Greenhouse Cooling by NIR-reflection

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Abstract

Wageningen UR investigated the potential of several NIR-filtering methods to be applied in horticulture. In this paper the analysis of the optical properties of available NIR-filtering materials is given including a calculation method to quantify the energy reduction under these materials and to estimate the contribution for greenhouse cooling. It can be concluded that the optimum NIR-filtering material is still not found but there is good potential for further developments. NIR-filtering multilayer coatings applied to plastic film or glass filter out NIR most effectively. NIR-filtering is not desirable during winter-time in most climatic regions. Therefore, NIR-filtering coverings should not be used in unheated greenhouses since they cause an undesirable temperature drop. NIR-filtering white washes still reduce PAR too much. NIR-filtering (moveable) screens could be an alternative in the future. Future studies should also investigate whether it is possible to use the reflected NIR energy for other processes or cost-effectively storage.

INTRODUCTION

Global radiation enters the greenhouse and can be divided into ultraviolet radiation UV (300-400nm), photosynthetic active radiation PAR (400–700nm) and near infrared radiation NIR (800–2500nm). PAR absorbed by the crop is important for growth and photosynthesis, NIR is less absorbed by the crop but it is absorbed by installations and construction elements of the greenhouse and increases air temperature. In greenhouses the heating effect caused by global radiation is desirable during cold periods, but during hot periods the temperature in the greenhouse can increase to undesirable levels so that plant production becomes impossible. In fact, to prevent high temperatures or to reduce the cooling load in greenhouses during high temperature periods has been one of the most important problems to be solved in protected cultivation in most countries worldwide.

For many years scientists and companies have worked on greenhouse covering materials to reduce greenhouse inside temperatures significantly. Since about 1939 water films have been used for the limitation of maximum temperatures in glasshouses and it has been generally considered that the absorption of infrared radiation was the main method by which this was achieved (Brown, 1939). Investigations to optimise the water-filled liquid-roof-system followed, also $CuSO_4$-solutions and other coloured solutions in fluid-roof-systems were used to reduce NIR more selectively (van Bavel et al., 1981; Gale et al., 1996). First detailed investigations on a greenhouse with a NIR-filtering liquid-roof were carried out by Morris et al. (1958). Other research groups followed with further improvements, simulations and practical tests (Canham, 1962; Damagnez; 1975; Sebesta and Jeksrud, 1989). The liquid in the roof lowers the solar energy and can be used for heating and cooling purposes. Depending on the liquid and its concentration, NIR is reduced more than PAR. However, a reduction of PAR cannot be avoided, which limits the applicability of the system.

Since a fluid-roof greenhouse also needs considerable construction investment and must be free of leakages, it was suggested by Shen et al. (1992) to focus more on the development of horticultural plastic films. Recently the research focus is indeed more on developing solid materials with NIR-filtering, like plastic films or glass for greenhouses (Verlodt and Verschaeren, 1997; Hemming et al., 2004; Abdel-Ghany et al., 2001) or

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moveable screens (Runkle et al., 2002; Tanaka, 1997). Also NIR-filtering shading paint has been developed (von Elsner and Xie, 2003). NIR can be kept out of the greenhouse at the covering surface by absorption, reflection and interference (Hoffmann and Waaijenberg, 2002). Using NIR-reflection or NIR-interference the unwanted energy is reflected back out of the greenhouse, whereas a NIR-absorbing material will heat up by energy absorption and will then emit only part of the energy out of the greenhouse, the other part is emitted into the greenhouse and will contribute to warming the greenhouse air. Different techniques like pigments, dyes, permanent or removable coatings are suitable to incorporate the NIR filtering principle into the covering material.

Commercial plastic film products were developed by the plastic film producer Hyplast (Belgium), containing interference pigments of Merck Company (Germany), which reflect parts of the visible spectrum and therefore lead to a shading effect. Moreover they give a diffusive character to the film (Verlodt et al., 1995). New generations of interference pigments and plastic films act more in the NIR, the reduction of PAR is much smaller. These films lead to a significant reduction in greenhouse inside temperature, especially during periods with high irradiation (Verlodt and Verschaeren, 1997). Hemming et al. (2004) investigated new plastic film prototypes developed by Oerlemans (The Netherlands) containing NIR-reflecting pigments with several concentrations and showed that a reduction of NIR (700-1100nm) up to 25.7% was possible. At the same time PAR was reduced 8.7%. The effect of these films on energy reduction and greenhouse inside temperature was evaluated in experiments in tropical regions. Results were used to develop a new greenhouse climate model.

Different NIR filtering plastic film prototypes were developed by Mitsui Chemicals (Japan). Abdel-Ghany et al. (2001) conducted a simulation study to examine the effects of three types of NIR-filtering plastic films and a fluid-roof cover (polycarbonate panel filled with a 1.5% $CuSO_4$-water solution) on air, plant and soil temperatures in Japan. Closed fluid-roof and ventilated plastic film greenhouses with moist soil were calculated at different plant densities on hot sunny days. The results showed that at high plant densities, the ventilated plastic film greenhouse gave lower soil and plant temperatures than the closed fluid-roof greenhouse. The plant temperature in the closed fluid-roof greenhouse was unacceptably high at high plant densities. The authors suggested the use of plastic film greenhouses rather than fluid-roof covers with a complex structure in hot climates.

As well as incorporating pigments or dyes into greenhouse covering plastic films, solid coatings can be applied to plastic films or glass. Very effective interference multilayer coatings on glass act selectively in the NIR range of the spectrum and transmit almost all PAR. These materials are used for heat reflection and cooling in civil buildings or as optical filters (e.g. Prinz Optics, 2006). However, such materials are not available for horticultural practice yet due to high costs and limited dimensions. Runkle et al. (2002) investigated a new multilayer NIR-filtering plastic film material developed by 3M (USA) used as a moveable screen inside the greenhouse. The plastic film material was produced as a solid screen and as a woven curtain. The two materials were compared with a neutral metalized shading screen. The researchers found that both NIR-filtering screens transmitted more PAR, but less NIR compared to the neutral screen. However, total energy transmission under the NIR-filtering screens was higher than under the neutral screen. This resulted in higher average air temperatures, while average plant temperatures under all three materials were comparable. However, the ratio PAR to total energy under the NIR-filtering screens was higher than under the neutral screen.

NIR-filtering properties were also integrated in shading paint, which can be applied as a removable coating to the greenhouse cover. In Japan, work was carried out in the nineties on the development of an effective shading material against near infrared radiation which does not contribute to photosynthesis. A filter was used which cut out 60% of the NIR and 30% of the PAR. That filter could decrease the cooling load of the greenhouse by about 8% compared with a greenhouse with neutral shading, which only reduced PAR by 30% (Tanaka, 1997). Recently the University of Hanover (Germany) carried out investigations with the NIR-interference pigments of Merck (Germany) integrated in shading paint to selectively reduce NIR inside the greenhouse (von Elsner and Xie, 2003). Two different pigments in different concentrations were mixed in a white paint and applied on PE covered plastic film tunnels during summertime. Depending on pigment concentration either the PAR levels recorded under the NIR-filtering shading paint were higher than under conventional shading paints or the heat load in the greenhouse was reduced, because of the lower transmittance of NIR radiation (von Elsner and Xie, 2003). These investigations led to a commercial product for the horticultural market distributed by Mardenkro (The Netherlands).

The effectiveness of NIR-filtering materials on the reduction of greenhouse air and crop temperatures and on the increase of crop production depends on several factors, though. Some authors point out that a large amount of NIR has to be kept out of the greenhouse to have an effect. Moreover, the ventilation capacity of the greenhouse, plant density and crop transpiration are important factors. Until now there has not been a detailed analysis of the potential of several NIR-filtering methods. Therefore, Wageningen UR investigated the potential of several NIR-filtering methods (covering material, internal or external moveable screens, removable coatings like white wash) to be applied in Dutch horticulture (Hemming et al. 2005a). The effects of several NIR filtering technologies on greenhouse climate (air temperature, humidity, energy consumption, CO_2-concentration), and crop parameters (leaf temperature, transpiration, photosynthesis, yield) of a tomato crop were quantified (Hemming et al. 2005b). In this paper the analysis of the optical properties of available NIR-filtering materials is given including a calculation method to quantify the energy reduction under these materials and to estimate the contribution for greenhouse cooling.

MATERIALS AND METHODS

Several potential greenhouse covering materials with NIR filtering properties were investigated. Traditional greenhouse floatglass 4mm (denoted as Glass) was chosen as the reference. Additionally two different heat reflecting mirrors made from Borofloat® glass 3.3mm (Glass IR3 and Glass IR5) from Prinz Optics GmbH (Germany) and two heat reflecting mirrors made from Borofloat® glass 2.7mm (Glass SIR) and 1.7mm (Glass SIR-IR) from Präzisions Glas & Optik GmbH (Germany) were investigated. All heat reflecting mirrors had different NIR-reflecting coatings. A car glass with a NIR-reflecting coating from Glaverbel (Glass GB) was also included in the investigations. Another group of materials studied were several polyethylene films, a neutral film from Oerlemans Packaging bv / Plasthill bv 200µm (PE film PH0) and the same film with a NIR-reflecting pigment incorporated in two different concentrations (PE film PH1 and PE film PH2). Another neutral polyethylene film from an anonymous source was 200µm (PE film SF0) and the same film containing a NIR-absorbing pigment in two concentrations (PE film SF1 and PE film SF2) were evaluated. Two recently developed NIR-filtering PET films with a thickness of 60µm (PET film M1) and a thickness of 100µm (PET film M2) were compared to a commercial transparent PET screen from Ludvig Svensson bv (The Netherlands) (PET screen). The last group of materials were two white washes, a neutral (ReduSol) and a NIR-filtering (ReduHeat) material. The concentration of the coatings was chosen, so that the NIR-filtering was comparable.

The spectral transmission in the range 300-2500nm was measured using a Perkin Elmer 19 spectrophotometer. The equipment contained a Xenon lamp as the light source and a diode-array spectrophotometer as the measuring device. With this device the whole wavelength range from 300-1100nm could be investigated with a resolution of 1nm. The sample size was about 45 mm x 45 mm. Furthermore, the spectral transmission for direct light under different angles of incidence (0^o, 15^o, 30^o, 45^o, 60^o, 75^o) was determined using an integrating Ulbricht sphere. The size of the samples was 100mm*100mm. The optical properties were determined following NEN 2675 for determination of PAR transmission and EN410 for determination of solar energy transmission. All materials were characterised by the transmission, reflection and absorption for PAR (400-700nm), NIR

(800-2500nm) and solar energy (300-2500nm). The factors are given unweighted. The NIR-filtering factor was calculated by multiplying the transmission factor for each wavelength with the standard solar energy distribution for that wavelength given by CIE 85 (1989) for clear and clouded days. Moreover, photosynthetic photon flux densities PPFD (400-700nm) under the materials was calculated by multiplying the transmission factor of each wavelength with the photon flux density of that wavelength. The ratio PPFD to total solar energy transmission characterizes the plant growth potential under a material. The ratio of red (600-700nm) to far-red (700-800nm) radiation is calculated because of its importance for plant photomorphogenesis.

The greenhouse climate model KASPRO (de Zwart, 1996) was used to analyse the effects of NIR-filtering materials on greenhouse climate parameters.

RESULTS AND DISCUSSION

Several potential greenhouse covering materials with NIR filtering properties were investigated with respect to their suitability for use in horticulture. First the optical properties were determined, with PAR transmission and NIR filtering being the most important. The results of the laboratory measurements are summarized in Table 1. Most materials have a suitable PAR transmission of 90% and higher. A NIR-filtering multilayer coating on glass does not necessarily have to reduce the PAR transmission of the material when the layer design is optimized for horticultural use. Glass IR3 and SIR show that a high PAR transmission can be combined with effective NIR-filtering. The advantage of the NIR-filtering coating on glass is that the heat is kept out of the greenhouse by reflection. Whereas NIR-filtering pigments used in PE films are less effective and lead to a substantial decrease in PAR transmission. The NIR-absorbing pigments used in the PE films SF1 and SF2 seem to decrease PAR more that the NIR-reflecting pigment used in PE films PH1 and PH2. The results for PET films with NIR-reflecting coatings were similar to those for the glasses; the PAR transmission was still high and the NIR-reflection could be optimized. Both white washes reduced the PAR transmission depending on their concentration.

If we compare the ability to keep solar energy out of the greenhouse, the lowest solar energy transmission is shown by the NIR-reflecting glasses. Also the NIR-reflecting PE films PH2 and SF2 and the PET film M1 show a reasonably low solar energy transmission. Moreover, both the neutral white wash and the NIR-reflecting white wash show low values. However, it has to be pointed out that low solar energy transmission factors can be the result of a low NIR-transmission or a low PAR-transmission or both. It is therefore of major importance to analyze the spectral transmission of the materials. In Fig. 1 the spectral transmission factors of materials are given for all wavelengths in the solar range (300-2500nm). It is important in which wavelengths the NIR-filter is acting. Since radiation of 800nm contains more energy than radiation of 2500nm and the sun emits more energy in the range of 800-1100nm, less energy will pass into the greenhouse through a material that filters radiation in the range of 800-1100nm. For example less energy will be transmitted through PET film M1 compared to PE film SF2, since PET film M1 is selectively active in the range 900-1100nm whereas PE film SF2 is more active above 1100nm. So the greenhouse inside temperature will be less under the PET film M1, and a relatively better cooling effect will be obtained. The NIR-filtering glasses SIR and SIR-IR show almost comparable NIR-filtering properties. Both start filtering NIR above 700nm. SIR is slightly more effective up to 1200nm, though SIR-IR is clearly more effective above 1200nm.

To take these effects into account, the spectral transmission factors are weighted with the solar energy distribution given by CIE 85 (1989). Since also the amount of global radiation and the spectral distribution changes throughout the year with different solar inclinations and cloudiness, an analysis of the materials' performance is made for different situations. The results for a clear summer day and a very clouded day are given in Table 3. Most NIR-filtering materials are able to increase the photosynthetic photon flux density PPFD per unit global radiation energy, which is transmitted through the material into the greenhouse. Glass SIR, SIR-IR and GB show the highest values, followed by Glass IR3 and IR5. But also PET film M1 shows a reasonable increase, whereas the other plastic film materials and the white washes only show a minor increase. The PPFD per unit global radiation energy is directly linked to plant growth performance. Differences between materials are relatively higher on clear days than on clouded days.

NIR-filtering plastic film materials are able to reduce the amount of NIR energy by up to 25%, NIR-filtering glasses are able to reduce the amount of NIR energy by 50-70% (Fig. 3). It is conspicuous that the neutral PE film even lets through more NIR energy than neutral glass. However, that normally does not lead to a higher temperature in a plastic film greenhouse compared to a glass greenhouse since the energy losses in the far infrared are higher under a PE film compared to glass (data not shown). Another important property is the change of the R:FR ratio under different materials. Glass IR3, IR5 and SIR increase the R:FR ratio the most (Table 2). This can have a positive effect on stem elongation of several ornamental plants. It is also possible to affect flowering and other plant growth parameters. These effects should be carefully checked when NIR-filtering materials are applied that change the R:FR ratio. The influence of PE film PH2, SF2, PET film M1 and ReduHeat is only minor. The spectral transmission of some of the NIR-reflecting materials also depends on the angle of incidence. Table 2 shows the data for glass IR3. Due to the multilayer coating the maxima of the spectral transmittance is changed towards longer wavelengths by smaller angles of incidence. NIR-reflecting coatings have to be optimized considering this evidence. NIR-filtering should start at 800nm preferably to cover all energy-rich wavelengths, however PAR should not be reduced due to light incidence under lower angles.

Model simulations with the greenhouse climate model KASPRO showed in standard Dutch Venlo-type greenhouses that the mean air temperature can be reduced during summer months by about 1 degree (Fig. 4), during periods with high irradiation that value can be higher (Hemming, 2005b). In unheated greenhouses the temperatures would drop significantly during the winter, in heated greenhouse gas consumption rises (data not shown). The absolute temperature reduction or energy use increase depends on the greenhouse type, mainly through ventilation rates, but also the cropping system has an influence. Crop transpiration is significantly affected by NIR-filtering measures. While the crop needs to maintain high transpiration rates during hot periods to cool itself, the transpiration rate can be about 30% lower under a 100% NIR-filtering greenhouse cover during the summer months. A 50% NIR-filtering cover still reduces transpiration rate by 10-15%. The advantage of the two white washes are, that temperatures and transpiration rates are only reduced during summer months, when the white wash is applied to the cover and when NIR-filtering is needed. However, in contrast to the NIR-filtering cover materials both white washes reduce the amount of PAR in the greenhouse, which directly reduces photosynthesis of most crops and will reduce production of major crops like tomatoes, cucumbers and sweet peppers. The NIR-filtering product lets through more PAR than the neutral product.

It can be concluded that the best NIR-filtering material has still not been found. NIR-reflecting materials are more efficient than NIR-absorbing materials. Wavelengths from 800-1100nm rather than 1100-2500nm should be reflected out of the greenhouse. NIR-filtering multilayer coatings applied to plastic films or glasses filter out NIR most effectively. The angle dependent spectral transmission should be optimized. NIR-filtering is not desirable during winter-time. NIR-filtering covers should not be used in unheated greenhouses in most climatic regions since they cause an undesirable temperature drop. NIR-filtering white washes can be applied during periods when needed. However, they still reduce PAR too much. NIR-filtering (moveable) screens could be an alternative in the future. They should have a very high PAR transmission and should be installed in such a way that they do not limit greenhouse ventilation. Future studies should investigate whether it is possible to use the reflected NIR energy by storing this energy or using it for other processes. First ideas have been developed by Sonneveld et al. (2006).

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Tables

Table 1. PAR-transmission (400-700nm) following NEN2675 and solar energy transmission (300-2500nm) following EN410 of several NIR-filtering materials.

Material	PAR direct 400-700nm NEN2675	Solar energy direct 300-2500nm EN410	Material	PAR direct 400-700nm NEN2675	Solar energy direct 300-2500nm EN410
Glass	0.893	0.850	PE film PH0	0.896	0.845
Glass IR3	0.938	0.661	PE film PH1	0.805	0.728
Glass IR5	0.8756	0.625	PE film PH2	0.773	0.681
Glass SIR	0.922	0.596	PE film SF0	0.843	0.848
Glass SIR-IR	0.873	0.551	PE film SF1	0.746	0.697
Glass GB	0.729	0.439	PE film SF2	0.714	0.656
PET screen	0.832	0.819	ReduSol	0.600	0.602
PET film M1	0.853	0.677	ReduHeat	0.758	0.675
PET film M2	0.881	0.717			

Table 2. Optical properties of several NIR-filtering materials on a clear summer day and a very clouded day; Global radiation (Glob 300-2500nm), photosynthetic active radiation energy (PAR 400-700nm), near infrared radiation (NIR 700-2500nm), ratios of PAR:Glob, NIR:Glob, PAR:NIR, red:far-red ratio (R:FR 600-700nm:700-800nm) and the photosynthetic photon flux per transmitted global radiation (PPFD:Glob)

Material	PPFD:Glob [µmol*m^{-2}*s^{-1} per W*m^{-2}]	Glob [W*m^{-2}]	PAR [W*m^{-2}]	NIR [W*m^{-2}]	PAR: Glob [-]	NIR: Glob [-]	PAR: NIR [-]	R:FR [-]
Clear summer day								
Sun radiation	2.1	679	308	332	0.45	0.49	0.93	1.20
Glass	2.2	578	275	274	0.48	0.47	1.00	1.24
Glass IR3	3.0	441	288	138	0.65	0.31	2.09	2.05
Glass IR5	2.9	420	271	131	0.64	0.31	2.07	2.84
Glass SIR	3.2	401	283	105	0.71	0.26	2.69	1.77
Glass SIR-IR	3.3	379	268	96	0.71	0.25	2.79	1.50
Glass GB	3.4	304	224	79	0.74	0.26	2.82	1.48
PE film	2.2	578	276	297	0.48	0.51	0.93	1.20
PE film PH2	2.3	465	237	223	0.51	0.48	1.06	1.37
PE film SF2	2.2	450	218	218	0.48	0.48	1.00	1.17
PET film M1	2.5	489	271	209	0.55	0.43	1.29	1.20
ReduSol	2.1	408	184	206	0.45	0.50	0.89	1.22
ReduHeat	2.3	458	233	207	0.51	0.45	1.13	1.35
Clouded day								
Sun radiation	2.5	199	109	74	0.54	0.37	1.46	1.97
Glass	2.6	171	97	61	0.57	0.36	1.58	2.03
Glass IR3	3.4	135	101	28	0.75	0.21	3.65	3.38
Glass IR5	3.4	128	96	25	0.75	0.20	3.81	4.71
Glass SIR	3.6	125	100	20	0.80	0.16	4.95	2.94
PE film	3.5	124	95	24	0.76	0.19	3.99	2.47
PE film PH2	2.7	166	97	67	0.58	0.40	1.46	1.97
PE film SF2	2.8	134	84	49	0.62	0.37	1.70	2.24
PET film M1	2.6	141	80	54	0.57	0.38	1.49	1.92
ReduSol	2.7	133	76	51	0.58	0.38	1.51	1.91
ReduHeat	3.0	147	96	48	0.65	0.33	2.00	1.97

Figures

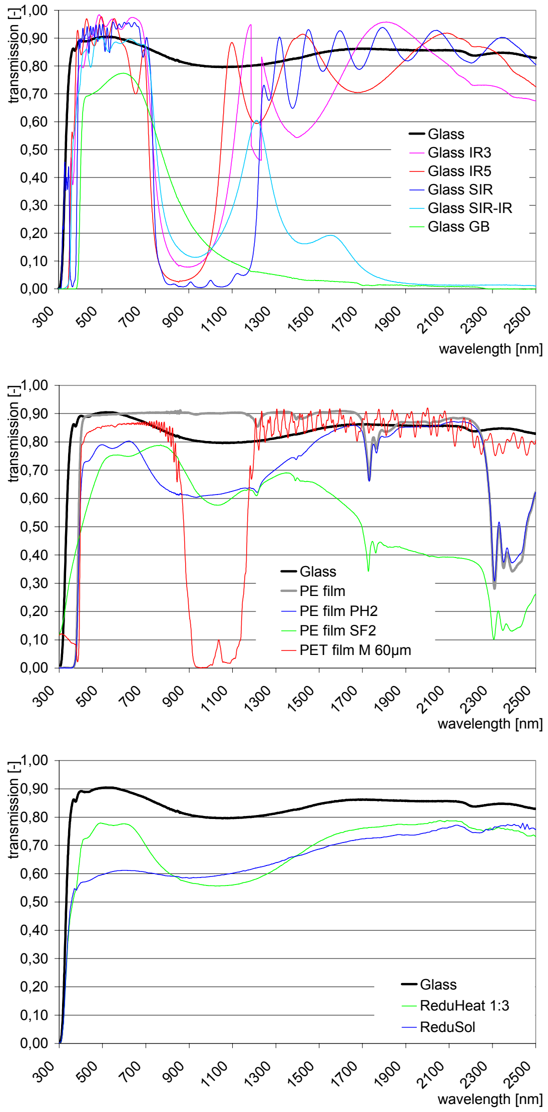

Fig. 1. Spectral transmission of several NIR-filtering materials

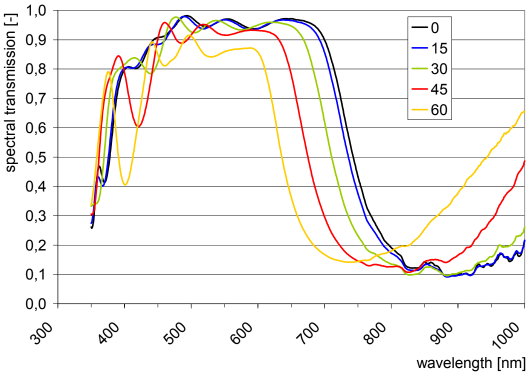

Fig. 2. Spectral transmission of Glass IR3 depending on the angle of incidence (0°, 15°, 30°, 45°, 60°, 75°, with 0° as perpendicular)

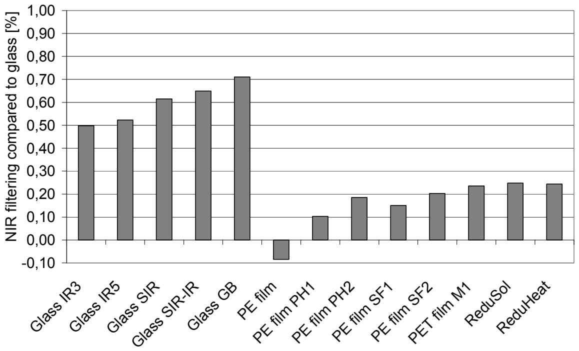

Fig. 3. NIR-filtering properties of several materials compared to traditional greenhouse glass

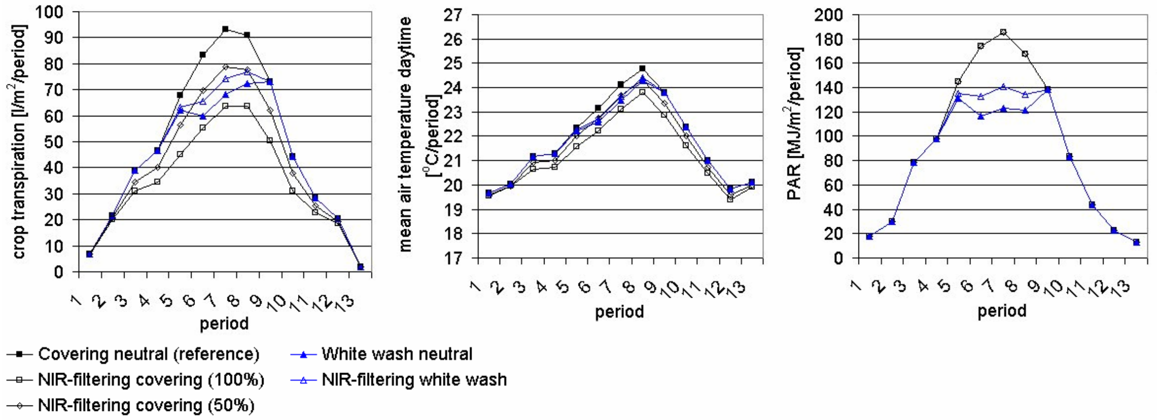

Fig. 4. Mean air temperature, crop transpiration and PAR per period of 4 weeks during an average Dutch year, based on calculations with the climate model KASPRO.