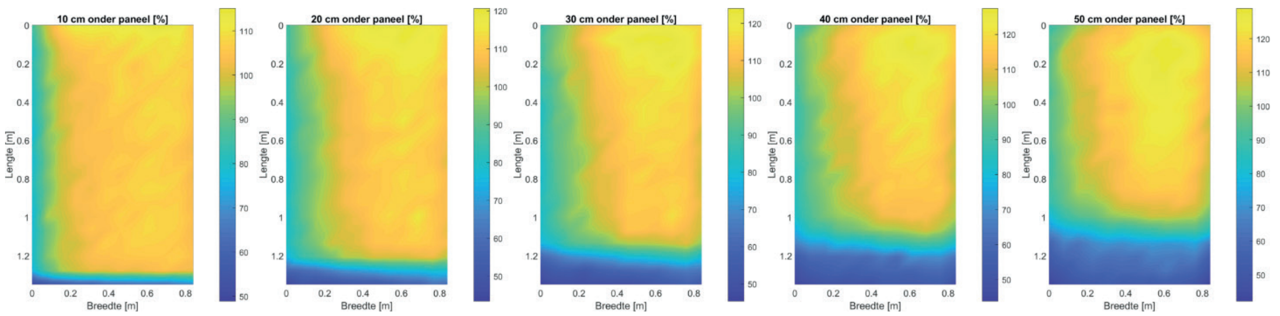
b. Black cover on sides



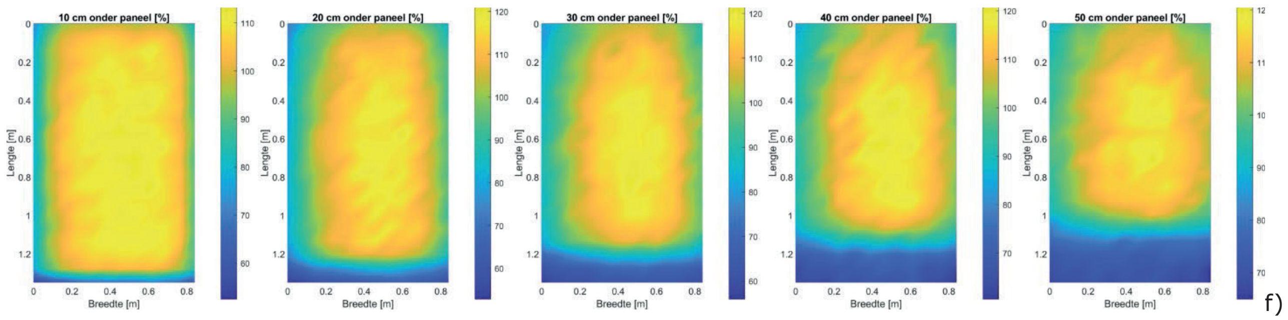
c. Mirror



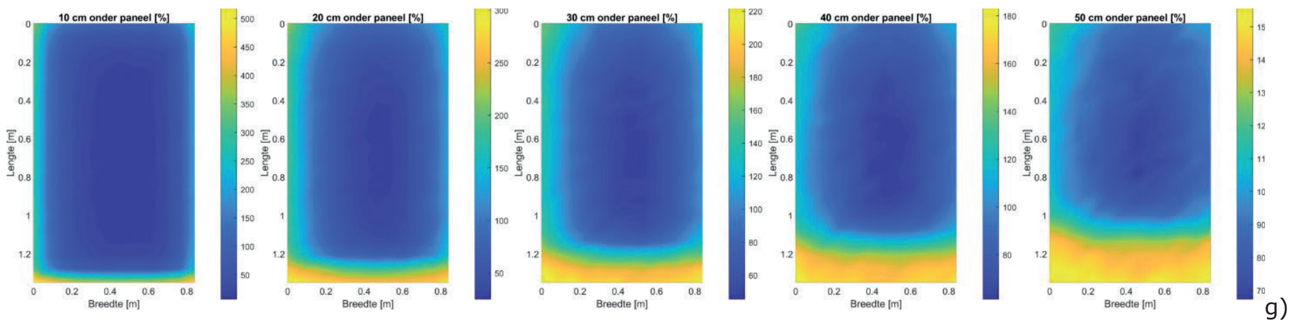
d. Mat partial reflector



e. Lambertian diffuser



f. Horizontal foil T=30% glass T=100%



g. Horizontal foil T=70% glass T=0%

Figure 12 *Results of simulations. Light sum of the period from April to August (Bleiswijk 2018, both diffuse and direct) relative to the mean sum of the whole surface.*

Results indicate that increasing distance from the plants is limiting in all cases the area with more homogeneous light distribution. However, we know from last year that even at a distance of 50 cm, on very sunny and hot days the darkening ECG glass heats up when it gets dark, and therefore it gets extremely hot below the glass, what could damage the plants irreversibly if placed closer to the glass.
We also need to allow space for the plants to grow (in 24 weeks they might reach 35-40 cm). We will therefore keep the distance of 50 cm used last year.

To minimize the amount of light intercepted by plants that has not been transmitted by the glass, and in view of the results from the simulations, we will install a horizonal shading screen which offers a similar results as a side black vertical curtain but generates less temperature problems.

Also, for extreme weather days we allow the use as back up of the shading screen of the greenhouse.

3.3 Light levels under the glass treatments

3.3.1 Darkening electrochromic glass

The average PAR light intensity inside the greenhouse and below the different treatments during the hours in which PAR radiation inside the greenhouse was above 300 μmol/m^{2}s, which marks the desired light level (yellow line) is shown in Figure 13. In general, the two repetitions of the ECG treatment and the two repetitions of the reference treatment maintain average daily values which are close to the desired level. The average PAR intensities below the two repetitions of the ECG treatment are on a daily basis closer to the desired value than under the two repetitions of the reference treatment. It is worth highlighting that the greenhouse PAR sensor had too much structural shading at the beginning of the crop. From the 28th of may it was positioned in a better location with hardly any shade. In addition, and to prevent the greenhouse compartment temperatures becoming too high and damaging the crop, the greenhouse screen was initially closing when outside radiation exceeded 800 W/m^2, which was analysed to be too conservative, so from 23rd of April onwards, the set point was risen to 850 W/m^2 and on the 4th of May it was risen again to 1000 W/m^2. This explains why the average values of PAR under both treatments are slightly below the desired set point on very sunny days.

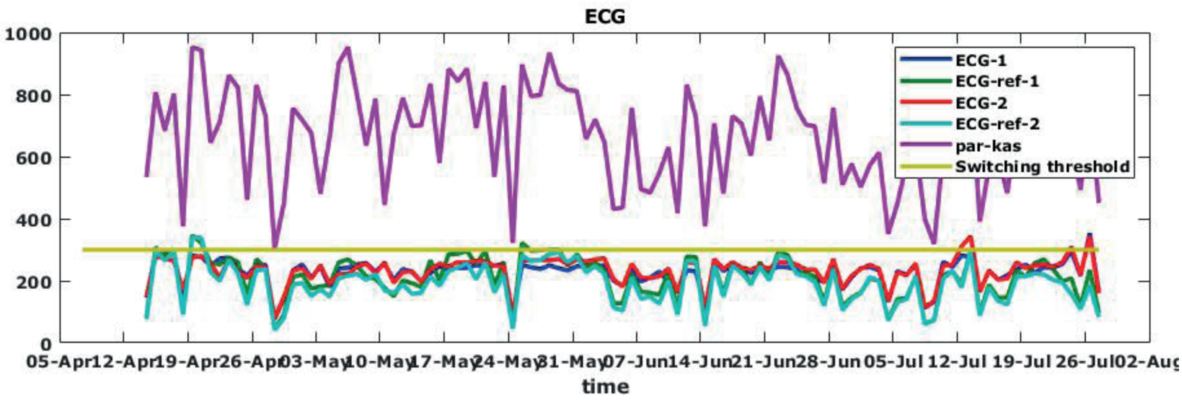


Figure 13 *Average PAR intensity (when PAR>270 µmol/m²s) below the two ECG glass panes (ECG-1 and ECG-2) and the two reference coated glass panes (ECG-ref1 and ECG-ref2).*

3.3.1.1 Daily cycle mean

The daily cycle mean of PAR values (Figure 14) gives more insight and confirms that PAR is higher and closer to the desired value of 300 µmol/m² s under the ECG glass panes than under the coated panes. The lower values under the reference glass panes are mostly caused by excessive shading on cloudy days. There is a relevant difference in the values below ECG-1 and ECG-2 during the morning period, which shows consistent higher values for ECG-2. This can only be explained on the basis of a structural shading on the sensor in ECG-1. In the afternoon this difference is reversed, but it is much smaller, indicating that the shading effect on the sensor is also less pronounced.

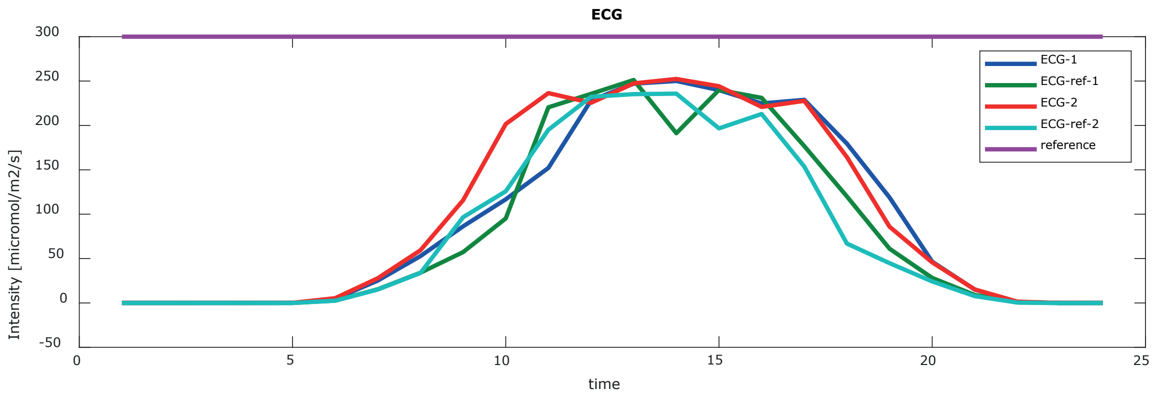


Figure 14 *Daily cyclic mean of PAR intensity below the two ECG glass panes (ECG-1 and ECG-1) and the two reference coated glass panes (ECG-ref1 and ECG-ref2) and the desired PAR value (reference).*

3.3.1.2 Example of light regulation on a sunny day

For a better insight on the beneficial effect of using ECG to maintain the desired PAR level, we focus on both on a very sunny and clear day (Figure 15, May 25th) and on a cloudy day (Figure 16, July 6th). The capacity to regulate the PAR intensity below the ECG glass panes, maintains values closer to the desired set point during most of the daytime hours, whereas in the reference, values exceed the desired set point. The strong decrease observed on ECG-ref-1 slightly after noon must be caused by a structural shading on the sensor, (table position effect) because this is not observed in ECG-ref-2 (Figure 15).

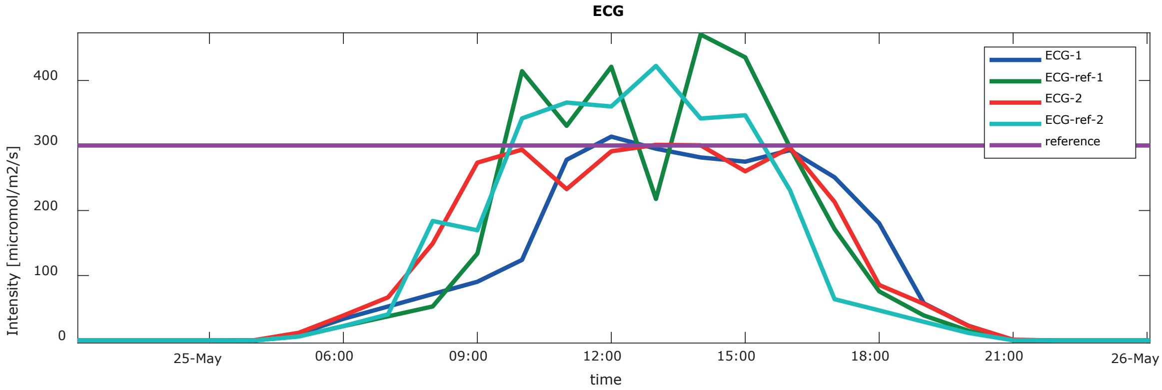


Figure 15 *Evolution of PAR intensity below the two ECG glass panes (ECG-1 and ECG-1) and the two reference coated glass panes (ECG-ref1 and ECG-ref2) on a sunny day and the desired PAR intensity (25th May).*

3.3.1.3 Example of light regulation on a cloudy day

On a cloudy day (Figure 16), the possibility of the ECG glass to keep a clear state with higher PAR transmission maintains higher PAR levels, closer to the desired threshold, whereas under the coated glass, in the reference treatment, PAR values are below the desired level.

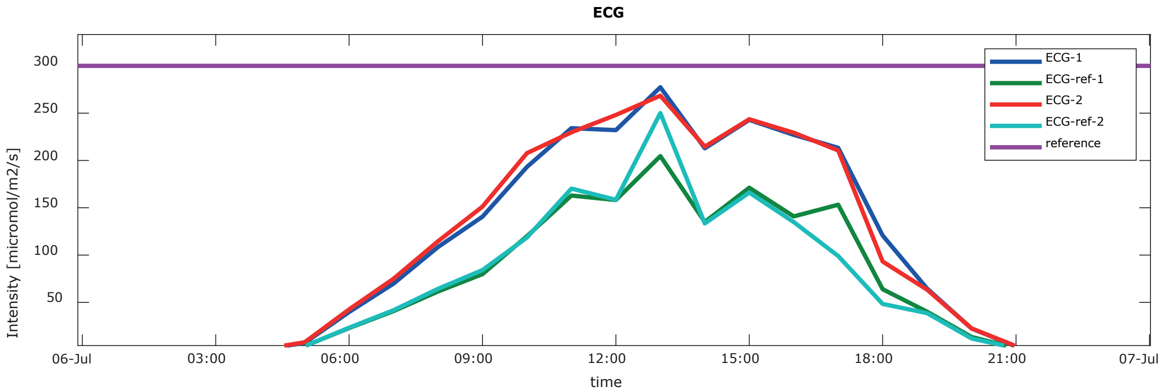


Figure 16 *Evolution of PAR intensity below the two ECG glass panes (ECG-1 and ECG-1) and the two reference coated panes (ECG-ref1 and ECG-ref2) on a cloudy day and the desired PAR intensity (6th July).*

3.3.1.4 Total PAR sum under each glass treatment

The measured final sum of PAR is larger under the two ECG repetitions than under the two reference repetitions, especially under ECG-2, whose sensor was less shaded during the morning period (Figure 17).

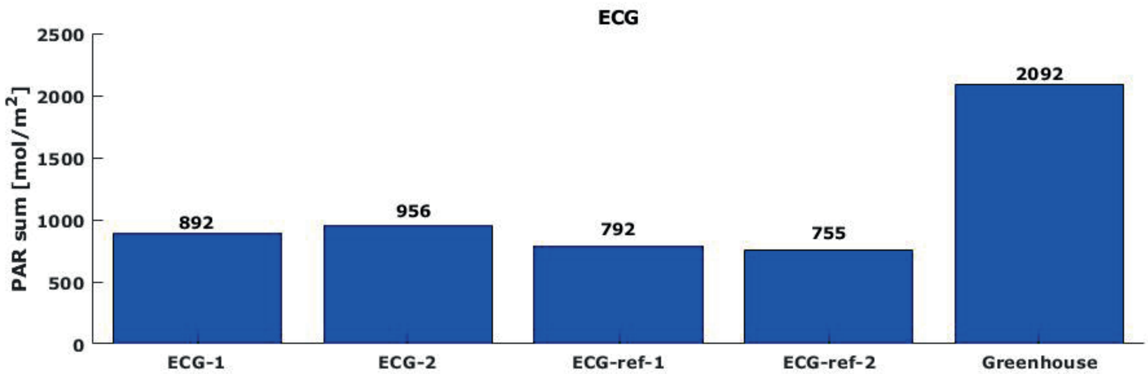


Figure 17 *PAR sum measured in the greenhouse and below the different treatments.*

3.3.1.5 Number of hours per treatment with optimal PAR values

The number of hours that the PAR values are comprised within a close to optimal range is much larger under the ECG treatments than under the reference shading screen treatments (Table 4).

Table 4
Number of hours that PAR values are within an optimum range.

	Number of hours 250<PAR<300 μmol/m²s
ECG-1	344
ECG-2	410
ECG-Ref-1	107
ECG-Ref-2	107

3.3.1.6 Average daytime PAR per treatment

The desired situation for the experiment was that both tables with one treatment (repetitions) have the same PAR levels. Obviously, the PAR values under the ECG glass repetitions are different from the PAR values under the reference treatment, which confirms that the ECG has been successfully controlled to regulate better allowing more light sum without exceeding the threshold. The average daytime PAR is shown in Table 5.

Table 5
Mean PAR values below the two darkening ECG glass panes (ECG-1 and ECG-2) and the two reference coated panes (ECG-ref1 and ECG-ref2).

Treatment	Mean daytime PAR value (μmol/ m²s)
ECG-1	131.2
ECG-ref1	116.5
ECG-2	140.7
ECG-ref2	111.2

3.3.2 Diffusing electrochromic glass

Unlike the tested darkening ECG, the diffusing PVL glass does not regulate different levels of PAR transmission. It only has two states: a clear one and a diffuse one. The switch from clear to diffusive state was set at 430 μmol/ m²s. The difference in hemispherical light transmission between both states is small (only 3% less transmission in diffuse state). In periods when PAR inside the greenhouse was high (above 430 μmol/m²s) the average PAR values measured below the glasses are slightly lower under the PVL than under the reference coated panes, which indicates their successful activation, leading to (only slightly) lower PAR intensity values (Figure 18). During the last weeks of the cycle, the Schefflera plants experienced an intense growth and shaded the sensors in all the treatments at times, but especially in the PVL-ref-1 treatment.

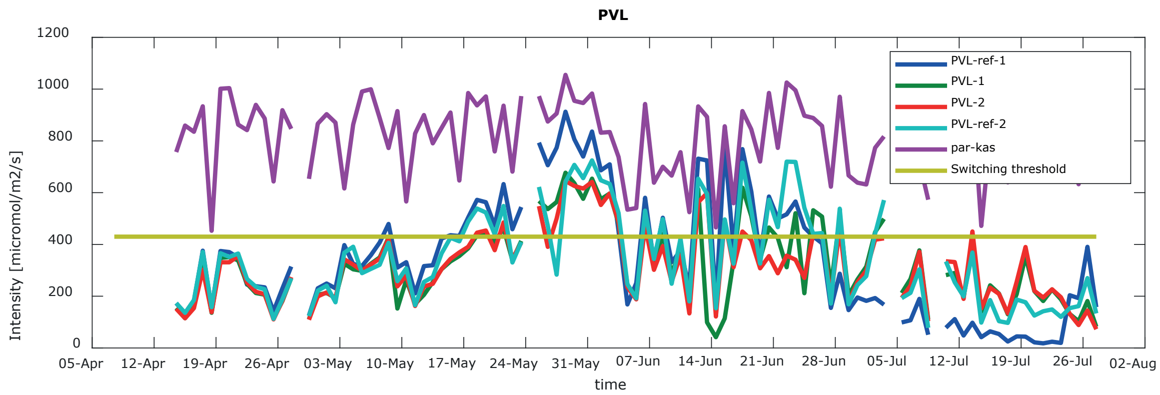


Figure 18 *Average PAR intensity (when PAR>430 μmol/m²s) below the two PVL glass panes (PVL-1 and PVL-2) and the two reference coated panes(PVL-ref1 and PVL-ref2).*

The period between May 15th and July 1st shows more clear differences between treatments.

3.3.2.1 Daily cycle mean

A daily cyclic mean in this period indicates that PAR levels during the high radiation (central) hours of the day were higher under the two reference repetitions than under the two PVL repetitions (Figure 19). The differences in PAR between the two reference repetitions are more pronounced than under the two PVL repetitions.

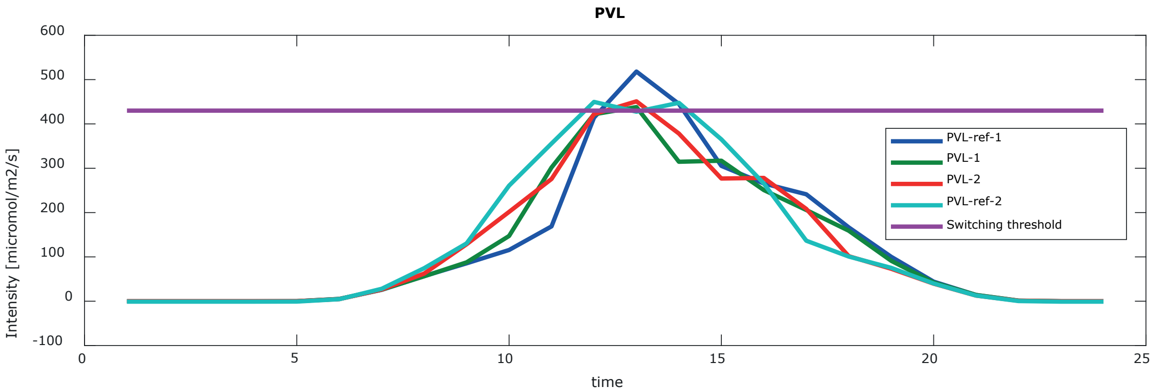


Figure 19 *Daily cyclic mean of PAR intensity below the two PVL glass panes (PVL-1 and PVL-2) and the two reference coated panes(PVL-ref1 and PVL-ref2).*

3.3.2.2 Total PAR sum under each glass treatment

The final PAR sum is very similar in the two PVL repetitions, and only slightly lower than the two reference repetitions, which also exhibit a slightly larger difference between them, most likely caused by differential shading of the sensors by structural elements and from neighbouring compartments in the two greenhouse positions (Figure 20). In general the small differences between the PAR sum under the two treatments are in agreement with the small differences in transmissivity between clear and diffuse states of the PVL glass.

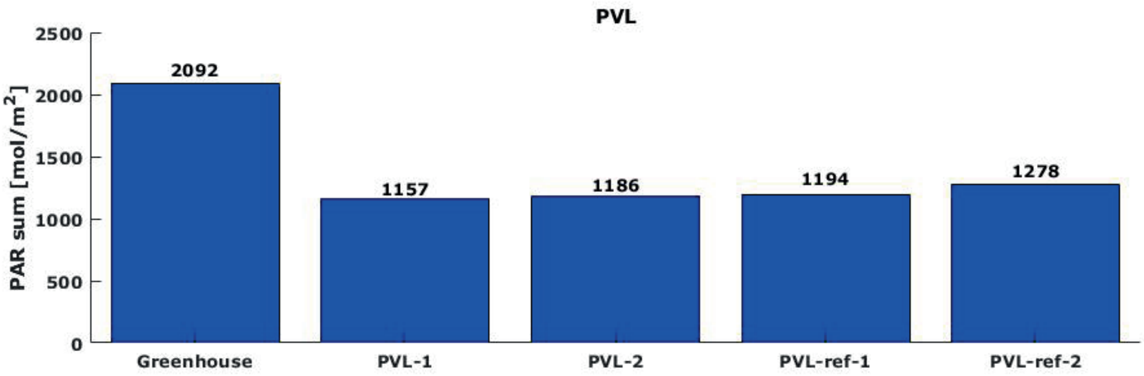


Figure 20 *PAR sum measured in the greenhouse and below the two PVL glass panes (PVL-1 and PVL-2) and the two reference coated panes(PVL-ref1 and PVL-ref2).*

3.3.2.3 Average daytime PAR per treatment

The average PAR intensities were very similar in the two treatments during the whole cycle (Table 6), with some minor differences caused by the switching to diffuse state and other minor differences caused by differential structural shading on the two reference tables.

Table 6
Mean PAR values below the two diffusing ECG glass panes (PVL-1 and PVL-2) and the two reference coated panes (PVL-ref1 and PVL-ref2.

Treatment	Mean daytime PAR value (µmol/ m^{2}s)
PVL-ref-1	175
PVL-1	169
PVL-2	176
PVL-ref-2	187

3.4 Temperature under the glass treatments

3.4.1 Darkening ECG, surface temperatures

The surface temperature of one of the ECG glasses and one of the reference coated glasses were monitored. The ECG glass becomes increasingly dark as it switches to a higher shading state, absorbing more radiation, which in addition to the heat released by the electric current, increases very much its surface temperature, especially on sunny days (Figure 21). Indeed, maximum daily ECG surface temperatures reach values exceeded 55 °C in a large number of days, whereas the maximum values of surface temperature of the reference coated glass hardly ever exceeded 45 °C (Figure 21).

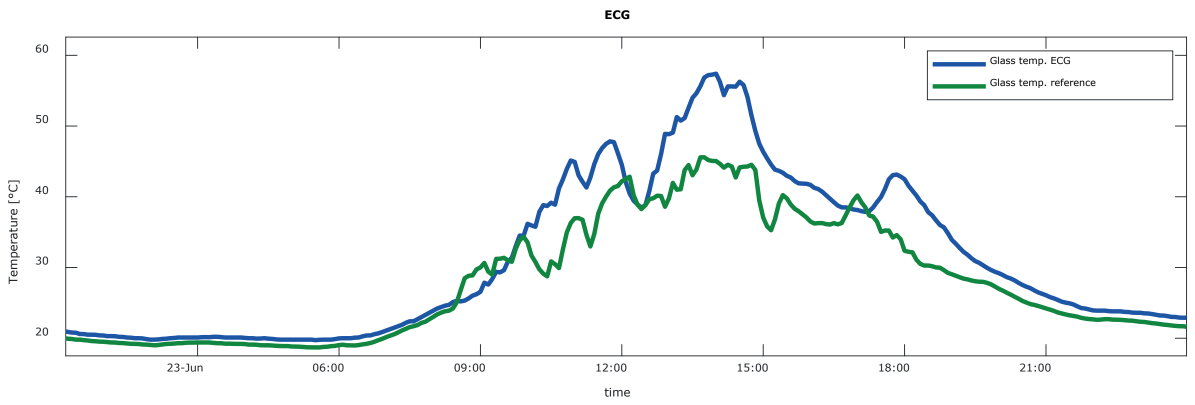


Figure 21 *Evolution of glass surface temperatures in the ECG glass and the reference coated along a sunny day(23rd June).*

3.4.2 Darkening ECG, air temperature below the glass

This overheating of the glass has an effect on the air temperatures below the ECG glass panes, which rise above the air temperatures under that of the coated glass. The increase in air temperature is more limited than that for the glass, with smaller differences in maximum values between both treatments than those observed for surface glass temperature (Figure 22). The air temperature below ECG-2 is relatively higher than under ECG-1, just as for surface temperature (Figure 21). Air temperature values hardly ever exceeded 35 °C, and when they did, it occurred for relatively short periods (Table 7).

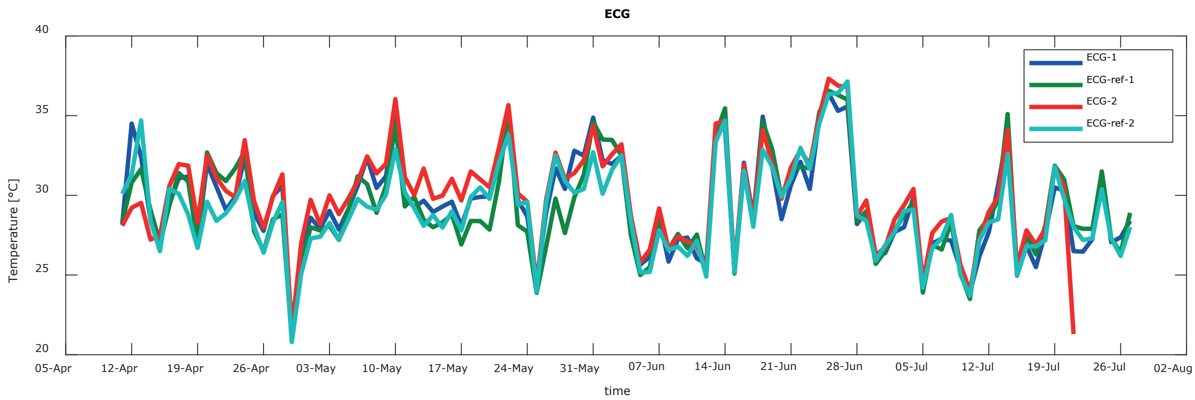


Figure 22 *Evolution of maximum daily air temperature values values below the two ECG glass panes (ECG-1 and ECG-1) and the two reference coated panes (ECG-ref1 and ECG-ref2).*

Air temperature values are within an optimum range under the ECG glasses for a very similar amount of time during the experiment for 3 of the 4 glass treatments (ECG-ref2 has lower temperatures induced perhaps by position effects - longer shading). The amount of time at supra-optimal temperatures is quite similar in all repetitions and only represents a small portion of the time (Table 7) We can conclude that the overheating of the glass panes lead to hotter air below the glass, but not as extreme as the glass surface would lead to expect. This indicates a better air exchange or air below the glasses with the compartment thanks to the set up with horizontal screens, in relation to the previous experiment, in which the screens fully surrounded the plants below the glass.

Table 7

Percentage of hours that air temperature values are within the optimum range (20 to 30°C) and at supra-optimal values (> 30°C).

	% hours T_{air}>30 °C	% hours T_{air}>35 °C	% hours 20°<T_{air}<30 °C
ECG-1	4.9	0.2	78.5
ECG-2	5.8	0.4	76.8
ECG-Ref-1	5.5	0.4	79.4
ECG-Ref-2	4.4	0.3	70.7

Table 8

Mean Air Temperature values below the two ECG glass panes (ECG-1 and ECG-1) and the two reference coated panes (ECG-ref1 and ECG-ref2).

Treatment	Mean air temperature value (°C)
ECG-1	23.5
ECG-ref1	23.7
ECG-2	23.4
ECG-ref2	23.3

3.4.3 Diffusing electrochromic glass

When the PVL glass switches to diffuse state, its absorptivity of solar radiation does not substantially change and therefore, its surface temperature should not substantially change when it switches state. Therefore, we did not monitor the surface temperature of the glass panes in this experiment. There are some differences in air temperature between the treatments, and between the repetitions within each treatment (Figure 23). The 24 hours cyclic mean shows that the air temperature values are consistently higher under the reference coated glass than under the PVL glass panes both during day and night time periods. There are small differences between the two repetitions within each treatment, which agree with the differences in PAR values observed in Figure 18 (higher average PAR intensities in a repetition correspond to higher average air temperatures).

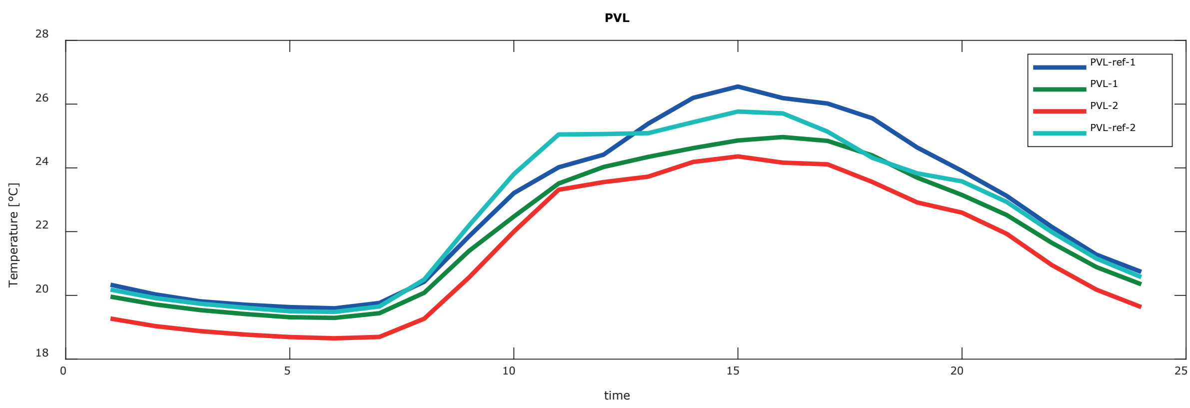


Figure 23 *Daily cyclic mean of air temperature means below the two PVL glass panes (PVL-1 and PVL-2) and the two reference coated panes(PVL-ref1 and PVL-ref2).*

The air temperature values are within an optimum range for a very similar amount of time in all treatments, except for PVL-2, for which the percentage of time that the air was within the optimum temperature range is lower than for the other treatments. This is explained by the fact that in this treatment there was a period of warm and sunny days in which the sensor was malfunctioning, affecting the distribution of temperatures in the optimum range.

Table 9
Percentage of hours that air temperature values a within the optimum range (20 to 30 °C) and at supra-optimal values.

	% hours T_{air}>30 °C	% hours T_{air}>35 °C	% hours 20°<T_{air}<30 °C
PVL-ref-1	2.7	0.3	73
PVL-1	1.3	0	70
PVL-2	0.1	0	61
PVL-ref-2	2	0.3	72

Table 10
Average air temperature below the two PVL glass panes (PVL-1 and PVL-2) and the two reference coated panes(PVL-ref1 and PVL-ref2).

	Mean air temperature (°C)
PVL-ref-1	22.8
PVL-1	22.1
PVL-2	21.3
PVL-ref-2	22.6

3.5 Relative humidity under the glass treatments

3.5.1 Darkening electrochromic glass

Relative humidity values are consistently lower during the daytime period under the ECG glass panes than under the reference coated glass (Figure 24, Figure 25). This can be partly explained by the higher air temperature below the ECG glass panes (Figure 22), or by closure of the stomata by the leaves of the plants due to stress by high leaf temperatures (Figure 29) . When stomata close, plants do transpire less, and the surrounding air becomes dryer.

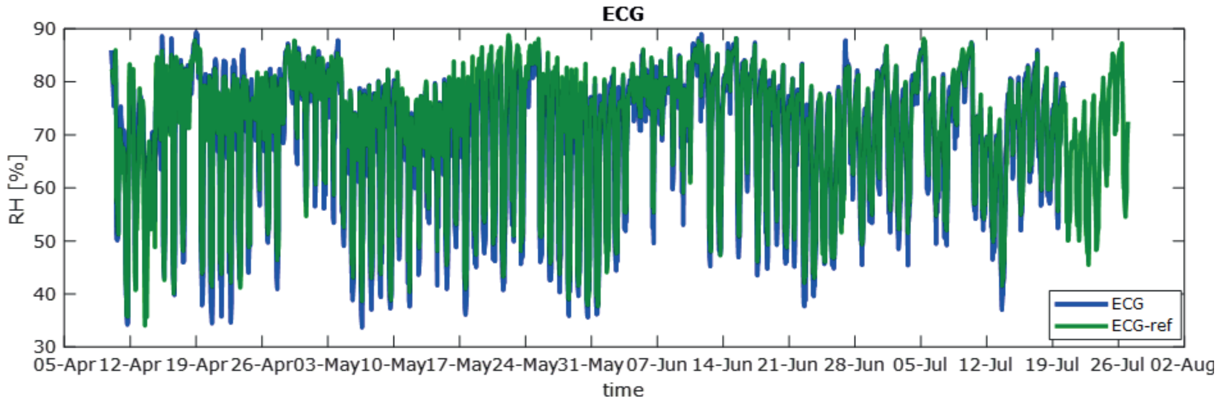


Figure 24 *Evolution of average R.H. values below the two ECG glass panes (ECG-1 and ECG-1) and the two reference coated panes (ECG-ref1 and ECGref2).*

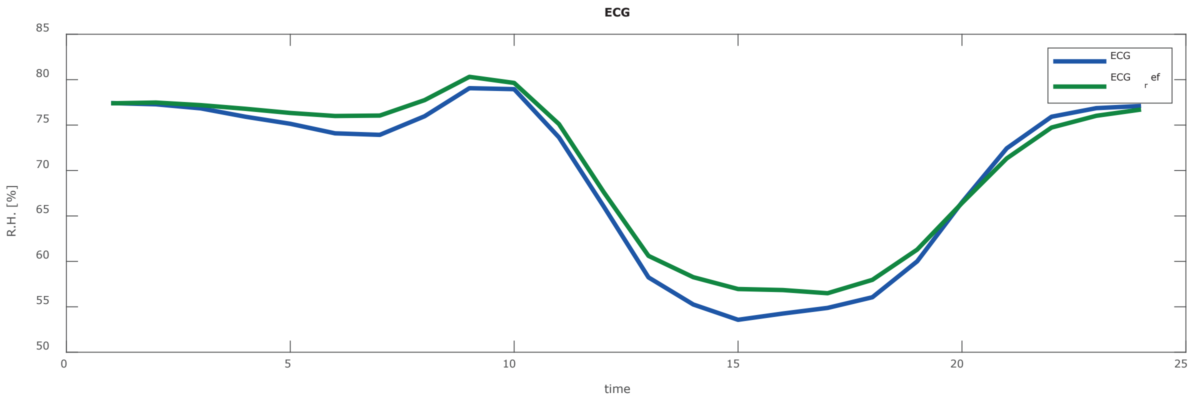


Figure 25 *24 hours cyclic mean of R.H. values below the two ECG glass panes (ECG-1 and ECG-1) and the two reference coated panes (ECG-ref1 and ECG-ref2).*

On average, the differences between the treatments are small, see Table 11 with the Mean RH values

Table 11
Mean daytime RH values below the darkening EC Glass.

	Mean daytime value (%)
ECG-1	70.8
ECG-ref-1	67.8
ECG-2	67.8
ECG-ref-2	73.1

3.5.2 Diffusing electrochromic glass

Under the diffusing glass treatments, R.H. values are very similar below all treatments. The daily cyclic mean of the average values of both repetitions of each treatment along the whole growing cycle, shows almost negligible differences between 17:00 pm and sunrise and only slightly higher humidity under the PVL treatments during the morning and afternoon hours (Figure 26). However, these differences are always lower than 5%.

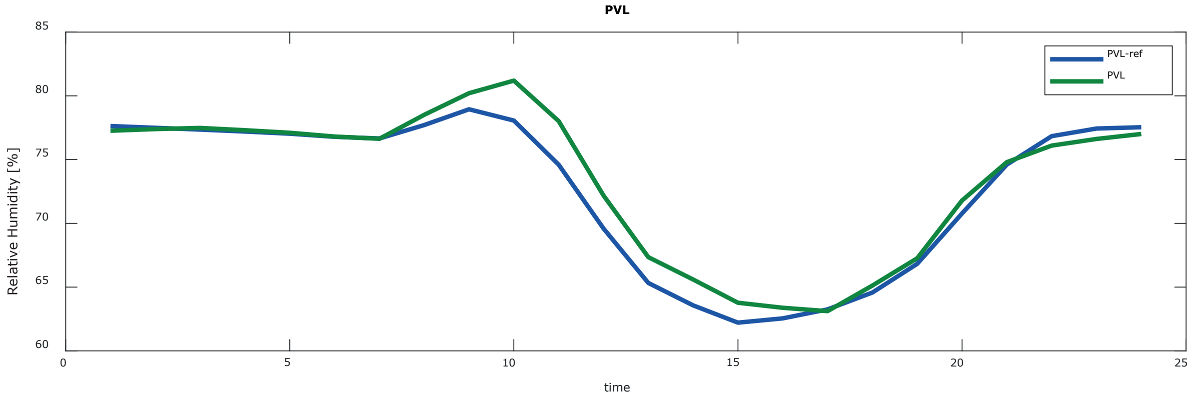


Figure 26 *24 hours cyclic mean of R.H. values below the two PVL glass panes (PVL-1 and PVL-2) and the two reference coated panes (PVL-ref1 and PVL-ref2).*

Table 12
Mean daytime RH values below the Diffusing EC Glass.

	Mean daytime value (%)
PVL-1	74.6
PVL-ref-1	70.9
PVL-2	74
PVL-ref-2	74.5

3.6 Leaf temperatures (anthurium, measured with PAM)

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 PAM was in use between 28-5 and 28-7.

A thermocouple sensor measures the leaf temperature, and a RH sensor at the leaf level measures the boundary layer RH. For anthurium these measurements are relevant as the leaves close their stomata if the leaf temperature rises above 32°C, especially when R.H. values are below 50%. In the treatments ECG-2 and ECG-ref2, two plants were monitored; in ECG1 and ECG-ref1, one plant.

A significant amount of hours, the leaf temperature exceeded the threshold value in all the treatments and sensors, (Figure 27, Figure 28 and Figure 29). Leaf temperatures are consistently higher in the leaves under the ECG glasses than under the reference coated glasses, following the same pattern observed for the temperatures of the glass surface and the air temperatures (Figure 22). The differences for leaf temperature are larger than for air temperature. For instance, average leaf to air temperature difference in ECG-ref is 0.3 °C (maximum difference of 3.2 °C) whereas for ECG-1 the average difference is 1.1 °C (maximum difference is 13.4°C).

This indicates that leaf transpiration is hampered when temperature of the leaf becomes too high, and the leaf overheats due to unproper evaporative cooling. There is a certain number of days for which the 32 °C temperature threshold is exceeded under the ECG and not below the reference.

There is a certain difference between repetitions, as we observe a higher number of days above the threshold of 32 °C in ECG-1 and ECG Ref1 (Figure 27) than in the two other plants measured in ECG-2 and ECG Ref2 (Figure 28). This is probably caused by position effects.

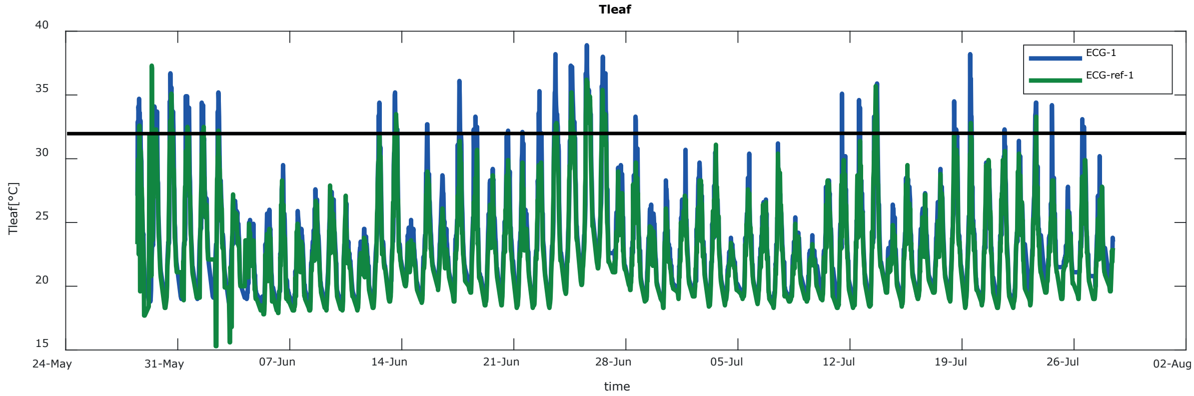


Figure 27 *Evolution of leaf temperature under the ECG-1 and ref.-1 treatments along the monitoring period with the HexPam.*

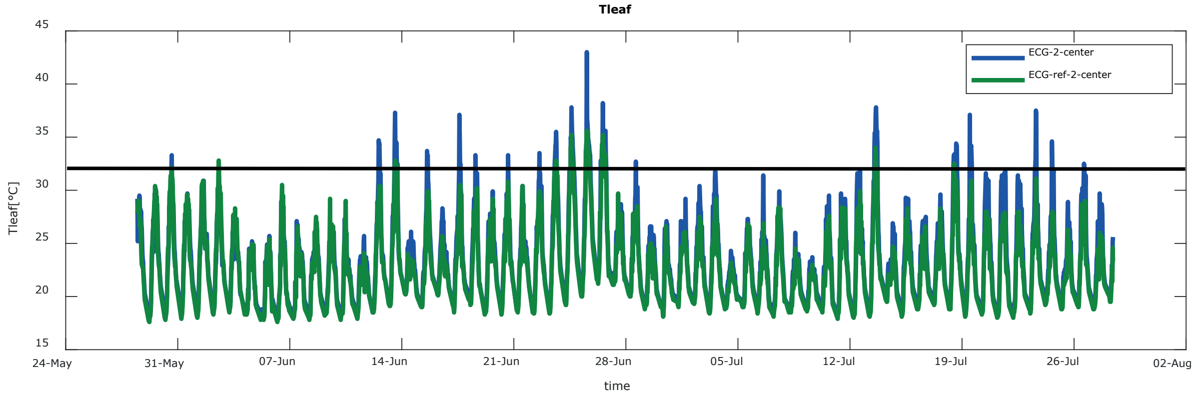


Figure 28 *Evolution of leaf temperature under the ECG-2 and ref.-2 treatments along the monitoring period with the HexPam in plants located in the centre of the table.*

To gain insight on the daily pattern, the daily cyclic mean has been calculated and plotted. Data were monitored between 04:30 and 22:30 each day (18 hours), which explains the scale in the x-axe. A similar behaviour is observed in both repetitions, for the leaves monitored in plants in the centre of the table (Figure 30 and Figure 31), with leaf temperature been consistently higher under the ECG glass than under the coated glass for an average value consistently higher by 1 °C.

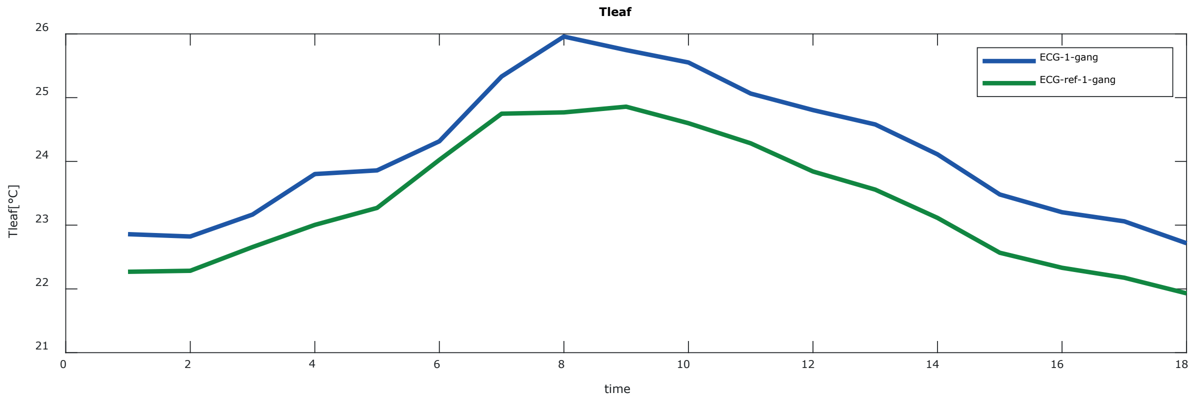


Figure 29 *Cyclic mean of the daily measurement period of leaf temperature under the ECG-1 and the ref-1 repetitions on plants located in the centre of the table along the monitoring period with the HexPam.*

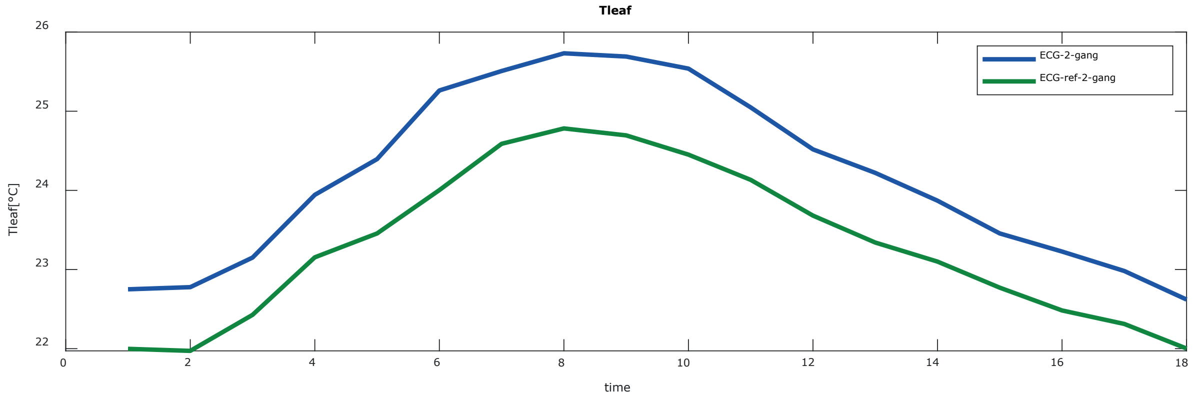


Figure 30 *Cyclic mean of the daily measurement period of leaf temperature under the ECG-2 and the ref-2 repetitions on plants located in the centre of the table along the monitoring period with the HexPam.*

3.7 Boundary layer R.H. (anthurium, measured with PAM)

The minimum daytime relative humidity values at the boundary layer level are often lower under the ECG than under the reference coated glass for all treatments (Figure 31, Figure 32). The average difference between R.H. values (during the periods that the reference R.H>ECG R.H.) was only 1.7% for ECG1-ECG ref-1 and 0.85% for ECG2-ECGref2. However, the cycle mean graphs (Figure 34, Figure 35) show 5% lower R.H. at boundary layer level of the plants under the Electrochromic glass that several hours of the day, compared to those under the reference coated glass.

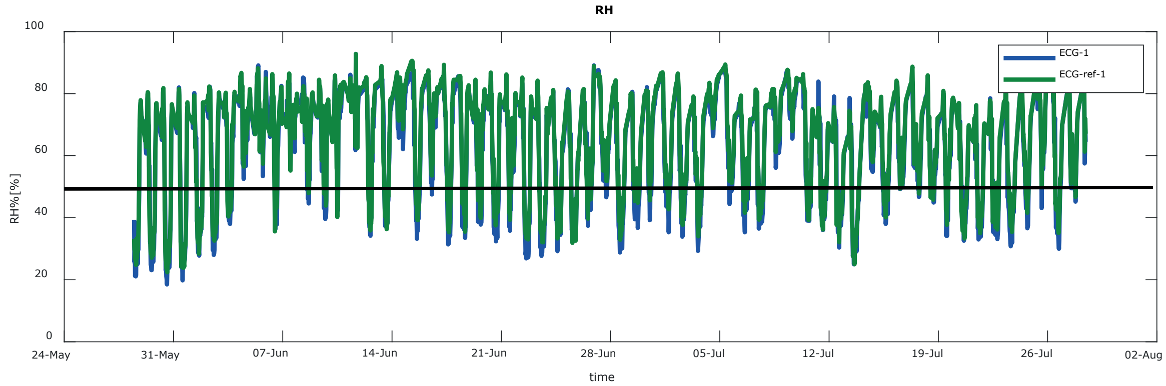


Figure 31 *Evolution of boundary layer relative humidity values under the ECG-1 and ref.-1 treatments along the monitoring period with the HexPam.*

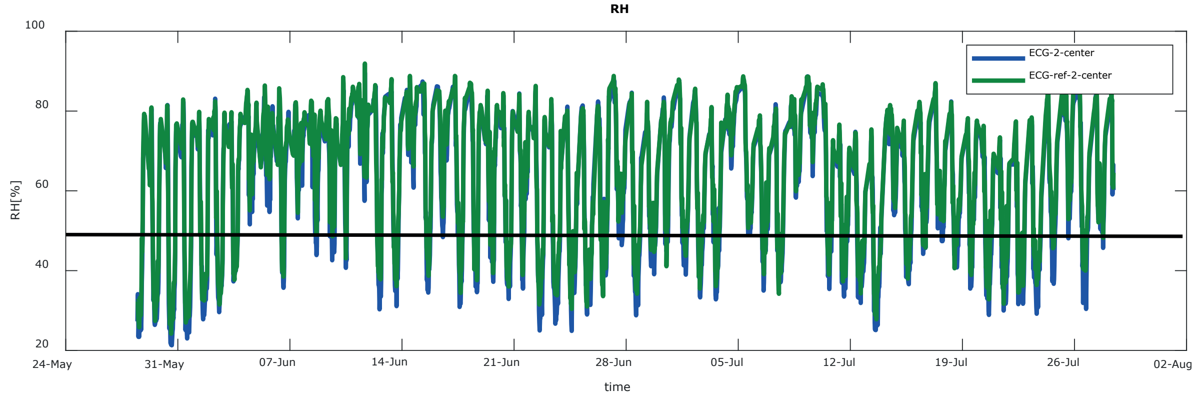


Figure 32 *Evolution of boundary layer relative humidity values under the ECG-2 and ref.-2 treatments along the monitoring period with the HexPam.*

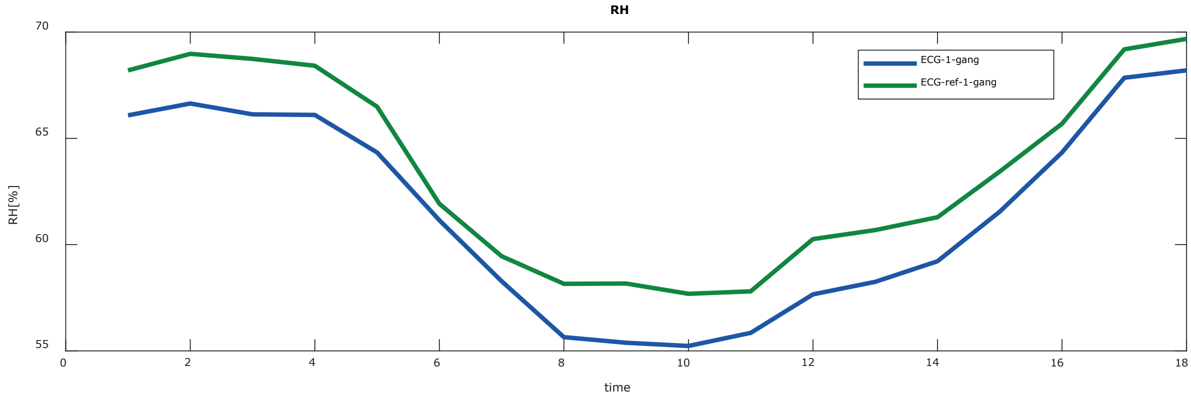


Figure 33 *Cyclic mean of the daily measurement period of boundary layer relative humidity values under the ECG-1 and the ECG-ref-1 treatments.*

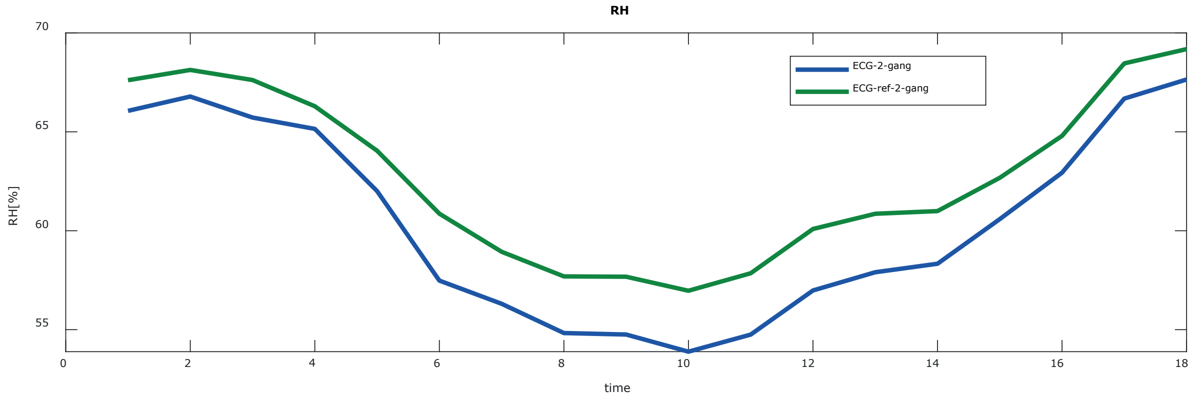


Figure 34 *Cyclic mean of the daily measurement period of boundary layer relative humidity under the ECG-2 and the ECG ref-2 treatments.*

3.8 Limiting conditions

We can calculate the number of hours that the conditions were the most limiting for the plants, that is, having simultaneously a leaf temperature above 32 °C and a boundary layer R.H. below 50%. The total duration of the experiment was 1099 hours (Table 13). The number of hours with limiting conditions due to low R.H. is larger than those in which temperature exceeds the threshold. Again, we observe that under the ECG the period with conditions deriving in limitation in the opening of the stomata, and as a consequence, perhaps limiting photosynthesis, are higher under the ECG glass than under the coated glass, induced by the high glass temperature already analyzed. The moments of limiting conditions are only a small percentage of the total time, and they did not lead to visible leaf damage.

In the next paragraphs we will analyze how the limiting conditions affected photosynthesis and plant growth and development.

Table 13
Hours with limiting temperature and humidity conditions for normal stomatal activity.

	Number of hours T_{leaf}>32 °C	Number of hours that R.H.<50%	Number of hours that T_{leaf}>32°C & R.H.<50%
ECG-1	72	318	68
ECG-ref1	30	281	26
ECG-2	49	347	47
ECG-ref2	24	287	22

3.9 Photosynthesis anthurium (chlorophyll fluorescence, PAM)

The calculated efficiency of the photosystem 2 (PS2) based on the fluorescence measurements in the different treatments is shown in Figure 35 to Figure 38. The graphs 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.

For good measurements, the device is moved to a different leaf once a week. In this way, on measuring weeks 1, 6 and 7, the efficiency of PS2 was slightly higher under the ECG-1 than under the reference treatment (ECG-ref1) whereas on weeks 2, 5 it was the opposite. On the remaining weeks values were very similar on both treatments (Figure 35). A daily cyclic mean of the whole measuring periods indicates that on average, values of PS2 efficiency where similar or slightly higher under the reference treatment. However, average differences were very small, in the range of 0-0.04. The efficiency dropped around noon, when the plants experienced the most limiting conditions of high temperature and VPD. The drop was clearly higher under the ECG glass during most measured days. We do not detect major drops in Fv/Fm ratio on two consecutive days in any of the treatments, indicating that no major damage was induced to the PS2 systems during the measuring period. However, we do observe for weeks 1 and 4 a trend of constant and small decrease of Fv/Fm during the week, for both treatments which shows perhaps an accumulated partial small damage. On weeks 5 and 7, values decrease slightly during the first 4 days and then remain constant at the end of the week. In general, this variations are not large and therefore, not very significant.

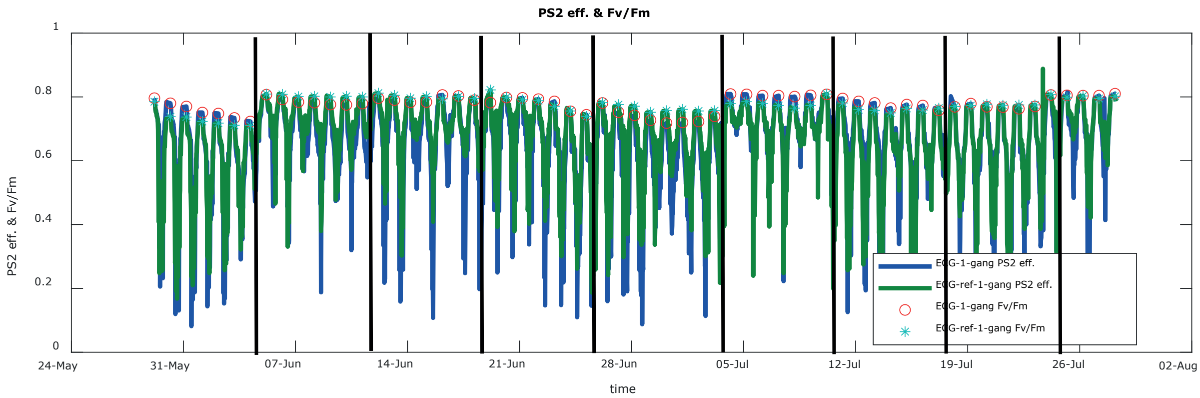


Figure 35 *Evolution of PS2 efficiency and Fv/Fm ratio of plants under electrochromic glass ECG1 and the reference coated glass treatment ECG-ref1.*

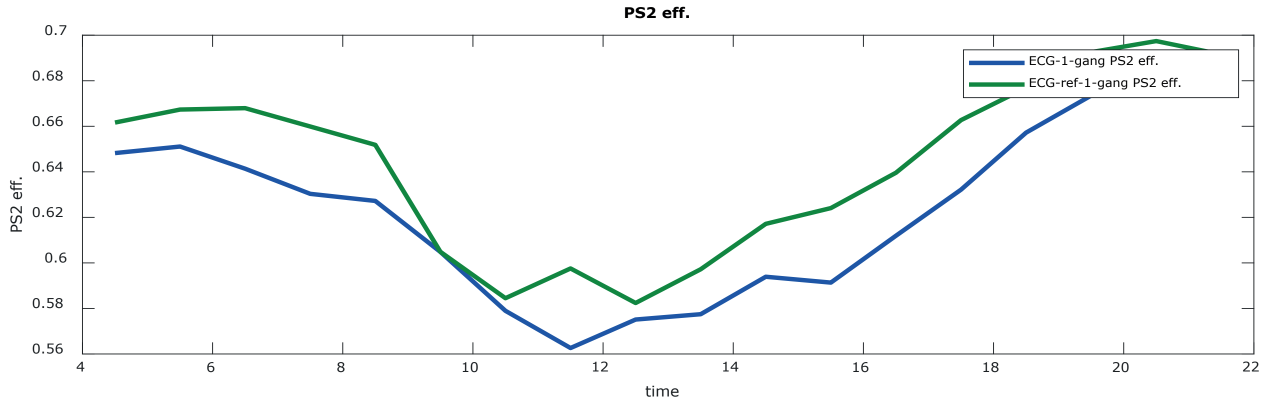


Figure 36 *Cyclic mean of the daily measurement period for PS2 efficiency under electrochromic glass ECG-1 and the reference coated glass ECG-ref-1.*

The differences are bigger in the PS2 efficiency and Fv/Fm between the ECG-2 and ECG-ref2 treatments. For all weeks, Fv/Fm is higher under the reference glass (Figure 37), being this difference larger on weeks 3 and 5. The cyclic means (Figure 38) confirms that PS2 efficiency is consistently higher during the whole period for the leaves monitored under the reference coated glass than under the ECG glass. The differences are larger than between ECG-1 and ECG-ref-1, and are as high as 0.1 just before noon. Fv/Fm follows a decreasing pattern under the ECG glass all weeks except the last two, confirming a damage to PS2, which is not observed on the leaves of the reference treatment.

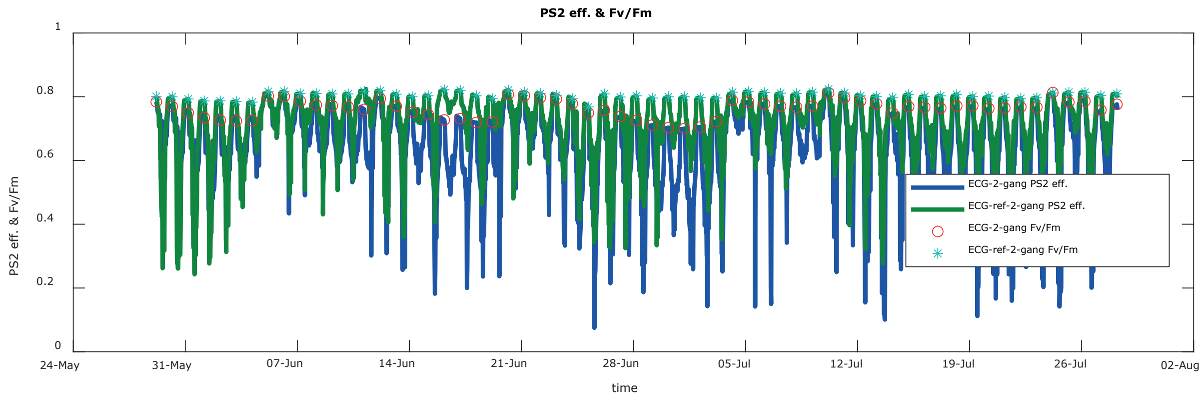


Figure 37 *Evolution of PS2 efficiency and Fv/Fm ratio of plants under electrochromic glass ECG2 and the reference coated glass treatment ECG-ref2.*

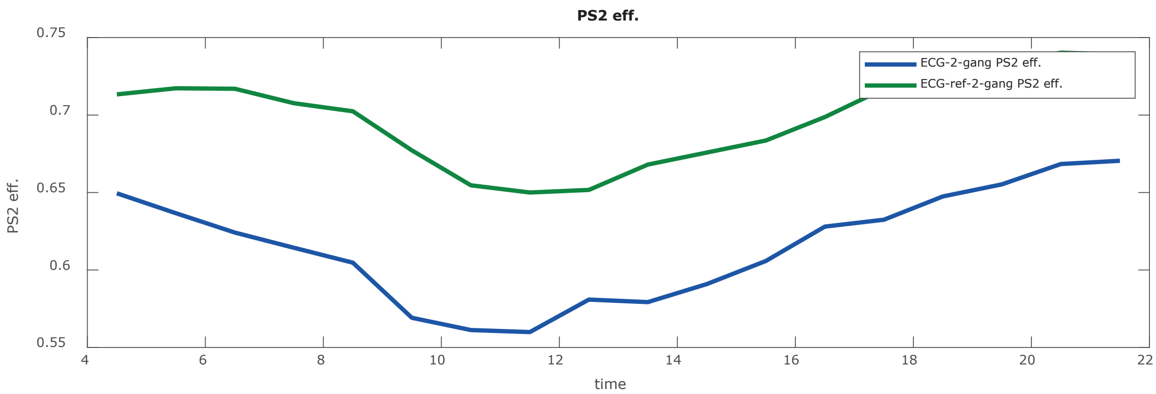


Figure 38 *Cyclic mean of the daily measurement period for PS2 efficiency under electrochromic glass ECG-2 and the reference coated glass ECG-ref-2.*

3.10 Plant growth and development

3.10.1 Anthurium, darkening electrochromic glass

The Anthurium plants grew well in all treatments as it can be expected from the good light regulation and a reasonably good control of the temperatures and humidity below the glass panes, with the experience learned from the previous experiment and with very few extremely hot days.

The pictures below show representative plants (the plants labelled for measurements) at arrival of the plants from the grower before placing them under the glass treatments (Week 0, Figure 39). The next picture shows plants three weeks after the start of the trial (Figure 40). How they looked after the second spacing moment (week 8) is shown in Figure 41, and at the end of the experiment (week 16, Figure 42).

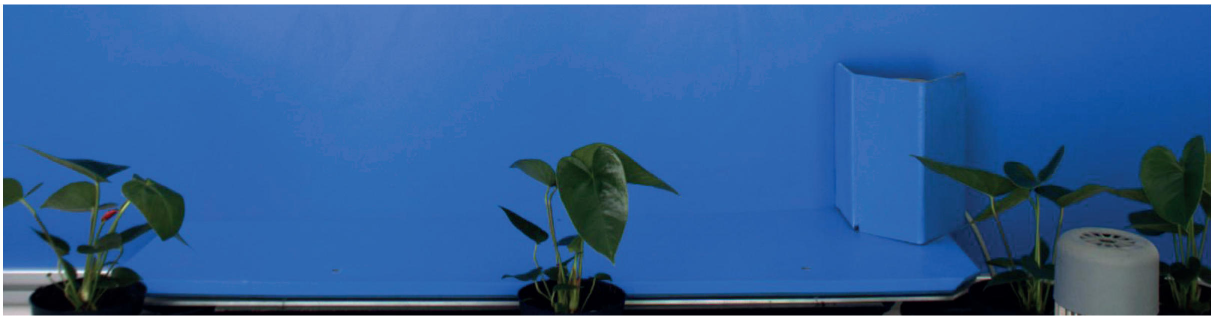


Figure 39 *Images taken by the WUR Plantalizer for the start measurements. Four young plants are visible, one of them with one flower bud.*

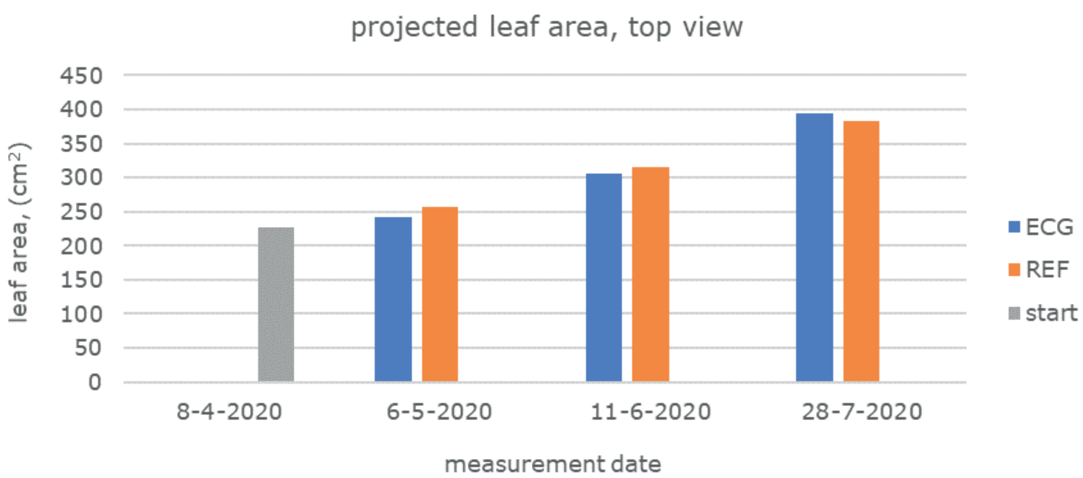
Figure 40 *The Anthurium plants on Mei 1, (3 weeks after de start of the trial). Left, under ECG-1, right under ECG-Ref-2.*

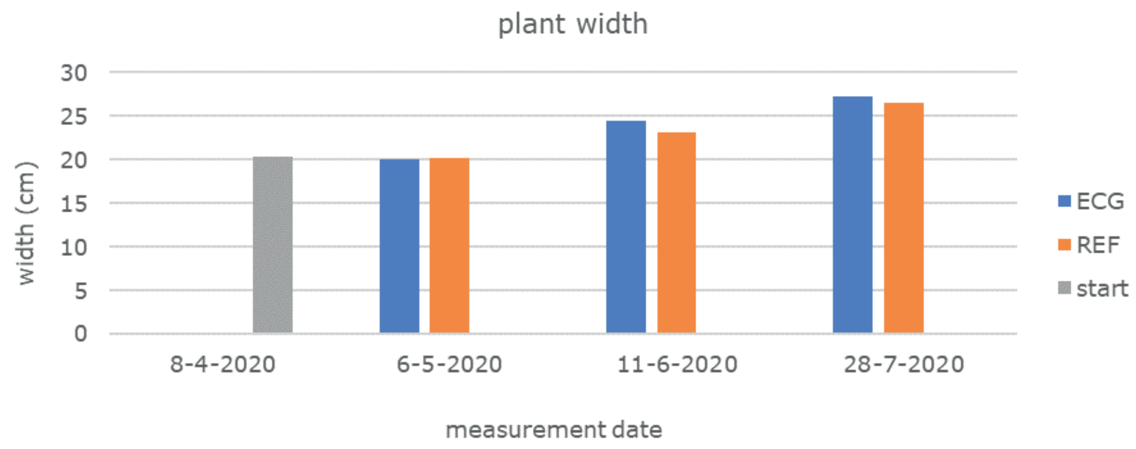
Figure 41 *The plants at the second spacing episode, 10th of June, after 8 weeks of cultivation. Left, plants cultivated under the darkening Electrochromic glass. Right, plants cultivated under the reference treatment (coated glass).*

The plants were measured non-destructively (with the WUR Plantalizer) in different times during their development. Plant height, plant width, the projected leaf surface, and the number of flowers (top view) are shown in the histograms for both treatments (Figure 43). The first measurement (grey bars in the histograms) was conducted on arrival, and is therefore common for both treatments. During this first measurement, most of the plants had no developed flowers yet but only one or more flower buds that were still not unfolded, therefore no visible for the WUR Plantalizer.

Both the Figures and the pictures show that the plants developed the same in both treatments. No significant differences have been found in any of the measured parameters (5% ANOVA). Data are shown in Annex 1, including the results of the statistical analysis

Figure 42 *The plants at the end of the experiment (27-07-2020, after 16 weeks of cultivation).*





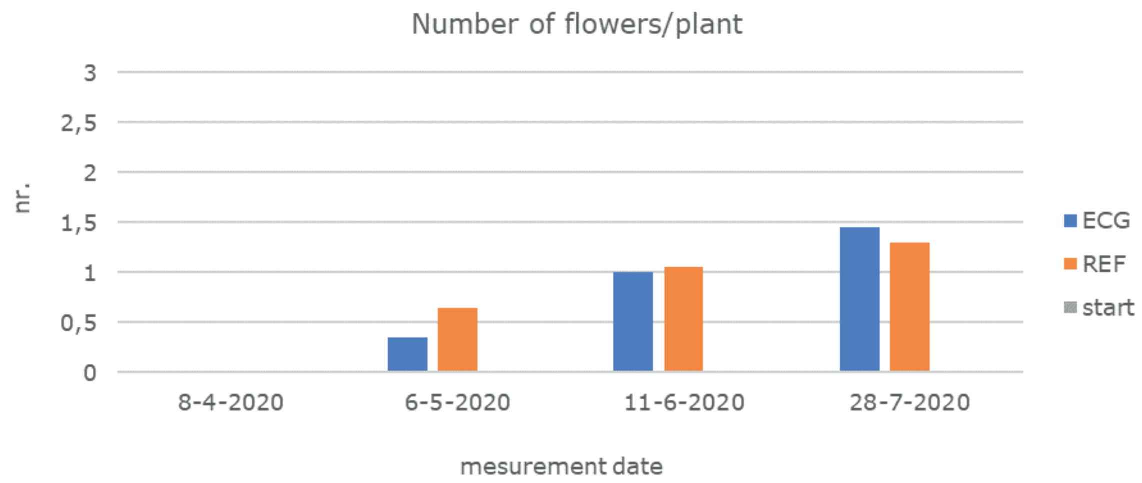


Figure 43 *Non-destructive plant measurements in time, from top to bottom: average leaf area per plant (projected, top view), plant height, plant width and average number of flowers per plant. Values are means of the same 20 plants on each measurement date.*

At the end of the experiment (28-07), the plants were measured destructively, in order to be able to calculate the produced biomass (fresh and dry weight). This allowed to count the number of flower buds and leaves as well. The results, shown in Table 14, confirm that there was neither a difference in the number of leaves and flower buds or their fresh and dry weight.

Table 14

Results of destructive measurement, after 16 weeks of cultivation. Values are means of 20 plants per treatment. Different letters indicate significant differences (5% ANOVA). l.s.d.= least significant difference.

Treatment	#flowers l.s.d 0.8	#buds l.s.d 0.5	#leaves l.s.d 1.1	FW flowers l.s.d 3.5	FW leaves l.s.d 5.3	% dm flowers l.s.d 0.7	% dm leaves l.s.d 0.3
ECG	2.8a	1.7a	17.7a	14.9a	53.1a	10.3a	15.3a
ECG REF	3.3a	1.25a	18.0a	16.5a	54.1a	10.9a	15.1a

3.10.2 Schefflera, diffusing electrochromic glass

The Schefflera plants grew fast in all treatments. The development was very heterogeneous, and the bigger the plants became, the greater the differences in length and number of leaves among the plants.

Heterogeneity during the development is, according to growers, normal in this cultivar; in order to supply plants of the same height and similar number of leaves, growers normally sort the plants according to their height three times during the development. As this sorting would interfere with our measurements it was decided not to sort the plants but continue measuring the numbered plants.

The commercial stage of the plants is reached when the plants grow to a height of 50 cm, that would correspond with a developmental stage somewhere between our second spacing episode (Figure 41) and the final measurement (Figure 49).

The pictures below show representative plants at delivery (Week 0, Figure 39), after 2 weeks (Figure 45), at first spacing (Figure 46), at second spacing (week 8, Figure 41) and end of the experiment (week 15, Figure 42). At the start, most of the plants consisted of only one leaf (the cutting leaf); incidentally, plants could have the first one or two leaves developing from the axyl of this cutting leaf.

Figure 44 *Images taken by the WUR Plantalizer for the start measurements. Top, four young plants are visible from the side. Bottom: three plants in top view; left is most common (only the cutting leaf), middle and right cuttings with developing axillary leaves.*

Figure 45 *The Schefflera plants in week 2 after de start of the experiment.*

Figure 46 *The Schefflera plants on May 1 (left), during the measurements corresponding tot the first spacing in May 11 (centre) and July 3 (right).*

The plants were measured non-destructively (with the WUR Plantalizer) at different moments during their development. Plant height, plant width and the leaf surface (projected, top view) and the number of leaves and flowers are shown in the histograms for both treatments (Figure 47). The start measurement (grey bar in the histograms) is common for both treatments. The values including the statistical analysis (5% ANOVA) can be found in Annex 1.

The plants grown under the glass with diffusive coating (reference treatment) were higher and had a larger leaf area (projected) than the plants grown under the diffusive electrochromic glass.

At the end of the experiment, after 15 weeks of cultivation, a destructive measurement was performed, in order to calculate total biomass (fresh and dry), and count number of leaves. As all the leaves were already detached, the "real" leaf area (the WUR Plantalizer measured "projected" leaf area, so leaves on top of each other are seen as one), was measured with the Licor leaf surface meter.

Results (Table 15) show that the plants of the reference treatment (diffuse coating) were significantly (5% ANOVA) higher, had more leaves per plant and a higher leaf area, and higher dry matter percentage than the plants under the diffusing electrochromic glass.

Table 15

Results of destructive measurements after 15 weeks of cultivation. Values are means of 20 plants per treatment. Different letters indicate significant differences (5% ANOVA). l.s.d.= least significant difference.

Treatment	Stem length l.s.d. 9.5	Plants with split apex	# leaves on main stem l.s.d. 4.0	Leaf surface l.s.d.277	Fresh weight total l.s.d.29.3	% dm leaves	% dm stem
PVL	38.9 a	20	21.5 a	1692 a	136 a	15.8	10.9
PVL REF	58.5 b	6	35.5 b	1973 b	163 a	17.5	14.8

The destructive measurements of these plants made evident why some of the plants had stayed shorter than others: they had a split apex or a massive ramification of the apex (Figure 50). These effects (split apex) were found in almost all the plants growing under the Diffusing Electrochromic glass, and in only a few of the plants growing under the reference (diffuse coated) glass. When the apex splits, the length growth is affected (reduced) as it is the number of leaves on the main stem.

In a recent experiment with artificial lighting of Schefflera, this effect was observed as well in most of the plants. It could be an expression of light damage during the moments in which the light was not diffuse (always below a light intensity of 430 μmol).

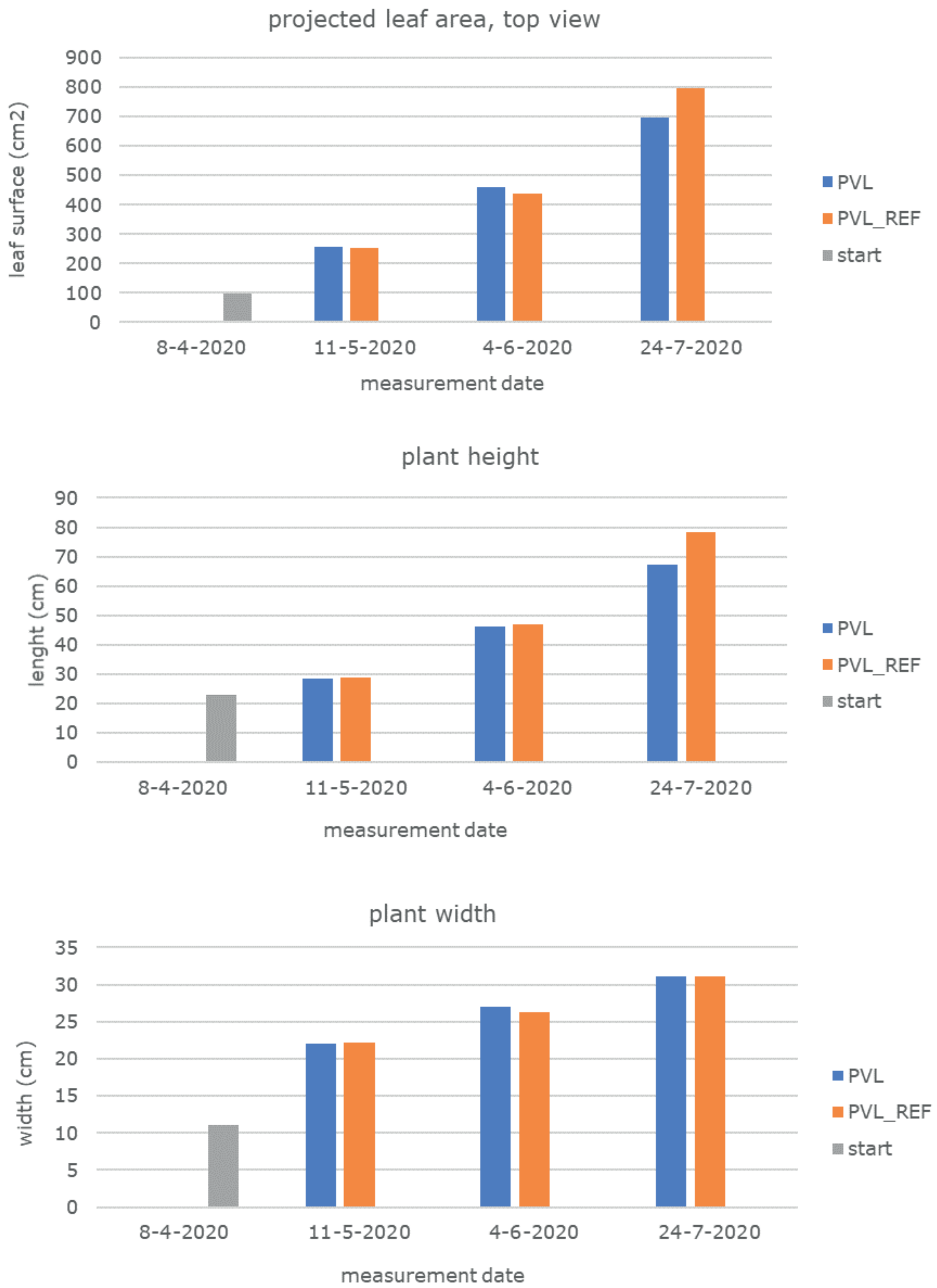


Figure 47 *Non-destructive plant measurements in time, from top to bottom: average leaf area per plant (projected, top view), plant height and plant width. Values are means of the same 20 plants on each measurement date.*

Figure 48 *The plants at the second spacing episode, 4th of June, after 8 weeks of cultivation. Left plants from the reference treatment (coated glass); right, plants from the PVL Electrochromic glass. Up and down the plants of another set of repetitions.*

Figure 49 *The plants at the end of the experiment (24-07-2020 after 15 weeks of cultivation).*

Figure 50 *Ramifications of the apex giving many growing points instead of one.*

4 General discussion

4.1 Darkening electrochromic glass

The light level below the darkening electrochromic glass has been well controlled, and allowed for PAR to be a larger number of hours close to the desired set point of 300 µmol/m^{2}s than the reference coated glass. On very clear days the threshold was not exceeded and on cloudy days a higher PAR sum was possible than in the reference coated glass. This resulted in a higher PAR sum under the electrochromic glasses than under the reference coated glasses. It could be expected that this higher PAR sum should have translated in more plant growth. However, when analysing plant growth in time, we do not observe any statistically relevant increased growth in any of the analysed parameters compared to the reference.

The most likely explanation lies in the reduction of the photosynthesis efficiency measured in leaves under the electrochromic glass on very sunny and warm days. This was due to excessive leaf temperature, coincident in many cases with low R.H. values, conditions in which Anthurium stomata close. This higher leaf temperature values were the logical consequence of the large increase of the temperature of the electrochromic glass in its darker stages required to shade more on sunny days. The electrochromic glasses have electronics inside. Since they regulate the light level every 10 seconds, this might result in some heat production. Besides that, the glass becomes dark because it absorbs the excess light. Spectrum measurements (García Victoria *et al.* 2020) showed absorption and a shift of the sun light spectrum under the glass to wavelengths with more energy (relatively more green and yellow and less red and far red), which are less efficient for Photosynthesis, whereas under the coated glass, there are no major spectral changes.

Despite a better control of the air temperature and relative humidity below the electrochromic glass than in the previous experiment conducted in 2019 (García Victoria *et al.* 2020) with the closed cubicles, the results described confirm those obtained in the previous experiment: Due to the small distance between the glass and the crop, the hot glass warmed the leaves by convection and radiation. This may have counteracted the potential positive effect of having more constant light and a higher PAR sum.

Perhaps increasing the distance from the plants to the electrochromic glass would prevent the overheating of the leaves, or some device to cool the glass.

4.2 Diffusing electrochromic glass

Diffusing EC Glass gave good control of the light conditions as programmed: diffuse light whenever the set threshold was reached.
The periods that the glass was not in diffuse state and therefore allowed for a 5% more PAR than the coated glasses did not result in a higher light sum, probably because of differential shading of some tables in relation to the others due to neighbouring compartments. In any case, differences are rathe small.
The changing light diffusing conditions did not result in faster crop growth, or better plant quality. On the contrary: the plants from the diffusing glass treatments were at the end of the experiment shorter, had less leaf area (projected and measured) and suffered more often a split apex. All this indicates that this crop seems to benefit from constant diffuse light rather than a combination of direct light at low light levels and diffuse light at higher light levels.

5 Conclusions

5.1 Darkening electrochromic glass

- Darkening EC Glass gave very good control of the light conditions : more constant light, less peaks on very sunny days, more light on clouded days, resulting in higher light sum without exceeding the threshold set.
- However, this did not result in faster crop growth, higher number of flowers or better plant quality in any way, dan a reference coated glass.

Possible explanations are:
- 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 absorbs light and 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 light advantage was counteracted by (leaf) temperature increase that lead to stomata closure and less efficient PS2.

5.2 Diffusing electrochromic glass

- Diffusing EC Glass gave good control of the light conditions as programmed: diffuse light whenever the set threshold was reached.
- The diffusive state lead to a slightly lower light sum than the reference coated glass
- However, the changing conditions did not result in faster crop growth, or better plant quality, on the contrary: the plants from the diffusing glass treatments were at the end of the experiment shorter, had less leaf area (projected and measured) and suffered more often a split apex
- The crop seems to benefit from constant diffuse light rather than a combination of direct light at low light levels and diffuse light at higher light levels.

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Annex 1 Plant measurements

Anthurium Royal Champion, darkening electrochromic glass

The Table shows the WUR Plantalizer measurements, in time. Different letters indicate significant differences (l.s.d. 5% ANOVA), bold.

Date	Treatment	N flowers (#)	Flower height (cm)	Plant height (cm)	Projected Leaf Area Top (cm^2)	Flower Area (cm^2)	Leaf inclination	Plant diameter (cm)
08-04	start	-	-	25.3	227.2	-	-2.4	20.3
06-05	*l.s.d.(5%)*	*0.39*	*2.81*	*3.59*	*32.6*		*5.34*	*1.66*
	ECG	0.40 a	25.0 a	30.9 a	242 a		-1.9 a	20.1 a
	REF	0.65 a	26.4 a	30.1 a	256 a		-5.8 a	20.2 a
11-06	*l.s.d. (5%)*	*0.50*	*1.76*	*1.33*	*35.9*		*4.19*	*3.16*
	ECG	1.05 a	33.3 a	33.5 3	306.3 a		-2.4 a	24.5 a
	REF	1.25 a	32.5 a	33.6 a	315.2 a		-4.0 a	23.2 a
28-07	*l.s.d.(5%)*	*0.56*	*1.75*	*0.93*	*38.8*	*19.0*	*3.8*	*1.69*
	ECG	2.30 a	37.2 a	36.6 a	394.5 a	65.1 a	-7.4 a	27.3 a
	REF	2.40 a	38.2 a	37.1 a	383.6 a	79.2 a	-4.3 a	26.6 a

Schefflera, diffusing electrochromic glass

The Table shows the WUR Plantalizer measurements, in time. Different letters indicate significant differences (l.s.d., 5% ANOVA), bold.

Date	Treatment	Plant height (cm)	Projected Leaf Area (Top), (cm^2)	Projected Leaf Area (side), (cm^2)	Leaf inclination	Plant diameter (cm)
08-04	start	22.9	99	21.3	-	-
11-05	*l.s.d.(5%)*	*1.40*	*33.7*	*15.8*	*3.29*	*1.67*
	PVL	28.5 a	256 a	99 a	3.80 a	22.1 a
	REF	28.8 a	252 a	105 a	3.45 a	22.1 a
04-06	*l.s.d. (5%)*	*3.12*	*55.8*	*34.3*	*2.42*	*1.28*
	PVL	46.1 a	460 a	263 a	5.10 a	27.1 a
	REF	46.8 a	438 a	254 a	7.45 a	26.3 a
28-07	*l.s.d.(5%)*	*6.59*	*93.4*	*79.4*	*3.30*	*2.20*
	PVL	**67.3 a**	**697 a**	484 a	7.31 a	31.1 a
	REF	**78.4 b**	**796 b**	555 a	5.95 a	31.1 a

To explore the potential of nature to improve the quality of life

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