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Are smart glasses with switchable optical properties the future greenhouse covers for high value crops?

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Abstract

Within the public-private collaboration project Smart Materials, electrochromic glasses (EC glass, able to instantaneously switch light intensity or scattering) were evaluated on their potential for production of high value ornamental crops that are assumed to benefit from relatively low sunlight levels. Growers use shading screens or temporary coatings on glass during the summer, which react slowly to changing outside light conditions. EC glass allows timely light intensity control and therefore more constant light conditions. Experiments were carried out with pot *Anthurium* and *Schefflera*. Research questions were: Is EC glass able to control light intensity to a constant level with changing outside sunlight conditions? Does this improve crop growth and quality? The light levels were well controlled under EC glass. As a result, the plants were exposed to a higher light sum attained by more constant light, less peaks on sunny days and more light on clouded days. However, this did not translate into faster growth, more flowers nor better plant quality. The achieved light control advantage by the EC glass was counteracted by the thermal radiation behavior of the glass: light was absorbed, which lead to high glass temperatures, thus high leaf temperatures. That lead to stomata closure and lower photosynthesis efficiency during sunny periods. More research is needed to evaluate the potential of smart glasses as greenhouse covers for high value crops.

Keywords: *Anthurium*, *Schefflera*, electrochromic glass, leaf temperature, photosynthesis, crop growth, shading

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 (Long et al., 1994; Kasahara et al., 2002; Chen et al., 2005; Li et al., 2009). For the successful commercial production of such plants in greenhouses, shading is needed to maintain the light intensity below damage thresholds (Li et al., 2014). Two methods are typically used in temperate climates to reduce the light intensity in greenhouses. The first method is to apply a temporary coating (whitewash) on the greenhouse glass cover and sidewalls that reflects part of the incident light, reducing also the associated heat inside the greenhouse. Coatings are generally applied from spring (March-April) to autumn (October) in northern climates. Because of its permanent character, the coating reduces light also on dark, cloudy days . A shortage of light reduces the growth rate of the plants, affects the plant shape and number of flowers (Van Telgen et al., 2004) and delays their time to market (Van der Knaap et al., 2002). The second method is to install and use movable shading screens. Screens are available in different materials, and they can be mounted inside or outside the greenhouse. Growers can choose materials with the desired level of light transmission. The screens are connected to the climate computer and can be programmed to automatically unfold or fold depending on the outside light intensity, so they keep folded on dark and clouded days, and unfolded when it is too sunny for the plants inside the greenhouse. The drawback of a screen, besides the static shading fraction, is the late or slow control in days with variable clouds, as unfolding usually takes several minutes. This forces growers to choose a conservative screening strategy or combine them with an additional shading such as the above-mentioned

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white washing of the cover. Another drawback of screens is that they can negatively interact with ventilation, leading to an increase instead of decrease of temperature (García-Balaguer et al., 2017).

Within the Public-Private Partnership (PPP) project "Smart Materials" different research groups and companies have worked on the development of new smart materials for application in greenhouse horticulture. Fundamental material development (Timmermans et al., 2020), as well as applied crop physiological experiments are part of the project. Development focuses on the instantaneous control of light intensity (from transparent to dark) and scattering (from transparent to diffuse/opaque) through these materials (Baeza et al., 2020). 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. The following benefits might be expected from this type of light regulation:

- The higher light sum per unit time underneath the electrochromic glasses might increase crop growth per unit time.
- The reduction of undesirable peaks of light intensity underneath the darkening ECG (Electrochromic glass, AGC Nederland Holding B.V.) with continuous control could increase plant growth rate, (reduce the time to market), decrease risk of leaf burn and improve the quality of the plant.
- The higher light scattering activated at high light intensities of the diffusing PVL (PRIVA-LITE, Saint-Gobain) glass could result in more homogeneous and lower leaf temperatures, which could result in less risk of leaf burn and improved quality of the plant, and a higher PPFD sum than a unvarying diffusing cover, due to the slightly higher transmission of the PVL glass in clear state.

Small-scale experiments were carried out to explore the performance and benefits of two types of switchable glass as greenhouse cover with pot *Anthurium* and *Schefflera*.

MATERIALS AND METHODS

The objective was to evaluate the effect on light availability and the crop responses under two types of electrochromic glasses: 1. Darkening electrochromic glass (ECG), which can switch from transparent state to progressively darker states (Figure 1), when increasing voltages are applied. Two glass panes of 0.84×1.35 m were used; 2. Diffusing electrochromic glass (PVL), which can switch from clear state to highly light scattering state (from Hortiscatter 0 to Hortiscatter 80%). Unlike the darkening glass, there were only two possible states. The material had a transmission of 73% in clear state and 68% in diffuse state. Two glasses of 2.57×1 m were used.

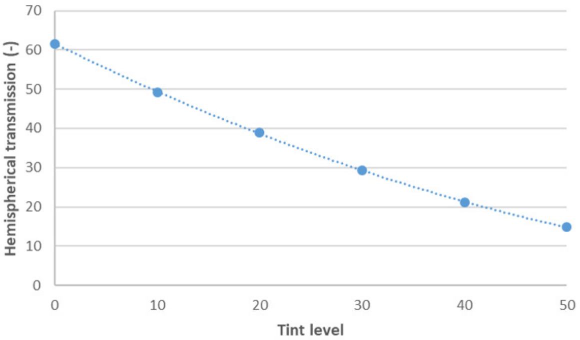

Figure 1. Hemispherical transmission of the darkening EC glass depending on the tint level of the glass which is increasing with increasing voltage.

Two high value crops were cultivated during 15 weeks (April 6 – till July 28, 2020): 12-cm pots *Anthurium andreanum* 'Royal Champion' (Anthura, Bleiswijk, The Netherlands), under darkening glass (ECG) and 13 cm pots *Schefflera arboricola* 'Nora' (Kw. Mostert, Nieuwerkerk, The Netherlands) under the diffusing glass (PVL). The electrochromic glass material available was too limited to cover even a small greenhouse, so a "greenhouse in a greenhouse" approach was chosen: In a 144 m^2 greenhouse, eight "smaller greenhouses" were created by placing the electrochromic glass or a reference glass on a heightened aluminum frame over cultivation tables of 4×1.78 m (7.12 m^2). Irrigation and fertigation was by ebb flood. The relative humidity (RH) of the air was increased whenever it dropped below 70%, by means of a high-pressure fogging system. Carbon dioxide (CO_2)was supplied to maintain a concentration of 650 ppm. In the greenhouse, climate parameters such as temperature, relative humidity, CO_2 concentration, photosynthetic photon flux density (PPFD), etc., were recorded at 5-min intervals.

Per glass type one reference (material with temporary coating) was added. The resulting treatments (Table 1) were duplicated and laid as a randomized block design.

Table 1. Treatments, glass type and management of the electrochromic glasses and crops.

Treatment	Glass type	Light regulation	Crop
ECG 1	Darkening glass	Glass managed to regulate light intensity at 300 µmol m^{-2} s^{-1}	*Anthurium*
ECG 2	Darkening glass	Repetition of ECG 1	*Anthurium*
ECG Ref 1	Float glass coated (Redusol, 1:4) to transmission 40%	Reference for ECG	*Anthurium*
ECG Ref 2	Float glass coated (Redusol, 1:4) to transmission 40%	Repetition of reference ECG	*Anthurium*
PVL 1	Diffusing glass	Glass managed to switch to diffuse at PAR >430 µmol m^{-2} s^{-1}	*Schefflera*
PVL 2	Diffusing glass	Repetition of PVL1	*Schefflera*
PVL Ref 1	Float glass coated (Redufuse, 1:4), to transmission 68%	Reference for PVL	*Schefflera*
PVL Ref 2	Float glass coated (Redufuse, 1:4), to transmission 68%	Repetition of reference PVL	*Schefflera*

The light transmission of the compartment was measured perpendicularly on a cloudy day on multiple spots per table with the side screens closed to avoid light from the sides. On average only 40% of the light reached the tables. To minimize the amount of light intercepted by plants that has not been transmitted through the glass, horizontal shading screens (Ludvig Svensson B.V., Hellevoetsluis, The Netherlands), were placed surrounding the glass (Figure 2). For *Anthurium*, around the darkening ECG glass and its reference a screen with a hemispherical transmissivity of 40%, (Harmony 6020 O E FR) was used. For *Schefflera*, around the diffusing PVL glass and its reference a screen was placed with a transmissivity of 67% (Harmony 3315 O FR).

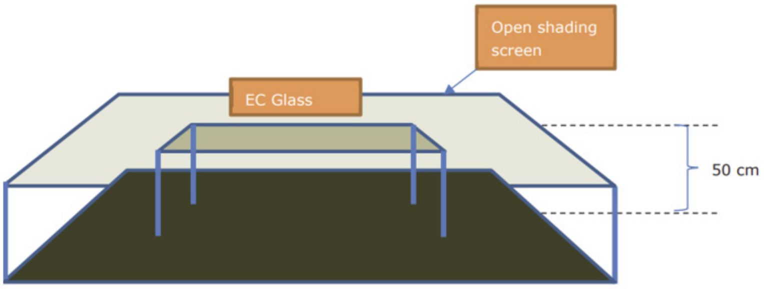

Figure 2. Scheme of the "small greenhouse" construction with the EC glass and a surrounding shading screen.

Although all 14 tables in the greenhouse were filled with plants to create a realistic growing environment, only 8 tables were dedicated to the treatments. Plants were supplied by commercial growers. *Anthurium* plants had an initial height (including the pot) of 16-18 cm and were placed directly after arrival on the tables at a density of 72 plants m^{-2}. After 4 weeks, the plants were spaced for the first time to 50 plants m^{-2} and 5 weeks later for the second time to their final density of 33 plants m^{-2}.

Young cuttings of *Schefflera* plants (mostly one leaf) were placed tight against each other (about 50 plants m^{-2}) at the start. After 4 weeks they were spaced to a density of 33 plants m^{-2}. After four more weeks plants were spaced for the second time to a final density of 21 plants m^{-2} and wood sticks were used to keep them growing upright. At this stage, the faster plants were 50 cm tall and ready to market about 2-4 weeks later.

An Apogee Q-500 quantum-sensor below each glass was used to measure the PPFD light at 5 min intervals. The ECG glass was controlled based on this sensors. The glass controlled the light level once every 30 s, becoming from transparent to dark if the average light intensity of the last 30 s was higher or lower than the setpoint (300 µmol m^{-2} s), The PPFD sensor below the glass was also used to control the PVL glass switch: when the light level under the PVL exceeded 430 µmol m^{-2} s, the glass switched to diffuse. At levels below this threshold, the glass was transparent.

Air temperature and relative humidity sensors were installed under each glass treatment. The condition of the *Anthurium* plants was monitored at mature leaf level with a Hex-PAM sensor consisting of six Micro-PAM (Pulse-Amplitude-Modulation) stand alone heads, (Heiz Walz, GmbH, Effeltrich, Germany) sensor that gives readings of leaf temperature, humidity, PPFD and photosynthesis activity. This latter parameter is measured by the electron transport speed (ETR), based on chlorophyll fluorescence quantum yield. Two contact temperature sensors (pt100 patch surface sensor, RT) monitored the surface temperature of the darkening glass and its reference glass, as it was known from a previous experiment (García Victoria et al., 2019) that it could become very hot.

Plant measurements were conducted at the start, at the spacing moments and at the end of the experiment. For non-destructive measurements, an earlier validated automatized WUR-developed device based on vision technique was used. By means of an upper and lateral camera, each plant was photographed 12 times from above and from the side while turning the plant 360 degrees. Images were processed automatically and used for measures. Both non-destructive (ND) and destructive (D) measurements were performed, in order to quantify: 1. Projected leaf area (ND); 2. Plant height (ND); 3. Number of flowers (ND, if present); 4. Leaf angle (ND); 5. Flower and leaf color (ND); 6. Number of leaves (D); 7. Leaf area (projected, ND and D with a leaf area meter (LI-3100C, Li-Cor inc., Lincoln, USA); 8. Fresh and dry weight (D) of leaves including the stems after drying for 48 h at 80°C in a ventilated oven. The plants for the destructive measurements (10 per treatment) were randomly selected for each measurement. For the non-destructive measurement, 10 plants per treatment were randomly taken from the sampling area (center of the glass), then labeled to be followed in time. The obtained results (both destructive and non destructive) were statistically analyzed using a General Analysis of Variance ANOVA (Genstat 19th edition).

RESULTS AND DISCUSSION

Light, temperature and relative humidity under the glass treatments

1. Darkening electrochromic glass.

ECG glass showed good control of the PPFD during the hours in which radiation inside the greenhouse was above the 300 µmol m^{-2} s^{-1}, which was the desired value, as can be seen in Figure 3. ECG glass maintained values closer to the desired set point of PPFD during most of the daytime hours, whereas under the reference glass, measured values exceeded the desired value on sunny days and remained considerably below the desired value on clouded days.

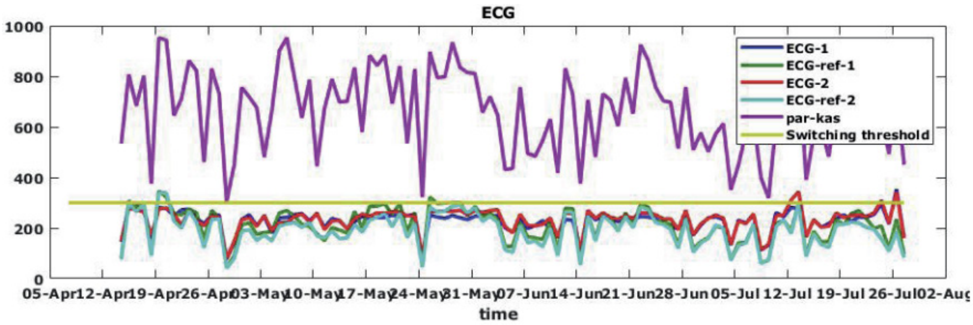

Figure 3. Daily average PPFD (for all measurements above PPFD >300 µmol/m^{2}s) as measured below the two ECG glass panes (ECG-1 and ECG-2) and the two reference glass panes (ECG-ref1 and ECG-ref2).

As a result of the light advantage on cloudy days, the measured final sum of PPFD was larger under the two ECG repetitions (ECG-1=892 mol m^{-2} and ECG-2=956 mol m^{-2}) than under the two reference repetitions (ECG-ref1=792 mol m^{-2} and ECG-ref2=755 mol m^{-2}). The mean daily PPFD was also higher under both ECG treatments than under the reference treatments (131, 141, 116 and 111 µmol m^{-2} s^{-1} for ECG-1, ECG-2, ECG-ref1 and ECG-ref2, respectively.

The measured air temperatures under the electrochromic glass on sunny days were higher than the reference glass. Presumably this was the consequence of increased surface temperature of the glass material: The maximum daily ECG surface temperatures reached values exceeding 55°C on a large number of days, while the maximum values of surface temperature of the reference glass hardly ever exceeded 45°C (data not shown). 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 applied for the light regulation, increases its surface temperature. Therefore, relative humidity values were slightly lower under the ECG glass treatments, on sunny days than under the reference glass (data not shown).

2. Diffusing electrochromic glass.

Unlike the tested darkening ECG, the diffusing PVL glass does not regulate PPFD 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 m^{-2} s^{-1}. The difference in hemispherical light transmission between both states is small (ca. 3% less transmission in diffuse state). In periods when PPFD inside the greenhouse was high (above 430 µmol m^{-2} s^{-1}) the average PPFDs measured below the glasses were slightly lower under the PVL than under the reference glasses, which indicates their successful activation, leading to (only slightly) lower PPFD values. During the last weeks of the cycle, the *Schefflera* plants grew rapidly and shaded the sensors in all the treatments at times, but especially in the PVL-ref-1 treatment. The final PPFD sum was very similar in the two PVL repetitions (1157 and 1158 mol m^{-2} for PVL-1 and PVL-2), and only slightly lower than the two reference repetitions (1194 and 1278 mol m^{-2} for PVL-ref1 and PVL-ref2), which also exhibited a slightly larger difference between them, most likely caused by differential shading of the sensors by structural elements and from neighboring compartments in the two greenhouse positions. The average PPFD intensities during daytime hours were very similar in the two treatments during the whole cycle, 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. Under the PVL glass, only minor differences in temperature and relative humidity were observed between treatments (data not shown).

Leaf temperatures and photosynthesis (only on the ECG *Anthurium* experiment)

The Hex-PAM was in use from 28 May to 28 July. For anthurium these measurements are relevant as the leaves close their stomata if the leaf temperature rises above 32°C, especially when RH is below 50% (Van Noort et al., 2013). In the treatments ECG-2 and ECG-ref2, two plants were monitored: in ECG1 and ECG-ref1, one plant. For a significant number of hours, the leaf temperature exceeded the threshold value in all the treatments. Leaf temperatures were consistently higher in the plants under the ECG glasses than under the reference glasses, following the same pattern observed for the temperatures of the glass surface and the air temperatures (data not shown). The differences for leaf temperature were larger than for air temperature. For instance, average leaf to air temperature difference in ECG-ref was 0.3°C (maximum difference of 3.2°C) whereas for ECG-1 the average difference was 1.1°C (maximum difference of 13.4°C). This indicates that leaf transpiration is hampered when the temperature of the leaf becomes too high, and the leaf overheats due to insufficient evaporative cooling, and translated into a drop in plant photosynthesis efficiency on sunny days under the ECG treatments (data not shown) compared to the reference glass.

Plant growth and development

1. Darkening electrochromic glass.

Anthurium plants grew well in all treatments as expected from the good light regulation and reasonably good control of the temperature and humidity below the glass panes. The plants developed the same in both treatments. No significant differences have been found in any of the non-destructively measured parameters (5% ANOVA, Table 2). At the end of the experiment (28 July), the plants were also measured destructively, to calculate the produced biomass (fresh and dry weight). This allowed to count the number of flower buds and leaves as well. There was neither a significant difference in the number of leaves and flower buds nor fresh and dry weight (data not shown).

Table 2. Plant parameters *Anthurium*.

Date	Treatment	Flowers (#)	Flower height (cm)	Plant height (cm)	Projected leaf area top (cm^2)	Flower area (cm^2)	Plant diameter (cm)
8 April	start	-	-	25.3	227.2	-	20.3
6 May	l.s.d.(5%)	*0.39*	*2.81*	*3.59*	*32.6*		*1.66*
	ECG	0.40 a	25.0 a	30.9 a	242 a		20.1 a
	REF	0.65 a	26.4 a	30.1 a	256 a		20.2 a
11 June	l.s.d.(5%)	*0.50*	*1.76*	*1.33*	*35.9*		*3.16*
	ECG	1.05 a	33.3 a	33.5 a	306.3 a		24.5 a
	REF	1.25 a	32.5 a	33.6 a	315.2 a		23.2 a
28 July	l.s.d.(5%)	*0.56*	*1.75*	*0.93*	*38.8*	*19.0*	*1.69*
	ECG	2.30 a	37.2 a	36.6 a	394.5 a	65.1 a	27.3 a
	REF	2.40 a	38.2 a	37.1 a	383.6 a	79.2 a	26.6 a

2. Diffusing electrochromic glass.

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. At the end of the experiment, the plants grown under the glass with diffusive coating (reference treatment) were taller and had a larger leaf area (projected) than the plants grown under the diffusive electrochromic glass (Table 3).

The destructive measurement at the end of the experiment confirmed the results: the plants of the reference treatment (diffuse coated) were significantly (5% ANOVA) taller, had more leaves per plant and a larger leaf area, and higher dry matter percentage (data not shown) than the plants under the diffusing electrochromic glass. The destructive measurements made evident why some of the plants stayed shorter than others: they had a split apex or a massive ramification of the apex. These effects (split apex) were found in almost all the plants growing under the PVL glass, and in only a few of the plants growing under the reference (diffuse coated) glass. When the apex splits, the height is reduced as does the number of leaves on the main stem.

Table 3. Plant parameters a measured in the *Schefflera* experiment.

Date	Treatment	Plant height (cm)	Projected leaf area (top) (cm^2)	Projected leaf area (side) (cm^2)	Leaf inclination	Plant diameter (cm)
8 April	start	22.9	99	21.3	-	-
11 May	*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
4 June	*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 July	*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

In a recent experiment with artificial lighting of *Schefflera*, this effect was observed as well in most of the plants (M. Mahakena, pers. commun., 2020). It could be an expression of light damage when light was not diffuse (always below a light intensity of 430 µmol).

CONCLUSIONS

Darkening electrochromic glass gave very good control of the light intensity below the glass, with PPFD levels close to the desired set point of 300 µmol m^{-2} s^{-1} and higher PPFD sum under the EC glasses than under the reference glasses. However, this did not lead to a higher growth rate by the plants. The most likely explanation lies in the reduction of photosynthesis efficiency measured in leaves under the EC glass on sunny and warm days due to excessive leaf temperature, coincident in many cases with low RH values, conditions in which *Anthurium* stomata close. This higher leaf temperature was the consequence of the large increase in the temperature of the EC glass in its darker stages. For application in greenhouse covers, it is therefore desirable that light transmission is reduced by increasing reflection, rather than absorption.

Diffusing EC glass also had good control of the light conditions as programmed: diffuse light whenever the set threshold was reached, and clear glass below the threshold. However, when the glass was not in a diffuse state and therefore allowed for 5% more PPFD than the coated glasses, did not significantly increase the light sum. The changing light diffusing conditions did not increase biomass production and dit not lead tofaster 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 for *Schefflera,* 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.

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