Effects of a near infrared-reflecting greenhouse roof cover on microclimate and production of tomato in the tropics

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Abstract: The effects of a shading paint containing near infrared-reflecting (NIR-reflecting) pigments applied to the roof of an experimental greenhouse on microclimate, plant response of a tomato crop, fruit yield, and quality were studied under the tropical climate conditions of Central Thailand. The experiments were carried out in both rainy and dry seasons in the years 2005 and 2006, respectively. The maximal reduction of 2°C and 0.6°C in the inside air temperatures of the NIR-reflecting roof paint greenhouse was observed during the dry and rainy seasons, respectively. In addition, the temperature was 2.8°C lower than that of in the control greenhouse (without shading paint). The magnitude in the temperature reduction was influenced by the time of application in relation to stage of plant growth. Cumulative water consumption between the 4th and 17th week after transplanting was reduced by 8.8% and 6.2% during the dry and rainy season, respectively. However, this did not significantly influence (p<0.05) the overall water use efficiency. Reduction in the transmission of the photosynthetic active radiation did not significantly influence yield. Shading had negligibly small influence on plant height, number of trusses, leaf area index, and dry matter partitioning.

Keywords: shading, heat stress, greenhouse cooling, plant response

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1 Introduction

In tropical regions, plant production in greenhouses is frequently hampered by excess solar radiation, resulting to high temperatures exceeding plant growth optima and unfavourably high relative humidity levels. Sufficient ventilation and cooling must be provided to maintain the temperature within the optimal range for plant growth. However, natural ventilation depends on prevailing conditions especially wind speed and direction, and the size of vent openings may not cool greenhouses sufficiently especially during hot and calm periods (Boulard et al., 2002; Fatnassi et al., 2002). In order to prevent entry of pests, the size of the vent opening may be reduced. Mounting of insect-proof nets in front of the ventilation openings is becoming increasingly common in integrated plant production (IPP) systems, as a measure to prohibit the entry of certain insect pests into greenhouses. This in turn reduces the dependence on pesticides (Teitel, 2007; Max et al., 2012). However, recent research has shown that these insect-proof nets reduced the ventilation efficiency of greenhouse vents (Ajwang et al., 2002; Kittas et al., 2003). Use of mechanical (forced) ventilation like exhaust fans or evaporative cooling by fan and pad systems could improve the cooling capacity of a greenhouse, although these measures are associated with additional investment costs and operating expenses,

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which may compromise the profitability of horticultural enterprises especially in countries where profit margins are low or for small scale farmers. It has also been demonstrated, that evaporative cooling systems become ineffective or even disadvantageous when ambient air humidity levels exceed 60% (Fuchs et al., 2006; Max et al., 2009).

Photo-selective films could also be used to not only protect crops from the pests but also as a measure to reduce heat load inside the greenhouses (Mutwiwa et al., 2005; Nguyen et al., 2009). Reducing the transmission of near infra-red (NIR, wavelength 700 to 2300 nm) radiation into greenhouses contributes significantly to lowering the greenhouse heat load (Elsner and Xie, 2003; Hemming et al., 2006; Mutwiwa, 2007). In this way, the heat stress to plants which are exposed can be alleviated or even avoided. Shading or white-washing of the cover material as a method of reducing heat load in greenhouses decreases transpiration of the plants as reported by Baille et al. (2001) and Gonzalez-Real and Baille (2006), also influences the quality of radiation transmitted into the greenhouse (Raveh et al., 2003; Cohen et al., 2005) affecting the growth, morphogenesis and architecture of plants (Li et al., 1999). Most shading paints reducing NIR transmission have been shown to significantly reduce the intensity of photosynthetic active radiation (PAR, wavelength 400 to 700 nm) (Elsner, 2005; Hemming et al., 2005; Max et al., 2012), hence may negatively influence yield. Moreover, many of the NIR reflecting or absorbing materials commercially available today are effective only for a short period of one or two growing seasons (Max et al., 2012). Thus, reapplication of paints or exchange of film materials would be required within a short time making these materials economically less reasonable.

Although NIR-reflecting greenhouse covers appear to be a promising approach in the alleviation of heat stress induced problems in greenhouse crops, there is still huge potential for improvements and need for more research. In this study, the effect of combining natural ventilation and a shading paint containing NIR-reflecting pigments on greenhouse microclimate and plant growth was investigated under tropical conditions in different seasons. It was proved that the reduction of irradiance in the NIR range lowers the heat load inside the greenhouses especially during periods of high irradiation, and thereby contributes to improving crop yields and quality.

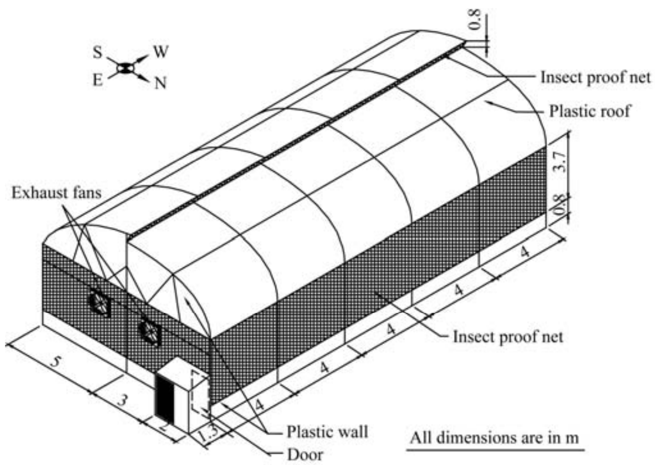
2 Materials and methods

2.1 Experimental site

The experiments for this study were conducted at the experimental site of the “Protected Cultivation Project” at the Asian Institute of Technology (AIT) campus, situated 44 km north of Bangkok in Khlong Luang, Pathum Thani, Thailand (14°04′N, 100°37′E, altitude 2.3 m). The experiments were conducted during the dry season running from 07.11.2005 to 30.03.2006 and during the rainy season running from 08.05.2006 to 31.08.2006.

2.2 Greenhouse description

Two greenhouses constructed with the gutters oriented east-west were used for this study. Each greenhouse was 20 m long by 10 m wide, with a height of 6.4 m at ridge and 3.8 m at gutter (Figure 1). The roof of all the greenhouses was covered with a 200 μm thick, anti-dust and anti-fogcoated ultraviolet (UV) -absorbing polyethylene (PE) film (Wepelen™, FVG, Dernbach, Germany). All greenhouses were equipped with a two-door entrance system with a footbath between the two doors which were filled with a disinfectant to help maintain high phytosanitary standards inside the greenhouses. The sidewalls of both greenhouses were covered with Wepelen™ PE film up to a height of 0.8 m above ground while the remaining portion was covered with a 78-mesh insect-proof net (Econet-T, Ab Ludvig Svensson, Kinna, Sweden) up to the gutter (3 m above the plastic film). The same net was used to cover the end-to-end roof vents which were facing north and had a dimension of 0.8 m × 20 m (W × L). Both greenhouses were equipped with each two exhaust fans (diameter 1 m, capacity 550 m^3 s^{-1}, Munters euroemme S.p.A., Chiusavecchia, Italy) on the eastern end which were operated when internal air temperatures exceeded 30°C. The total area of ventilation openings was 228 m^2 while the surface to floor area and surface area to ventilation ratio was 2.25 and 1.06, respectively.



Note: This sketch is modified from Tantau and Salokhe (2006).

Figure 1 Sketch of the experimental greenhouse at the campus of the AIT in Central Thailand

The floor of the greenhouses was covered with a black and white PE film (Siloplus™, FVG, Dernbach, Germany) with the white surface on the topside (ReduHeat Mardenkro BV, Baarle Nasau, the Netherlands). A shading paint with a NIR-reflecting pigment was thoroughly mixed with tap water in the ratio 1: 2.5 (water: pigment) and sprayed onto the roof of one of the greenhouses on a clear sunny day, using a high pressure system. During the application, care was taken to ensure a uniform spread of the shading paint on the roof. The first application was done on 18.07.2005. After almost one year (28.06.2006), NIR-reflecting pigment was reapplied on the same greenhouse in the same ratio. In this publication, the terms "treatment" and "control" shall be used to denote the greenhouse with or without NIR-reflecting shading paint on the roof, respectively.

The spectral transmission properties of plastic films for both control and treatment were determined in the laboratory at the Biosystems and Horticultural Engineering Department (BGT, Liebniz University Hannover, Germany) using a UV/VIS/NIR spectrophotometer (Lambda 900, Perkin-Elmer Instruments, Norwalk, USA). This was done by measuring the spectral transmission for the different wavelengths for UV 300-400 nm, photosynthetic active radiation (PAR) 400-700 nm, while the NIR was defined as NIR-A 700-1500 nm and NIR-B 1500-3000 nm.

2.3 Crop management

Seeds of indeterminate tomato, *Solanum lycopersicum* L, cv. FMTT260 (AVRDC, Shanhua, Taiwan) were sown in sowing trays, kept inside a fan and pad cooled nursery greenhouse and transplanted into 10 L white plastic pots two weeks after sowing. A commercial potting substrate (Dinwondeekankasat, Ayutthaya, Thailand) was used, consisting of 28% organic matter with a pH of 5.3. The texture of the inorganic proportion of the substrate was 30% sand, 39% silt, and 31% clay. In both greenhouses, 300 plants were arranged in rows at spacing of 0.30 m intercrop and 1.60 m inter-row (6 rows of 50 plants each) giving a planting density of 1.5 plants m^{-2}. Plants were grown with two shoots using a high wire growing systems as described by Kleinhenz et al. (2006). Side shoots were removed twice a week from the beginning to the end of the experiment. After the first harvest, all senescent leaves were removed regularly up to the oldest fruit-carrying-truss and the plants were laid down according to necessity. Insecticides were sprayed weekly (alternating 2 mL L^{-1} Cypermethrin™, 1.5 mL L^{-1} Abamectin™ or 1.5 mL L^{-1} Spinosad™). However, after the first harvest only Spinosad™ was applied at a lower frequency, i.e. every third week. Mancozeb™, 4 mL L^{-1} was sprayed against fungal diseases according to demand.

Fertigation was automatically controlled by a central computer unit. Nutrient solutions were prepared from concentrated stock solutions of Kristallon™ 6+12+36+3+Micro (% N, P, K, Mg) and Calcinit™ 15.5+0+0+19 Ca (both Yara, Oslo, Norway) in a ratio of 70:30 using a fertilizer mixer (Micro 100, GV-System, Odense, Denmark) and delivered to the plants through a drip irrigation system. Average composition of the nutrient solution was in mM: N 7.4, P 0.8, K 5.9, Ca 3.1, Mg 0.7, S 1.7, Na 1.8 and in μM: B 6.0, Fe 4.2, Cu 5.3, Mn 3.8, Mo 1.1, Zn 1.4. The electrical conductivity (EC), of the fertigation solution was set at 1.5 mS cm^{-1} and 1.8 mS cm^{-1} prior to and after the first harvest, respectively maintaining the same element ratio.

Irrigation frequency was based on the solar radiation integral, except in the morning hours (before 09:00 h) and late afternoon (after 16:00 h), during daytime. The duration of the dripper intervals was regularly adjusted according to plant age, increasing from one minute at the beginning to 12 minutes at the end of the trial. On average 9 irrigation cycles per day of 33 mL min^{-1} were delivered with an average over-drain of 25% of the supply in order to avoid salt accumulation in the substrate.

2.4 Data collection

Plant height and number of clusters were recorded weekly from 10 to 25 randomly selected plants. Every fortnight, three plants were randomly selected from each greenhouse and the leaf area (LA) was measured through destructive sampling using a leaf area meter (LI-3100, LI-COR, Lincoln, Nebraska, USA). After LA measurements, the dry matter of leaves, trusses (both flowers and fruits) and stems was determined. Drying was done at 80°C for 72 hours for the fruits and 48 hours for all other plant parts. Ripe fruits were harvested weekly and graded into marketable and non-marketable classes. The marketable class consisted of high quality fruits without defects weighing more than 50 g. The non-marketable class had three categories consisting of fruits which were either affected by blossom-end rot (BER), fruit cracking (FC) or being undersized (<50 g) or misshapen. Plant water consumption was estimated daily from the difference between dripper solution and leachate collected in three measuring cylinders randomly placed in each greenhouse. Air temperature and relative humidity (ambient and inside the greenhouses) were measured using aspirated psychrometers (BGT, Liebniz University Hannover, Germany). The psychrometers consisted of thin sheathed type K (NiCr-Ni) thermocouples enclosed in a radiation shield open on one end and fitted with a small fan on the other with accuracy of ±0.3 K. Two psychrometers were positioned along the centre at a height of 1.5 m above the ground with a 10 m distance between them in each greenhouse. Substrate temperature was measured using similar thermocouples inserted in the pot to a depth of 10 cm below the surface.

Global radiation inside the greenhouses was measured using CM 5 pyranometer (Kipp and Zonen, Delft, the Netherlands) with an accuracy of within the measuring range 8 to 15 μV W m^{-2} positioned horizontally 4 m above the ground. Ambient intensity of global radiation was measured at a height of 2.5 m at the meteorological station of the project. Data of these climatic parameters were recorded every five minutes using a datalogger purposely developed by BGT. Due to technical problems of the datalogger at 10 weeks after transplanting (WAT) in the rainy season 2006 data from this period are missing. The intensity of PAR (both inside and outside the greenhouses) was measured on selected sunny days (14.12.2005 and 31.12.2005 during the dry season, and 07.06.2006 and 29.07.2006 during rainy season) using a line quantum sensor (LI-191) attached to a LICOR 1400 datalogger (both LI-COR Biosciences, LincolnN. E., USA). On 14.12.2005, interception of PAR by the plants was measured by placing the line quantum sensor under the canopy just above the pot containing the plants.

2.5 Data analysis

The data was analysed statistically using SAS (2001) obtained from SAS Institute Inc., Cary N. C., USA. For the comparison of climatic data (weekly means) between the greenhouses, differences were subjected to PROC LOESS procedure for smoothing. In all cases, a smoothing parameter of 0.5 was used. Differences were taken to be significant when all of the plots (predicted, upper and lower confidence intervals) were above zero. Seasonal means were separated using Student Newman Keuls (SNK) test for factors with three or more levels while Student t-Test was used for two level factors. Data on marketable and non-marketable yields were analysed as weight. The various proportions of the non-marketable yield were analysed as count data after square-root transformation using Students t-test. Unless otherwise mentioned, all analyses were performed at a 5% level of significance.

3 Results and discussion

3.1 Spectral properties of the cladding materials used

The application of the shading paint with NIR-reflecting pigments decreased the transmission of NIR-A by 27.9%, although there was a 17.7% reduction in PAR as well (Table 1). Results from laboratory measurements indicate that the application of the shading paint doubled the reflection of UV and PAR while that of NIR-A was tripled. Moreover, the reduction in PAR transmission recorded inside the treatment and control greenhouses on selected dates was were not significantly different (p<0.05) except when the paint was reapplied (Table 2). The 26.2% increase in the reduction of PAR transmission after re-application of the paint may be attributed to the shading effects of the remnants of the initial coat. The results are in line with the previous studies by Elsner and Xie (2003), Garcia-Alonso et al. (2006) and Mutwiwa et al. (2008), in which the commercially available NIR-reflecting greenhouse covering materials were found to reduce PAR transmission, which reduces photosynthesis and crop productivity as discussed by Blanchard and Runkle (2010). While the reflection of PAR is undesirable, reduction in the quantities of UV and NIR mostly have positive effects in protected cultivation in tropical climates. Reduced pest infestation on crops grown in UV deficient greenhouses has been recommended as a non chemical control measure (Mutwiwa et al., 2005; Nguyen et al., 2009) while the reduction of NIR radiation may result in lower heat loads inside greenhouses (Sonneveld et al., 2006).

Table 1 Spectral transmission of PE film with (treatment) or without (control) a shading paint with NIR-reflecting pigments

Spectral range	Wavelength, nm	Transmission, %		Reflection, %	
		Control	Treatment	Control	Treatment
UV	300-400	12.2	30.3	6.5	17.7
PAR	400-700	76.8	59.1	12.5	27.5
NIR-A	700-1500	83.3	55.4	11.0	36.5
NIR-B	1500-2300	81.9	69.4	8.7	19.6
Total	300-2300	78.2	60.3	10.6	27.5

It is thus recommended to remove the previous paint before reapplication in commercial greenhouse production in order to minimise the negative effects associated with reduced PAR transmission.

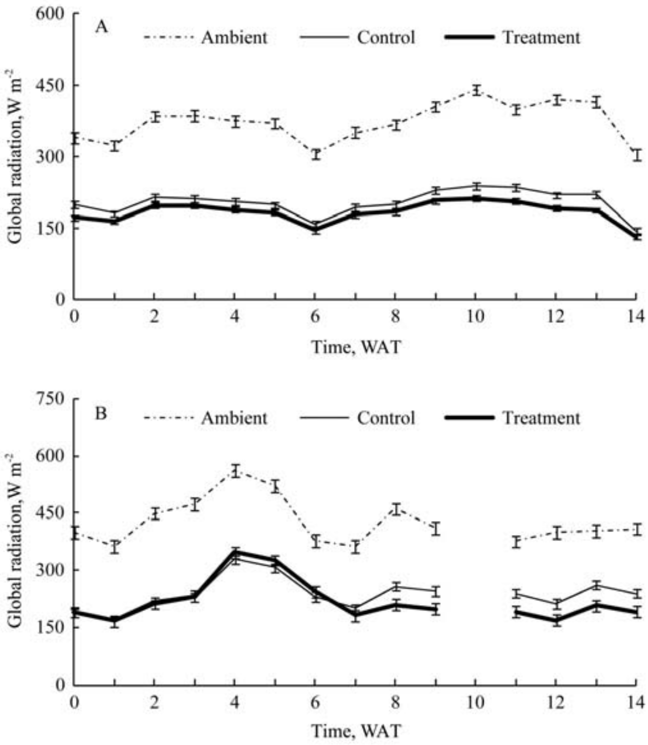
Table 2 Intensity of PAR, μmol m^{-2} s^{-1}, recorded outside and inside naturally ventilated greenhouses above the canopy in naturally ventilated greenhouses with (treatment) or without (control) NIR-reflecting pigments on cloudless sunny days in central Thailand

Date	Ambient	Above canopy		Reduction by shading, %
		Control	Treatment	
14.12.2005	1184.0a	633.4b	606.8b	4.2 %
31.12.2005	1220.8a	616.8b	602.1b	2.4 %
07.06.2006	1475.5a	959.2b	945.5b	1.4 %
29.07.2006	1510.6a	955.4b	704.9c	26.2 %

Note: Means in the same row followed by different letters are significantly different between greenhouse types (SNK-test, p<0.05)

3.2 Greenhouse microclimate

In both seasons, the intensity of global radiation recorded inside the greenhouses was higher in control than in treatment although, this effect was significant (p<0.05) only during the dry season (Figure 2). The initial application of the shading paint resulted in an overall greenhouse transmission for global radiation of 54.5% and 49.1% in control and treatment, respectively. Respective values after re-applying the paint in the rainy season were 55.6% and 51.5%.

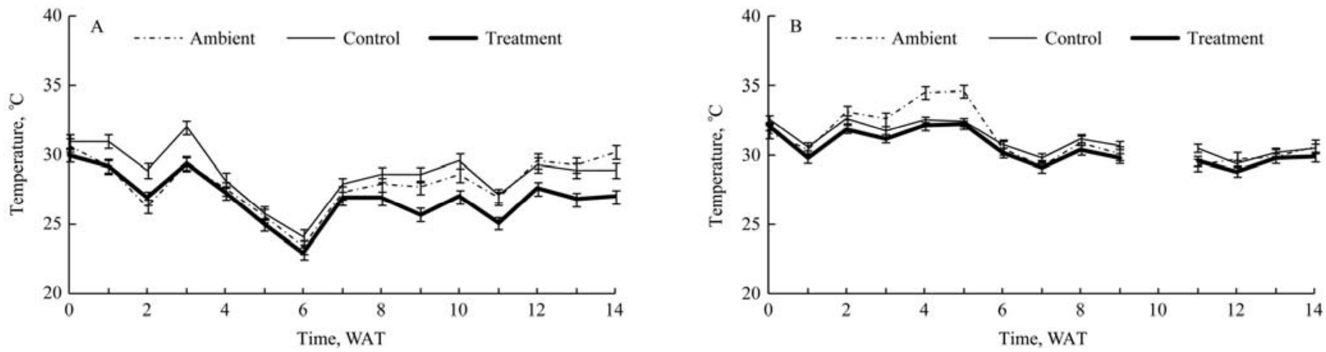


Note: Error bars represent the upper and lower 95% confidence intervals.

Figure 2 Daytime intensity of global radiation (weekly average) recorded outside and inside greenhouses with (treatment) or without (control) a shading paint with NIR reflecting pigments during the 2005/2006 dry (A) or 2006 rainy (B) season in central Thailand

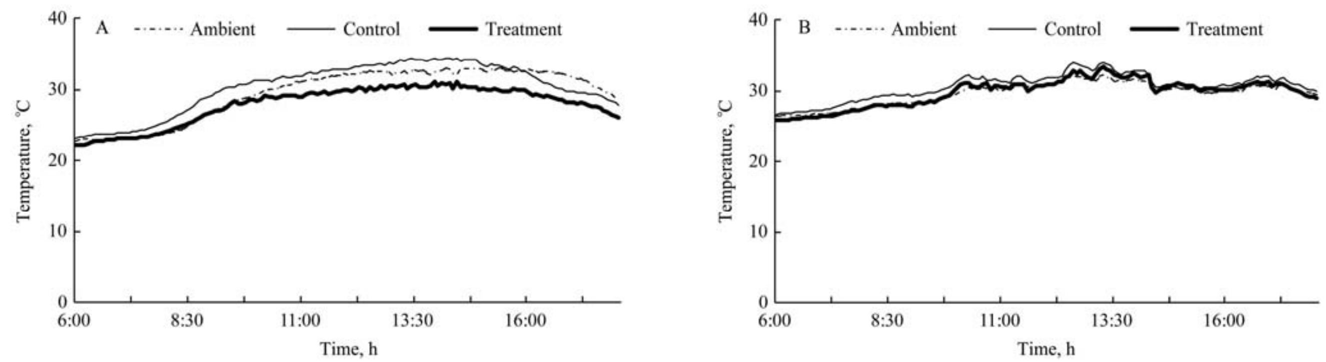
The small differences in the intensity of global radiation and air temperature between treatment and control towards the end of the experiments could be due to a decreased NIR-reflecting effect of the shading paint with time, or accumulation of dirt in the control. This decrease in the performance of the shading paint could be due to the degradation of the NIR-reflecting pigment by UV and/or erosion by heavy rains. To conclusively clarify the reasons for this effect and to improve the service life of NIR-reflecting pigments, additional research is required.

Applying NIR reflective shading paint reduced the air temperature inside treatment by 2.7°C during the dry season. Generally, the air temperature in treatment averaged 1.7°C lower than in control and 1.1°C lower than outside. The respective mean values for the rainy season were 0.7°C and 0.6°C. Maximum temperature differences between control and treatment were recorded during early to late afternoon when global radiation levels were highest (Figures 3 and 4), especially when the crop was young. The reduction in air temperature is attributed to the ability of the shading paint to reflect NIR which warms both the greenhouse environment and the crop (Mutwiwa, 2007). This finding is in line with results of Elsner and Xie (2003), Garcia-Alonso et al. (2006) and Hemming et al. (2006). The observed cooling effect is due to the fact that NIR contributes greatly to heating of surfaces inside greenhouses, including the plant canopy (Blanchard and Runkle, 2010). On the other hand, NIR is not used by the plants for photosynthesis (Max et al., 2012). The smaller difference in temperature between treatment and control, when the tomato crop was mature, is attributed to transpiration cooling effect (Gonzalez-Real and Baille, 2006). When plants have a fully developed leaf canopy and are actively growing without water stress, the greenhouse air temperature was lowered through the cooling effect associated with transpiration. This is because during transpiration there is a phase change of water into vapour, a process which requires energy. Furthermore, the process is accompanied by transfer of sensible into latent heat.



Note: Error bars represent the upper and lower 95% confidence intervals.

Figure 3 Daytime air temperature (weekly average) recorded outside and inside greenhouses with (treatment) or without (control) a shading paint with NIR reflecting pigments during the 2005/2006 dry (A) or 2006 rainy (B) season in central Thailand.



Note: No significant differences between the greenhouse types were observed.

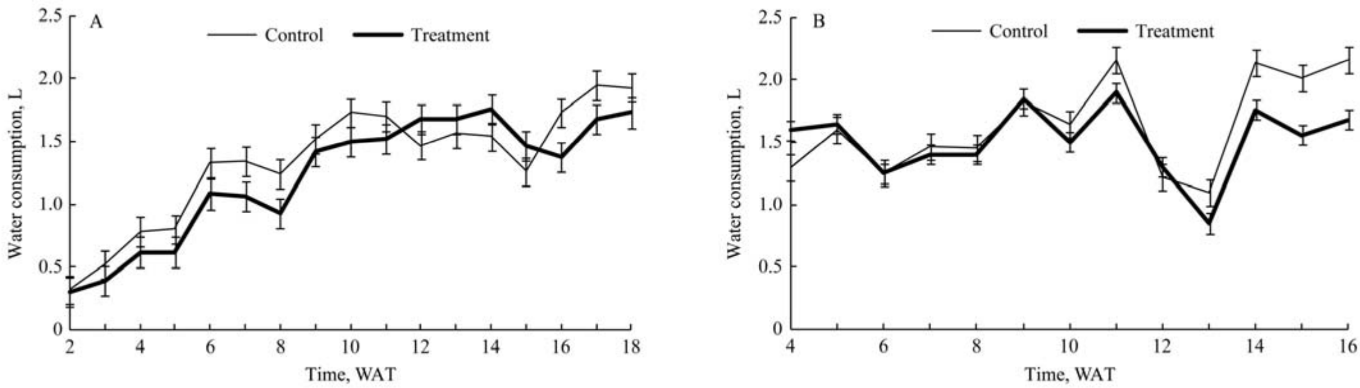
Figure 4 Daytime air temperature profiles recorded outside and inside naturally ventilated greenhouses with (treatment) or without (control) a shading paint with NIR reflecting pigments on two typical days (A) on 17.01.2006 during the dry season 2005/2006, and (B) on 11.07.2006 during the rainy season 2006 in central Thailand

The reduction in temperature should correspond to reduced transpiration during the day as solar radiation is one of the most decisive factors driving transpiration. High temperatures induce faster rates of metabolism and assimilate transport. This is accompanied by an increase in photorespiration, which reduces photosynthesis if CO_2 concentration is not increased (Zeroni and Singh, 1996). This indicates that NIR-filtration may improve crop production, especially in passively cooled greenhouses in the tropics.

The magnitude of temperature reduction by the shading paint was dependent on the ambient weather conditions especially the intensity of global radiation and possibly wind speed. This is in line with results of Garcia-Alonso et al. (2006) who observed smaller differences in diurnal temperature between greenhouses covered with NIR filtering PE film and control (NIR transmitting) in winter in Spain. The large ventilation openings of the naturally ventilated greenhouses used in this research influenced air exchange rate (as a result of higher ambient wind speeds), thus may have lowered the magnitude of temperature reduction by the shading paint. Although global radiation enters a greenhouse through the roof as well as the sidewalls, application of the shading paint on the roof alone may not give maximum results.

Average seasonal values for substrate temperature during the dry season were 30.0°C and 26.9°C for control and treatment, respectively. Substrate temperature influences evapotranspiration, with higher values corresponding to increased water consumption by plants. Moreover, substrate temperature directly influences uptake of plant nutrient by altering root growth, morphology, and uptake kinetics (Pregitzer and King, 2005).

The shading paint reduced cumulative water consumption between 4 and 17 WAT by 8.8% and 6.2% during the dry and rainy season, respectively. Water use efficiency (WUE) during the dry season was 0.328 kg L^{-1} and 0.339 kg L^{-1} in control and treatment, respectively. The corresponding values for the rainy season were 0.110 kg L^{-1} and 0.100 kg L^{-1}. The differences in WUE, however, were statistically not significant (p<0.05).



Note: Error bars represent the upper and lower 95% confidence intervals.

Figure 5 Mean daily water consumption (L $plant^{-1}$ day^{-1}) of tomato plants grown in naturally ventilated greenhouses with (treatment) or without (control) a shading paint with NIR-reflecting pigments during the 2005/2006 dry (A) or 2006 rainy (B) season in central Thailand

3.3 Plant growth and yield

On average, in both seasons plants were shorter in treatment than in control, the difference being significant (p<0.05) at 4, 9 and 12 WAT in the dry season. Maximum plant height at 18 WAT during the dry season was 404.6 and 394.1 cm in control and treatment, respectively. During the rainy season, the plants reached a maximum height of 314.1 and 305.8 cm in control and treatment, respectively at 16 WAT. Since the differences in plant height were experienced during both dry and rainy seasons, this could be attributed to change in Red to Far Red (R: FR) ratio as reported by Rajapakse et al. (2001). There was no difference in number of trusses in the two greenhouses, neither during the dry nor the rainy season.

Temperature reduction by shading did not appear to greatly influence dry matter partitioning (Table 3). The dry matter content of the leaves increased continuously with time from 1 to 10 WAT, during both seasons, in both greenhouses. At the time of first harvest (10 WAT), the dry matter content of the leaves accounted for 40% of the total dry matter content of the plants during both seasons. The small difference in dry matter production of vegetative plant parts is consistent with findings of Stanghellini et al. (2009).

Shading did not significantly influence leaf area index (LAI), which means LA per unit ground area (m^2 m^{-2}) (Table 4). However, towards the end of the cropping period, in both seasons there was a slight trend to increased LA in treatment. This could be due to the lower

PAR levels or as an attempt to increase the area available for light interception and transpiration. This tendency could also be interpreted as an adaption to high vapour pressure deficits as described similarly by Liu et al. (2006) for a rose crop.

Table 3 Mean dry matter content (g plant^{-1}) of leaves, stems and trusses (fruits) of tomato plants grown in naturally ventilated greenhouses with (Treatment) or without (Control) a shading paint with NIR-reflecting pigment on the roof cover during the dry season 2005/2006 and the rainy season 2006 in central Thailand

	WAT	Leaves		Stems		Fruits	
		Control	Treatment	Control	Treatment	Control	Treatment
Dry season 2005/2006	2	2.72	2.61	0.64	0.63	0.00	0.00
	4	29.13	29.53	11.08	11.90	1.23	0.97
	6	75.83	102.23	33.72	39.44	8.06	43.90
	8	82.74	85.56	42.18	40.93	58.81	46.96
	10	108.67	99.48	59.11	47.89	86.37	91.10
	12	81.18	95.29	56.61	68.82	156.48	162.73
	14	87.38	61.03	81.08	66.34	93.81	52.76
	16	75.26	78.53	88.33	96.50	67.23	74.60
Rainy season 2006	2	2.38	1.68	0.62	0.41	0.00	0.00
	4	24.17	23.51	10.60	10.34	0.36	0.13
	6	60.42	53.72	35.24	30.38	9.52	6.10
	8	101.24	62.20	59.75*	43.20*	28.67	17.14
	10	111.94	92.24	76.98	62.24	71.51	43.91
	12	106.83*	131.02*	83.89*	92.61*	190.92*	79.73*
	14	121.84	121.04	98.12	89.87	98.40	100.64
	16	147.18	148.57	115.08	109.69	121.62	111.95

Note: Under the same main column, means in the same row under the same season followed by an asterisk (*) differ significantly at p=0.05, T-test.

Table 4 LAI of tomato plants grown in naturally ventilated greenhouses with (Treatment) or without (Control) shading paint containing NIR-reflecting pigments during the dry season 2005/2006 and the rainy season 2006 in central Thailand

Time WAT	Dry season		Rainy season	
	Control	Treatment	Control	Treatment
2	0.08	0.08	0.12	0.09
4	0.47	0.52	0.48	0.41
6	1.58	1.52	0.72	0.72
8	1.71	1.77	0.99	0.86
10	2.23	2.42	1.00	1.32
12	2.01	2.46	0.90	1.24

Note: No significant differences between treatments were observed at P=0.05, T-test.

Although there was no significant difference in marketable yield per plant from the two greenhouses, a slightly higher yield was obtained in control compared to treatment in both seasons (Mutwiwa et al., 2008). The total yield from 12 harvests, during the dry season was 6.653 kg plant^{-1} (99.79 tha^{-1}) and 6.457 kg plant^{-1} (96.86 tha^{-1}), from control and treatment, respectively. The slightly higher productivity in control could be attributed to the higher PAR level. Heat stress has been shown to adversely affect vegetative as well as generative growth of many crop plants. High temperatures induce stomata closing leading to reduce leaf gas exchange and photosynthesis, whereas respiratory processes are enhanced (Morales et al., 2003). Eventually this may result in decreased biomass production and xylem transport rates (Adams and Ho, 1993), possibly entailing reduced yield and/or fruit quality.

Generally, shading reduced the quantity of non-marketable yield by 9.9% and 15.6%, during the dry and rainy season, respectively. The results are comparable to studies on In many vegetable crops, e.g. in tomato in which heat stress during day and night drastically impedes flowering (Dane et al., 1991), pollination (Adams et al., 2001), and fruit set (Peet et al., 1997) resulting in increased numbers of parthenocarpic fruits and finally lower marketable yields (Kleinhenz et al., 2006).Various authors (Liebisch et al., 2009; Max et al., 2010) also reported that fruit cracking is aggravated by heat stress. The results from this experiment seem to contradict this finding as more cracked fruits were noted in treatment. Reduced transpiration during the day due to lower global radiation and cooler temperatures may be the reason for the increased number of cracked fruits in treatment compared to control.

4 Conclusions

Although an efficient greenhouse system for use in the tropical regions like central Thailand is yet to be found, findings from this research show that selecting the right covering material and cooling method may improve microclimate and plant growth. The results indicate that the application of shading paint with NIR-reflecting pigment on the greenhouse roof reduced air temperatures but the magnitude of the temperature reduction was influenced by the time of application in relation to stage of plant growth. It is, thus, concluded that using NIR-reflecting greenhouse covering materials can contribute to reducing the heat load inside greenhouses employed in tropical climates, especially during very hot periods. The fact that the cooling effect did not lead to higher marketable yields indicates that research and development for NIR blocking greenhouse films should focus on pigments or other additives reducing NIR-transmission without affecting PAR. Moreover, materials with strongly extended service life would be required.

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