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COOLING OF GREENHOUSES IN THE HUMID TROPICS - PROBLEMS AND SOLUTIONS

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Abstract: The development of a greenhouse suitable for protected cultivation in the humid tropics is still far from being realized. Reducing the heat load without increasing humidity inside the greenhouse, pest exclusion without heavy reliance on chemicals and monitoring plant response to changes in the microenvironment are the main challenges. As such the development of a strategy that allows for rational use of resources for high quality plant production while ensuring maximum protection and sustainability of the environment is still being sought. The progress made in developing an adapted greenhouse that encourages biological pest control and simultaneously offers an optimum microclimate is discussed in the concept of integrated plant production in the humid tropics.

Key words: *Humid tropics, greenhouse, NIR-reflection, natural ventilation, evaporative cooling, pest control.*

INTRODUCTION

There are various challenges facing protected cultivation in the humid tropic: among them high temperature and high humidity. High rainfall (occasionally storms) and many hours of solar radiation contribute to an increase of both temperature and humidity inside the greenhouses which creates conditions suitable for fungal infestation. An efficient ventilation system is required in order to prevent excessive rise in internal air temperature, humidity and to increase the concentration of CO_2. Ventilation also affects plant growth by promoting gas and energy exchange between the plants and the surrounding air (Sase, 2006). In addition, infestations by pests and diseases lead to severe economic losses. The heavy reliance on chemicals to control pests and diseases leads to both the development of resistance by the pests and pollution of the environment.

- Thus, when designing a greenhouse for the humid tropics the following points should be taken into consideration:

- Sufficient ventilation to maintain an efficient air exchange in order to keep the temperature, humidity and CO_2 within the optimal ranges
- Ability to control the climate in order to maintain the physiological fluxes in the range of values considered adequate for crop growth, development and quality
- Ability to integrate biological pest and disease control
- Strong enough to withstand the storms that are prevalent in these regions

This paper addresses the main problems associated with ventilation of greenhouses in the humid tropics and the progress made in the development of an adapted greenhouse suitable for use in integrated vegetable production in these regions.

NATURAL VENTILATION

Natural ventilation is the least expensive greenhouse cooling method (Chauhan et al., 2002) and the most commonly used, because it permits reduction of the temperature for cultivation and the internal CO_2 deficit, and it provides much better environmental working conditions (Münoz et al., 1999). It is dependent on external climate mainly wind and temperature difference (Kittas et al., 1997), hence it may not be very efficient in summer when the heat load inside the greenhouse and the external air temperature are too high (Baille, 1999). Fixing insect proof screens on ventilation openings of naturally ventilated greenhouses is increasingly becoming popular because they physically block (Bethke, 1994) or optically prevent (Antignus et al., 1998) the entry of insects in to the greenhouse. However, these screens may influence the light transmitted into the greenhouse (Klose and Tantau, 2004) and have been found to reduce air exchange (Teitel, 2001) thereby leading to a rise in temperature and humidity. The degree of the reduction in air exchange is greatly influenced by the porosity of the insect-proof screen (Harmanto et al., 2006).

The performance of naturally ventilated greenhouses covered with insect-proof screens has been investigated by several researchers in the humid tropics (Ajwang, 2005; Harmanto 2006). Models simulating the effect of insect screen on air exchange and greenhouse microclimate for the humid tropics have also been developed (Ajwang and Tantau, 2005). Recent developments in modeling have been concentrated on the application of computational fluid dynamics to simulate greenhouse microclimate (Fatnassi et al., 2003; Boulard and Baille, 1995; Boulard et al., 2004).

Harmanto et al., (2006) investigated the effect of the porosity of three insect proof nets on air exchange and microclimate in naturally ventilated greenhouses in the humid tropics. Results show that the use of 78-mesh (Econet-T) and 52-mesh (Bionet) insect-proof screens reduced air exchange rate by 50 % and 40 %, respectively, compared to a 40-mesh insect proof screen. This reduction in air exchange resulted in humidity rise by 200 % and 50 %, for the 78-mesh and 52-mesh insect proof screens, respectively. Figure 1 shows the effect of net porosity on air temperature and CO_2 concentration inside naturally ventilated greenhouses with an actively growing tomato crop on a typical sunny day in Bangkok. The finer mesh changes the greenhouse microclimate by reducing air exchange rate thereby increasing temperature. A greenhouse clad with 78-mesh insect proof screen had a higher air and leaf temperature which resulted in higher leaf transpiration (Fig. 1 and 2). The concentration of CO_2 was slightly higher in the 52-mesh insect screen owing to the high porosity of the nets which enhanced air exchange (Fig. 3).

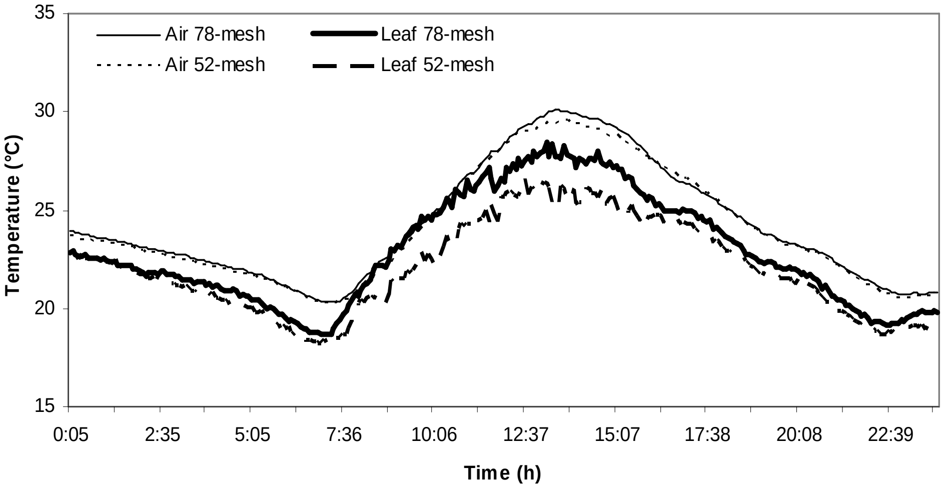

Figure 1. Air and leaf temperature profile inside the naturally ventilated greenhouses covered with 52-mesh (Bionet) and 78-mesh (Econet T) insect-proof screens on a typical sunny day (18th December 2005), with a young tomato crop (41 days after transplanting).

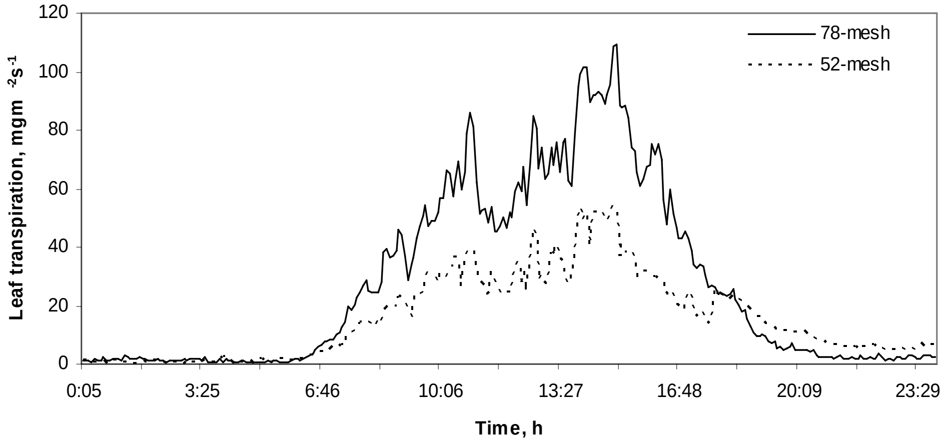

Figure 2. Leaf transpiration of tomato plants grown inside naturally ventilated greenhouses clad with 52-mesh (Bionet) and 78-mesh (Econet T) insect-proof screens on the sidewalls and ventilation openings on a typical sunny day (22nd June 2006). Transpiration was higher for the plants inside the greenhouse clad with the finer mesh.

An attempt should also be made to minimize the existence of temperature and humidity gradients both on the vertical and horizontal gradients (Soni et al., 2005) of naturally ventilated greenhouses in these regions.

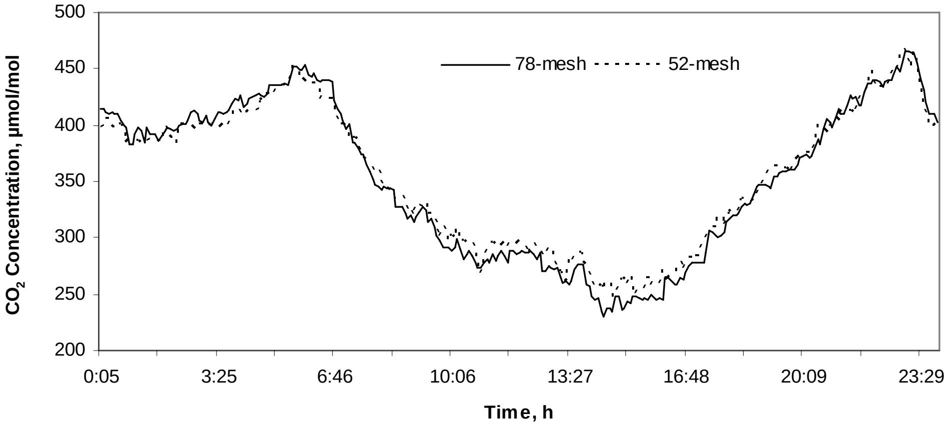

Figure 3. Concentration of CO_2 inside greenhouses clad with 52-mesh (Bionet) and 78-mesh (Econet T) insect-proof screens on the sidewalls and ventilation openings. Fine mesh size slightly reduces the concentration of CO_2 inside the greenhouse.

EVAPORATIVE COOLING

Evaporative cooling systems are based on conversion of sensible heat into latent heat through the evaporation of water and work well in areas with high values of outside air, (dry and wet bulb) temperatures associated with high solar radiation. Arbel et al., (2003) described the main types of evaporative cooling the benefits and disadvantages associated with each system. The main evaporative cooling methods used today are fan-and-pad and fogging (Kittas et al., 2003). Fan and pad systems require a draft of air which is forced to pass through wet pads, while fog systems are based on spraying water in the fog range, in the form of small droplets 2- 60 µm in diameter, in order to increase the water surface in contact with air (Montero, 2006). Both systems have their pros and cons, which have been extensively discussed in scientific and technical literature (Kittas et al., 2003; Arbel et al., 2003) The main disadvantage of evaporative cooling systems is the increase of humidity inside the greenhouse, wetting of the foliage thereby creating conditions favourable for the development of fungal diseases (Elad, 1989) and the demand for high quality water which is unavailable in some places (Montero, 2006). The main factors influencing fan and pad evaporative cooling systems have been discussed in detail by Bucklin et al., (2004). For fan and pad cooling systems, a cooler air temperature with higher humidity may be maintained at high ventilation rates, though water use would increase, at times to quantities greater than those used for irrigation (Sabeh et al., 2006). These authors suggested an operation strategy for a pad and fan cooling system that minimizes the use of water while maintaining the proper greenhouse climate for tomato crop production under semi-arid, summer conditions. In the humid tropics, the performance of evaporative cooling systems is limited due to the high humidity levels in the external air. Tomato plants grown in greenhouses equipped with fan and pad cooling system have low transpiration rate (due to low vapour concentration difference (leaf-air)) (Figure 4), were shorter and suffered more from fungal diseases compared to those grown inside naturally ventilated greenhouse.

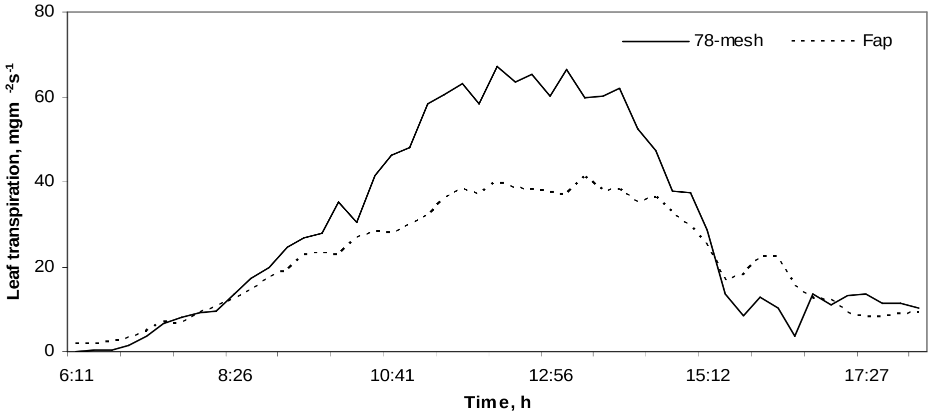

Figure 4. Leaf transpiration for young tomato plants (33 days after transplanting) grown inside a fan and pad evaporative cooled greenhouse (Fap) and in a naturally ventilated greenhouse covered with a 78-mesh insect proof screen on the sidewalls and ventilation openings (78-mesh) during the day on a typical day (10th December 2005).

Results from experiments conducted in Bangkok reveal that although differences exist between the microclimate inside a naturally versus fan and pad cooled greenhouses, the effect in net assimilation is minimal (table 1). Plant response to evaporative cooling is not always positive, since physiological disorders like Blossom End Rot (BER) may be fostered under high radiation and high humidity conditions (Montero, 2006). For a fan and pad cooled greenhouse, there is a build up in CO_2 concentration inside the greenhouse at night as a result of respiration coupled with poor air exchange since the fans may not be operated owing to low night temperatures (Fig. 5). A sudden decrease in CO_2 concentration when the fans start running is followed by a sudden drop in photosynthesis moments later but it takes some time before the same level of net assimilation is reached (Fig. 6). Low vapour pressure deficit is also responsible for fruit cracking in many crops (Aloni et al., 1999, Yao et al., 2000) thereby reducing both quality and shelf life of the marketable yield (Gonzalez-Real and Baille, 2006). In addition, high installation and operation costs may limit its application in the humid tropics.

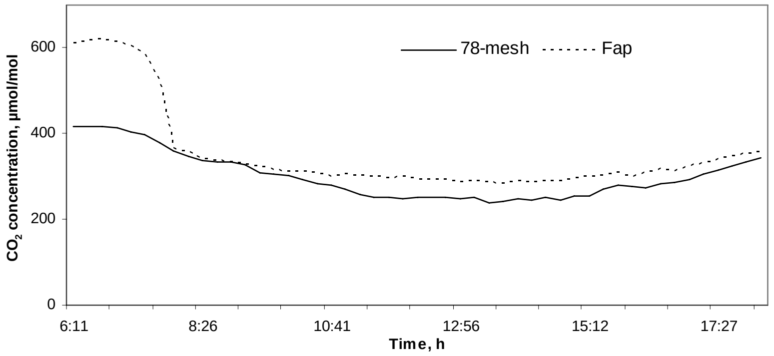

Figure 5. Profile of CO2 concentration inside fan and pad cooled greenhouse (Fap) and in a naturally ventilated greenhouse covered with a 78-mesh insect proof screen on the sidewalls and ventilation openings (78-mesh) during the day on a typical day (10th December 2005).

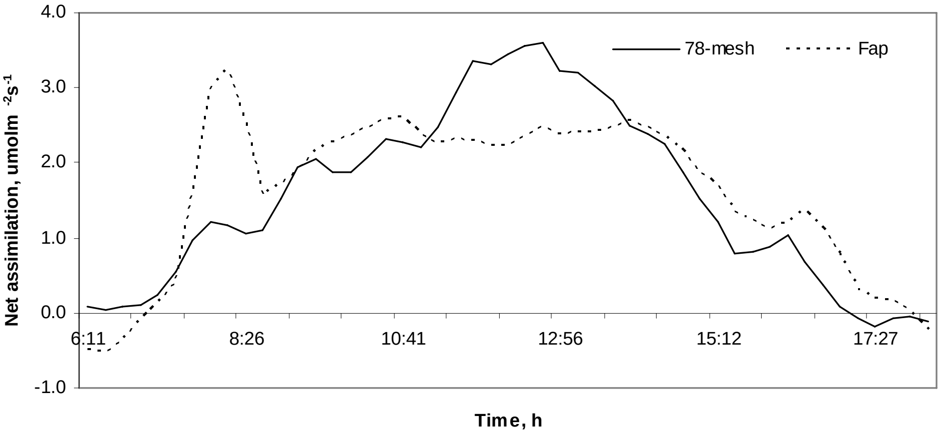

Figure 6. Comparison of net assimilation rates of young tomato plants (33 DAT) grown inside fan and pad cooled greenhouse (Fap) and in a naturally ventilated greenhouse covered with a 78-mesh insect proof screen on the sidewalls and ventilation openings (78-mesh) during the day on a typical day (10th December 2005).

Table 1. Comparison of air temperature & CO_2 concentration inside fan and pad cooled (Fap) and a naturally ventilated greenhouse clad with a 78-mesh insect-proof screen and their effect on tomato plants in the cool season (4 weeks after transplanting) (Mutwiwa et al., 2006).

House	CO_2 Concentration, µmol/mol	Air temperature, °C	Stomatal conductance, m/s	Transpiration, mg/m^{2}s	Photosynthesis, µmol/m^{2}s
Fap	349.3 ± 10.2a	27.3 ± 0.3a	34.0 ± 1.5a	23.1 ± 2.8a	1.8 ± 0.1a
78mesh	306.3 ± 6.1b	30.4 ± 0.5b	23.5 ± 1.2b	34.0 ± 1.6b	1.7 ± 0.1a

Means in the same column followed by the same letter are not significantly different (Students t-test, α = 5 %)

SHADING

Another passive method is to reduce the intensity of transmitted radiation in greenhouse by providing shade curtains or applying coating of white paint (whitewash) on covering. Whitening is inexpensive and presents positive effects on both microclimate and crop behaviour and thus should be considered as an efficient means for alleviating heat load during summer (Bailley et al., 2001). Whitening reduces the transmission of solar radiation into the greenhouse consequently reduces air temperature, vapour pressure deficit and canopy to air temperature difference (Bailley et al., 2001). Shading screens (cut out screens) are also used to block transmission of global radiation into the greenhouse. The transmittance and reflectance of the screening material are the main factors that determine the quantity and quality of radiation entering the greenhouse. A screening surface forming a closed cavity with the inside ground is always more efficient in blocking the admission of solar irradiation than any other shape (Miguel et al., 1994). According to Kittas et al., (2003), shading screens may be used to reduce radiation inside the greenhouse but the effective temperature reduction is not really proportional to the shading rate. The high radiation loads observed in summer lower plant water potential through faster transpiration, hence decoupling transpiration rate and root water uptake (Grange and Hand, 1987). Water deficits induced by the high radiation loads affects plant productivity by reducing the leaf area index, reduce water transfer to the fruit and enhance fruit transpiration (Leonardi et al., 2000). These stress conditions slow water accumulation by the fruit leading to the production of small fruits especially in tomatoes (Guichard et al., 2001), as observed in the hot season. Due to the high solar radiation (and consequently high temperature), the total marketable yield per plant in the hot season was only 10 % that of the cool season-mainly due to the production of small fruits (less than 50 gm) which were often parthenocarpic.

NEAR INFRA RED (NIR)-REFLECTION

More than half of the solar energy is near-infra-red radiation, NIR, which is of little use to photosynthesis but is a heat source. Van Bavel et al., (1981) indicated that reducing transmitted NIR was another type of cooling method worth considering. Von Elsner and Xie, (2003) carried out investigations with the NIR-interference pigments integrated in shading paint to selectively reduce NIR inside the greenhouse. Their results showed that both the PAR levels and heat load reduction varied with the concentration of the pigment applied on the plastic films. Hemming et al., (2006) analysed the optical properties of various NIR-filtering materials, and gave a calculation method to quantify the energy reduction under these materials and to estimate the contribution for greenhouse cooling. According to these authors, NIR-filtering multi layer coatings applied to plastic film or glass filter out NIR most effectively but should not be used in unheated greenhouses since they cause an undesirable temperature drop while NIR-filtering white washes still reduce PAR too much. Application of Reduheat, a commercial NIR-reflecting pigment (Madenkro, the Netherlands) in greenhouses in Bangkok area significantly reduced the transmission of global radiation into the greenhouse and consequently, air temperature, leaf transpiration and the net photosynthesis of tomato plants grown inside the greenhouse (Table 2).

Table 2. Microclimate and plant response inside naturally ventilated greenhouse with and without NIR-reflecting pigment on the roof in the hot season (May to September 2006) 8 weeks after transplanting

House	Global radiation, W/m^2	Air temperature, °C	Stomatal conductance, m/s	Transpiration, mg/m^{2}s	Photosynthesis, µmol/m^{2}s
With NIR	200.8 ± 8.9a	29.9 ± 0.2a	25.9 ± 0.6a	30.3 ± 1.5a	1.5 ± 0.1a
No NIR	243.9 ± 10.6b	33.2 ± 0.2b	34.7 ± 0.8b	43.3 ± 1.5b	1.8 ± 0.1b

Means in the same column followed by the same letter are not significantly different (Students t-test, α = 5 %)

However the NIR-reflecting pigment was more effective in the hot season as the differences were small in the cool season (Mutwiwa et al., 2006). Although, the NIR pigment reduced the overall greenhouse transmission, it might also have changed the quality of light inside the greenhouse, especially the ratio of red to far red, which has been reported to influence plant height (Rajapakse et al., 2001), but this was not observed. In the cool season, a small reduction in marketable yield (2.5 %) was complimented by 11.2 % reduction in non-marketable yield (especially small fruits and those affected by BER). Similar results were reported by Garcia et al., (2006) who tested plastic films that block the entry of NIR into the greenhouse.

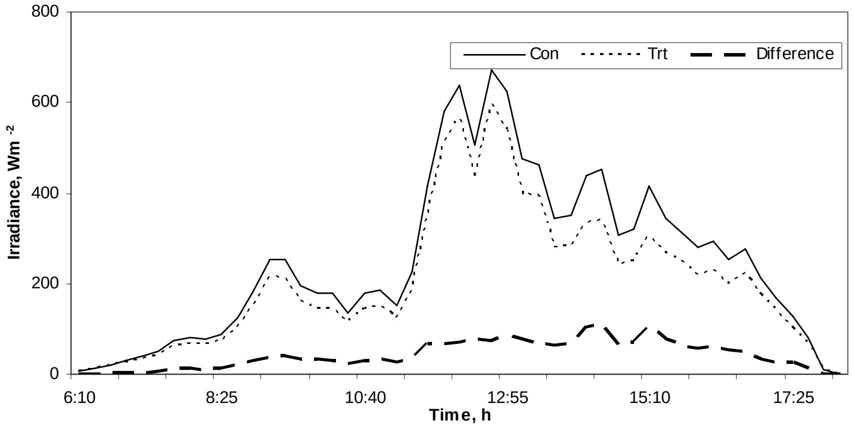

Figure 7. Profile of global radiation inside the naturally ventilated greenhouses with (Trt) and without (Con) near infra red- reflecting pigment on the roof on a sunny day (6th July 2006)

The possibility of using NIR-filtering (moveable) screens to block transmission of NIR radiation into the greenhouse could be an alternative in the future (Hemming et al., 2006). Although NIR-reflecting pigments are showing good performance, more research needs to be conducted in order to develop better methods of application that ensure uniform spread of the pigments of the greenhouse roof (especially for greenhouses covered with plastic films) in the right concentration.

INSECT PEST CONTROL

Various attempts are being made to develop sustainable plant protection methods that reduce the reliance on chemicals. Cladding of greenhouses either fully or partially with insect proof screens is becoming quite popular. Depending on the screens' pore size various insects can be excluded physically as described by Bethke (1994). However a balance between efficient insect pest exclusion and air exchange efficiency has to be found when using insect-proof screen for cladding greenhouses. Very fine screens will exclude most pests but this will reduces air exchange. According to Harmanto (2006), 50% less thrips were recorded inside a greenhouse clad with a 78-mesh insect proof screen compared to one clad with a 52-mesh insect-proof screen (Table 3).

Table 3. Mean (± SE) weekly insect pest population found trapped in greenhouses clad with insect-proof screens of different mesh-sizes in the cool season (Harmanto, 2006)

Insect population (number 10 cm^{-2})	Insect-proof screen mesh size		
	40 × 38	52 × 22	78 × 52
Whiteflies	0.34 ± 0.18 **a**	0.05 ± 0.10 **b**	0.02 ± 0.08 **b**
Thrips	42.88 ± 2.75 **a**	29.80 ± 2.30 **a**	11.57 ± 1.18 **a**

Within row, means followed by the same letter are not significantly different at P = 0.05, t-test (lsd).

Spectrally modifying insect screens have been found to significantly reduce the number of insect pest population inside a greenhouse and the viruses they transmit (Antignus et al., 1998). The use of UV-absorbing plastic films as greenhouse covers has also been reported to reduce both the population and dispersion of certain insect pests in greenhouses (Mutwiwa et al., 2005). A combination of both UV absorbing roof covers and UV-absorbing insect proof screens was reported to be most effective in protecting greenhouse plants from common pests and delay the appearance of virus symptoms on plants (Kumar and Poehling, 2006). Moreover, biological pesticides such as neem have been reported to have the potential of controlling various greenhouse pests prevalent in the humid tropics (Kumar, 2006). The combination of spectrally modifying insect-proof screens and covers with botanical pesticides may offer a solution to the pest and disease problems in greenhouses in these regions.

CONCLUSIONS

An environmentally friendly, efficient system to cool greenhouses in the humid tropics and to efficiently control pests and diseases is still to be found. Based on the information from the above mentioned studies the following is recommended for a greenhouse for sustainable vegetable production in the humid tropics:

- Should be clad with spectrally modifying covers in order to reduce the heat load by blocking the transmission of NIR, and reduce pest population by blocking the transmission of UV radiation.
- Have large ventilation openings on the sidewalls and roof (more than 60 % of floor area) clad with insect-proof screens that block insect entry both physically and optically (see figure 8).
- Have ventilation fans for use when temperatures exceed the optimum and to minimize temperature and humidity gradients.

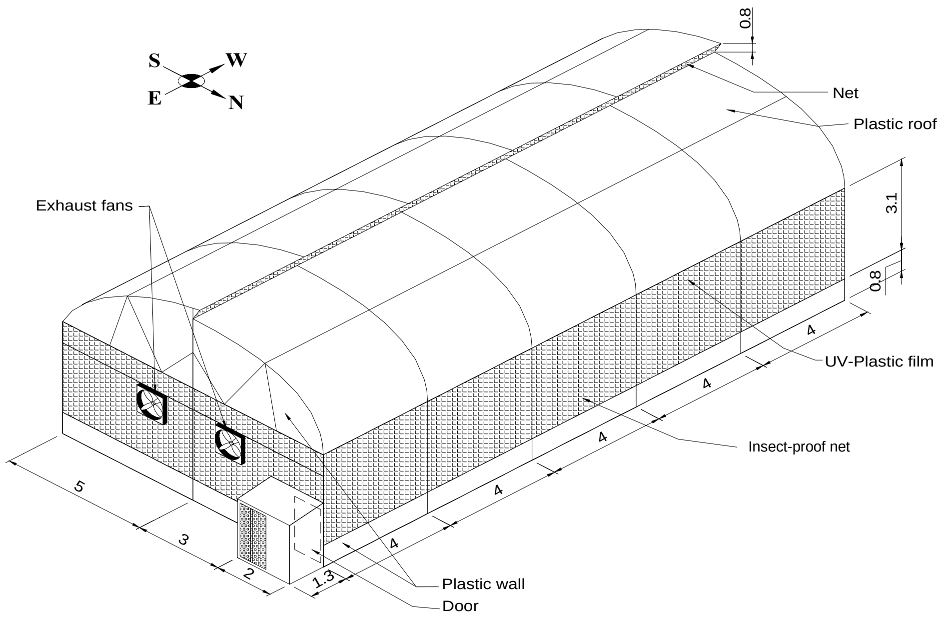

Figure 8. A naturally ventilated greenhouse used in one of the experiments conducted in central Bangkok. A greenhouse with large ventilation openings (both on the sidewalls and roof) covered with UV-absorbing insect-proof screens and a UV-absorbing plastic film incorporated with near infra red (NIR)-reflecting pigments on the roof is recommended. Exhaust fans should be installed to help enhance air exchange especially when outside wind speed is low.

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HLAĐENJE OBJEKATA ZAŠTIĆENOG PROSTORA U VLAŽNIM TROPSKIM USLOVIMA - PROBLEMI I REŠENJA

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Sadržaj: Konačno rešenje objekta zaštićenog prostora pogodnog za gajenje useva u vlažnim tropskim uslovima, još uvak nije nađeno. Glavni problemi su kako sniziti temperaturu u objektima a pritom ne povećati relativnu vlažnost vazduha i kako eliminisati insekte bez povećane upotrebe hemijskih zaštitnih sredstava. U svetu se sve češće predlažu nove strategije održive poljoprivrede čijom bi se primenom smanjila upotreba hemijskih zaštitnih sredstava i tako dikerktno uticalo na ekološki opravdaniju poljoprivrednu proizvodnju ne umanjujući time kvalitet na ovaj način dobijenih poljoprivrednih proizvoda. U radu se analizira mogućnost razvoja tehnološko-tehničkog sistema objekta zaštićenog prostora u kome bi bila moguća biološka kontrola insekata uz održanje optimalnih mikroklimatskih uslova.

Ključne reči: *vlažni tropski klimatski uslovi, objekti zaštićenog prostora, NIR refleksija, prirodna ventilacija, evaporativno hlađenje, kontrola insekata.*