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Quantifying optical and thermal properties of innovative screen materials and their effect on energy saving and crop growth

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Abstract

In Dutch greenhouses one or more movable screens are used for energy saving cultivation. Screens separate the lower warm, humid compartment with crops from the upper cold, dry compartment of the greenhouse roof. Screens, especially multiple screens, affect the insulation value of the greenhouse. The energy saving potential is depending on material properties and on screen usage strategies. Radiometric properties including transmissivity and emissivity for thermal infrared radiation (TIR), aerodynamic properties consisting of air permeability, humidity transport characteristics involving hygroscopy, the mechanism of humidity condensation on the lower side of the screen, transport through the material, and evaporation at the upper side have been shown to save energy. Materials with low TIR transmissivity, emissivity and low permeability show highest energy saving. However, energy saving is influenced by the amount of hours screens are closed. If screens are closed beyond dark nighttime hours, optical properties (hemispherical light transmissivity, light diffusion, light spectrum) are important. If screens are closed during light daytime hours, these properties determine not only the amount of incoming sunlight energy but also the availability of photosynthetic active light (PAR) for plant growth and development. In this study properties of different innovative energy saving screen materials were measured using standardized equipment and protocols. With the help of model calculations using the adapted dynamic climate and energy model KASPRO these properties were translated to energy saving potentials in a tomato crop. Materials with different light transmissivity were studied assuming different outside radiation levels, inside artificial lighting and screening strategies. Consequences for energy saving, crop growth and development are analysed to let growers make informed investment and operational choices and help screen manufacturers to develop improved materials.

Keywords: energy saving, screens, optical properties, hemispherical light transmissivity, photosynthetic active radiation (PAR), thermal properties, thermal infrared radiation (TIR), radiometric properties, tomato

INTRODUCTION

The reduction of CO_2 emission has a high priority in The Netherlands and can be reached by reducing the energy usage due to higher insulation of greenhouses (e.g., coverings, screens), improving the climate control strategies (e.g., light- and temperature integration, dehumidification, LED lighting) and replacing the remaining energy demand by non-fossil fuels. One or more movable screens can increase greenhouse insulation substantially. Screens separate the lower warm and humid compartment with crops from the upper cold and dry roof compartment. The amount of energy flux transferring through this separation layer depends on its material properties. Therefore, screens have an important role in energy saving. An important contribution is made by the material properties, which need to be determined with standardized measurement methods (Hemming et al., 2021). Radiometric properties (sensible heat loss by transmission and emission of thermal infrared radiation (TIR)) play an

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important role (e.g., Cohen and Fuchs, 1999). Next to that, the air permeability (e.g., Miguel et al., 1997) determines the convective air exchange through the screen (sensible and latent heat loss). Extra humidity (latent heat) passing through the material due to the process of condensation at lower part of screen, transport through the material by hygroscopy and evaporation at upper part of screen can create losses if textiles are used. Also, convective exchange at the screen (sensible heat loss) takes place depending on the insulation of the material itself or the installation by using multiple screen layers (Hemming et al., 2021). If screens are transparent they can also be used during daytime, extending screen usage and therefore insulation. At the same time when a screen is used, light transmissivity of the greenhouse on crop level and consequently the yield becomes limited. Growers search for a smart balance of energy saving and crop yield.

Such decisions can be supported by model calculations describing a virtual greenhouse with screens and their dynamic usage. Earlier De Zwart (1996) had developed a dynamic model of a full-scale virtual greenhouse for evaluating the energy saving performance based on the computation of relevant heat and mass balances, which was updated to include all related screen properties (Hemming et al., 2025a). With such a model the overall energy saving of a screen with different properties and its different usage strategies can be analysed, as was recently done by Hemming et al. (2025b) for innovative screens in nighttime situations.

This paper aims to analyse the effect of screens with different optical and thermal properties on the availability of light on crop level in daytime situations and the effect on energy consumption. The effect of screen properties and their usage, the use of humidity control by screen gaps or forced dehumidification in a tomato crop with and without additional artificial LEDs light is quantified in this paper. This helps to obtain an objective comparison of different screen material performance under predefined growing conditions, it helps growers to make informed choices of investment and practical usage and, it helps screen manufacturers to improve materials.

MATERIALS AND METHODS

Measurement of screen properties

1. Optical properties.

Optical properties of screens are measured following norm NEN2675+C1:2018 and the measurement protocol described. Transmittance, next to reflectance and absorbance, of total solar radiation energy (0.4-2.5 μm) determine the amount of incoming energy and light for crop yield during daytime. Hemispherical photosynthetic active radiation (PAR) transmittance (0.4-0.7 μm) is determined with the WUR Transvision device (Swinkels, 2012) at Wageningen University & Research in WUR LightLab, The Netherlands. The accuracy of the measurements is 0.5%.

2. Thermal properties.

The energy loss at a screen is moreover determined by the thermal infrared radiation energy (TIR 2.5-100 μm). When TIR hits a screen material, part of it is transmitted (τ_{TIR}), part is reflected (ρ_{TIR}) and a part is absorbed and emitted ($\alpha_{TIR}=\varepsilon$) by the material. For this study radiometric properties are measured by the TNO Emission device developed earlier by De la Faille et al. (2009) at WUR LightLab, The Netherlands. The repeatability of the device itself was determined to be 2.38%. Details can be found at Hemming et al. (2021). Screen materials are measured in dry conditions, properties under wet conditions are assumed following Table 1.

3. Air permeability.

The energy loss due to convective air exchange through a screen in mainly determined by the air permeability properties of the screen material. Air permeability can be characterised by generating a set of air velocities through the screen and recording the resulting pressure difference over the screen. For this study air permeability properties are

measured with a small vertical wind tunnel (Permea device) at WUR LightLab to obtain the air permeability. The repeatability of the device itself was determined to be 0.2%. Details can be found at Hemming et al. (2021). Screen materials are measured in dry condition and after application of condensation in wet conditions.

4. Humidity transport properties.

The energy loss due to humidity transport through a screen is on the one hand determined by convective latent heat transport through the screen due to its air permeability properties (see above) and by the latent heat transport due to condensation on the lower side of screen material, water transport through hygroscopy and evaporation at upper side of screen material. Screens are measured in a humidity transport device (TransHumid device) at WUR LightLab, The Netherlands, under dry and wet conditions to obtain the humidity transport in g m^{-2} h^{-1} as described by Hemming et al. (2021).

Screen model

In general, the energy fluxes in a greenhouse with special emphasis on a screen can be described by Figure 1. During daytime the incoming solar radiation energy flux is important (UV, PAR and NIR transmission, reflection, absorption of the covering and the screen if closed), among which the hemispherical PAR light transmission is strongly determining crop production. a) During day and nightime the outgoing thermal radiation energy fluxes are important (TIR transmission, TIR reflection and emission of the covering and the screen if closed); b) Furthermore, sensible heat fluxes (convective fluxes to and from the screen surface and convective air exchange through the screen due to air permeability of the material); c) and latent heat fluxes (convective air exchange through screen due to air permeability of the material and due to condensation on lower side of screen material, water transport through the material by hygroscopy and evaporation at upper side of screen material); d) determine the energy fluxes at a screen material.

For modelling the energy balance of a greenhouse earlier the dynamic greenhouse energy and climate model KASPRO has been developed and widely validated (De Zwart, 1996). The dynamic simulation model can simulate a full-scale virtual greenhouse based on given greenhouse construction and covering, given greenhouse equipment and capacities, and given set points for inside climate and the outside climate of a specific location and a defined crop. Among others, screen types can be selected and the measured properties of the corresponding screen materials are used as input. Outputs are several climate parameters and performance indicators, such as energy consumption. The model is based on the computation of relevant heat and mass balances (Bot, 1983). The heat balances describe both the convective and radiative processes. Greenhouse climate is controlled by a replica of commercially available climate controllers.

The KASPRO model has been further refined to include the input of all screen properties including the properties of screens in wet conditions (radiometric properties, air permeability properties, humidity transport due to hygroscopy) (Hemming et al., 2025a, b).

For dynamic calculations a standard Venlo-type greenhouse with a glass covering and Dutch weather conditions (Bleiswijk year 2023) were assumed. A tomato crop without artificial lighting was grown from December to end of October. Energy saving growing strategies were considered with details described in Hemming et al. (2021). Next to that a tomato crop with artificial light was assumed with an installed LED capacity of 200 µmol m^{-2} s^{-1} on crop level and a LED efficiency of 3.2 µmol W^{-1} electricity input. In other scenarios a tomato crop with artificial lighting was grown from August to end of June with maxium 18 lighting hours per day during September to April. Lighting was used up to an outside radiation of 200 W m^{-2} or DLI of 20 mol m^{-2} day^{-1}.

For this study different screen materials (RC18H, 23AA, 23MB, 24BI, 23CW) were used with different screen strategies (screen closure setpoint <14°C and 0-100 W m^{-2} outside radiation) and different humidity strategies (setpoint 80-90%). Humidity is controlled either by screen gaps (solid lines in Figures 2-5) or with additional forced dehumidification with a capacity of 5 m^3 m^{-2} h^{-1} and 70% heat-regain (dotted lines in Figures 2-5).

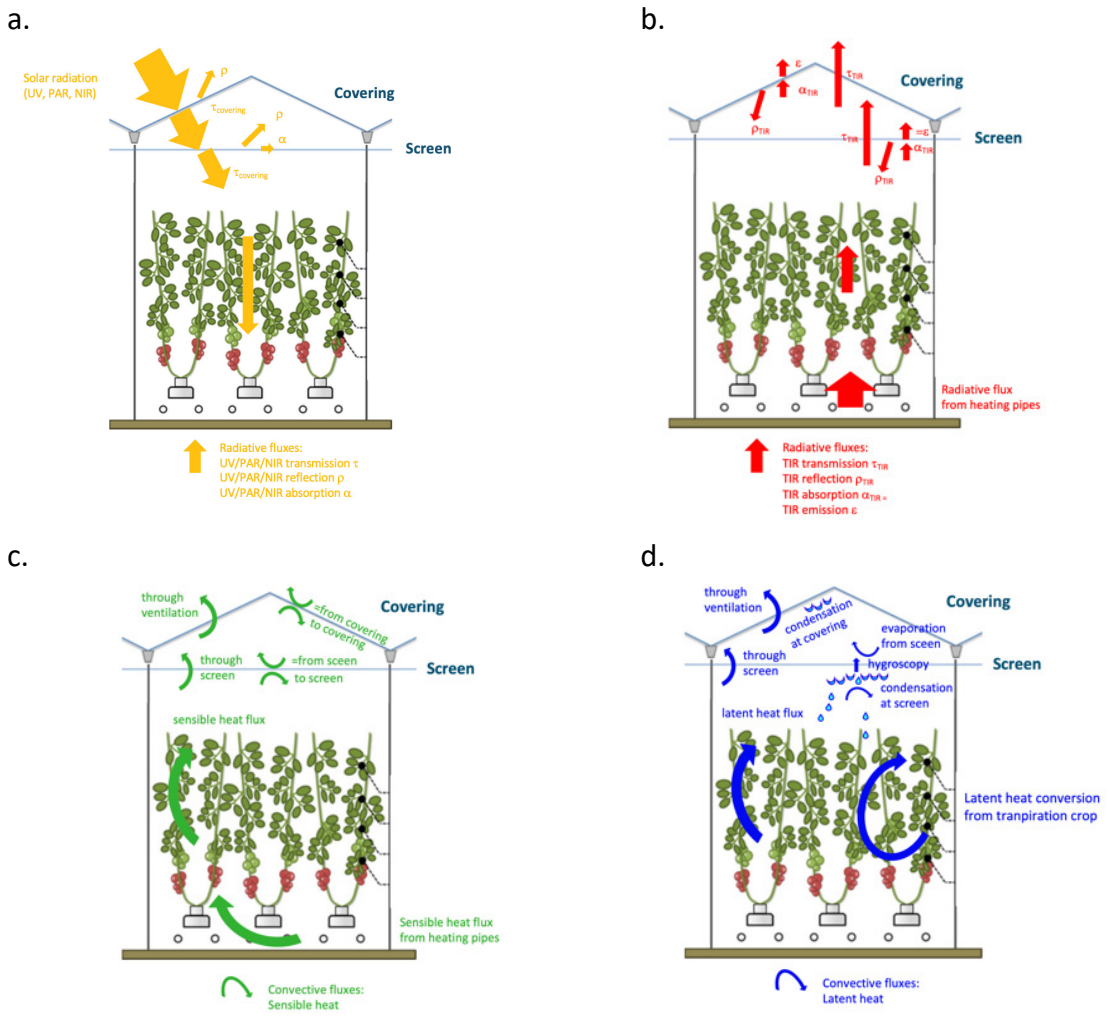

Figure 1. Energy fluxes at a greenhouse with focus on the screen if closed divided in radiative fluxes of a) incoming solar radiation (transmission, absorption, reflection of optical solar radiation), b) outgoing thermal heat radiation (transmission, emission and reflection of thermal infrared heat radiation); c) sensible heat fluxes (air exchange through screen due to air permeability of the screen material and convective fluxes around the screen surface); and d) latent heat fluxes (air exchange through screen due to air permeability of screen material and due to condensation on lower side of screen material, water transport through the material and evaporation at upper side of screen material).

Screen materials

Different screen materials of different producers with different material properties were used with the measured properties given in Table 1, both for dry and wet conditions. Air permeability is 0 for 23AA and 23CW, it is low for RC18H, 23MB and 24BI. Humidity transport is 0 for 23AA and 23CW, it is comparable ina a relatively low range for RC18H, 23MB and 24BI. However, materials have different thermal radiative properties under dry conditions, with increasing TIR reflection from 23AA < 23MB < 24BI < 23CW. While 23MB has a low emissivity, 23BI has a low TIR transmissivity, 23CW has both a low emissivity and a low TIR transmissivity. PAR light transmissivity decreases from 23AA < 23MB < 24BI < 23CW, in which 23CW is the only not transparent screen. The commercially available screen RC18H shows average optical and thermal properties.

Table 1. Measured screen material properties (PAR hemispherical light transmissivity, TIR transmission, emission and reflection, air permeability, humidity transport) under dry and wet conditions as input for the model calculations.

Screen code	PAR transmission hemispherical	TIR transmission	TIR emission	TIR reflection	Air permeability (10^{-7})	Humidity transport (g m^{-2} h^{-1})
Dry condition						
RC18H	69.4	30	51	19	0.53	11.6
23AA	87.0	31	65	4	0	0
23MB	72.8	73	3	25	0.17	6.7
24BI	59.0	6	32	62	0.85	5.0
23CW	0	1	6	93	0	0
Wet condition						
RC18H	69.4[a]	0.05[a]	0.9[a]	0.05[a]	0.52	24.8
23AA	87.0[a]	0.05[a]	0.9[a]	0.05[a]	0	0
23MB	72.8[a]	0.05[a]	0.9[a]	0.05[a]	0.07	27.6
23BI	59.0[a]	0.05[a]	0.9[a]	0.05[a]	0.94	31.0
WK23C	0	0.05[a]	0.9[a]	0.05[a]	0	0

[a]No measurements possible, assumption in model.

RESULTS AND DISCUSSION

Simulations were carried out dynamically yearround in a tomato crop without artificial light. The effect of different screen materials with different properties and the different usage of these materials under different humidity setpoints (80-90%) on the total energy demand (heating) is shown in Figure 2. Screens were used at nighttime only (screen closure <0 W m^{-2} outside radiation and 14°C outside temperature). 35-40% of energy saving can be realised by increasing the humidity setpoint from 80 to 90%. Compared to the good commercial screen materials RC18H, other materials with higher TIR reflectivity can improve energy saving with 10-15% (23AA < 24BI < 23MB < 23CW). 23MB seems to show additional benefits at high humidity setpoints, probably because more condensation is taking away the energy losses due to the high TIR transmissivity of the materials since water is opaque for TIR. 23MB properties in wet conditions are more comparable to 23CW. Earlier Hemming et al. (2025a, b) has shown that screen materials with low air permeability and low humidity transport substantially can save energy. All materials in this study already have a relatively low air permeability, so no large extra advantages of the film materials (23AA and 23CW) are visible.

Figure 3 (left) shows the effect of screen materials with different properties and the different usage of these materials under different closure setpoints during daytime (0-400 W m^{-2} outside radiation) on the total energy demand. Differences of materials are becoming larger (up to 30% difference in energy saving) when closing the screens more hours. Note that, 23CW is not a transprant screen and should be used at nighttime only, however is taken into the simulations to show maximum potential light loss if used also during daytime. Energy saving of all screens increases with 15-30% when closing them more hours, however, additional benefits on energy saving generally become smaller above a closure of 100-200 W m^{-2}. Depending on the screen type extra benefits are either limited due temperature limitations or due to humidity limitations. All screens benefit from the usage of forced dehumidification. 10-20% extra energy saving can be realised. Extra benefits from more homogeneous humidity distribution compared to humidity control by screen gaps can be expected but are not shown here; the dehumidification system capacity has not been optimised for all scenario's.

Figure 3 (right) also shows the effect of all screen materials having different optical properites and all screen usage strategies on the amount of available light on crop level. Remarkably, only at screen closures more than 100-200 W m^{-2} the light availability drops. It is up to 5% on a yearly base comparing 24BI (lowest PAR transmissivity of 59%) with 23AA

(highest PAR transmissivity of 87%). That is explainable since screens are mainly used during winter season in which under Dutch weather conditions ten times less total outside radiation is available (typically 2-5 mol day^{-1}) compared to summer season (up to 40 mol day^{-1}), so on a yearly base light loss is small. Looking closer to winter season (figure not shown), we can observe a smaller DLI (0.5 mol day^{-1} in average under 24BI compared to 23AA, assuming closure up to 200 W m^{-2} outside radiation), potentially leading to some crop delay. In the winter months (December to April) light availability under 24BI would then be in total 60 mol lower than under 23AA, which is equal to the need to produce 1 kg of tomato.

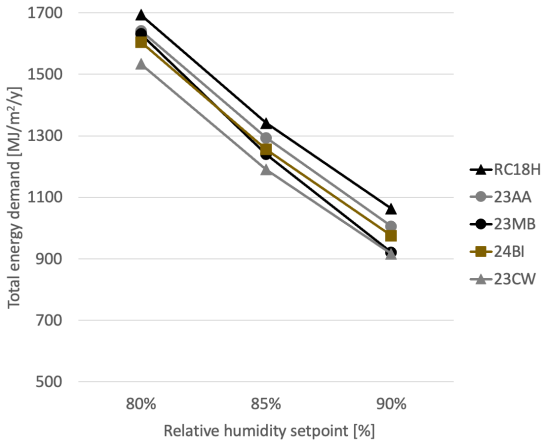

Figure 2. Effect of screen materials with different properties and the usage of these materials under different humidity setpoints (80-90%) in a tomato crop without artificial light on the total energy demand. Humidity is controlled by screen gaps. Screens were used at nighttime only, screen closure <0 W m^{-2} outside radiation and 14°C outside temperature.

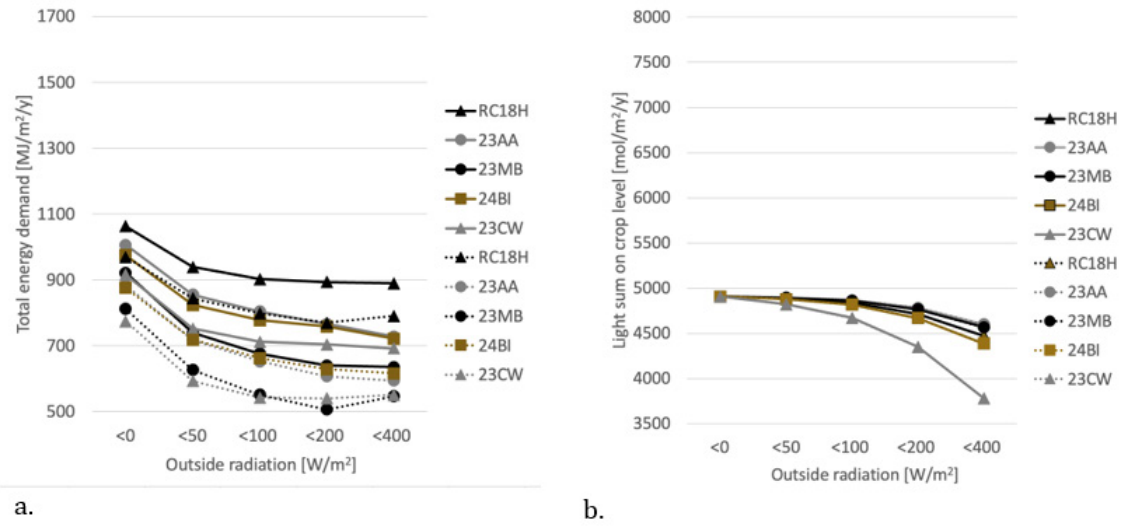

Figure 3. Effect of screen materials with different properties and the usage of these materials under different outside radiation setpoints (0-400 W m^{-2}) in a) a tomato crop without artificial light on the total energy demand, and b) total available light sum on crop level. Humidity is controlled by screen gaps (solid lines) or by forced dehumidification (dotted lines). Screens were used also at daytime, screen closure <90% inside humidity setpoint and 14°C outside temperature.

Figure 4 (left) shows the effect of different screen materials with different properties and the usage of these materials under different closure setpoints for a crop under artificial lighting. Also here, energy savings can be observed by increasing screen closure during daytime hours, depening on the screen material, however, savings are only 10-15%. Differences between material properties are smaller. Also here, forced dehumidification decreases energy consumption by 10-20%. However, due to the higher electricity consumption for LEDs also total energy demand is substantially higher for all scenarios. Due to the installed additional artificial LED light and its usage, the crop receives also 40-50% more light. Decpites of a lower PAR transmissivity of screen 24BI compared to 23AA, the difference in total available light is even smaller (only 1.5% at a yearly base). It seems that screen properties are more important in crops without artificial lighting.

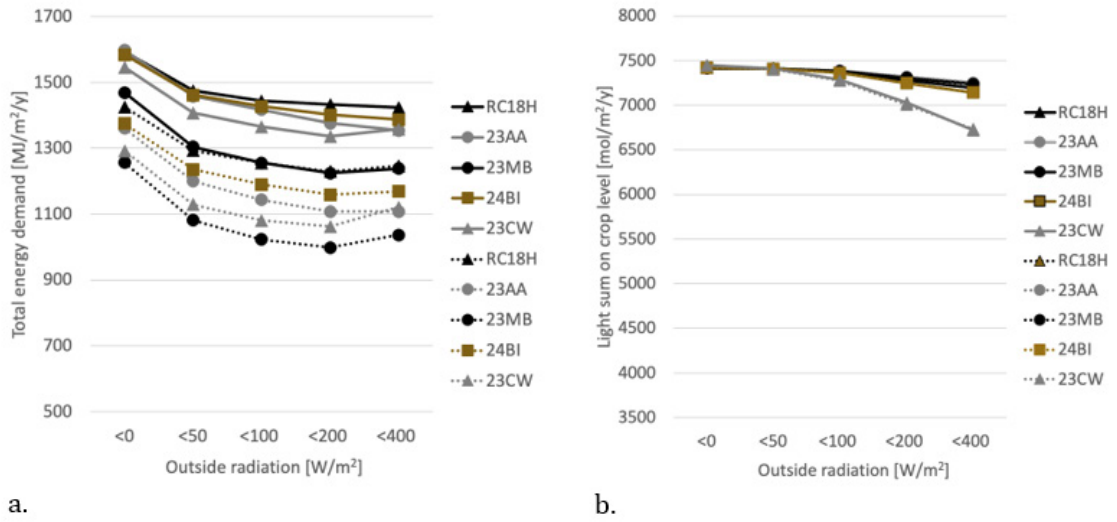

Figure 4. Effect of screen materials with different properties and the usage of these materials under different outside radiation setpoints (0-400 W m^{-2}) in a. a tomato crop with artificial LED light on the total energy demand, and b) total available light sum on crop level. Humidity is controlled by screen gaps (solid lines) or by forced dehumidification (dotted lines). Screens were used also at daytime, screen closure <90% inside humidity setpoint and 14°C outside temperature.

With the figures on energy demand and light availability above we can try to balance the screen usage for energy saving and crop production. Figure 5 shows the lightsum per energy consumption. We can observe that for most screens a usage up to 100-200 W m^{-2} is most beneficial. The use of forced dehumidification shows best results. All innovative screens and their usage calculated lead to an improvement for future use.

CONCLUSIONS

In this study a methodology to obtain the most important screen material properties using standardised measurement equipment and methods has been used to characterise screens under dry and wet conditions. A refined model based on KASPRO (De Zwart, 1996; Hemming et al., 2025a, b) has been used to analyse dynamic energy saving potentials for different screen materials based on their properties, different screen usage in interaction with different dehumidification methods (screen gaps and forced dehumidification) and with and without artificial lighting.

- Improved screen properties (more reflection thermal heat radiation and low emissivity) combined with low air permeability and low humidity transport increases energy saving (10-15%) compared to good commercially available screens;
- Increase of humidity setpoint (from 80 to 90%) can substantially increase energy

saving (35-40%);
- Keeping transparent screens more closed during daytime (from 0 to 400 W m^{-2}) increases energy saving (15-30%);
- Improved light transmissivity of screens (from 60 to 85% τ_h) increases the amount of available light on crop level per year up to 5% at frequent screen closure (400 W m^{-2}) in a crop without artificial light, but only up to 1.5% in a crop with artificial light;
- In all situations energy usage can be optimised choosing a high humidity setpoint, usage of forced dehumidification with heat regain and closing the screen at more hours during daytime.

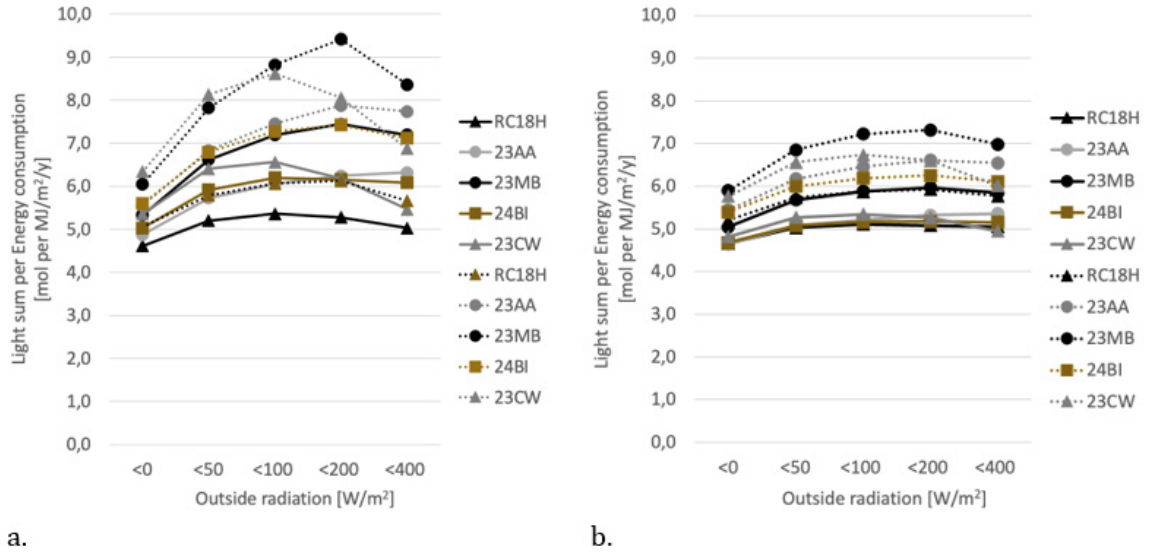

Figure 5. Light sum per energy consumption in the different scenario's of Figures 3 and 4. Screen usage under different outside radiation setpoints (0-400 W m^{-2}) in a) a tomato crop without artificial light, and b) with artificial lighting. Humidity is controlled by screen gaps (solid lines) or by forced dehumidification (dotted lines).

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Literature cited

Bot, G.P.A. (1983). Greenhouse climate: from physical processes to a dynamic model. Dissertation (The Netherlands: Landbouwhogeschool Wageningen).

Cohen, S., and Fuchs, M. (1999). Measuring and predicting radiometric properties of reflective shade nets and thermal screens. J. Agric. Eng. Res. *73* (*3*), 245–255 https://doi.org/10.1006/jaer.1999.0410.

De la Faille, B., Campen, J.B., and Oversloot, H. (2009). Emission and transmission of heat radiation through screens. TNO Report. 034-DTM-2009–04659.

De Zwart, H.F. (1996). Analysing energy saving options in greenhouse cultivation using a simulation model. Ph.D; dissertation (Wageningen, The Netherlands: Landbouwuniversiteit).

Hemming, S., De Zwart, H.F., Mohammadkhani, V., Raaphorst, M., Van Breugel, B., and Baeza, E.J. (2021). Wet screens - Characterization of physical properties of screens and quantification of their effect on greenhouse energy use. WUR Report. WPR-1099. https://www.doi.org/10.18174/558268.

Hemming, S., Mohammadkhani, V., Raaphorst, M., and de Zwart, F. (2025a). Modelling energy transport through greenhouse screen materials for a standardized property assessment. Acta Hortic. (in press).

Hemming, S., Mohammadkhani, V., Raaphorst, M., and de Zwart, F. (2025b). Quantifying energy saving by screens – the role of humidity transport. Acta Hortic. (in press).

Miguel, A.F., van de Braak, N.J., and Bot, G.P.A. (1997). Analysis of the airflow characteristics of greenhouse

screening materials. J. Agric. Eng. Res. *67* (*2*), 105–112 https://doi.org/10.1006/jaer.1997.0157.

Swinkels, G.L.A.M. (2012). Transvision: a light transmission measurements system for greenhouse covering materials. Acta Hortic. *956*, 563–568 https://doi.org/10.17660/ActaHortic.2012.956.67.