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# Effects of Different Cooling Methods on Microclimate and Plant Growth in Greenhouses in the Tropics

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# Effects of Different Cooling Methods on Microclimate and Plant Growth in Greenhouses in the Tropics

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# Effects of Different Cooling Methods on Microclimate and Plant Growth in Greenhouses in the Tropics

## Abstract

This research focused on the development of a greenhouse for the sustainable vegetable production in the tropics. The experiments were conducted in four greenhouses, each measuring 20 m long by 10 m wide, at the Asian Institute of Technology (Thailand). All greenhouses were covered with a UV-blocking polyethylene (PE) film on the roof. One greenhouse was completely covered with the same PE-film and equipped with an evaporative cooling system (FAP). A second greenhouse was covered with a 50-mesh insect-proof net on the sidewalls and roof ventilation openings (N50). The remaining two greenhouses were covered with a 78-mesh insect-proof net on the sidewalls and ventilation openings. A shading paint with NIR-reflecting pigment was applied on the roof of one of the greenhouses with 78-mesh insect-proof nets (N78S) while the other was left as control (N78). Tomato *Solanum lycopersicum* cv FMTT260 plants were grown inside the greenhouses at a density of 1.5 plants m$^{-2}$ and maintained following commercial practices. Plant response to different treatments was done by pair-wise measurements using a gas exchange system.

The results indicate that mesh size significantly influences the resistance to air flow across insect-proof nets. The spectral characteristics of the covering materials influenced the quality and quantity of light inside the greenhouses. The shading paint with NIR-reflecting pigment doubled the transmission of UV-radiation (300 - 400 nm) and decreased that of photosynthetic active radiation (400 – 700 nm, PAR) and near infra-red (700 - 1100 nm, NIR-A) by 17.7 and 26.5 %. The application of shading paint with NIR-reflecting pigment on the greenhouse roof reduced air ($\boldsymbol{T_a}$) and substrate ($\boldsymbol{T_s}$) temperatures by a maximum of 2.8 °C and 3.5 °C, respectively during the dry season. The magnitude of the temperature reduction was influenced by the time of application in relation to stage of plant growth. Air water content ($\boldsymbol{x}$) was reduced by 1.6 g kg$^{-1}$ and 0.4 g kg$^{-1}$ during the dry and rainy seasons, respectively. Leaf transpiration ($\boldsymbol{E}$) was lower in the shaded greenhouse than in the control. Consequently, cumulative water consumption between 4 and 17 WAT was reduced by 8.8 % and 6.2 % during the dry and rainy season, respectively. However, this did not significantly influence water use efficiency. Compared to control, shading reduced the number of blossom-end rot (BER) affected fruits by 43 % and 30 %, during the dry and rainy seasons, respectively. Consequently the proportion of non-marketable yield in N78S was reduced by 59 % and 16 %, during the respective time periods. On the other hand, shading increased the number of cracked fruits by 16.1 % and 43.1 % during dry and rainy season, respectively. Reduction in PAR transmission led to lower yield although this was not statistically significant. Shading had a slight influence on plant height, number of trusses, leaf area index (***LAI***) and dry matter (***DM***) partitioning.

Fan and pad cooling system reduced $T_a$ by 3.0 °C and 2.7 °C, during the dry and rainy seasons, respectively, compared to a naturally ventilated greenhouse (N50). However, this was accompanied by an increase in $x$ by 1.6 g $kg^{-1}$ and 0.8 g $kg^{-1}$ during dry and rainy seasons, respectively. Average air vapour pressure deficit (***VPD***) was lowered by 0.8 kPa during both seasons. Non-uniform conditions were observed in the microclimate inside FAP with differences as high as 20 % and 5 °C, for relative humidity (***rH***) and $T_a$ respectively, recorded between the pad and exhaust fans. The efficiency of the fan and pad cooling system was dependent on the ambient weather conditions. Crop water requirement and water use efficiency was higher and lower, respectively, in the naturally ventilated greenhouse.

Although decoupling of other environmental factors was not possible, the results suggest that mesh size significantly influences both $P_N$ and $E$. Moreover, results from FAP and N50, show that there is a time delay between when changes occur in the greenhouse microclimate and when the plants respond. The combination of NIR-filtration and large area of ventilation openings may provide the best cooling method for greenhouses in the humid tropics. However this may result in an unwanted temperature and light reduction during periods of low intensities of global radiation. Further research to improve the performance of the online measuring gas exchange system, the application and efficiency of the shading paint and its effect of the shading paint on plant growth is recommended.

***Key words:*** Natural ventilation, fan and pad cooling, insect-proof nets, shading, greenhouse, phytomonitoring, tomato.

# Einfluss unterschiedlicher Kühlungsmethoden auf Mikroklima und Pflanzenwachstum in Gewächshäusern in den Tropen

## Zusammenfassung

Das Ziel dieser Arbeit ist die Entwicklung eines Gewächshauses für die nachhaltige Produktion von Gemüse in den Tropen. Die Untersuchungen wurden in vier Teilaspekte unterteilt. Der erste Teil beschäftigte sich mit der Überprüfung von physikalischen und spektralen Eigenschaften diverser Insektenschutznetze und Polyethylen-Folien als Gewächshausbedachung oder als Mulchfolie. Die Eigenschaften verschiedener Insektenschutznetze wurden in einem Windtunnel untersucht.

Die pflanzenbaulichen Versuche wurden am Asian Institute of Technology (Thailand) in vier 20 m langen und 10 m breiten Gewächshäuser durchgeführt. Alle Gewächshausdächer waren mit UV-absorbierender PE-Folie gedeckt. Die Seitenwände des Gewächshauses, welches mit dem sog. “Fan and Pad” (Mattenkühlung) System ausgestattet war (FAP), bestanden ebenfalls aus UV-absorbierender Folie. Die Seitenwände des zweiten Hauses waren mit Insektenschutznetzen der Maschenweite 50 bespannt, ebenso wie die Ventilationsöffnungen am First (N50). Die Seitenwände und Ventilationsöffnungen der anderen zwei Häuser waren mit Insektenschutznetzen, Maschenweite 78 bedeckt. Auf das Dach eines dieser beiden Häuser wurde eine Schattierfarbe mit NIR-reflektierenden Pigmenten aufgebracht (N78S), wohingegen das andere als Kontrolle unbehandelt blieb (N78). Tomatenpflanzen (*Lycopersicon esculentum* cv FMTT260) wurden in den Gewächshäusern in einer Bestandesdichte von 1.5 Pflanzen $m^{-2}$ entsprechend einem praxisüblichen Standard kultiviert. Das Mikroklima wurde gleichzeitig in allen vier Häusern gemessen und paarweise verglichen, N78 mit N78S und FAP mit N50. Mit Hilfe eines Gaswechselmesssystems wurden Online-Messungen der Pflanzenreaktionen in den verschiedenen Gewächshäusern realisiert, wobei simultane Messungen jeweils in einem Gewächshauspaar stattfanden.

Die Ergebnisse zeigen, dass die Maschenweite einen signifikanten Einfluss auf den Luftwiderstand der Insektenschutznetze hat. Die spektralen Eigenschaften der

Dachfolien beeinflussen die Qualität und Quantität des Lichtes in den Gewächshäusern. In dem Haus dessen Dach mit der NIR-reflektierenden Schattierfarbe versehen war, wurde eine um das doppelte erhöhte Durchlässigkeit für UV-Strahlung (300 - 400 nm) festgestellt. Demgegenüber war die Durchlässigkeit für photosynthetisch aktive Strahlung (400 – 700 nm, PAR) um 17,7 %, sowie für Strahlung im nahen Infrarot (700 - 1100 nm, NIR-A) um 26,5% verringert. Die Effizienz des Pigmentanstriches nahm mit der Zeit ab, so dass sie nach 6 Monaten fast keine Wirkung mehr zeigte. Außerdem schützte der Anstrich die Folie vor Alterung insbesondere durch die Verbesserung der staubabweisenden Eigenschaften des Materials. Während der Trockenzeit führte das Auftragen der Schattierfarbe mit NIR-reflektierenden Pigmenten zu einer Reduzierung der Luft- ($\boldsymbol{T_a}$) und Substrattemperatur ($\boldsymbol{T_s}$) um bis zu 2.8 °C bzw. 3.5 °C. Die Luftfeuchtigkeit ($\boldsymbol{x}$) wurde um 1.6 g $kg^{-1}$ in der Trockenzeit und um 0.4 g $kg^{-1}$ in der Regenzeit gemindert. Im beschatteten Gewächshaus war die Transpiration der Blätter ($\boldsymbol{E}$) geringer als in der Kontrolle. Daraus kann errechnet werden, dass der Wasserverbrauch zwischen der 4. und 17. Woche nach dem Umpflanzen um 8.8 % (Trockenzeit) und 6.2 % (Regenzeit) reduziert wurde. Jedoch wurde die Wassernutzungseffizienz dadurch nicht signifikant beeinflusst. Im Vergleich zur Kontrolle nahm die Anzahl der mit Blütenendfäule (BER) befallenen Früchte um 43 % bzw. 30 % während der Trocken- bzw. Regenzeit ab. Im selben Zeitraum wurde daher die Ernte von unverkäuflichen Früchten in N78S um 59 % und 16 % reduziert. Andererseits hatte die Beschattung einen Anstieg von geplatzten Früchten um 16.1 % in der Trocken- und um 43.1 % in der Regenzeit zur Folge. Die (statistisch nicht signifikante) Verringerung des Gesamtertrags in dem beschatteten Haus könnte auf eine aufgrund der geringeren PAR-Intensität, reduzierte Netto-Photosyntheserate zurückzuführen sein. Die Beschattung hatte nur geringen Einfluss auf die Pflanzenhöhe, die Anzahl der Austriebe, den Blattflächenindex (leaf area index, LAI) und die Trockenmasse- (DM) Verteilung.

Im Vergleich zum Haus mit freier Lüftung (N50) wurde im Haus mit Mattenkühlung die Lufttemperatur $\boldsymbol{T_a}$ um 3.0 °C in der Trockenzeit und um 2.7 °C in der Regenzeit reduziert. Dies ging jedoch mit einer Erhöhung der Luftfeuchte um 1.6 g $kg^{-1}$ und

0.8 g $kg^{-1}$ einher (Trocken- bzw. Regenzeit). Das Wasserdampf-Sättigungsdefizit (VPD) wurde in beiden Jahreszeiten um 0.8 kPa verringert. In FAP wurden größere Luftfeuchtigkeits- und $T_a$-Gradienten festgestellt. Die Differenzen betrugen bis zu 5 °C zwischen den Matten und dem Ventilator. Die Effizienz der Mattenkühlung hing stark von den äußeren Witterungsbedingungen ab. Krankheiten (insbes. Pilzbefall) und Nährstoffmangel traten häufiger in FAP als in den natürlich belüfteten Häusern auf. Außerdem stieg der Bedarf an Wasser mit sinkender Wassernutzungseffizienz.

Die Untersuchung der Pflanzenreaktion zeigte, dass die NIR-reflektierenden Pigmente eine Abnahme von $E$, der Netto-Photosyntheserate ($P_N$) und daraus resultierend eine Ertragseinbuße zur Folge hatten. Andererseits wurde durch FAP $P_N$ verbessert, indem $T_a$ und die Blatttemperatur ($T_L$) gesenkt und der Austausch von $CO_2$ mit der Umgebung begünstigt wurden. Obwohl die Entkopplung von anderen Umgebungsfaktoren nicht möglich war, weisen die Ergebnisse darauf hin, dass die Machenweite signifikanten Einfluss auf $P_N$ und $E$ hat. Weiterhin war in den FAP- und N50-Gewächshäusern, eine Zeitverzögerung zwischen Veränderungen im Gewächshausklima und der Pflanzenreaktion zu beobachten.

Ein System mit erzwungenem Luftaustausch (Ventilatoren) und NIR-reflektierenden Bedeckungsmaterialien, könnte die beste Klimatisierung von Gewächshäusern in den Tropen bieten. Der Einsatz von NIR-filternden Materialien sollte in Monaten mit niedriger Einstrahlung (Winter) vermieden werden, da dies zu einer ungewollten Temperatur- und Lichtreduzierung führen kann. Weitere Untersuchungen sind erforderlich, um das Gasmessungssystem zu optimieren und den Einsatz, die Effizienz und den Effekt von Schattierfarbe auf das Pflanzenwachstum noch weiter zu untersuchen.

***Key words:*** Natürliche Belüftung, Mattenkühlung, Insektenschutznetze, Schattierfarbe, Gewächshäuser, Phytomonitor, Tomaten.

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## Symbols and Abbreviations

| | |
|---|---|
| $A_i$ | Cross-sectional area inlet, m$^{2}$ |
| BER | Blossom-end rot |
| BGT | Biosystems and Horticultural Engineering Section |
| $C_d$ | Coefficient of discharge |
| DAT | Days after transplanting |
| DM | Dry matter content, g |
| $\mathrm{DM_F}$ | Dry matter content of fruits and flower parts, g |
| $\mathrm{DM_L}$ | Dry matter content of leaves, g |
| $\mathrm{DM_S}$ | Dry matter content of stems, g |
| $E$ | Transpiration, mg m$^{-2}$ s$^{-1}$ |
| EC | Electrical conductivity mS cm$^{-1}$ |
| FAP | Greenhouse with fan and pad cooling system |
| $G$ | Global radiation, W m$^{-2}$ |
| $G_d$ | Difference in global radiation, W m$^{-2}$ |
| GES | Gas exchange system |
| IPM | Integrated pest management |
| IPP | Integrated plant production |
| $K$ | Permeability of an insect-proof net |
| LAI | Leaf area index, m$^{2}$ m$^{-2}$ |
| NIR | Near infra red radiation, W m$^{-2}$ |
| N50 | Greenhouse with 50-mesh insect proof nets on the sidewalls |
| N78 | Greenhouse with 78-mesh insect-proof net on the sidewalls |
| N78S | Greenhouse with 78-mesh insect-proof net on the sidewalls and shading paint with NIR-reflecting pigment on the roof |
| PAR | Photosynthetic active radiation, W m$^{-2}$ |
| $P_i$ | Static pressure inside the screened area, kPa |
| $P_N$ | Net photosynthesis, µmol mol$^{-1}$ |
| $P_o$ | Static pressure outside screened area, kPa |

| | |
|---|---|
| Q | Discharge, $m^3 s^{-1}$ |
| $S_C$ | Stomata conductance, $m s^{-1}$ |
| *SE* | Standard error of the mean |
| $T_a$ | Air temperature, °C |
| $T_d$ | Temperature difference, °C |
| $T_L$ | Leaf temperature, °C |
| UV | Ultra violet radiation, $W m^{-2}$ |
| *VCD* | Vapour concentration difference, $g kg^{-1}$ |
| *VPD* | Vapour pressure deficit, kPa |
| WAT | Weeks after transplanting |
| $x$ | Air water content, $g kg^{-1}$ |
| $\boldsymbol{\varepsilon}$ | Porosity of an insect-proof net |
| Ø | Diameter |
| η | Evaporative cooling efficiency |

# 1 INTRODUCTION

## 1.1 General Introduction

The world population is expected to rise in the next 43 years by 2.5 billion, to reach a total of 9.2 billion in 2050 (United Nations, 2007). In order to feed these people, there is a need to increase the quantity and quality of food produced in a sustainable way. One way of doing this is by optimising the factors for plant growth and pest control in an integrated approach (referred to as integrated plant production, IPP).

Greenhouses allow producers to grow plants at a time (and location) when it would be impossible to grow outside because of the adverse climate, pests and diseases (Hanan, 1998). In order to achieve maximum returns from greenhouse cultivation, it is important to maintain an environment that promotes optimum plant growth and production all year round. The growth factors namely: light, temperature, humidity and air composition (and nutrition) should be delivered and maintained at optimal levels (von Elsner et al., 2000a). To maintain this optimum growing environment, greenhouses ought to allow high light transmittance, low heat consumption, sufficient ventilation efficiency, adequate structural strength and good overall mechanical behaviour, low construction and operating costs (Giacomelli and Roberts, 1993; Briassoulis et al., 1997a; von Elsner et al., 2000a). In addition, greenhouse structures should maintain pest populations below economic thresholds by utilizing suitable techniques that protect both environment and non-target species.

In tropical regions, plant production in greenhouses is hampered by too high temperatures (due to high solar radiation) and too high relative humidity inside the greenhouse. Consequently, sufficient ventilation and cooling must be provided, especially when the mean maximum temperature is more than 27 °C (Ajwang, 2005; Baudoin and Zabeltitz, 2002). Cooling can be done either actively by the use of mechanical fans and/or evaporative cooling systems, or passively through natural ventilation and/or shading (Willits, 2003). Active cooling systems are unsuitable in regions with high ambient humidity since they may increase the humidity inside the greenhouse thereby increasing the risk of fungal infections, require a lot of capital, consume a lot of energy, some require the use of high quality water, and create temperature and humidity gradients (Bucklin et al., 2004; Fuchs et al., 2006; Willits, 2000a; Mutwiwa et al., 2007). Natural ventilation may not cool greenhouses sufficiently especially in summer since they depend on prevailing conditions especially wind speed and direction, and on the size of vent openings (Boulard et al., 2002; Fatnassi et al., 2002) which may be reduced in order to discourage entry of pests. In IPP systems, the fixing of insect-proof nets in front of the ventilation openings is common since it prohibits the entry of some insect pests into the greenhouse and at the same time keeps beneficial insects within the greenhouse which reduce the dependence on pesticides (Albright and Both, 1990; Bethke, 1994; Bell and Baker, 1995; Antignus et al., 1998; Mears and Both, 2000; Berlinger et al., 2002; Teitel, 2007). However recent research has shown that these insect-proof nets reduce the ventilation efficiency of greenhouses (Sase and Christianson, 1990; Ajwang et al., 2002; Bartzanas et al., 2002; Fatnassi et al., 2002; Kittas et al., 2003a; Harmanto et al., 2006a).

The use of photo-selective films as greenhouse covers has several benefits. Reducing the intensity of near infra-red (NIR) radiation (wavelength 700 nm to 2300 nm) transmitted into a greenhouse contributes significantly to reducing the greenhouse heat load (von Elsner and Xie, 2003; Hemming et al., 2006; Mutwiwa et al., 2007). Unfortunately, most of the shading paints that reduce NIR transmission have been shown to significantly reduce the intensity of photosynthetic active radiation (PAR) wavelength 400 nm to 700 nm (von Elnser, 2005; Hemming et al., 2005) hence may influence yield. Newly developed plastic films and shading paints with NIR-reflecting pigments may effectively reduce greenhouse heat load hence improve crop yield (Garcia-Alonso et al., 2006). Reduction of the radiation load inside a greenhouse by shading or white-washing of the cover material decreases transpiration of the plants (Leonardi et al., 2000; Baille et al., 2001; Gonzalez-Real and Baille, 2006). In addition, shading influences the quality of radiation transmitted into the greenhouse (Kittas et al., 1999; Raveh et al., 2003; Cohen et al., 2005) thereby affecting growth, morphogenesis and architecture of plants (Smith, 1982; Kittas et al., 1999; Li et al., 2000; Gonzalez-Real and Baille, 2006). Moreover, blocking the transmission of ultra violet (UV) radiation (wavelength 300 nm to 400 nm) has been reported to enhance the performance of non-chemical plant protection methods (Reuveni and Raviv, 1992; Antignus et al., 1996, 1998, 2000; Costa et al., 2002; Mutwiwa et al., 2005a & b; Kumar and Poehling, 2006; Doukas and Payne, 2007). Different greenhouse climate modification strategies may influence plant growth differently.

The development of intelligent systems for judging plant response to greenhouse microclimate is important since it avoids intensive and expensive technical measurements and may help to alleviate stress situations. Intelligent systems for detecting various stress situations have been developed e.g. plant water stress (Haiyie et al., 2003; Schmidt and Exarchou, 2000; Beck and Schmidt, 1998), and stomata conductance (Schmidt, 2002). The direct monitoring of a crop is preferable since it does not require a full knowledge of all biotic and abiotic factors in the crop environment (Ehret et al., 2001), but offers physiologically valuable interpretation of plant measured data (Ton, 1997). Since many problems in plants are initiated by stress conditions caused by biotic or abiotic factors, data from continuous measurements of the plant reaction to the greenhouse microclimate will be useful in early detection of stress causes so that corrective actions could be taken. The incorporation of the data into greenhouse control programs will contribute greatly in the optimisation of the greenhouse climate to overcome such stresses.

Therefore there is a need for more research to investigate the effect of insect-proof nets, fan and pad cooling systems and shading using NIR-filtering cover materials on greenhouse microclimate. There is insufficient information especially on the effect of these cooling methods on the physiological plant processes. In this research, through the process of phytomonitoring, the influence of active and passive greenhouse cooling methods on the growth and production of plants were investigated. More specifically, the effects of the porosity of insect-proof nets, fan and pad cooling system and a combination of natural ventilation and shading using paint with NIR-reflecting pigments on the greenhouse microclimate and plant growth, were studied under tropical conditions in different seasons.

## 1.2 Research Objectives and Hypothesis

The main goal of this research is to investigate the physical and technical basis of an integrated management system for the sustainable production of vegetables in greenhouses under tropical climate conditions. In an interdisciplinary approach, the dependency of plant yield and quality on the greenhouse cover material, microclimate, plant nutrition and plant protection as well as the interactive influence of these factors from the different disciplines are investigated. In initial phases of this research greenhouse covering materials that transmit PAR and filter both UV and NIR were sought for use as roof covers. When a material with both characteristics could not be found, a method of modifying the properties of the PE film to meet the requirements of this research was developed. Insect-proof nets that physically or optically block the entry of insect pests into the greenhouse without significantly reducing air exchange rate was identified for covering the ventilation openings. The effects of these covering materials on greenhouse microclimate and plant growth were investigated. To better understand the effects of the microclimate on plant physiological processes, online monitoring of plant response was done through phytomonitoring. In a particular, the optimisation of greenhouse climate control is sought and the development of an adapted greenhouse for the tropics is envisaged. The specific objectives of this research are:

1. To identify and study the physical properties of cover materials and/or methods that reduce greenhouse heat load by lowering NIR-transmission without decreasing PAR
2. To investigate the effects of NIR-filtering covering materials on greenhouse microclimate, plant growth and yield.
3. To investigate the effects of natural ventilation and evaporative cooling on greenhouse microclimate, plant growth and yield
4. To investigate the effect of the above mentioned greenhouse cooling methods on plant physiological processes.

For this research, it was hypothesised that a large ventilation open area may improve the microclimate inside greenhouses in the tropics. Covering greenhouses with UV-absorbing films and fixing insect-proof nets in front of the ventilation openings may lower insect pest infestations. The use of specially formulated pigments/dyes that reduce the amount of near infra-red radiation transmitted into a greenhouse may lower the air temperature during periods of high irradiation. Online measurements and monitoring of the plant response to the variations in greenhouse microclimate may help to optimize climate control and detect stressful situations before negative effects on plant growth.

### 1.2.1 Scope of the present research

The scope of this research may be described as an investigation of the influence of covering material and cooling method on microclimate, growth and production of tomato plants in greenhouses located in the tropics. Plant physiological processes are influenced by the greenhouse microclimate, which changes according to the season. It is important to determine the changes in physiological processes caused by seasonal changes of the greenhouse microclimate. The results from this research will be useful in determining and preventing stressful situations in greenhouse crops. In addition, the results may be incorporated in existing models for greenhouse climate control and plant growth.

### 1.2.2 Brief outline of this thesis

In chapter 2 a literature review of various methods for cooling greenhouses is presented. An overview of the effects of insect-proof nets on greenhouse microclimate and pest exclusion as well as online measurement of plant bioprocesses is discussed.

Chapter 3 describes the materials, equipment and methods used in this research. The layout of the various experiments conducted to achieve the afore-mentioned objectives is described.

In the first part of chapter 4, the results of the physical properties of the greenhouse covering materials are presented. The second part in this chapter presents the results of the effect of NIR filtration on greenhouse microclimate and plant growth. Part three of chapter 4 deals with the effect of natural ventilation and evaporative cooling on greenhouse microclimate and plant growth. The last part in this chapter presents the results from the online measurement of plant response to different greenhouse cooling methods.

In chapter 6, the results from the various experiments are discussed and compared with literature.

Finally, in chapter 6 general conclusions and recommendations are drawn and suggestions are made for future work.

# 2 LITERATURE REVIEW

## 2.1 Greenhouse Cooling

High heat loads and humidity and the desire to achieve optimum growing conditions inside greenhouses stimulate the use of various cooling methods. Cooling the greenhouse air is an important issue for greenhouse operators during the warmest months, because the climatic conditions potentially limit crop yield and quality and constrain benefits (Baille et al., 2006). Greenhouse cooling can be done either actively by use of forced ventilation or passively through natural ventilation or shading.

### 2.1.1 Shading

Reduction of solar radiation transmission by use of various shading screens or paints is a common practice adopted by farmers to reduce the heat load. Shading screens either fixed or mobile, as a climatic conditioning system, allow to reduce the inside greenhouse temperature and evaporative demand during periods of high radiation (Lorenzo et al., 2006). The application of paints on the greenhouse cover, commonly known as whitewashing, is a common means of reducing the heat load by reducing the transmission of solar radiation (Kittas et al., 1996; Baille et al., 2001; von Elsner and Xie, 2003). However, this has the negative effect of reducing PAR transmission, and consequently the productivity of fruits and vegetables (Fuchs et al., 2006; Hemming et al., 2006).

Over the years, attempts have been made to selectively filter the NIR portion of the global radiation from the greenhouse. Filtration of NIR can be achieved at the covering surface either by absorption, reflection or interference (Hoffmann and Waaijenberg, 2002). Using NIR-reflection or NIR-interference, the unwanted energy is reflected back from the surface of the greenhouse cladding material. On the other hand a NIR-absorbing material gets heated up by energy absorption part of which is emitted out of the greenhouse while the other is emitted into the greenhouse thereby contributing to warming the greenhouse air. Filtration of NIR using $CuSO_4$ solution and/ or other coloured fluids in the roof of the greenhouse has been investigated (van Bavel et al., 1981; Gale et al., 1996). Research has also focused on the development of solid materials which filter NIR like plastic films or glass (Verlodt and Verschaeren, 1997; Abdel-Ghany et al., 2001; Hemming et al., 2004; Garcia-Alonso et al., 2006), screens (Runkle et al., 2002; Tanaka, 1997) or shading paints (Verlodt et al., 1995; von Elsner and Xie, 2003; von Elsner 2005).

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. They suggested the use of plastic film greenhouses rather than fluid-roof covers with a complex structure in hot climates. Von Elsner and Xie, (2003) investigated the effect of interference pigments in shading paints on greenhouse climate and reported that the magnitude of NIR, and hence temperature depended on the concentration of the pigment.

Hemming et al. (2004) investigated new plastic film prototypes containing NIR-reflecting pigments with several concentrations and showed that a reduction of NIR-A (wavelength 700 nm-1100 nm) up to 25.7 % was possible but at the same time, PAR was reduced by 8.7 %. They evaluated the effect of these films on energy reduction and greenhouse inside temperature in experiments in tropical regions and developed a new greenhouse climate model. Hemming et al. (2005) quantified 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. They reported positive effects on microclimate, transpiration reduction and crop yield.

Hemming et al., (2006a) investigated the potential of several NIR-filtering methods to be applied in horticulture and presented an analysis of the optical properties of available NIR-filtering materials including a calculation method to quantify the energy reduction under these materials. They concluded that the optimum NIR-filtering multilayer coatings applied to plastic film or glass filter out NIR most effectively. According to these authors, NIR-filtering is not desirable during winter-time in most climatic regions hence should not be applied in unheated greenhouses since they cause an undesirable temperature drop.

Garcia-Alonso et al., (2006) evaluated the performance of a new generation of cool plastic films that block a part of the NIR in Spain, Colombia, Mexico and the Dominican Republic. They reported that these films reduced maximum diurnal temperature being larger in summer and lower in winter coupled by an increase in the height of pepper, *Capsicum annum* cv Almuden, their vegetative development, and their commercial yield as well as a reduction in the number of non-marketable fruits.

Studies on the performance of shading paints with NIR-reflecting pigments in the tropics were conducted by Mutwiwa et al., (2006 a & b). These authors reported a significant reduction in air temperature, leaf transpiration and net photosynthesis. A reduction in crop water requirement, electric power consumption by ventilation fans as well as a decrease in the number of fruits affected by blossom end-rot (BER) was found although this coincided with an increase in fruit cracking.

### 2.1.2 Natural ventilation in greenhouses fitted with insect-proof nets

Natural ventilation systems are used in greenhouses where the flow of air through a ventilation opening is produced by the pressure difference created by wind and/ or by the temperature difference between the inside and outside of the greenhouse (Bailey et al., 2003). When an insect-proof net is fixed in front of the ventilation opening, the air flow will be influenced by the discharge coefficient of the material (Sase and Christianson, 1990; Kosmos et al., 1993).

Miguel (1998) investigated the flow of air through various porous materials and found that the shape of the yarn and mesh geometry have a negligible influence on the airflow characteristics of the screening material. This author found that net permeability (***K***) is related to its porosity (***ε***) by the equation:

$$K = 3.44 \times 10^{-9} \varepsilon^{1.6}$$ Equation 1

While ***ε*** is related to the inertia factor (***Y***) by:

$$Y = 4.30 \times 10^{-2} / \varepsilon^{2.13}$$ Equation 2

Munoz et al. (1999) studied the influence of insect-proof nets on ventilation rate and on the wind–effect coefficient, and reported a reduction of both wind–effect coefficient and overall ventilation rate. Kittas et al. (2003a) investigated the influence of an insect-proof net on ventilation rate in a multi-span glass–covered greenhouse equipped with a continuous roof vent. They reported that the discharge coefficient was correlated to the aerodynamic properties of the net using porous media flow analysis.

Shilo et al. (2004) investigated the airflow patterns, ventilation rates and heat fluxes in roof-ventilated four-span greenhouse with insect-proof nets. They reported an increase in leeward ventilation rate with wind velocity. A good agreement between ventilation rates measured by the tracer gas and energy-balance methods was achieved. According to these authors, the direction of air flow within the greenhouse at plant level was nearly opposite to that of the external wind. Both the mean and turbulent latent heat fluxes through the roof openings were much larger than the sensible heat fluxes. In addition, both the sensible and latent turbulent heat fluxes had high values when the roof openings were opened, and then decayed with time. Their directions at the level of the openings were from the greenhouse towards the outside while at plant level they generally followed the direction of the ambient wind.

Teitel et al. (1999) developed a theoretical model based on energy and mass conservation for greenhouses equipped with either 50-or 22-mesh insect-proof net. The results from the model simulations and experimental measurements showed a dependence of temperature on mesh size with a greater temperature reduction in the greenhouse equipped with the 22-mesh insect-proof nets. Miguel and Silva (2000) developed a theoretical approach describing the climate behaviour of greenhouses fitted with insect-proof nets and reported that the climate conditions inside a greenhouse depend on the physical characteristics of the net (permeability and porosity) and the apertures, as well as the wind velocity. Fatnassi et al. (2002) studied the ventilation performances of a large canarian type greenhouse equipped with insect-proof nets and then developed a model to simulate the effect of several nets on greenhouse ventilation performances and the resulting microclimate. The simulations showed that:

- The ventilation rate increases proportionally with the wind speed and the size of the opening and;
- The size of the contribution of the chimney effect in ventilation is significant at low wind velocities and;
- Insect-proof net induced a strong additional pressure drop though the opening which reduced significantly the ventilation rate and increased air temperature.

Bailey et al. (2003) studied airflow resistance of greenhouse ventilators with and without insect-proof nets. They reported that the discharge coefficient increased with aspect ratio and flow through the opening varied with the sine of the flap angle. According to these authors, the discharge coefficient of a screened ventilator decreases with the fibre thickness and air speed. Moeller et al. (2004) achieved a good agreement between model results and measurements of the transpiration of sweet pepper crops grown in insect-proof screenhouses. Model sensitivity analysis showed that reduced radiation, wind speed and modified vapour pressure deficit were the main factors influencing transpiration. Ajwang (2005) developed a mass and energy balance model to predict the internal climate of the greenhouse and evapo-transpiration from external climatic data and properties of insect screens. Good agreement was achieved between simulated and measured results.

In experiments conducted in small tunnels covered with different mesh sizes, Soni et al (2005) observed temperature gradients (up to 5.7 °C) in both the vertical and horizontal axes which increased with plant density. Plant transpiration was higher in the tunnels covered with the more porous insect-proof net. According to Harmanto et al. (2006a & b), an insect-proof net with a fine mesh increases the internal air temperature although the effect is small when the greenhouse has large ventilation openings. They reported that air temperatures inside the greenhouse with a mature crop or when left empty were increased by 1.5 °C and 4.5 °C, respectively, when the ventilation opening area was decreased by 80 %, while humidity was increased by 37.5 % when the ventilation opening area was decreased by 40 %. These authors recommended a ventilation opening to floor area ratio of 0.6 as the minimum requirement to create a suitable microclimate in greenhouses in the tropics.

### 2.1.3 Evaporative cooling

Evaporative cooling systems are based on the conversion of sensible heat into latent heat through the evaporation of water. As water evaporates, energy is lost from the air causing its temperature to drop (Hanan, 1998; Bucklin et al., 2004). A suitable combination for supplying a flow of air through the greenhouse and for supplying water to be evaporated, in accordance with the environmental conditions (radiation, temperature and relative humidity of the outside air), is an essential requirement for maintaining the required conditions in the greenhouse (Arbel et al., 2003). According to Arbel et al., (1999), the three main evaporative cooling methods are sprinkling or spraying water on the surface of the canopy using sprinklers (Cohen et al., 1983), fan and pad, and fogging.

Arbel et al. (2003) conducted experiments using high pressure spray nozzles with the highest possible uniformity of distribution, fans at both ends of the greenhouse (north and south) placed at ground level, roof openings and two side openings (east and west). The results obtained revealed that optimum (air temperature and relative humidity of 28.8 °C and 80 %, respectively) and uniform (lengthwise and vertical directions) climatic conditions were maintained inside the greenhouse during the summer. In contrast to that, there was significant variation across the width of the greenhouse, although this was not the case with fully developed crops or with the windward openings closed. They concluded that in order to obtain completely uniform climatic conditions throughout the volume of the greenhouse, it is desirable to install fans in all four sides.

A fan and pad cooling system consists of exhaust fans at one end of the greenhouse and a pump circulating water through and over a porous pad installed at the opposite end of the greenhouse. From the wet pad, this air flows through the greenhouse, absorbing heat and water vapour, and is removed by the fans at the opposite end. Although this system is simple to operate and does not wet the foliage, the main disadvantage is high cost of installation and operation, creation of temperature and humidity gradients inside the greenhouse, and an increased risk of fungal diseases due to the high humidity (Arbel et al., 2003; Kittas et al., 2003b). Results from measurements conducted in a greenhouse with a rose crop, *Rosa indica* L cv 'Mercedes Long', show that the numerical solution of the energy balance equation predicts crop transpiration, foliage temperature, air temperature and humidity inside the greenhouse accurately (Fuchs et al., 2006). The evaporative pad cooled the air considerably; but the lowering of transpiring leaf temperature was only minor, while evaporation from the pad decreased when external humidity increased.

Kittas et al. (2003b), proposed a simple climate model which incorporates the effect of ventilation rate, roof shading and crop transpiration to predict the temperature gradients along a greenhouse. Measurements were performed in a commercial greenhouse equipped with fans and pads and shaded in the second half. Experimental data show that the cooling system was able to keep the greenhouse air temperature at rather low levels. They concluded that high ventilation rates and shading contribute to reduce thermal gradients.

With the objective to identify the best cooling method for greenhouses in tropical regions, Shen and Yu (2002) simulated the effects of several cooling methods on leaf temperature reduction using a greenhouse climate model in conjunction with a leaf temperature model. The results indicated that a cooling system, consisting of ventilation fans with covering materials having near-infrared reflection capability, is suitable for the humid tropics.

Simulation results from a model developed by Willits (2003) suggested that in an evaporative cooled greenhouse, both air and canopy temperatures decline with increasing airflow rates. Increasing canopy size was shown to be more influential in reducing air temperatures when evaporative pad cooling was used than when not. However, its effect on canopy temperature was expected to be approximately the same regardless of whether evaporative pad cooling was used or not. Moreover, these authors reported that evapotranspiration coefficient i.e., the ratio of energy used for transpiration to incoming solar energy is halved when the evaporative pad cooling is used.

According to Sabeh et al. (2006) under semi arid conditions, lowering the cooling efficiency of the fan and pad at higher ventilation rates caused a reduction in cooling. However, the lower ventilation rates limited air exchange and reduced cooling efficiency. Controlling the air exchange rate to maintain the greenhouse temperature at

24 °C/18 °C during day and night, increased water use by fan and pad (14.8 L $m^{-2}$ $day^{-1}$) compared to the tomato irrigation system (8.9 L $m^{-2}$ $day^{-1}$).

## 2.2 Online Measurement of Plant Response

Various mathematical models have been developed to describe crop growth and greenhouse climate (Acock et al., 1978; Bruggink and Heuvelink, 1987; Jones, 1991; Marcelis, 1989; Dayan et al., 1993a,b; Papadakis et al., 1994; Gary et al., 1996; Heuvelink, 1999; Trigui et al., 2001a,b; and Boonen 2005). However, most of these models are either too complex or inaccurate (or both) and have been developed or validated in sophisticated greenhouses. Thus there is a need to generate data from research that can be used to improve and/ or simplify the application of model-based process monitoring and control.

Although a whole range of sensors to measure different parameters in protected cultivation are available, it is necessary to monitor plant reaction more accurately. Most of these sensors can be divided into three categories: mass balance of $CO_2$ (e.g. photosynthesis), or water (e.g. transpiration) and finally energy balance (e.g. leaf temperature) (Boonen (2005). The “speaking plant” approach (Udink et al., 1978) is based on the assumption that knowledge of external factors alone is not sufficient for drawing accurate conclusions about plant conditions. Only the plant itself can show reliably its physiological status (O’toole et al., 1984; van Leeuwen et al., 2001). Over the past few years, interest is increasing in the development of methods to automatically and continuously detect crop stress, water use, growth and nutrition in greenhouse crops (Ehret et al., 2001). Image processing using video cameras has been applied to analyse plant growth (Suzuki, 1995; Takakura, 1992) fruit development (Hatoh, 1995; Choi et al., 1995), plant health (Ling et al., 1995), nitrogen deficiency (Meyer et al., 1990), plant water status (Murase et al., 1995) and plant temperature (Li and Ling, 1996). Intelligent systems for detecting various stress situations have also been developed e.g. for plant water stress (Haiyie et al., 2003; Schmidt and Exarchou, 2000;

Beck and Schmidt, 1998), or stomata conductance (Schmidt, 2002). Direct monitoring (Phytomonitoring) of crop is preferable since it does not require a full knowledge of all biotic and abiotic factors in the crop environment (Ehret et al., 2001). In addition, it offers physiologically valuable interpretation of plant measured data (Ton, 1997).

According to Boonen (2005), for a real efficient control and monitoring of plant growth in protected cultivation, at least two conditions have to be fulfilled:

1. There has to be a measurable feedback of the variable(s) to be controlled or of one or more variables that influence them, and
2. There has to be a reliable prediction (dynamic model) that describes how the measured variable(s) respond to a variation of the control input(s).

Phytomonitoring technology combines data acquisition system based on specific sensors and data processing software, which presents measuring information in terms of plant physiology and agronomy (Ton et al., 2001). According to these authors, the hierarchy of a phytomonitoring system is as follows:

a) Basic **measuring system** for collecting and displaying data.

b) An **information system** converts data into physiologically valuable format that generally meet standards accepted in horticultural literature and handbooks.

c) An **expert system** incorporates crop information that helps to evaluate crop response and to make necessary decisions.

d) A **control system** is extremely specific because of unique combination of crop variety and greenhouse facilities.

Through these four steps, the phytomonitoring methodology enables to elicit highly representative derivative characteristics of a crop from non-representative primary data of point monitoring. These characteristics allow to detect many physiological disorders and to tune climate and irrigation control in greenhouses using trial-and-error approach (Ton and Kopyt, 2003).

At the Lithuanian institute, phytomonitoring methodology was used to investigate the physiological processes of tomato hybrids and their parents in conditions of different temperature during the day in greenhouses, the effect of different lamps on seedlings, growth hormones and the dynamics of water uptake (Brazaityte, 2002). Most recently, Boonen (2005), measured and modelled dynamic plant responses to variations in the microenvironment. She concluded that the data-based mechanistic modelling approach is a suitable tool for the development of simple and meaningful dynamic models. This can make the 'speaking plant', approach a success, under the premise that the surrounding environment and the microenvironment of the plant are known.

## 2.3 The Role of Greenhouses in Biological Plant Protection

A greenhouse should provide the necessary conditions for optimal plant growth and production through-out the year. High light transmission, low heat consumption, sufficient ventilation efficiency, adequate structural strength and good overall mechanical behaviour with low maintenance and operational costs are important characteristics of a good greenhouse (Giacomelli and Roberts, 1993; Briassoulis et al., 1997 a & b; von Elnser et al., 2000 a & b). Over the years, there has been an increase in the proportion and designs of greenhouses covered with plastic films (Briassoulis et al., 1997a; von Elsner et al., 2000a). Several reasons may be attributed to this rapid expansion among them low cost, simple designs, and advancements in technology which has led to the development of plastic films tailored to meet specific needs.

The spectral characteristics of a plastic film influence the quality and quantity of radiation inside the greenhouse (Kittas et al., 1999) which in turn influences both biotic and abiotic factors inside the greenhouse (Kittas and Baille, 1998). Photo-selective plastic films and nets have been reported to offer several benefits especially in integrated plant production and protection. Reduction in the transmission of UV radiation by the greenhouse cover (or reflection by mulch) limits the establishment of certain pests (Antignus et al., 1998; Costa et al., 2002; Mutwiwa et al., 2005; Kumar and Poehling, 2006), improves the management of fungal diseases (Reuven and Raviv, 1992) reduces incidences of viral diseases (Antignus, 2000; Kumar and Poehling, 2006) and may increase the performance of entomopathogenic organisms (Costa et al., 2001).

Information on the effects of UV-absorbing plastic films on the behaviour of various biological control organisms is insufficient. Chiel et al. (2006) studied the effect of UV-absorbing plastic films on the attraction of the crop to and host location ability of three different parasitoids: *Aphidius colemani* Viereck (Hymenoptera: Bracodiae) a parasitoid of *Myzus persicae* Sulzer (Homoptera: Aphididae), *Diglyphus isaea* Walker (Hymenoptera: Eulophidae) a parasitoid of *Liriomyza bryoniae* Burgess (Diptera: Agromyzidae) and *Eretmocerous mundus* Mercet (Hymenoptera: Aphelinidae) a parasitoid of *Bemicia tabaci* Gennadius (Homoptera: Aleyrodidae) in the laboratory and field conditions. They reported that lack of UV radiation did not affect the parasitization rates of *A. Colemani* and *D. isae* although it reduced the host location ability of *E. mundus*.

Doukas and Payne (2007) reported that *E. formosa* would search for whitefly hosts even in a UV-blocked environment, although they showed a small preference for tunnels with UV light. On the contrary, electroretinogram analysis of the compound eyes of the greenhouse whitefly *Trialeurodes vaporariourum* Westwood (Homoptera: Aleyrodidae) and its parasitoid *Encarsia formosa* Gahan (Hymenoptera: Aphilinidae) revealed that the eyes of *E. formosa* responded more significantly in the UV region than those of *T. vaporariorum* (Mellor et al., 1997). Chyzik et al., (2003) reported that the fecundity of *Aphidius matricarea* was not affected in greenhouses covered with UV-absorbing plastic films. According to Dyers and Chittka (2004), the absence of UV does not affect the visual ability and foraging efficiency of the bumble bee *Bombus terrestris*, Linnaeus (Hymenoptera: Apidae), which is used to facilitate pollination of greenhouse crops. Laboratory results have shown that light intensity, photoperiod and temperature influence the efficiency of *E. formosa* and *E. eremicus* (Zilahi-Baloch et al., 2006). These results imply that covering greenhouses with spectrally modifying plastic films may increase the success of biological control programs.

# 3 MATERIALS AND METHODS

## 3.1 Experimental Site

The research was carried out 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). Two distinct seasons can be distinguished in central Thailand: the rainy season, lasting from mid-May to October in average years and the dry season from November to mid-May (Takahashi and Yasunari, 2006), whereof the latter can be divided in a cooler dry season (November to February) and a hot dry season (March to mid May) (Kleinhenz et al., 2006). Average daily mean temperatures and average monthly precipitation are in the range of 27 °C/24 mm, 30 °C/105 mm and 29 °C/220 mm during the cool-dry, hot-dry and rainy season respectively. Long-term averages for annual mean temperatures and sum of precipitation are 28.5 °C and 1500 mm, respectively. Four experiments were conducted:-

1. During the rainy season running from 14.07.2005 to 30.10.2005
2. During the dry season running from 07.11.2005 to 30.03.2006
3. During the rainy season running from 08.05.2006 to 31.08.2006.
4. During the rainy-dry season running from 11.09.2006 to 22.12.2006

Experiment 1 and 4 were very short and the seasons overlapped thus, the data is not presented in this report.

## 3.2 Determination of Physical Properties of the Greenhouse Covers

In order to select the appropriate materials for covering or mulching the greenhouses, various polyethylene (PE) films and insect-proof nets were evaluated at the Biosystems and Horticultural Engineering Section (BGT), Institute of Biological Productions Systems, Leibniz University of Hannover, Germany. The spectral characteristics of the nets and PE films were measured in the photo-laboratory using a Perkin-Elmer Lambda 900 UV/VIS/NIR spectrometer (Perkin-Elmer Instruments, Norwalk, USA). The transmission and reflection of radiation with wavelengths between 300 nm and 2300 nm was measured in 1 nm steps. The average transmission and/ or reflection was calculated for the following classes: UV radiation (300 nm to 400 nm), PAR (400 nm to 700 nm), NIR-A (700 nm to 1400 nm), NIR-B (1400 nm to 2300 nm) and NIR (700 nm to 2300 nm). To visualise the effect of the covers on the spectral distribution of global radiation energy inside greenhouse in the study location, an optical thickness of 2 (CIE, 1989, table 2) was used to adapt the results as this was the closest value to 1.4 suggested by Peetchaw et al. (2004) for Thailand.

Laboratory determination of the discharge coefficients for different insect-proof nets was carried out using a modified wind tunnel (Fig. 3.2.1). The apparatus comprised of a wooden box (2 m × 2 m × 2 m) open on one end, a tapered cylindrical duct and a variable speed fan connected at the end of the cylindrical section of the duct. For each insect-proof net, a small piece (2 m long × 2 m wide) was tightly stretched and fixed to a wooden frame then fitted on the open end of the wooden box. The inside surface of the frame was flush with the inside surfaces of the wind tunnel, so the airflow did not exert a force directly on the frame (Fig. 3.2.2).

Both static and dynamic pressures for each insect-proof net were measured at different air velocities, which were generated by adjusting the speed of the fan by means of a variable resistor. The static pressure difference between the outside and inside of a square screened inlet was measured using Betz differential precision manometer (AVA, Goettingen, Germany) (Fig. 3.2.3). One manometer tube was placed in the atmosphere i.e. outside the box and free from obstruction, while the other was positioned on the four walls of the box at the inlet side, just after the insect-proof net. An inclined manometer (30 ° angle of inclination) was used to measure the dynamic pressure drop at the cylindrical section of the duct (Fig. 3.2.3).

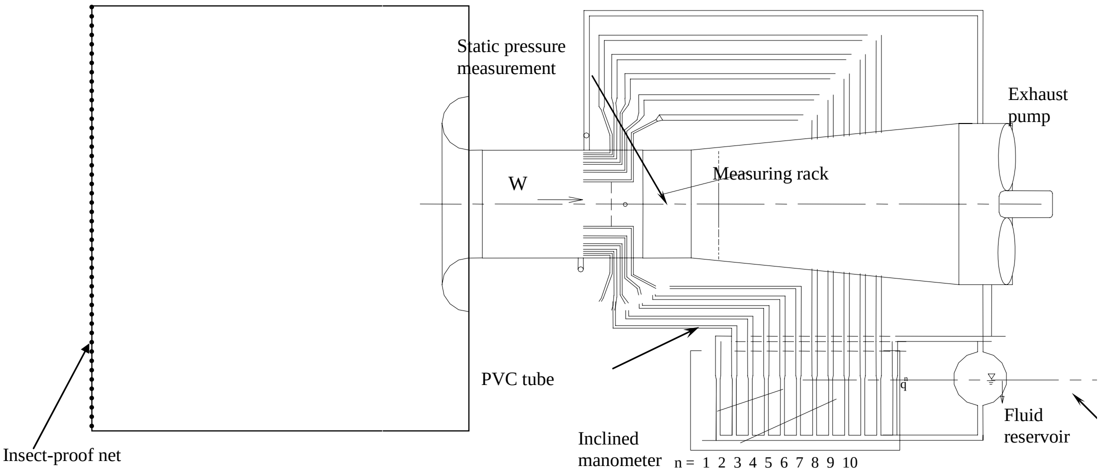


**Figure 3.2.1:** Cross-section of the wind tunnel used to measure the pressure drop across the insect-proof nets. The airflow rate through the insect-proof net (placed on the open end of the square box opposite the fan) was measured at different velocities by changing the speed of the fan using a variable resistor.

**Figure 3.2.2:** A photograph of the wind tunnel used to measure the pressure drop across the insect-proof nets. An insect-proof net can be seen placed on the end of the wooden box ready for measurement. The fan is located at the end of the cylindrical duct.

Eight tubes positioned against the inward bound air stream were connected to the inclined manometer while two other tubes were connected at diametrically opposite positions on the duct wall to determine the static pressure. The difference between the height of the fluid in the two columns and the other tubes provided the dynamic pressure head. The air velocity through the duct was computed from the dynamic head as described by and Klose and Tantau (2004).

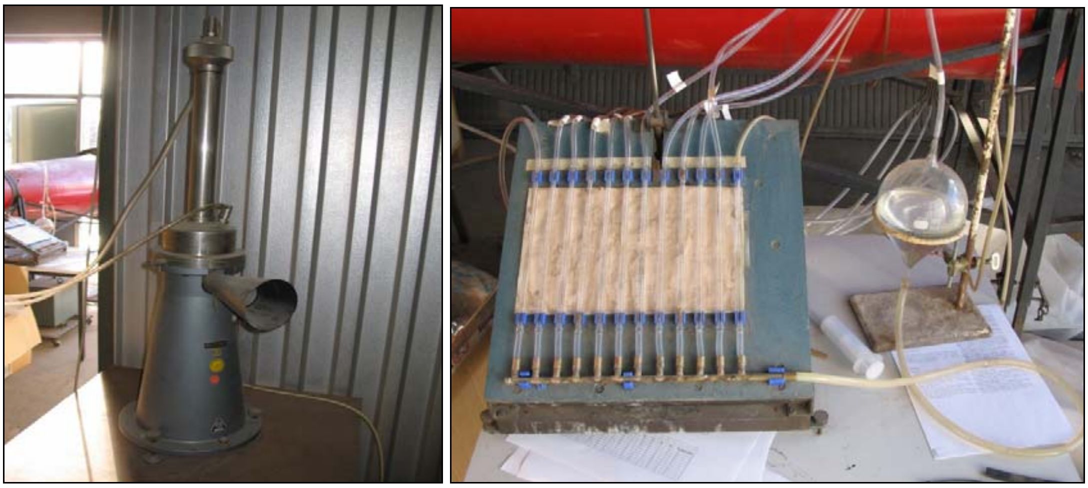


**Figure 3.2.3:** Photographs of the Betz (left) and inclined (right) manometers that were connected to the wind tunnel to measure static and dynamic pressures respectively, across insect-proof nets.

The discharge coefficient (***C<sub></sub>***$C_d$) was then calculated from the volumetric airflow rate (calculated from the area and velocity) using Bernoulli equation written for outside and inside the screened opening as using equations 3 and 4.

$$\Phi_a = C_d \Phi_i \qquad \text{Equation 3}$$

Thus by rearranging equation 3:

$$C_d = \Phi_a / \Phi_i \quad \text{with } \Phi_i = A_i \left[ 2 \frac{(P_o - P_i)}{\rho} \right]^{0.5} \qquad \text{Equation 4}$$

Where:

$\Phi_a$ is the actual volumetric airflow rates [$m^{-3}$ $s^{-1}$]

$\Phi_i$ is the ideal volumetric airflow rates [$m^{-3}$ $s^{-1}$]

$C_d$ is the discharge coefficient [-]

$A_i$ is the inlet cross-sectional area, [$m^{-2}$]

$P_o$ is the static pressure outside of the screened duct [Pa]

$P_i$ is the static pressure inside of the screened duct [Pa]

$\rho$ is the density of air, [kg $m^{-3}$]

In addition to the wind tunnel measurements, the fibre thickness and pore dimensions of some of the insect-proof nets were measured under a microscope (ZEISS Axioskop40, Carl Zeiss MicroImaging GmbH, Goettingen, Germany).

From the results of the spectral measurements, a UV-absorbing transparent polyethylene (PE) film (Wepelen™, FVG, Dernbach, Germany) and a black-white PE film (Silo plus™, FVG, Dernbach, Germany) were chosen as roof cover and mulch, respectively. White–black mulch (white surface on top) was selected in order to reflect radiation entering the greenhouse to the crop canopy (photo-morphogenesis) or outside of the greenhouse (temperature control).

Two insect-proof nets were chosen to cover the ventilation openings. The first insect-proof net had an additive to reduce transmission of UV and had a mesh size 50 (BioNet, Klayman Meteor Ltd, Petach-Tikva, Israel). The second insect-proof net was UV-transmitting with a mesh size of 78 (Econet-T (Ab Ludvig Svensson, Kinna, Sweden). The UV-absorbing materials were chosen in order to optically protect the crop from insect pests. The finer net, 78-mesh, was chosen to physically prevent the entry of small insects especially thrips in to the greenhouse.

## 3.3 Greenhouse Description

A total of 4 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 (Fig. 3.3.1). The roof of all the greenhouses was covered with the 200 µm thick, anti-dust and anti-fog UV-absorbing PE film (Wepelen™, FVG, Dernbach, Germany). All greenhouses were equipped with a two-door entrance system with a footbath between the two doors which was filled with a disinfectant to help maintain high phytosanitary standards inside the greenhouses.

For the naturally ventilated greenhouses, the sidewalls were covered with the UV-absorbing PE film up to a height of 0.8 m above the ground while the remaining portion was covered with either the 78-mesh or the 50-mesh insect-proof net up to the gutter (3 m above the plastic film). In addition, another ventilation opening measuring 0.8 m wide by 20 m long was included on the roof (facing the north) and covered with the same insect-proof net.

These greenhouses were equipped with two exhaust fans (diameter (∅): 1 m, capacity (Q): 550 $m^3 s^{-1}$) on the eastern end to help maintain a homogenous microclimate inside especially when internal air temperature rose above 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.

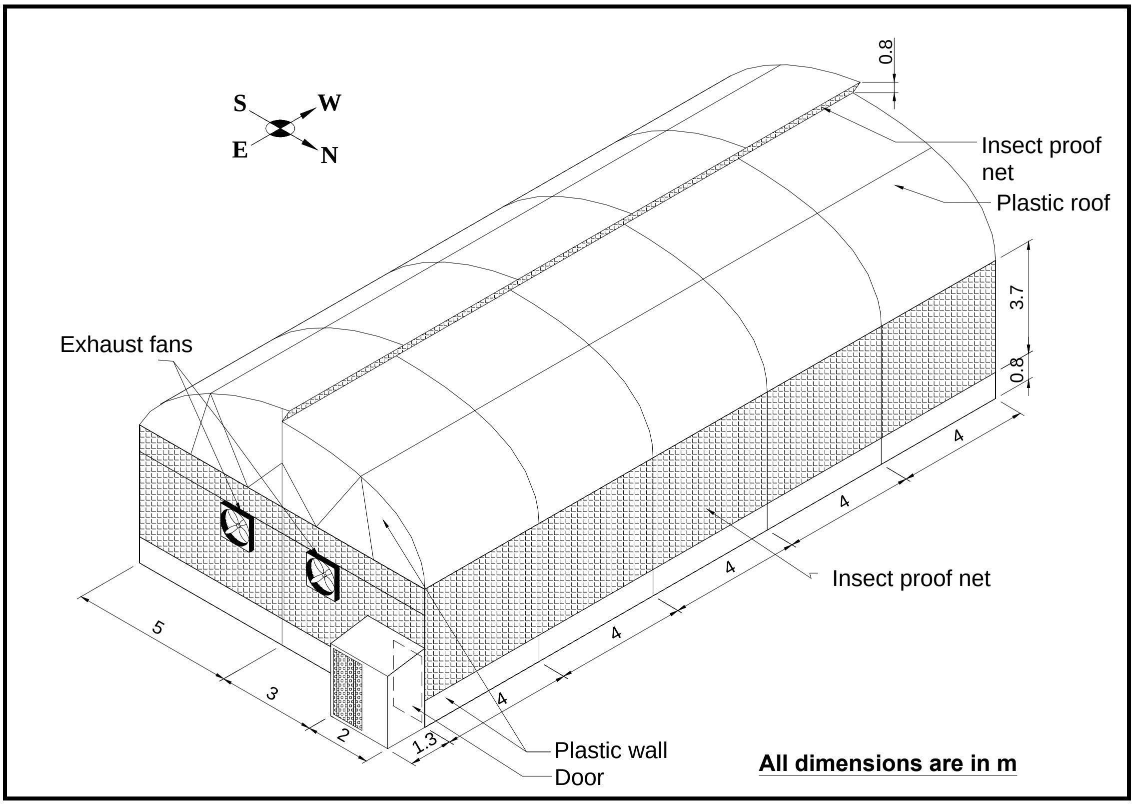


**Figure 3.3.1:** A sketch of the naturally ventilated greenhouse used for some of the experiments. The sidewalls and roof ventilation opening were covered with either a 50- (BioNet) or 78- (Econet-T) mesh insect-proof net. A UV-absorbing polyethylene film was used to cover the greenhouse roof, gable sides and the portion of the sidewalls near the ground (Harmanto, 2006, Modified).

The fan and pad greenhouse was completely covered with the UV-absorbing plastic film i.e. both on the roof and sidewalls (Fig.3.3.2). The cooling pads (dimensions: length: 9.7 m, height: 1.8 m and thickness: 0.15 m) were installed on the eastern gable ends. Inside the greenhouses, one horizontal airflow fan (HAF) EDC 24 (with ∅ and Q of 0.465 m and 100 - 120 $m^3$ $s^{-1}$, respectively) was positioned 4 m away from the pad and 6 m above the floor of the greenhouse. Three exhaust fans (consisting of two EMS 50 and one EMS 30) were positioned on the side opposite to the pads i.e. western end. The two

EMS 50 (∅: 0.138 m, Q: 380 - 600 $m^3$ $min^{-1}$) were positioned 1.2 m above the ground) while the third fan EMS 30 (fans (∅: 0.095 m, Q: 100-220 $m^3$ $s^{-1}$) was positioned 3.5 m above the ground exactly between the two bigger fans and directly opposite the HAF inside the greenhouse. The cooling pads and all the fans were manufactured by Munters Euroemme S.p.A. Italy. The operation of the HAF and the cooling pad started when air temperature inside the greenhouse reached 26 °C and 28 °C, respectively. To prevent the sucking of insect pests in to the greenhouse, a 50-mesh (BioNet) insect-proof net was used to cover the external side of the pads.

**Figure 3.3.2**. A photograph of the greenhouse equipped with a fan and pad cooling system (FAP) use for the experiments in Central Thailand. The cooling pad can be seen protruding behind the gable wall on the eastern end of the greenhouse.

The floor of the greenhouses was covered with the black and white PE mulch film with the white surface on the topside (FVG, Dernbach, Germany). The greenhouses were equipped with an automatically controlled drip irrigation system. Fine ballast was spread around all greenhouses and weeds were controlled by fortnightly spraying of herbicides. The position of the experimental greenhouses in relation to the others is as shown in Fig. 3.3.3.

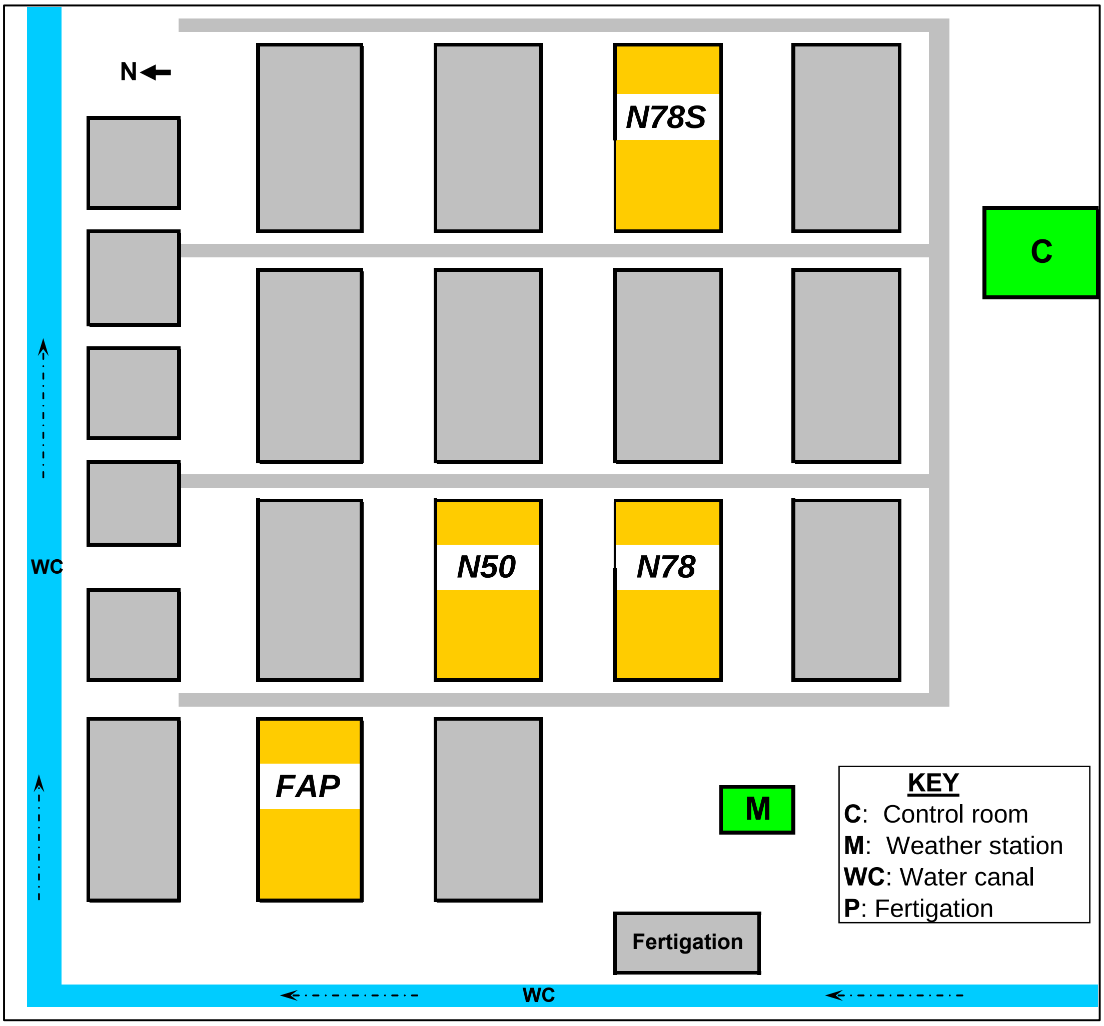


**Figure 3.3.3:** Position of the experimental greenhouses namely; the evaporative cooled (FAP), naturally ventilated with 50-mesh net (N50), 78-mesh net without shading (N78) and 78-mesh net with shading (N78S) on the roof. The local meteorological station (M), control room (C) and water canal (WC) are shown.

ReduHeat, a newly developed shading paint with a near infra-red reflecting pigment, (Mardenkro BV, Baarle Nasau, The Netherlands) was thoroughly mixed with fresh tap water in the ratio 1:2.5 (water : pigment). The mixture was then sprayed onto the roof of one of the greenhouses clad with the 78-mesh insect-proof net on a clear sunny day, using a high pressure system. A crane mounted on a truck was used to lift and maintain the technician in place when spraying the shading paint on the greenhouse roof. 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.

The acronyms ***FAP*** and ***N50*** shall be used to denote the greenhouse with fan and pad cooling system and the one clad with the 50-mesh (BioNet) insect proof net on the sidewalls, respectively. In addition, the acronyms ***N78S*** and ***N78*** shall be used to denote the greenhouse covered with 78-mesh insect-proof net on the sidewalls with or without shading paint with NIR-reflecting pigment on the roof, respectively.

## 3.4 Crop Management

Seeds of indeterminate tomato, *Solanum lycopersicum* L, cv FMTT260 (AVRDC, Shanhua, Taiwan) were sown in nursery trays placed on the benches inside a fan and pad cooled greenhouse (nursery) and transplanted into 10 L white plastic pots two weeks later. The substrate consisted of 28 % of organic matter with pH of 5.3. The substrate texture was 30 % sand, 39 % silt and 31 % clay (Dinwondeekankasat, Ayutthaya, Thailand). In all the 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$^{-2}$. The double stem technique for tomato production recommended by Chen and Lal (1999) for tropical regions where temperatures are expected to exceed 30/23 °C day/night was used. One side shoot, which emerged from the first node below the first truss of the stem was allowed to develop into a second stem (the resulting foliage protected the fruits from sun burn). For staking, the plants were trained according to the high wire system (van de Vooren et al. 1986) using “Bato hangers (Bato Trading B.V., Zevenbergen, The Netherlands) attached to metal wires 4 m above the ground with 0.40 m distance between individual stems.

Whenever necessary, pruning was done twice a week from the beginning to the end of the experiment. After the first harvest, all the senescent leaves were removed regularly up to the oldest fruit-carrying-truss and the plants were laid down according to necessity. Besides using blue and yellow sticky traps, insecticides were sprayed weekly (alternating Cypermethrin™ [2 ml $L^{-1}$], Abamectin™ [1.5 ml $L^{-1}$] or Spinosad™ [1.5 ml $L^{-1}$]) due to the heavy prevalence of insect pests in the area. 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 black leaf mould (*Pseudocercospora fuligena*) according to demand.

Fertigation (irrigation and fertilizer application) 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 daytime 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 (Max, 2006, personal communication). The electrical conductivity, EC, of the fertigation solution was set at 1.5 and 1.8 mS $cm^{-1}$ prior to and after the first harvest, respectively maintaining the same element ratio.

Except in the morning hours (before 09:00 h) and late afternoon (after 16:00 h), during daytime, irrigation frequency was based on the solar radiation integral. The duration of the dripper intervals was regularly adjusted according to plant age, increasing from 1 minute at the beginning to 12 minutes at the end of the trial. On average 9 irrigation cycles per day (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.

The following points are highlighted:

1. In the experiment conducted during the dry season, 5 tomato plants cv King Kong were randomly placed in each row to compare the performance of the two tomato cultivars (collaborating project (P3) but the data is not presented in this report.
2. In both experiments, two night time fertigation treatments, one solution with high EC (3.0 mS $cm^{-1}$) and the other with low EC (0.5 mS $cm^{-1}$) were included in FAP and N50. The rows where this was applied were randomly chosen and fixed at the beginning of the experiment, in a pattern that gave two rows of the same treatment in each greenhouse. Since the high and low EC treatments were applied at night, a 60 minute timer controlled irrigation with the normal solution (EC 1.5 mS $cm^{-1}$) was applied between 06:00 h - 09:00 h to flush out any solution remaining on the pipes before the normal irrigation resumed.
3. Plant data from FAP and N50 presented in this report were collected from the rows with normal irrigation i.e. EC 1.5 mS $cm^{-1}$ only.

## 3.5 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) measured through destructive sampling using a leaf area meter (LI-3100, LI-COR, Lincoln, Nebraska, USA). After LA measurements, the plant materials namely; leaves, trusses (both flowers and fruits) and stems were separated and oven dried at 80 °C for 48 hours (fruits 72 hours) after which, the dry weights were measured. Ripe fruits were harvested weekly and graded into marketable and non-marketable classes. The marketable class consisted of high quality fruits weighing more than 0.05 kg and without defects. The non-marketable class had 3 categories consisting of fruits which were either affected by blossom end rot, cracked, too small or had an abnormal shape. Plant water consumption was estimated daily from the difference of dripper solution and leachate (Fig. 3.5.1 left). For this purpose, 6 pots i.e. 3 pots to collect dripper solution and 3 for leachate from the pot carrying the tomato plant were randomly positioned in the greenhouse and the volume of the solution measured once a day.

**Figure 3.5.1**: Measurement of plant water consumption: the manual measurements of dripper solution and leachate, collected in separate buckets (left) and the lysimeter with an electronic balance used to measure evapotranspiration (right) inside the greenhouses in Central Thailand.

During the rainy season, a lysimeter consisting of an electronic balance (Model FBG34EDE-H, Sartorius AG, Goettingen, Germany) was set up to estimate evapotranspiration of the plants (Fig. 3.5.1 right). The balance had a readability of 0.1 g and a maximum capacity of 34 kg. Three plants were supported on the weighing platform of the balance by a metallic frame. Plants were grown in pots and placed on top of a bucket (for collecting the drainage water) and supported using a thread attached to the top. Over-drain irrigation water was siphoned out once in a day and measured. However, due to noise from the ventilation fans and traffic which created a lot of vibrations on the lysimeter, and the harsh conditions (temperature and humidity beyond the manufacturer's specification), the data were not reliable.

### 3.6 Climate Data

Air temperature (***$T_a$***) and relative humidity (***rH***) (ambient and inside the greenhouses) were measured using aspirated psychrometers developed at BGT. The psychrometers consisted of thin sheathed type K (NiCr-Ni) thermocouples (∅: 0.5 mm) enclosed in a radiation shield open on one end and fitted with a small fan on the other (accuracy ± 0.3 K). In each greenhouse, two psychrometers were positioned along the centre at a height of 1.5 m above the ground with a 10 m distance between them. The temperature of the substrate (***$T_s$***) in the pots was measured using the same thermocouples at a depth of 10 cm below the surface. The intensity of ***G*** inside the greenhouses was measured using CM 5 pyranometer (Kipp and Zonen, 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 ***G*** was measured at a height of 2.5 m at the meteorological station of the project (Fig. 3.3.3).

Data of these climatic parameters were recorded every 5 minutes by a purpose build datalogger (Biosystems and Horticultural Engineering section (BGT), Leibniz University Hannover, Germany). At 10 weeks after transplanting (WAT) during the rainy season 2006 the datalogging system developed technical problems hence data from this period is not included. Daily mean wind speed and direction data were acquired from the AIT campus meteorological station. 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) using a Line Quantum Sensor (LI-191) attached to a LICOR 1400 datalogger (both LI-COR Biosciences, Lincoln, 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.

## 3.7 Plant Response

Plant physiological parameters (response) i.e. transpiration and net photosynthesis and the bio-climate around the plant i.e. vapour concentration difference (leaf-air), air and leaf temperature, relative humidity and $CO_2$ concentration, were measured using a gas exchange unit “Plantputer Phytomonitor EPM-2006” (Steinbeis Transfer Centre, Energy-Environment-Information, Berlin, Germany) (Fig. 3.7.1). This gas exchange system (herein after referred to as GES) measures the gas exchange of leaves and the properties of the ambient air. It consists of a small diaphragm pump that sucks a stream of air over the surface of the leaf enclosed in small chambers (cuvettes) (Fig. 3.7.2 left).

The air was then collected, mixed and directed into dewar vessels for measurement of $T_a$, ***rH*** and $CO_2$ concentration. Absolute values of both the reference (i.e. incoming) and sample (i.e. leaf cuvettes) $T_a$ and $CO_2$ content were measured continuously. Material of the leaf cuvettes has been carefully selected to ensure maximum light transmission, air movement and to avoid injury on the leaf.

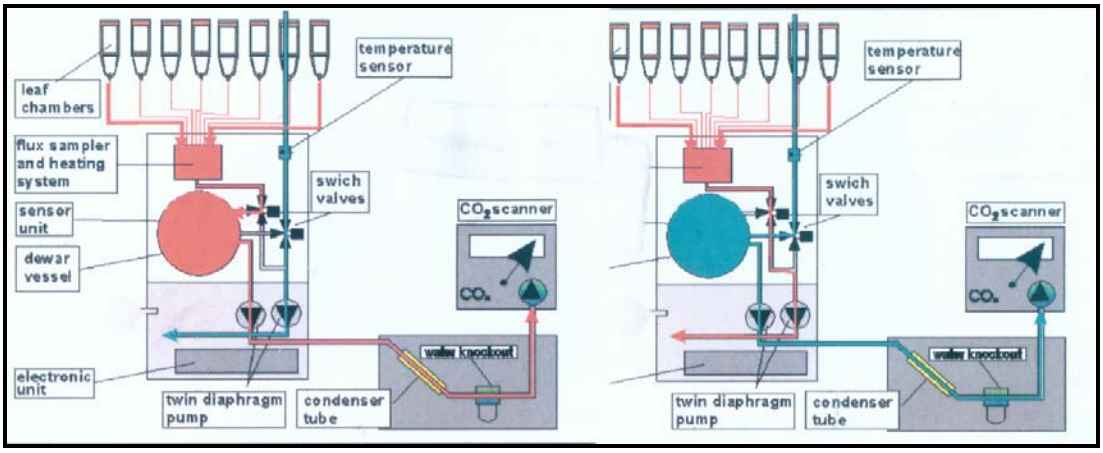


**Figure 3.7.1:** The layout of the various components of the gas exchange system (EPM 2006 phytomonitoring system) used for online measurement of plant response to microclimate inside greenhouses cooled using different methods in Central Thailand (Source: Schmidt, 2006).

Canopy temperature was calculated from the mean leaf temperature measured using thin thermocouples clipped on the underside of the leaf using small magnets (Fig. 3.7.2 right). One leaf temperature sensor was positioned under a leaf on the top part of the canopy i.e. leaf exposed to solar radiation, while the second one was positioned under a leaf inside the canopy i. e. shaded from solar radiation).

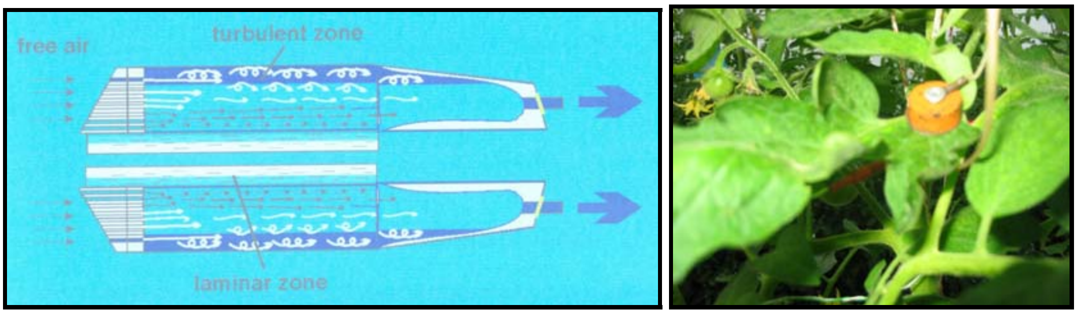


**Figure 3.7.2:** Cross-section of one of the cuvettes (left) used to enclose the leaves during the measurements with the gas exchange system. On the right is a photograph of the thermocouples used to measure leaf temperature.

Only two GES devices were available so the measurements were done by pair-wise comparison of any two greenhouses (N78 versus N78S, N78 versus N50 and FAP versus N50) starting from when the plants were 4 weeks old. During the measurements the gas exchange system was placed at the centre of the greenhouses as shown in Fig. 3.7.3.

Four healthy growing plants were identified and chosen. One or several fully expanded leaves were inserted into each cuvette. The cuvette was then supported and held in a horizontal position using a thread. Usually the top 4th, 5th or 6th leaf was chosen since these leaves are actively growing and fully exposed to sunlight (Gonzalez-Real and Baille, 2006). Four leaf cuvettes (one per plant) were used for each greenhouse and each time the leaf filled at least 70 to 100 % of the cuvette area. The GES was protected from direct solar radiation by a special housing equipped with a fan on the top. Data from the GES was recorded on a computer every 5 minutes.

**Figure 3.7.3:** Experimental setup of the online measurement of plant response in the greenhouses in Central Thailand. The leaf cuvettes (with one or several leaves inside) were placed in a horizontal position and connected to the mixing chamber using small pipes.

## 3.8 Data Analysis

A pair-wise comparison of the data was done i.e. **FAP** versus **N50** and **N78** versus **N78S.** For all statistical analyses the SAS statistical software (SAS, 2001, SAS Institute Inc., Cary N.C., USA) was used.

For the comparison of climatic data (weekly means) between any pair of 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 (Sokal and Rohlf, 1995) for factors with three or more levels while Student t-Test was used for two level factors.

For plant physiological response data from any given pair of measurements conducted over several days i.e. repeated over time, were checked for homogeneity of variance using the Hovtest = Levene option of SAS (SAS, 2001) and only pooled when variance homogeneity for the intensity of global radiation could be assumed. Data were subjected to MIXED and MANOVAR under PROC GLM, with greenhouse and time (Hour) treated as a fixed while the other factors were treated as random effects as described by Potvin et al. (1990) and Littel et al. (2000). For the analysis of greenhouse effects within the same hour, differences in least square means were compared using the same procedure. Mean values calculated for 15 minutes from measurements taken every 5 minutes were used in all correlations in plant response results.

Data on marketable and non-marketable yields was analysed as weight. For N78 and N78S, 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.

# 4 RESULTS

## 4.1 Physical Properties of the Cover Materials

### 4.1.1 Spectral properties

The 78-mesh insect-proof net had the highest transmission for radiation with wavelength between 300 and 2300 nm compared to the other materials (Table 4.1.1). Out of the insect proof-nets, the 50-mesh transmitted much less UV and PAR compared to the 78-mesh. Due to the complex nature of the greenhouses and lack of resources (especially good equipment) it was not possible to achieve a uniform distribution of the shading paint on the roof cover (Fig 4.1.1).

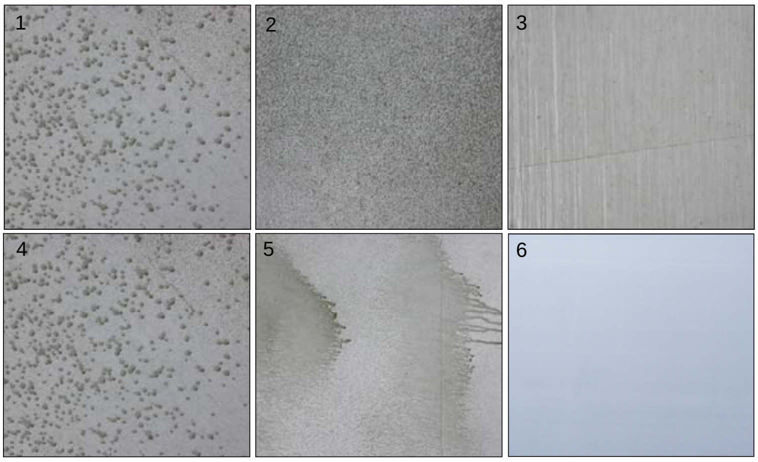


**Figure 4.1.1:** Photographs of sections of greenhouse roof cover with (1-5) or without (6) the shading paint with the NIR-reflecting pigment.

The application of the shading paint with NIR-reflecting pigment increased the transmission of UV radiation and reduced that in the other wavelengths (Fig. 4.1.2). Shading decreased the transmission of PAR and NIR-A by 17.7 % and 32.9 %, respectively. The PE mulch reflected up to 70.8 % of PAR compared to 8.1 % by a tomato leaf (Table 4.1.2 & Fig. 4.1.3). Reflection of UV radiation by the tomato leaf and PE film without shading is less than 10 %. The application of the shading paint doubled the reflection of UV and PAR while that of NIR-A was tripled. The spectral transmission and reflection of the shading paint did not remain constant with time. Except for UV radiation, the spectral transmission increased while reflection decreased with time (Fig. 4.1.3).

**Table 4.1.1:** Spectral transmission, %, of new 78-mesh and 50-mesh insect-proof nets, and PE film with or without the shading paint with NIR-reflecting pigment. Measurements were done in the laboratory using a UV-VIS-NIR spectrophotometer.

| **Definition** | **Wavelength, nm** | **Polyethylene film** | | **Insect-proof net** | |
|---|---|---|---|---|---|
| | | Without shading | With shading | 50-mesh | 78-mesh |
| UV | 300-400 | 12.2 | 30.3 | 43.6 | 81.7 |
| PAR | 400-700 | 76.8 | 59.1 | 64.7 | 84.8 |
| NIR-A | 700-1500 | 83.3 | 55.4 | 73.6 | 85.7 |
| NIR-B | 1500-2300 | 81.9 | 69.4 | 80.5 | 84.3 |
| TOTAL | 300-2300 | 78.2 | 60.3 | 73.5 | 84.8 |

**Table 4.1.2**: Spectral reflection, %, of the topside of a young tomato leaf, new PE mulch and PE film with or without the shading paint with NIR-reflecting pigment. Measurements were done in the laboratory using a UV-VIS-NIR spectrophotometer.

| Definition | Polyethylene film | | Tomato leaf | PE mulch |
|---|---|---|---|---|
| | Without shading | With shading | | |
| UV | 6.5 | 17.7 | 5.0 | 10.9 |
| PAR | 12.5 | 27.5 | 8.1 | 70.8 |
| NIR-A | 11.0 | 36.5 | 43.5 | 46.5 |
| NIR-B | 8.7 | 19.6 | 17.9 | 18.3 |
| TOTAL | 10.6 | 27.5 | 26.1 | 37.1 |

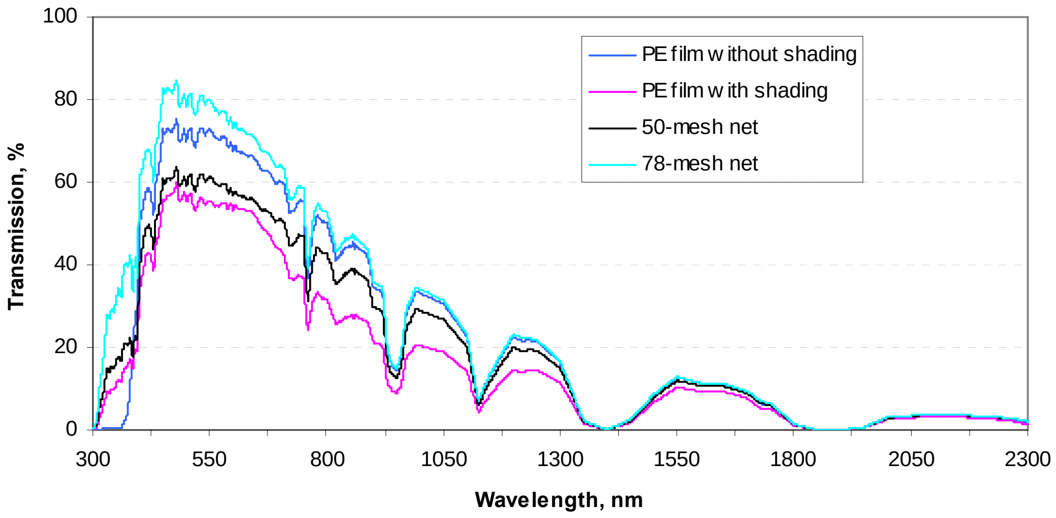


**Figure 4.1.2:** Spectral transmission, %, of 78-mesh (Econet-T) and 50-mesh (BioNet) insect-proof nets, and PE film with or without the shading paint with the NIR-reflecting pigment. Samples were measured in the laboratory using a UV-VIS-NIR spectrophotometer, the results were then adapted according to CIE 1985 table 7 column 2.

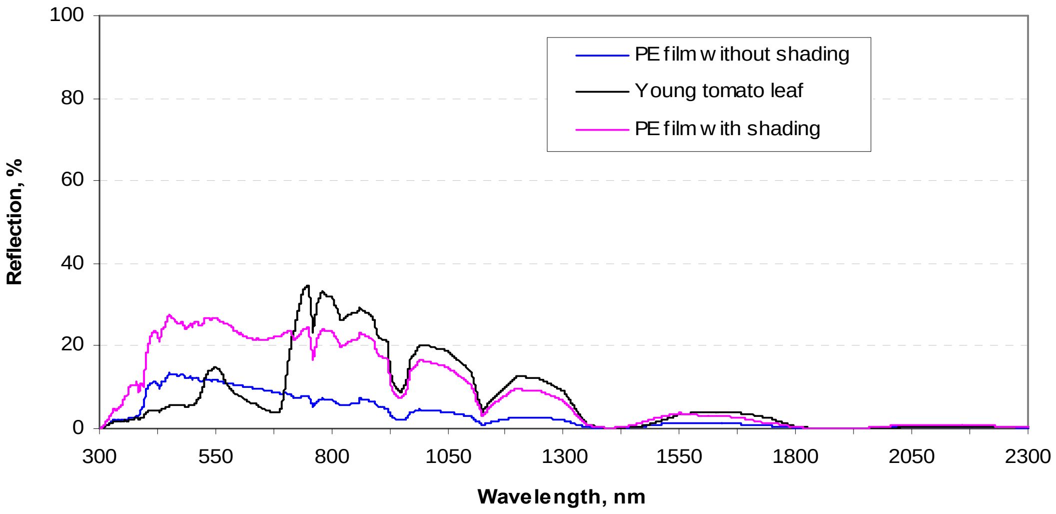


**Figure 4.1.3:** Spectral reflection, % of a young tomato leaf and the PE film with or without the shading paint with the NIR-reflecting pigment. Samples were measured in the laboratory using a UV-VIS-NIR spectrophotometer, the results were then adapted according to CIE 1985, table 7, column 2.

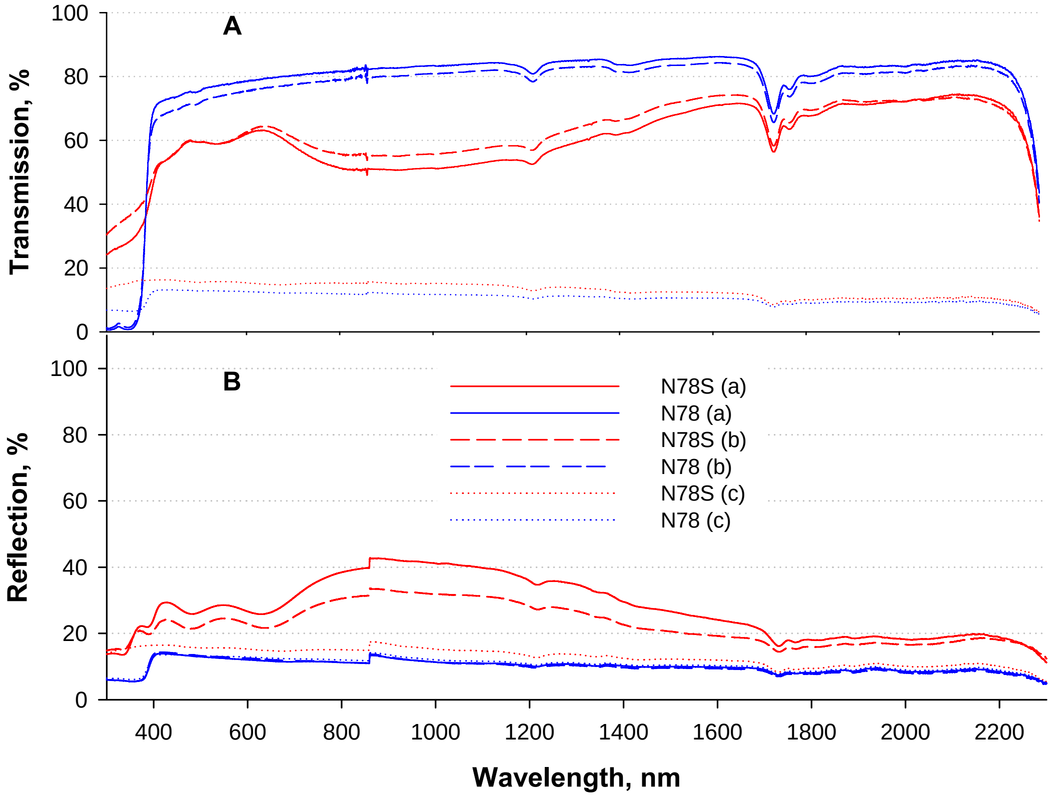


**Figure 4.1.4:** Spectral transmission, %, (A) and reflection (B) of the polyethylene films used to cover the greenhouse roof without (N78) and with (N78S) the NIR-reflecting pigment on various dates (a): 30.06.2005, (b) 15.11.2006 and (c) 19.02.2007. Samples were measured in the laboratory using a UV-VIS-NIR spectrophotometer.

### 4.1.2 Porosity of the insect-proof nets

A small deviation was found between the measured dimensions of the insect-proof nets and those given by the manufacturer (Table 4.1.3). The 50-mesh insect-proof net was made of slightly thicker threads and the pore opening was larger compared to the 78-mesh insect-proof net. Screen porosity ($\varepsilon$), defined as the fraction of total volume of a net occupied by void space (Kittas et al., 2002) was found to be 0.40 and 0.32 for the 50- and 78- mesh, respectively. Using the equations given by Miguel (1998), the permeability ($\boldsymbol{K}$) of the 50- and 78-mesh insect-proof nets was found to be $7.93 \times 10^{-10}$ and $5.56 \times 10^{-10}$, respectively. The inertia factor was found to be $6.11 \times 10^{-3}$ and $3.79 \times 10^{-3}$ for the 50- and 78-mesh insect-proof nets respectively.

**Table 4.1.3:** Characteristics of the 50- and 78-mesh insect-proof nets used to cover the sidewalls and ventilation openings of the naturally ventilated greenhouses in central Thailand.

| **Type of insect-proof net** | **Manufacturer information** | | | **Measured dimensions** | | |
|---|---|---|---|---|---|---|
| | Mesh size (mm) | Area ($mm^2$) | Fibre size (mm) | Mesh size (mm) | Pore area ($mm^2$) | Fibre size (mm) |
| 50-mesh | 0.82×0.28 | 0.21 | 0.24 | 0.93×0.23 | 0.21 | 0.23 |
| 78-mesh | 0.35×0.15 | 0.05 | 0.15 | 0.30×0.16 | 0.05 | 0.17 |

For all insect-proof nets investigated, pressure drop increased with approach velocity although the increment was higher for the finer net (Fig. 4.1.5A). Spider net had the highest pressure drop at all measured velocities with 5.5 kPa and 24.0 kPa recorded at the lowest (0.30 m $s^{-1}$), and highest (0.85 m $s^{-1}$) approach velocities, respectively. Econet-T (78-mesh) offered a slightly lower pressure drop than the combination of 2 layers of BioNet (50-mesh). Furthermore, pressure drop offered by Econet-T was almost double that measured for BioNet with the difference increasing with increase in approach velocity.

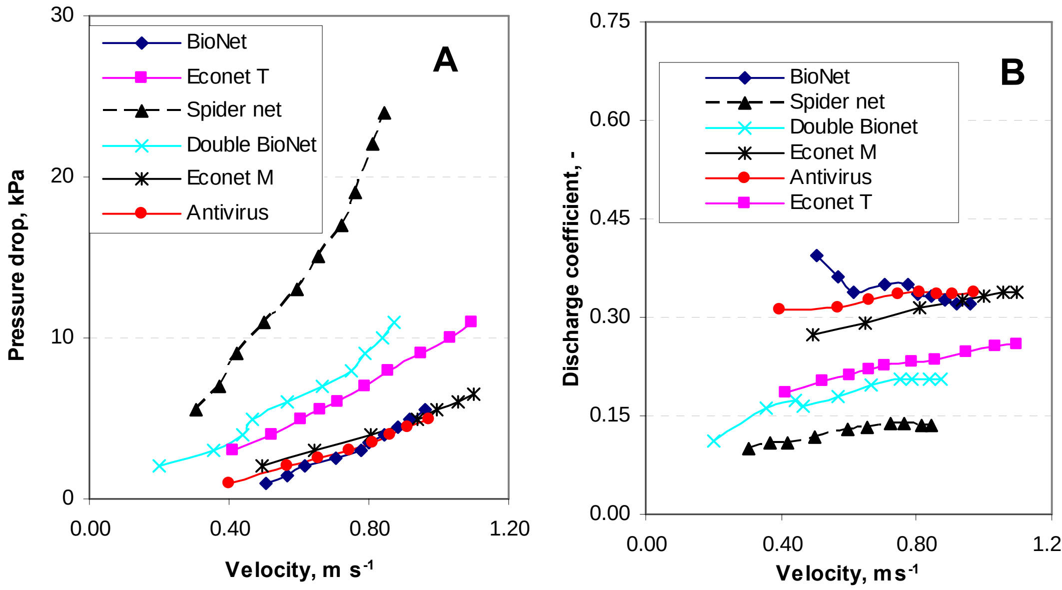


**Figure 4.1.5:** Pressure drop (A) and the discharge coefficient (B) of various insect-proof nets measured in a wind tunnel at different air velocities at the Biosystems and Horticultural Engineering Section, Institute of Biological Production Systems, Leibniz University Hannover.

The **$C_d$** of the different insect-proof nets increased with increase in velocity (Fig.3.1.4B). The insect-proof net with the smallest hole size i.e Spider-net had the lowest **$C_d$**, increasing from 0.101 at the lowest velocity (0.30 m $s^{-1}$) to 0.135 at the highest velocity (0.85 m $s^{-1}$). The **$C_d$** of Econet-T increased gently from 0.186 at a velocity of 0.41 m $s^{-1}$ to a maximum of 0.259 at the highest velocity (1.09 m $s^{-1}$). For BioNet **$C_d$** values of 0.40 and 0.32 were calculated at the lowest (0.51 m $s^{-1}$) and highest (0.96 m $s^{-1}$) velocities respectively. The combination of two layers of BioNet (double BioNet) offered more resistance to air flow compared to a single layer of either net on its own. Average values for **$C_d$** calculated at various approach velocities were 0.12, 0.23, 0.34, 0.32 and 0.18 for Spidernet, Econet-T, BioNet, and double BioNet, respectively.

## 4.2 Effect of Shading on Microclimate and Plant Growth

### 4.2.1 Microclimate

#### 4.2.1.1 Global radiation

As the shading paint with NIR reflecting pigment was applied on the outer surface of the roof cover, the most obvious effect was a reduction in the transmission of ***G*** (Fig. 4.2.1). During the dry season, the average intensity of ***G*** calculated at the end of the season at 17 WAT was 373.8 W $m^{-2}$, 203.2 W $m^{-2}$ and 183.6 W $m^{-2}$ for ambient, N78 and N78S, respectively. This corresponds to a transmission of 54.7 % and 49.2 % for N78 and N78S, respectively. The intensity of ***G*** in N78 was significantly higher than in N78S with a mean difference of 9.6 % for the whole season. Moreover, the difference between the intensity of ***G*** in N78 and N78S, ($G_d$) was lower during cloudy than sunny days.

During the rainy season, higher intensities of ***G*** were recorded compared to the dry season. Moreover, the intensity $G_d$ in N78 was significantly increased after the re-application of the shading paint (Fig. 4.2.1B). Average values of ***G*** recorded from 1 to 14 WAT were 430.9 W $m^{-2}$, 237.5 W $m^{-2}$ and 222.7 W $m^{-2}$ for ambient, N78 and N78S, respectively. In the first half of the rainy season, i.e. before the re-application of the shading paint, greenhouse transmission of ***G*** was 2 % higher in N78S (54.7%) compared to N78 (52.7 %), while the average $G_d$ was -8.8 W$m^{-2}$. However, after the re-application of the shading paint, transmission of the greenhouses was 59.1 % and 47.3 % in N78 and N78S, respectively.

Compared to the dry season, higher intensities of ***G*** were experienced during the rainy season. Maximum intensity of ***G*** was 561.1 W $m^{-2}$, 329.1 W $m^{-2}$ and 347.4 W $m^{-2}$ for ambient, N78 and N78S, respectively recorded 4 WAT, while maximum $G_d$ was 49.3 W $m^{-2}$ at 8 WAT. The diurnal profile of ***G*** on two representative days after the re-application of the shading paint is depicted in Fig. 4.2.2.

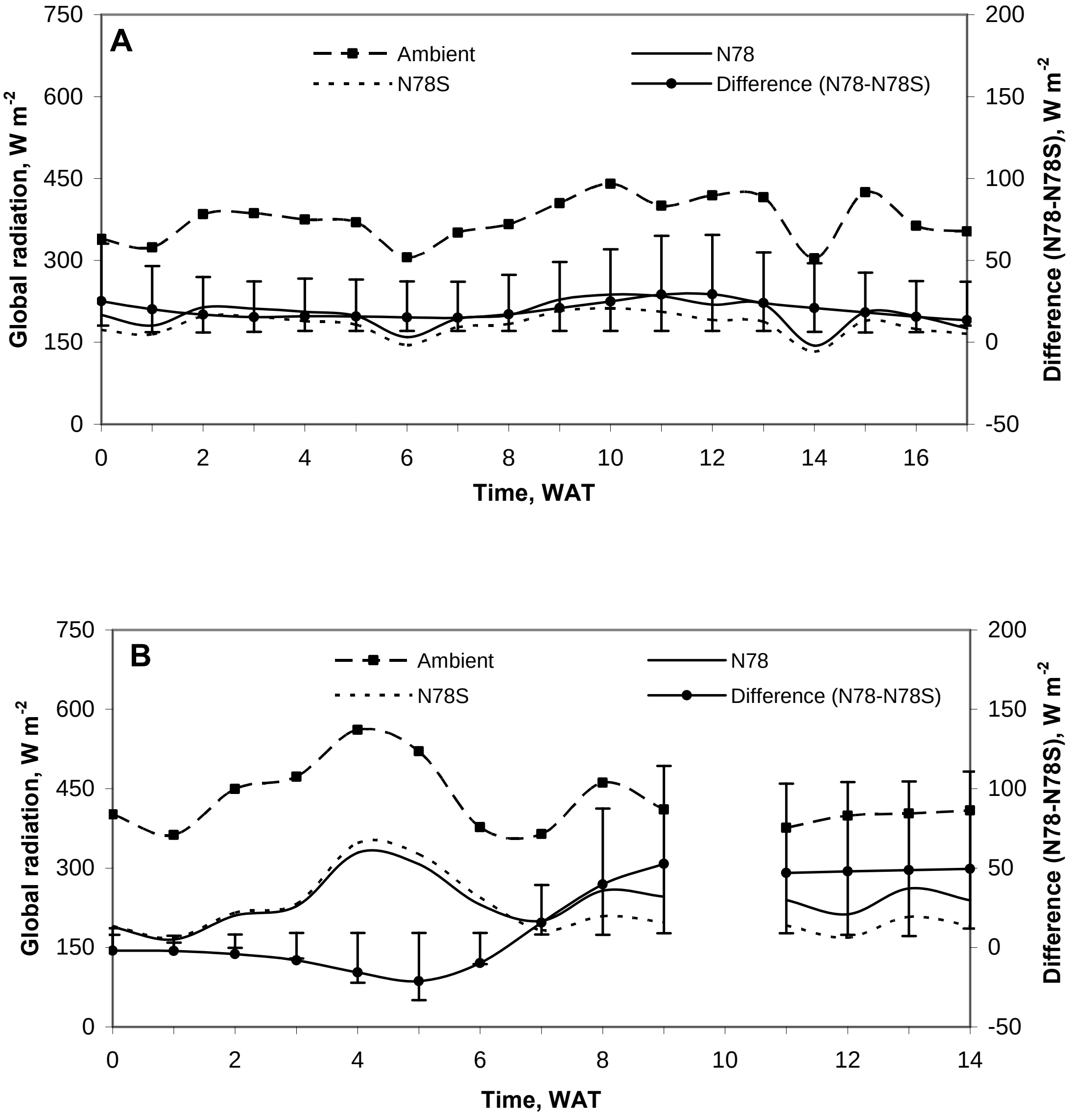
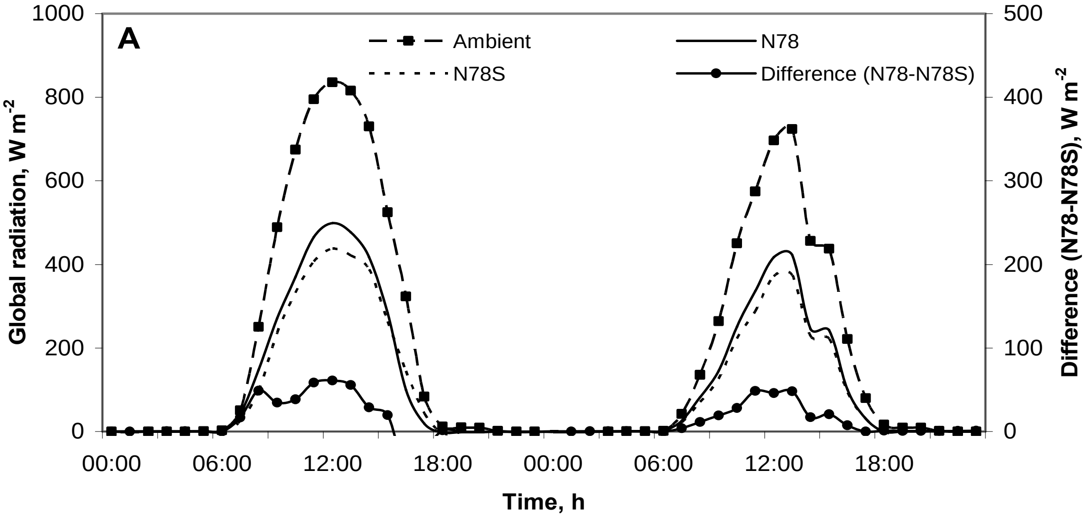


**Figure 4.2.1:** Daytime intensity of global radiation (weekly average) recorded outside (ambient), in the greenhouses with (N78S) or without (N78) the shading paint with NIR reflecting pigment and the difference between the two greenhouses (N78-N78S) during the 2005/2006 dry (A) or 2006 rainy (B) season in central Thailand. Error bars represent the upper and lower confidence intervals of the difference.



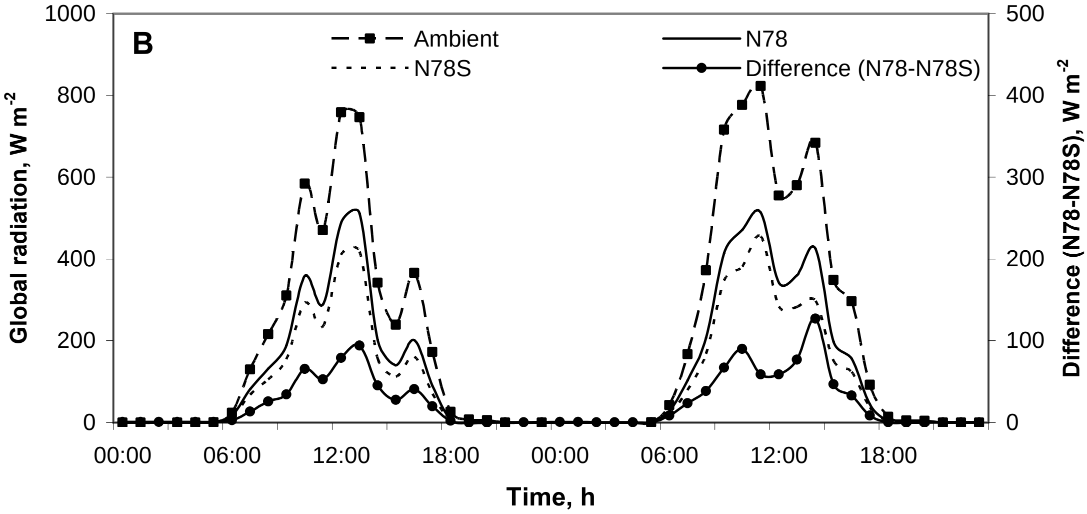


**Figure 4.2.2:** Global radiation profiles outside and in the greenhouses with (N78S) or without (N78) the shading paint with NIR-reflecting pigment on two days (A) 17-18.01.2006 during the dry season 2005/2006 and (B) 11-12.07.2006 during the rainy season 2006 in central Thailand.

### 4.2.1.2 PAR measurements

On all sampling dates, the intensity of PAR was significantly higher for ambient than inside the greenhouses (df = 2, 43; F= 648.5; *P* < 0.0001) (Table 4.2.1). During the dry season, the transmission of PAR through the greenhouse covers was 52 % and 50.3 % in N78 and N78S, respectively. During the rainy season, higher average intensities of PAR were recorded both outside (1493.0 µmol $m^{-2}$ $s^{-1}$) and (957.3 µmol $m^{-2}$ $s^{-1}$ and 825.2 µmol $m^{-2}$ $s^{-1}$ in N78 and N78S, respectively) inside the greenhouses. The re-application of the shading paint reduced transmission of PAR in N78S by 26.2 %. The tomato plants in N78 and N78S intercepted 76.0 % and 74.6 %, respectively, of the PAR reaching the top of the canopy on 14.12.2005 (Table 4.2.2).

**Table 4.2.1:** Intensity of photosynthetic active radiation, µmol $m^{-2}$ $s^{-1}$, recorded outside and above the canopy inside the naturally ventilated greenhouses with (N78S) or without (N78) the shading paint with NIR-reflecting pigment on typical sunny days during the experiments in central Thailand.

| **Date** | **Ambient** | **Above canopy** | | **Reduction by shading (%)** |
|---|---|---|---|---|
| | | **N78** | **N78S** | |
| 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 %** |

*Means in the same row followed by the same letter are not significantly different at 5 % level of significance according to PROC GLM, SNK test.

**Table 4.2.2:** Interception of photosynthetic active radiation, µmol $m^{-2}$ $s^{-1}$, by tomato plants grown in the naturally ventilated greenhouses with (N78S) or without (N78) the shading paint with NIR-reflecting pigment on 14.12.2005, in central Thailand.

| Greenhouse | Measurement point (canopy) | | Interception, % |
|---|---|---|---|
| | Above | Below | |
| N78 | 633.4 | 150.4 | 76.3 |
| N78S | 606.8 | 157.3 | 74.7 |

#### 4.2.1.3 Air temperature

By reducing the level of NIR radiation transmitted into the greenhouses, the air temperature, $\boldsymbol{T_a}$, in the greenhouse was reduced as depicted in Fig. 4.2.3A. During the dry season, the average daytime $\boldsymbol{T_a}$ in N78 (28.9 °C) was significantly higher than in ambient (27.9 °C) and N78S (27.1 °C) (df = 2, 299; F = 15.5; $P < 0.001$). The maximum difference in $\boldsymbol{T_a}$ between N78 and N78S, ($\boldsymbol{T_d}$), in this season was 2.7 °C.

During the rainy season, the average value of $\boldsymbol{T_a}$ recorded in N78S was lower than in ambient and in N78 (Fig. 4.2.3B). The average values of $\boldsymbol{T_a}$ were 31.5 °C, 31.2 °C and 30.6 °C for ambient, N78 and N78S, respectively. The effect of re-applying the shading paint (7 WAT) on $\boldsymbol{T_a}$ was not immediately noticeable as it was for the intensity of $\boldsymbol{G}$ (Fig. 4.2.1B). The average value of $\boldsymbol{T_d}$ changed from 0.5 °C to 0.7 °C before and after re-application compared to $\boldsymbol{G_d}$, which changed from -9.3 W m$^{-2}$ to 45.1 W m$^{-2}$ during the same period.

As shown in fig. 4.2.4A, $\boldsymbol{T_a}$ recorded in N78 was slightly higher than in N78S, while ambient $\boldsymbol{T_a}$ was similar to that in N78S. On the days displayed, maximum value for $\boldsymbol{T_a}$ were 32.7 °C, 34.3 °C and 30.9 °C for ambient, N78 and N78S, respectively, while $\boldsymbol{T_d}$ was 3.6 °C. After the re-application of the shading paint, there was a slight drop (0.9 °C) in $\boldsymbol{T_a}$ recorded in N78S (Fig. 4.2.4B). Higher $\boldsymbol{T_d}$ (up to 1.5 °C) was recorded before midday, but decreased to 0.5 °C in the afternoon. In addition, $\boldsymbol{T_a}$ in N78 was above that observed in N78S and ambient during both day and night times.

The mean values for the microclimate recorded at night during the dry and rainy seasons are displayed in table 4.2.3 and 4.2.4, respectively. There was no significant difference in $\boldsymbol{T_a}$ recorded in both greenhouses at night, except when the plants were mature especially in the rainy season (after 10 WAT).

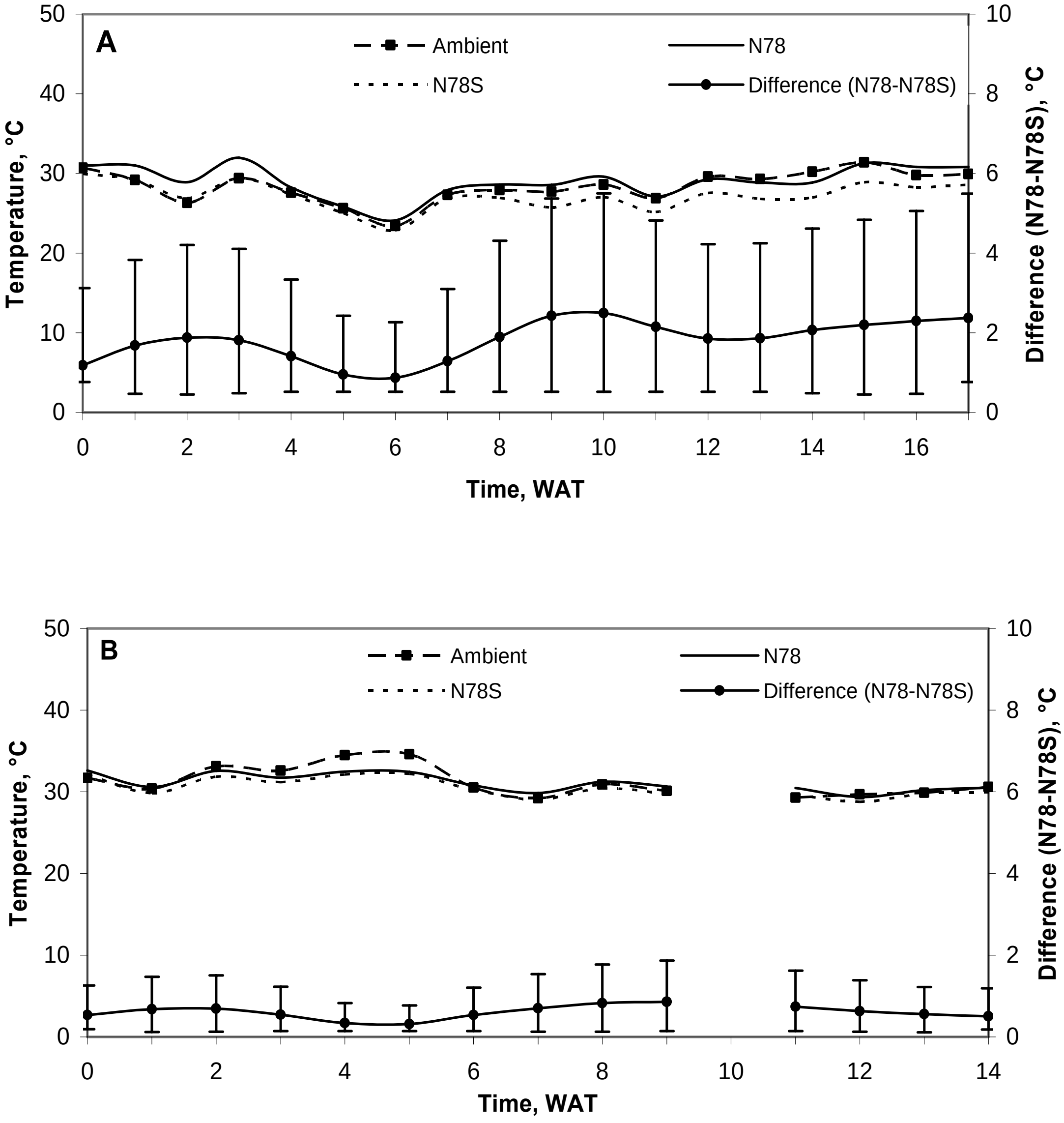
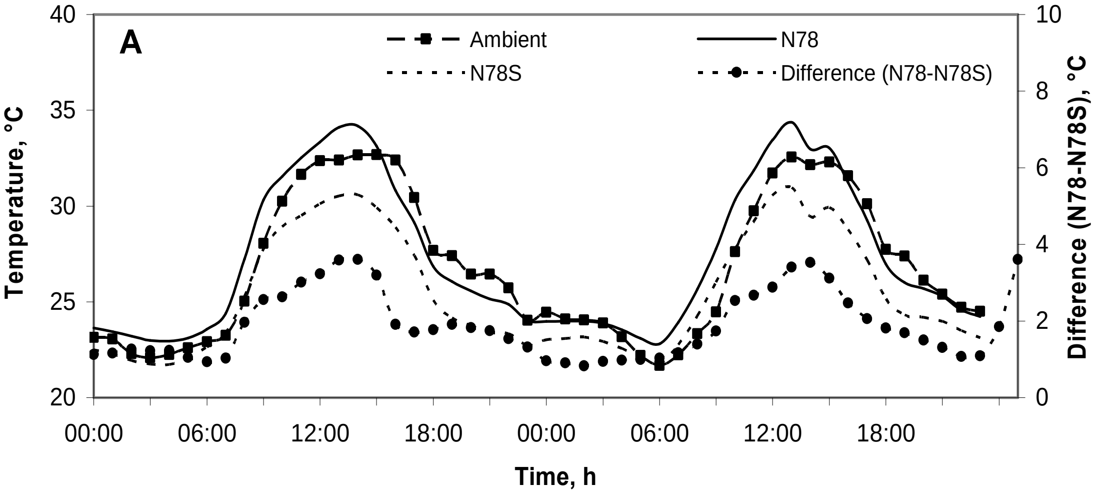


**Figure 4.2.3:** Daytime air temperature profile (weekly average) recorded outside (ambient), in the naturally ventilated greenhouses with (N78S) or without (N78) the shading paint with NIR reflecting pigment and the difference between the two greenhouses (N78-N78S) during the dry season 2005/2006 (A) or rainy 2006 (B) season in central Thailand. Error bars represent the upper and lower confidence intervals of the difference.



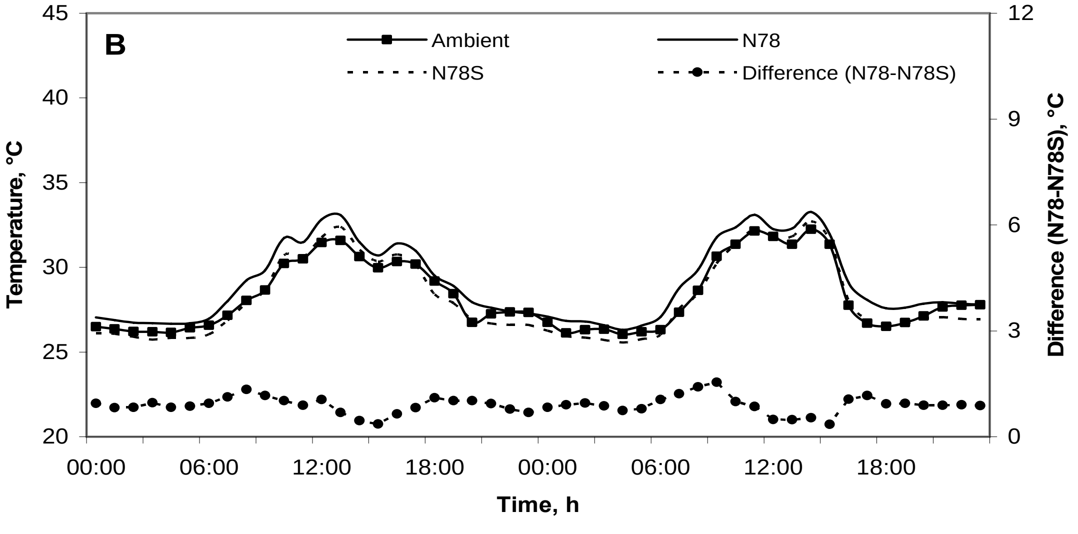


**Figure 4.2.4:** Diurnal temperature profiles outside and in the naturally ventilated greenhouses with (N78S) or without (N78) the shading paint with NIR-reflecting pigment on two representative days (A) on 17-18.01.2006 during the dry season 2005/2006, and (B) on 11-12.07.2006 during the rainy season 2006 in central Thailand.

#### 4.2.1.4 Water content of the air

Except in the first 2 WAT, the water content of the air (***x***) in N78 was significantly higher than in N78S (Fig. 4.2.5A). The ***x*** profile followed a trend similar to that of $T_a$ with the lowest and highest values recorded at similar times. The lowest and highest difference in ***x*** between N78 and N78S were 0.3 g kg$^{-1}$ and 2.6 g kg$^{-1}$at 4 and 9 WAT, respectively. The average ***x*** values for the whole season were 15.5 g kg$^{-1}$, 18.5 g kg$^{-1}$ and 16.9 g kg$^{-1}$ for ambient, N78 and N78S, respectively.

During the rainy season, ***x*** of the air in N78 was significantly higher than in N78S except at 2, 3, 4, 5 and 6 WAT. A significant increase in the difference of ***x*** between N78 and N78S (from -0.3 g kg$^{-1}$ to 0.9 g kg$^{-1}$) was noticed after re-application of the shading paint (Fig. 4.2.5B) while the differences between the ambient air and those recorded in the greenhouses were more visible. Seasonal mean values for ***x*** during the rainy season were 19.9 g kg$^{-1}$, 20.8 g kg$^{-1}$ and 20.4 g kg$^{-1}$ for ambient, N78 and N78S, respectively.

On a representative day, the water content of the air in the greenhouses increased with air temperature from morning to reach a peak at around noon and then started decreasing to reach a minimum in the night (Fig. 4.2.6A). The increase in the morning was much faster than the decrease in the evening. Ambient ***x*** remained below that in the greenhouses and the difference was bigger in the afternoon. After the re-application of the shading paint, ***x*** in N78 was higher than the ambient and N78S (Fig. 4.2.6B). Average diurnal values for ***x*** were 19.3 g kg$^{-1}$, 21.3 g kg$^{-1}$ and 20.4 g kg$^{-1}$ for ambient, N78 and N78S. The difference in ***x*** between the N78 and N78S was larger than that recorded in the days before re-application of the shading paint with an average of 0.9 g kg$^{-1}$.

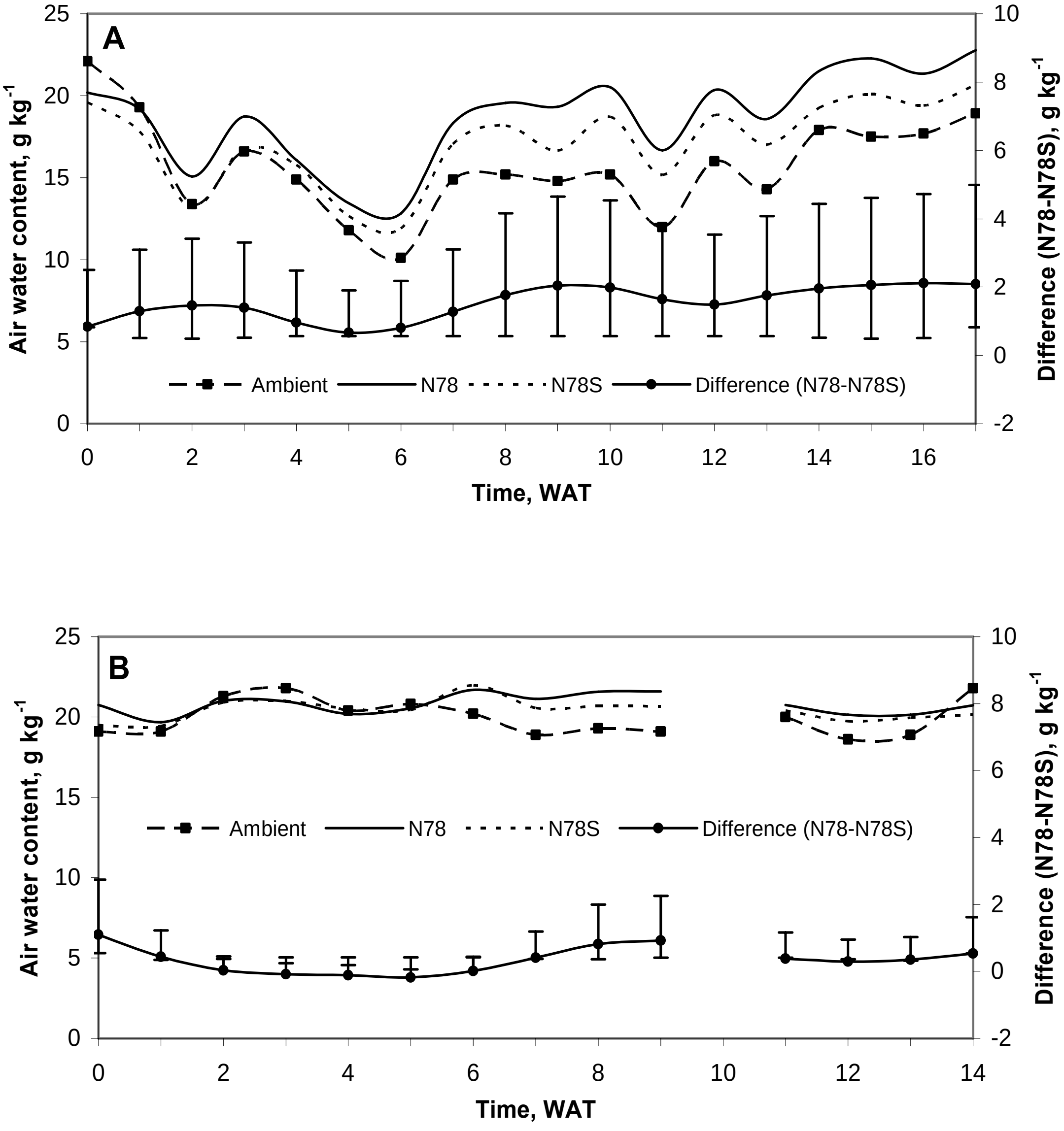


**Figure 4.2.5:** Daytime air water content profile (weekly average) recorded outside (ambient), in the greenhouses with (N78S) or without (N78) the shading paint with NIR reflecting pigment and the difference between the two greenhouses (N78-N78S) during the dry season 2005/2006 (A) or the rainy season 2006 (B) in central Thailand. Error bars represent the upper and lower confidence intervals of the difference.

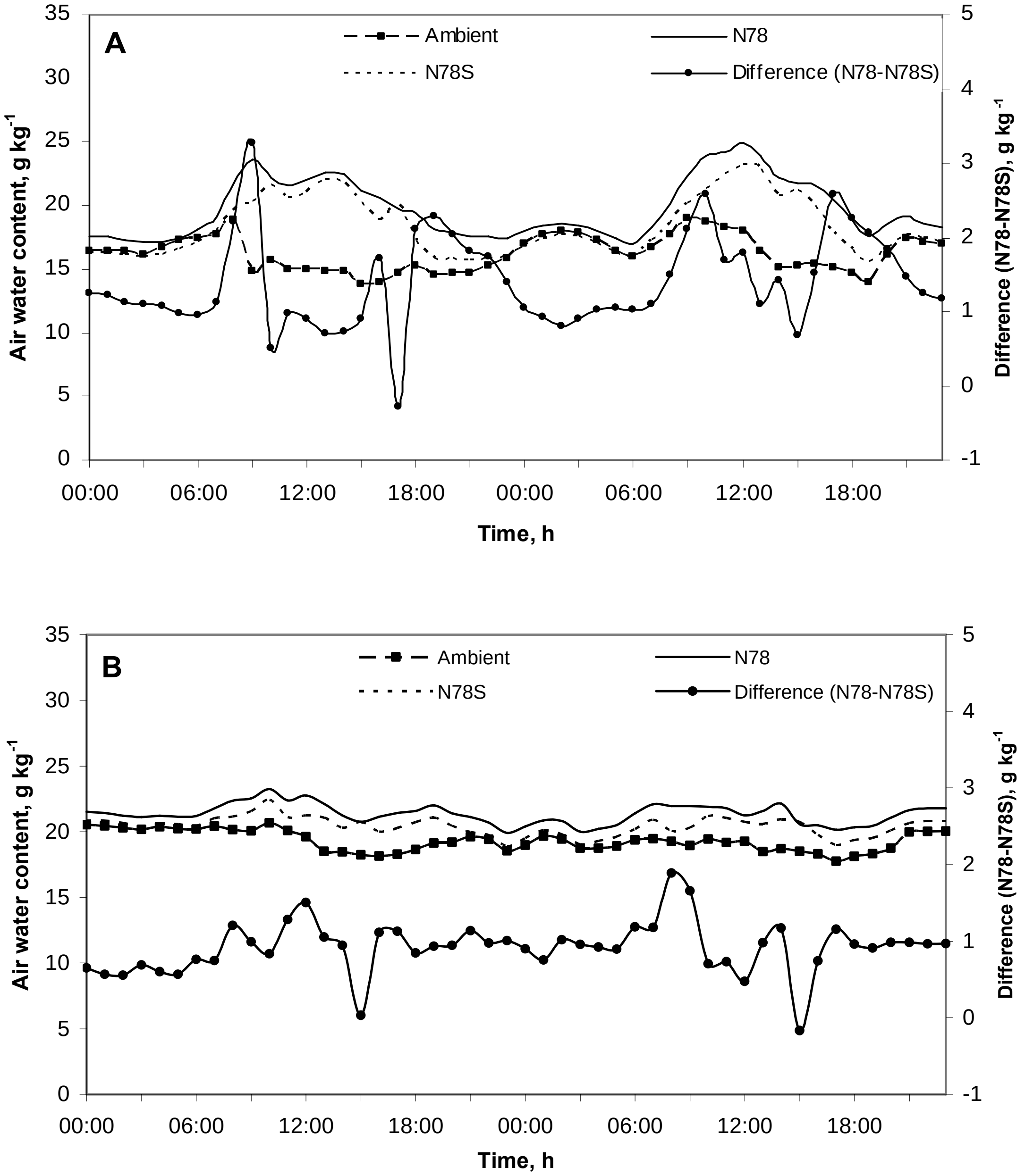


**Figure 4.2.6:** Diurnal profile of the water content of the air outside and in the greenhouse with (N78S) or without (N78) the shading paint with NIR-reflecting pigment on two days (A) on 18-19.01.2006 during the dry season 2005/2006 and (B) on 11-12.07.2006 during the rainy season 2006 in central Thailand.

#### 4.2.1.5 Air vapour pressure deficit

During the dry season, higher vapour pressure deficit, ***VPD*** (air) was recorded in the ambient air followed by N78 while N78S had the lowest. The average values for ***VPD*** (air) were 1.4 kPa, 1.1 kPa and 0.9 kPa for ambient, N78 and N78S, respectively. Although slightly higher ***VPD*** was observed in N78 compared to N78S, the differences were not significant (Fig. 4.2.7A). The difference in ***VPD*** recorded in the greenhouses and the ambient increased continuously between 6 and 13 WAT.

During the rainy season, significant differences were observed between the ambient and N78 in 2, 9, 12 and 13 WAT (Fig. 4.2.7B). ***VPD*** in the greenhouses was higher than the ambient in the first 4 WAT, after which the converse was true. High ***VPD*** was observed at 4 and 5 WAT, with a maximum of 1.9 kPa, 1.7 kPa and 1.8 kPa for ambient, N78 and N78S, respectively, which corresponded to the time when the highest temperature was experienced. The seasonal average VPD was 1.3 kPa, 1.3 kPa and 1.2 kPa for ambient, N78 and N78S, respectively.

Before the re-application of the shading paint, ***VPD*** of the ambient air was higher and increased faster than that in the greenhouses in the morning, while in the evening, the differences were small (Fig. 4.2.8). Higher ***VPD*** (around 3.0 kPa) was recorded before re-application compared to (below 2.0 kPa) after the re-application of the shading paint. On both occasions i.e. both before and after the re-application of the shading paint, ambient ***VPD*** was higher than that in the greenhouses. Moreover, ***VPD*** followed the same profile as $T_a$, increasing from morning to reach a peak around midday, while the lowest values were recorded just before daybreak.

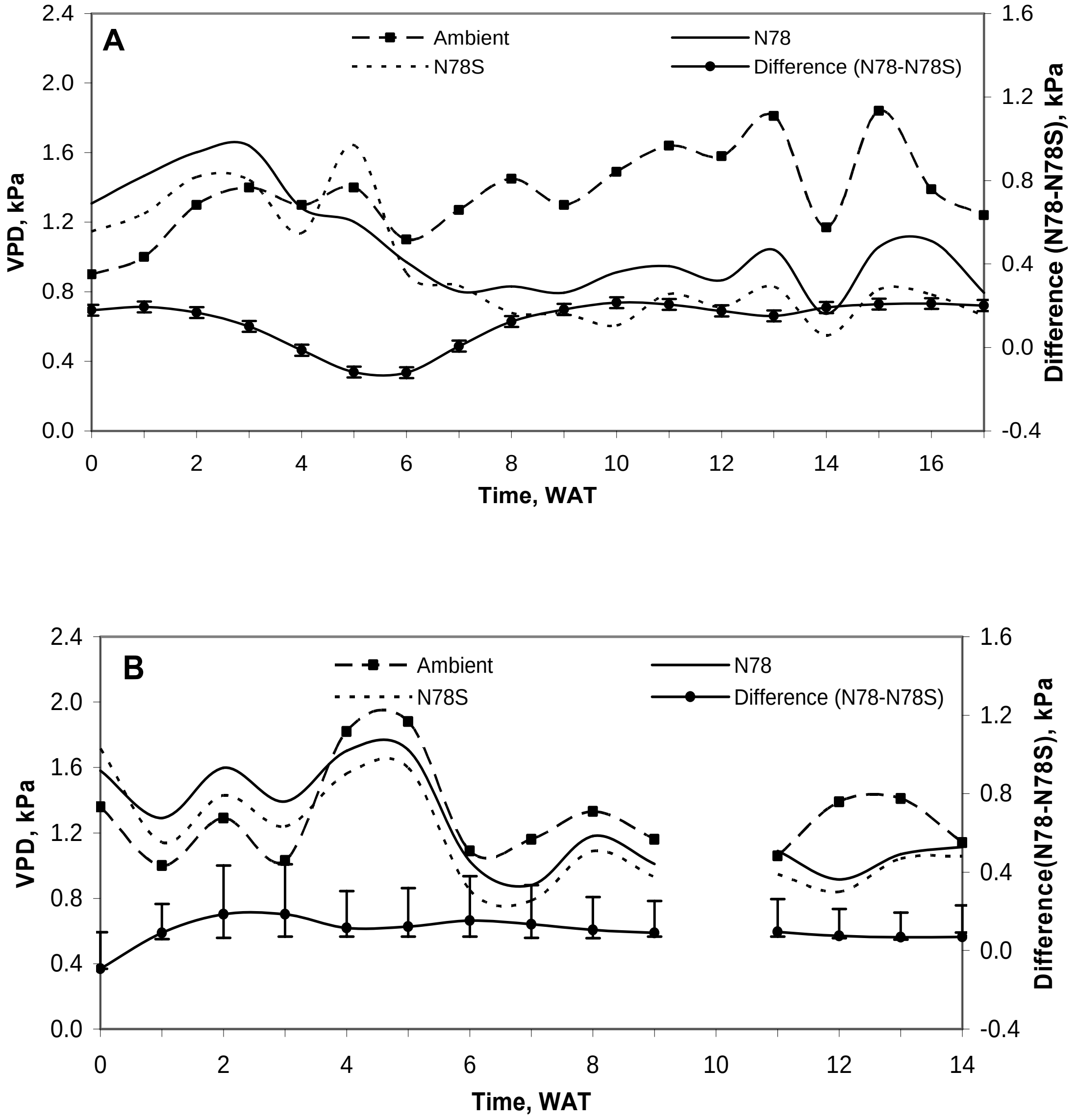
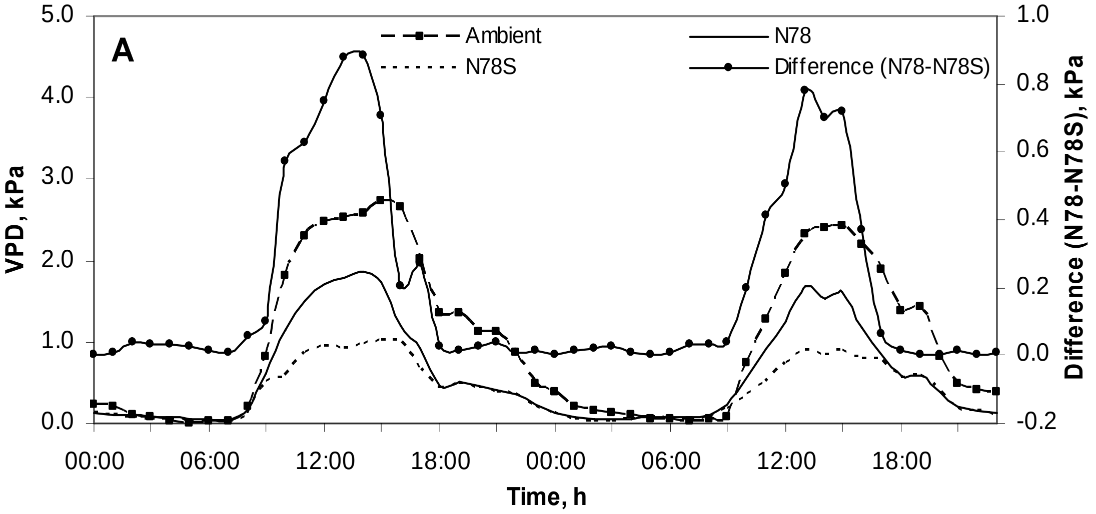


**Figure 4.2.7:** Daytime air vapour pressure profile (weekly mean) recorded outside (ambient), in the greenhouses with (N78S) or without (N78) the shading paint with NIR reflecting pigment and the difference between the two greenhouses (N78-N78S) during the dry season 2005/2006 (A) or rainy season 2006 (B) seasons in central Thailand. Error bars represent the upper and lower confidence intervals of the difference.



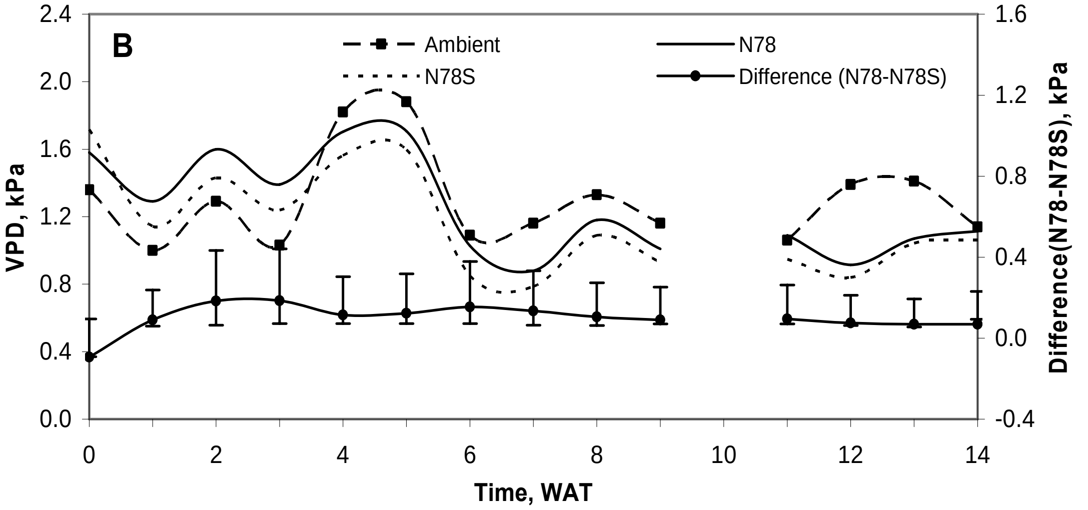


**Figure 4.2.8:** Diurnal vapour pressure deficit (air) profiles outside and in the naturally ventilated greenhouses with (N78S) or without (N78) the shading paint with NIR-reflecting pigment on two days (A) on 14-15.06.2006 before and (B) on 11-12.07.2006 after the re-application of the shading paint during the rainy season 2006 in central Thailand.

#### 4.2.1.6 Substrate temperature

A very close relationship was observed between $T_a$ and substrate temperature ($T_s$). During both seasons the two followed a similar profile although $T_s$ lagged behind $T_a$. Except in the first 2 WAT during the dry season, shading significantly reduced $T_s$ by an average of 3 °C (Fig. 4.2.9). Maximum $T_s$ was recorded in the 3rd WAT as 33.6 °C and 29.2 °C for N78 and N78S, respectively. The largest difference in $T_s$ between N78 and N78S was 4.7 °C recorded at 4 WAT. Average seasonal values for $T_s$ during the dry season were 30.0 °C and 26.9 °C for N78 and N78S, respectively. The average $T_s$ was 1.0 °C higher than $T_a$ in N78, while in N78S the two were similar. During the rainy season the difference in $T_s$ recorded in the two greenhouses was much lower than during the dry season. The $T_s$ was slightly higher in N78 (average 0.6 °C) than in N78S except at 8 and 9 WAT. However, a significant difference was observed at 1, 3, 4, 6, 7 12 and 13 WAT. The average values of $T_s$ during the rainy season was 32.2 °C and 31.5 °C, which were 2.0 °C higher than those recorded during the dry season.

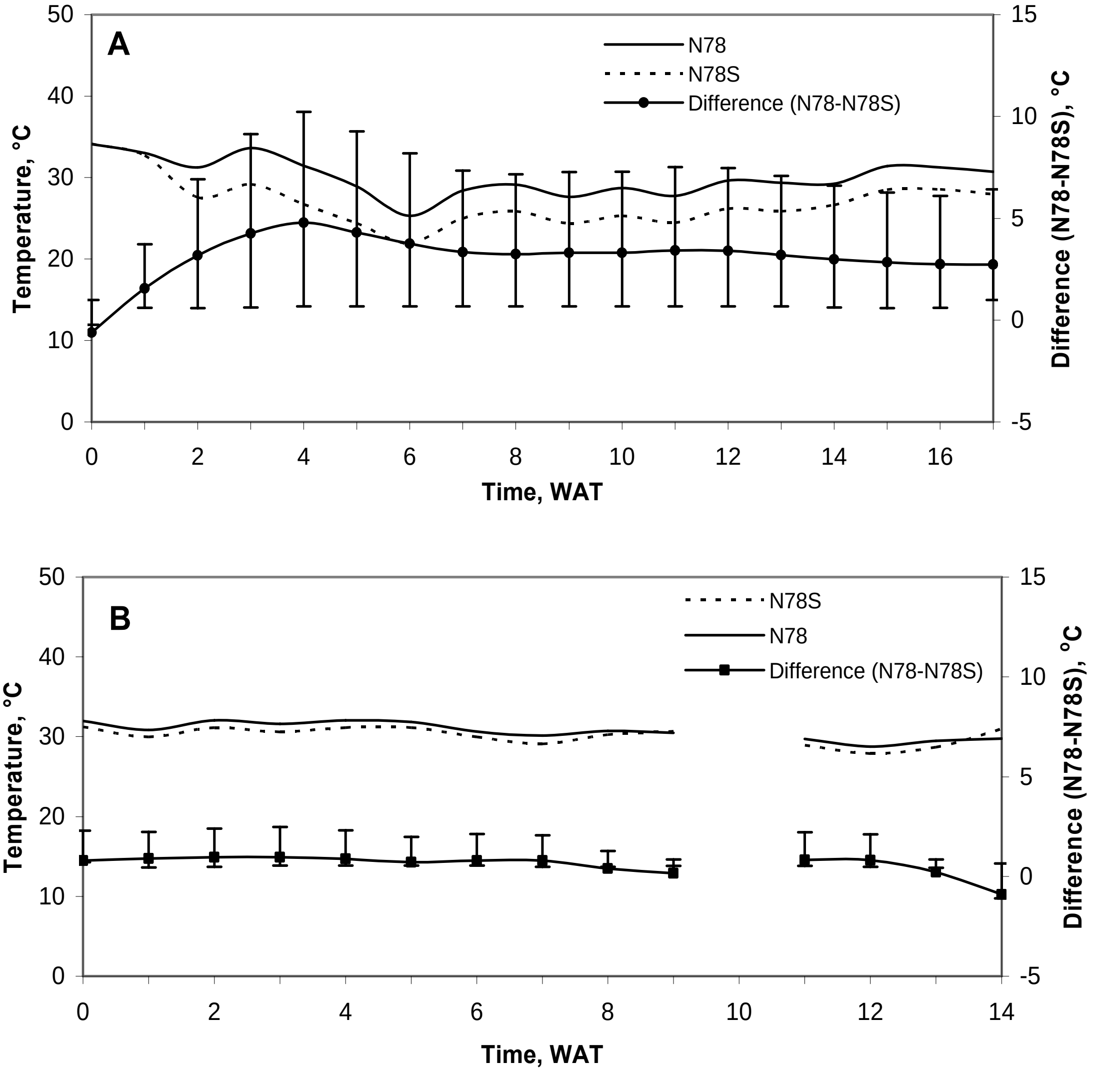


**Figure 4.2.9:** Daytime substrate temperature profile (weekly mean) recorded in the greenhouses with (N78S) or without (N78) the shading paint with NIR reflecting pigment and the difference between the two greenhouses (N78-N78S) during the dry 2005/2006 (A) or the rainy season 2006 (B) seasons in central Thailand. Error bars represent the upper and lower confidence intervals of the difference.

**Table 4.2.3:** Mean weekly night-time air temperature, °C, air water content, g kg$^{-1}$, air vapour pressure deficit, kPa, and mean 24 h ambient wind speed, m s$^{-1}$, recorded outside and in the naturally ventilated greenhouses with N78S or without N78 the shading paint with NIR-reflecting pigment during the dry season 2005/2006 in central Thailand.

| WAT | Temperature, °C | | | Water content, g kg$^{-1}$ | | | VPD, kPa | | | Wind speed, m s$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | Ambient | N78 | N78S | Ambient | N78 | N78S | Ambient | N78 | N78S | Ambient |
| 0 | 25.9ab | 26.1a | 25.4b | 19.3a | 19.8a | 19.4a | 0.38a | 0.25b | 0.18b | 0.13 |
| 1 | 26.4a | 26.5a | 25.8b | 18.9a | 19.5a | 18.6a | 0.44a | 0.39b | 0.38b | 0.19 |
| 2 | 23.7a | 23.7a | 22.9a | 14.0a | 14.5a | 13.2a | 0.74a | 0.64a | 0.70a | 0.30 |
| 3 | 25.9a | 25.7a | 24.8b | 17.5a | 18.4a | 17.2b | 0.57a | 0.39b | 0.41b | 0.10 |
| 4 | 24.9a | 24.6a | 23.8a | 15.8a | 16.8a | 16.2a | 0.66a | 0.44b | 0.39b | 0.24 |
| 5 | 24.3a | 23.9a | 23.0a | 12.9a | 13.5a | 12.7a | 0.97a | 0.87a | 0.78a | 0.84 |
| 6 | 20.4ab | 21.1a | 20.1b | 9.5a | 11.1a | 10.1a | 0.88a | 0.74a | 0.74a | 0.66 |
| 7 | 23.2ab | 23.5a | 22.6b | 15.6a | 16.9a | 16.0a | 0.36a | 0.22b | 0.20b | 0.29 |
| 8 | 25.5a | 24.8a | 23.9b | 16.7a | 18.0a | 17.1ab | 0.53a | 0.28b | 0.26b | 0.19 |
| 9 | 21.6a | 22.1a | 20.8a | 13.9b | 15.4a | 14.2b | 0.36a | 0.20b | 0.19b | 0.13 |
| 10 | 23.4a | 23.5a | 22.1a | 15.1a | 16.8a | 15.3a | 0.47a | 0.23b | 0.23b | 0.33 |
| 11 | 22.4a | 22.5a | 21.2a | 13.1a | 14.7a | 13.5a | 0.63a | 0.41b | 0.36b | 0.31 |
| 12 | 24.5a | 24.5a | 23.3a | 16.3a | 17.7a | 16.5a | 0.49a | 0.27b | 0.23b | 0.30 |
| 13 | 24.6a | 24.3a | 22.9b | 14.9a | 16.2a | 15.4a | 0.72a | 0.44b | 0.36b | 0.36 |
| 14 | 25.5a | 25.7a | 24.4a | 16.9a | 18.6a | 17.3a | 0.61a | 0.36b | 0.31b | 0.32 |
| 15 | 26.5a | 26.3a | 25.1a | 18.0b | 19.9a | 18.5b | 0.65a | 0.28b | 0.26b | 0.37 |
| 16 | 26.9a | 26.7a | 25.4b | 18.1b | 19.9a | 18.8b | 0.65a | 0.34b | 0.29b | 0.50 |

**Table 4.2.4:** Mean weekly night-time air temperature, °C, air water content, g kg$^{-1}$, air vapour pressure deficit, kPa, and mean 24 h ambient wind speed, m s$^{-1}$, recorded outside and in the naturally ventilated greenhouses with N78S or without N78 the shading paint with NIR-reflecting pigment during the rainy season 2006 in central Thailand.

| **WAT** | **Temperature, °C** | | | **Water content, g kg$^{-1}$** | | | **VPD, kPa** | | | **Wind speed, m s$^{-1}$** |
|---|---|---|---|---|---|---|---|---|---|---|
| | Ambient | N78 | N78S | Ambient | N78 | N78S | Ambient | N78 | N78S | Ambient |
| 0 | 26.7b | 27.8a | 27.2b | 19.2b | 20.8a | 19.7b | 0.47a | 0.48a | 0.50a | 0.29 |
| 1 | 25.9a | 27.1a | 26.4a | 18.6b | 19.7a | 19.4ab | 0.37a | 0.48a | 0.39a | 0.39 |
| 2 | 27.3a | 28.2a | 27.5a | 20.1a | 20.7a | 20.5a | 0.46a | 0.56a | 0.45a | 0.46 |
| 3 | 26.6a | 27.5a | 26.8a | 20.2a | 20.4a | 20.1a | 0.29a | 0.46a | 0.35a | 0.56 |
| 4 | 26.9a | 27.5a | 26.9a | 19.2b | 20.3a | 19.9a | 0.52a | 0.48a | 0.42a | 0.83 |
| 5 | 28.6a | 28.5a | 27.9a | 19.7a | 20.4a | 19.7a | 0.82a | 0.73a | 0.66a | 0.70 |
| 6 | 26.4b | 27.2a | 26.6b | 19.8b | 20.4a | 19.7a | 0.30a | 0.29a | 0.23a | 0.29 |
| 7 | 26.6ab | 27.2a | 26.5a | 18.5b | 20.3a | 19.6ab | 0.57a | 0.40b | 0.36b | 0.51 |
| 8 | 27.2ab | 27.5a | 26.7b | 19.3c | 20.9a | 20.0b | 0.55a | 0.38b | 0.34b | 0.46 |
| 9 | 27.5a | 27.8a | 27.0a | 18.7a | 20.4a | 19.7a | 0.71a | 0.53a | 0.46a | 0.71 |
| 10 | - | - | - | - | - | - | - | - | - | 0.67 |
| 11 | 27.2a | 26.8a | 26.1a | 18.9a | 19.8a | 19.1a | 0.61a | 0.39a | 0.36a | 0.64 |
| 12 | 27.2a | 26.6b | 26.0c | 17.9a | 18.6a | 17.9a | 0.77a | 0.52a | 0.52b | 1.13 |
| 13 | 27.3a | 26.8a | 26.3b | 18.7a | 19.4a | 18.8a | 0.68a | 0.45b | 0.44b | 1.13 |
| 14 | 28.0a | 27.2b | 26.7c | 20.3a | 19.9a | 19.3a | 0.54a | 0.44a | 0.45a | 0.72 |

## 4.2.2 Plant Growth and Production

### 4.2.2.1 Plant height

On average, plants were shorter in N78S than in N78, the difference being significant at 4, 9 and 12 WAT. Maximum height attained by the plants at 18 WAT during the dry season was 404.6 cm and 394.1 in N78 and N78S, respectively (Fig. 4.2.10A). During the rainy season, significant differences in plant height were observed at 1 and 3 WAT (Fig. 4.2.10B). The plants reached a maximum height of 314.1 cm and 305.8 cm in N78 and N78S, respectively at 16 WAT. Plants in both greenhouses were shorter during the rainy season compared to the dry season. For instance, at 16 WAT during the rainy season, plants were 56.2 cm and 53.5 cm shorter in N78 and N78S, respectively than in the dry season. During both seasons, height gain was oscillating with a week of fast increase followed by a week of relatively slow growth. At 8 WAT, plant height gain was 7.2 cm week$^{-1}$ and 5.1 cm week$^{-1}$ slower in N78 and N78S, respectively during the rainy compared to the dry season. Moreover, during the dry season, a sharp increase in height was observed at 13 WAT with 30.9 cm week$^{-1}$ and 32.9 cm week$^{-1}$ in N78 and N78S, respectively. The mean height gain per week for the dry season was 23.1 cm week$^{-1}$ and 22.4 cm week$^{-1}$ in N78 and N78S, respectively. However, during the rainy season height gain was 19.8 cm week$^{-1}$ and 19.6 cm week$^{-1}$ in N78 and N78S, respectively.

### 4.2.2.2 Flowering

There was no significant difference in the number of trusses in the two greenhouses during the dry and the rainy seasons (4.2.11). Moreover, flowering was very strongly correlated ($r^2$ = 0.98) to plant height with the first trusses occurring when plants attained a height of 80 cm. Flowering occurred one week earlier during the rainy season. Until 7 WAT, the number of trusses in both greenhouses was the same during the two seasons. At 13 WAT, plants had 3 more trusses during the rainy season compared to the dry season in both greenhouses.

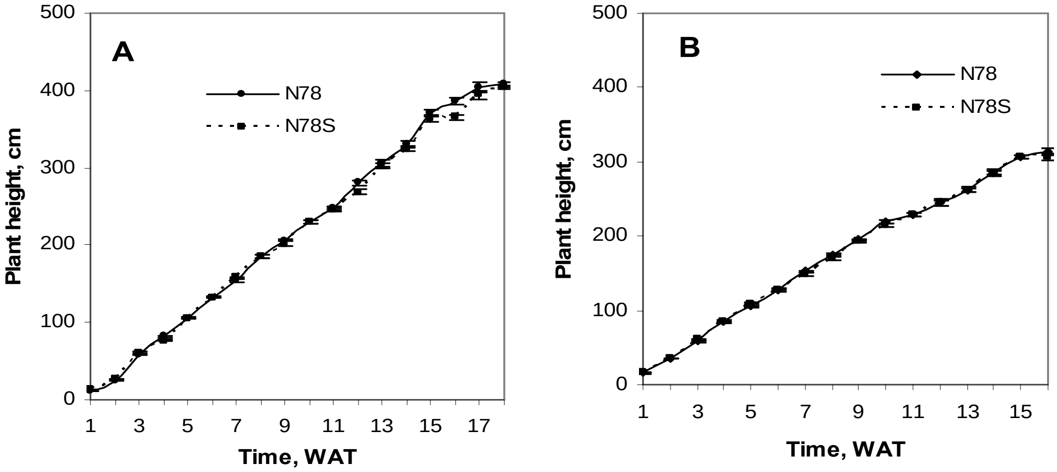


**Figure 4.2.10:** Height (mean ± SE) of tomato plants grown in the naturally ventilated greenhouses with (N78S) or without (N78) the shading paint with NIR-reflecting pigment during (A): the dry season 2005/2006 and (B): the rainy season 2006 in central Thailand.

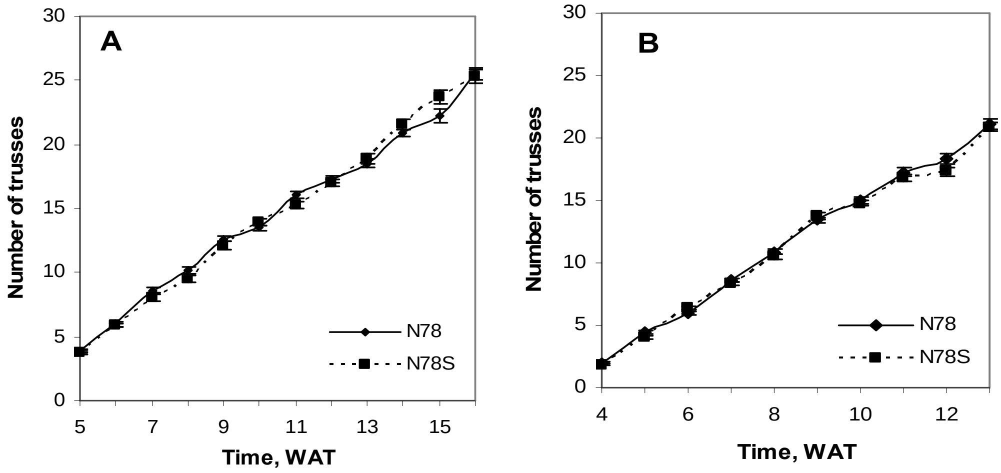


**Figure 4.2.11:** Average number of trusses (mean ± SE) observed on tomato plants grown in the naturally ventilated greenhouse with (N78S) or without (N78) the shading paint with NIR-reflecting pigment on the roof cover during (A): the dry season 2005/2006 and (B): the rainy season 2006 in central Thailand.

#### 4.2.2.3 Dry Matter Partitioning

***Leaves***

The dry matter content of the leaves (***$DM_L$***) increased continuously with time from 1 WAT to 10 WAT, during both seasons. Through the dry season, the tomato plants in N78 partitioned more resources to leaves compared to those in N78S (Fig. 4.2.12A). At 6 WAT, ***$DM_L$*** partitioning in N78 was 9.3 % higher than in N78S. However, in the rainy season, the proportion of resources allocated to leaves by plants in N78S was on average 2.7 % lower than in N78 with a significant difference at 12 WAT. Generally plants in both greenhouses allocated an average of 50 % of the total ***DM*** to leaves during both seasons. At the time of first harvest (10 WAT), ***$DM_L$*** accounted for 40 % of the total ***DM*** content of the plants during both seasons. Moreover, leaves were heavier during the rainy than during the dry season. Average weight of ***$DM_L$*** per plant was 84.5 g and 67.8 g in N78 while in N78S corresponding values were 79.3 g and 69.3 g during the rainy and dry season, respectively. Generally, plants allocated almost half of their ***DM*** to the leaves while stems and fruits received almost a quarter of the total ***DM*** each (Fig. 4.2.12D).

***Stems***

During both seasons, ***DM*** of stems (***$DM_S$***) increased continuously with plant growth (Fig. 4.2.12B). In both greenhouses, ***$DM_S$*** constituted 26 % of total ***DM*** of the plant during the dry season. However, between 8 and 12 WAT during the rainy season, ***$DM_S$*** in N78S was significantly higher (14 %) than in N78. The plants allocated 3 % more resources to the stem during the rainy than dry season. Just before pruning at 10 WAT, the ***$DM_S$*** per plant was 59.1 g and 47.9 g, and 77.0 g and 62.2 g during the dry and rainy season in N78 and N78S, respectively. However, looking at the whole plant, resource allocation was 23.3 % and 20.1 % in N78 and N78S during the dry season and 29.6 % and 31.4 % in N78 and N78S during the rainy season, respectively.

***Fruits***

The ***DM*** of fruits (***DM$_F$***) increased progressively with time to reach a maximum at 12 WAT, which coincided with the peak harvest (Fig. 4.2.12C). Shading did not negatively influence ***DM$_F$*** during the dry season although the converse was true for the rainy season. During the dry season, average ***DM$_F$*** weight was 59.0 g plant$^{-1}$ (24.5 %) in both greenhouses. Maximum ***DM$_F$*** per plant during the dry season was 156.5 g and 162.7 g in N78 and N78S, respectively. This translated to an allocation of 53.2 % and 49.8 % of total ***DM*** of the plants to fruits. However, during the rainy season, ***DM$_F$*** was significantly lower in N78S compared to N78 at 12 WAT. Shading reduced the allocation of assimilates to fruits by an average 4.2 % (20.2 g plant$^{-1}$) and delayed the time to the attainment of maximum ***DM$_F$*** by 2 weeks. At 12 WAT, ***DM$_F$*** in N78 was double that in N78S, while at 14 and 16 WAT it was similar in both greenhouses.

Although fruits were usually heavier than most other plant organs of a tomato plant, they had over 90 % water content (Table 4.2.5). The water content on leaves and stems was higher in N78S compared to N78 while the converse was true for fruits. The weekly average ***DM*** of the plants in both greenhouses increased with time during the two seasons (Fig. 4.2.12D). Maximum ***DM*** in N78 and N78S during the dry season was 294.3 g plant$^{-1}$ and 326.8 g plant$^{-1}$, respectively at 12 WAT. Throughout the rainy season, maximum ***DM*** in N78 and N78S was 383.9 g plant$^{-1}$ and 370.2 g plant$^{-1}$, respectively at 16 WAT. The effect of shading in the two seasons was contradicting in that ***DM*** increased by 1.4 g during the dry season and decreased by 30.6 g during the rainy season.

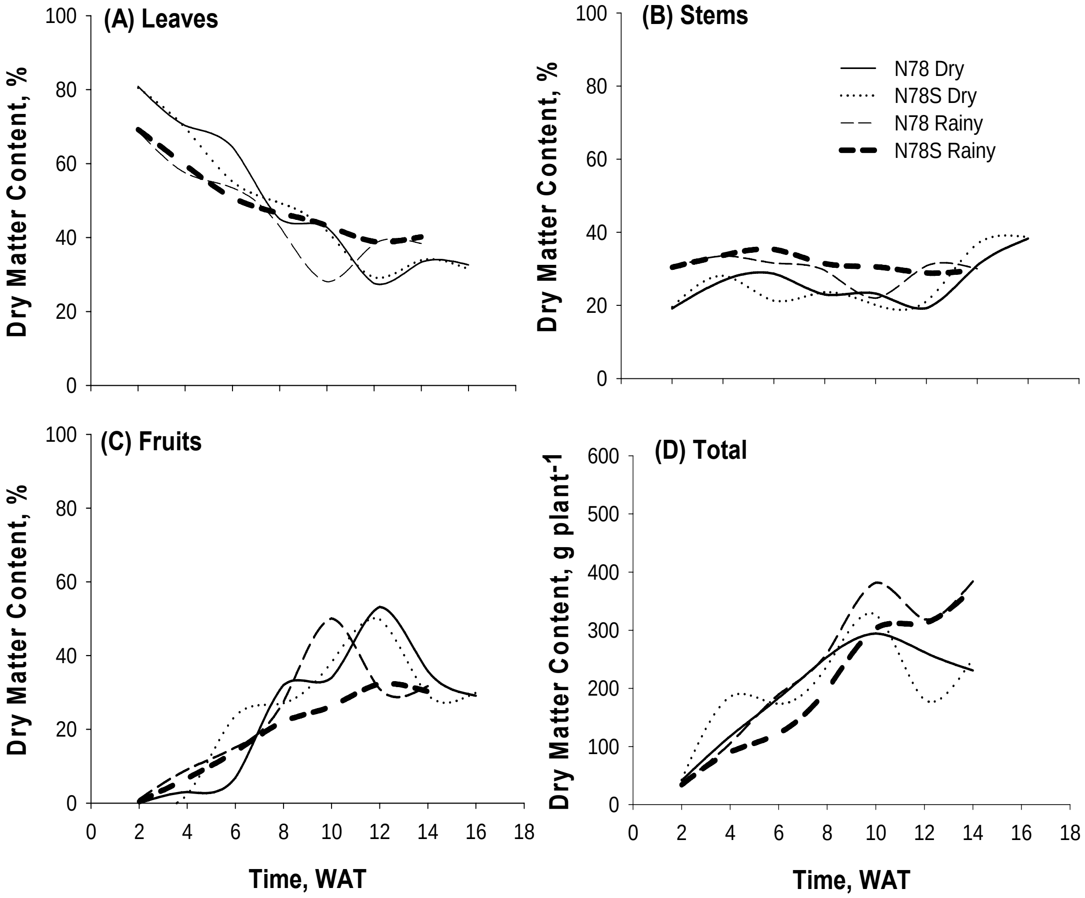


**Figure 4.2.12:** Dry matter content of leaves (A), stems (B), fruits (C) and the total dry matter of the plant (D) expressed in g plant$^{-1}$, for tomato plants grown in naturally ventilated greenhouses with (N78S) or without (N78) the shading paint containing NIR-reflecting pigments during the dry season 2005/2006 and the rainy season 2006 in central Thailand.

**Table 4.2.5:** Mean dry matter content, g plant$^{-1}$, of leaves, stems and trusses (fruits) of tomato plants grown in the naturally ventilated greenhouses with (N78S) or without (N78) the shading paint with NIR-reflecting pigment on the roof cover during the dry season 2005/2006 and the rainy season 2006 in central Thailand.

| Time, | **Leaves** | | | | **Stems** | | | | **Fruits** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WAT | Dry season | | Rainy season | | Dry season | | Rainy season | | Dry season | | Rainy season | |
| | N78 | N78S | N78 | N78S | N78 | N78S | N78 | N78S | N78 | N78S | N78 | N78S |
| 2 | 2.72 | 2.61 | 2.38 | 1.68 | 0.64 | 0.63 | 0.62 | 0.41 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4 | 29.13 | 29.53 | 24.17 | 23.51 | 11.08 | 11.90 | 10.60 | 10.34 | 1.23 | 0.97 | 0.36 | 0.13 |
| 6 | 75.83 | 102.23 | 60.42 | 53.72 | 33.72 | 39.44 | 35.24 | 30.38 | 8.06 | 43.90 | 9.52 | 6.10 |
| 8 | 82.74 | 85.56 | 101.24 | 62.20 | 42.18 | 40.93 | 59.75* | 43.20* | 58.81 | 46.96 | 28.67 | 17.14 |
| 10 | 108.67 | 99.48 | 111.94 | 92.24 | 59.11 | 47.89 | 76.98 | 62.24 | 86.37 | 91.10 | 71.51 | 43.91 |
| 12 | 81.18 | 95.29 | 106.83* | 131.02* | 56.61 | 68.82 | 83.89* | 92.61* | 156.48 | 162.73 | 190.92* | 79.73* |
| 14 | 87.38 | 61.03 | 121.84 | 121.04 | 81.08 | 66.34 | 98.12 | 89.87 | 93.81 | 52.76 | 98.40 | 100.64 |
| 16 | 75.26 | 78.53 | 147.18 | 148.57 | 88.33 | 96.50 | 115.08 | 109.69 | 67.23 | 74.60 | 121.62 | 111.95 |

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.

### 4.2.2.4 Leaf area

The most striking observation is that for both greenhouses, the leaf area index (***LAI***) during the rainy season was half of what was recorded during the dry season from 6 WAT to 12 WAT (Table 4.2.6). Shading increased ***LAI*** at some stage in both seasons although this was not significant. However, the increase was higher during the rainy season subsequent to the re-application of the shading paint. At 10 WAT, ***LAI*** was 2.23 $m^2 m^{-2}$ and 2.42 $m^2 m^{-2}$ in the dry season and 1.00 $m^2 m^{-2}$ and 1.32 $m^2 m^{-2}$ in the rainy season in N78 and N78S, respectively.

**Table 4.2.6**: Leaf area indices (leaf area per unit ground area), [$m^2 m^{-2}$] of tomato plants grown in naturally ventilated greenhouses with (N78S) or without (N78) shading paint containing NIR-reflecting pigments during the dry season 2005/2006 and the rainy season 2006 in central Thailand.

| **Time** | **Dry season** | | **Rainy season** | |
|---|---|---|---|---|
| WAT | N78 | N78S | N78 | N78S |
| 2 | 0.08a | 0.08a | 0.12a | 0.09a |
| 4 | 0.47a | 0.52a | 0.48a | 0.41a |
| 6 | 1.58a | 1.52a | 0.72a | 0.72a |
| 8 | 1.71a | 1.77a | 0.99a | 0.86a |
| 10 | 2.23a | 2.42a | 1.00a | 1.32a |
| 12 | 2.01a | 2.46a | 0.90a | 1.24a |

*Means in the same row under the same season followed by the same letter do not differ significantly at *P* = 0.05 T-test

### 4.2.2.5 Yield

Although there was no significant difference in marketable yield per plant from the two greenhouses, a slightly higher yield was obtained in N78 compared to N78S although the difference was not significant during both seasons (Fig. 4.2.13). For both greenhouses, harvested yield had an oscillating pattern with each big harvest followed by a slightly smaller one. During the dry season, yield increased weekly from 9 WAT to reach a peak at 13 WAT when 1.096 kg plant$^{-1}$ and 0.934 kg plant$^{-1}$ were harvested from N78 and N78S, respectively. A total of 5.92 kg plant$^{-1}$ (88.8 t ha$^{-1}$) and 5.79 kg plant$^{-1}$ (86.9 t ha$^{-1}$) of marketable yield was harvested from N78 and N78S, respectively. The overall production of the tomato plants i.e. total yield from 12 harvests, during the dry season was 6.653 kg plant$^{-1}$ (99.79 t ha$^{-1}$) and 6.457 kg plant$^{-1}$ (96.86 t ha$^{-1}$), from N78 and N78S, respectively.

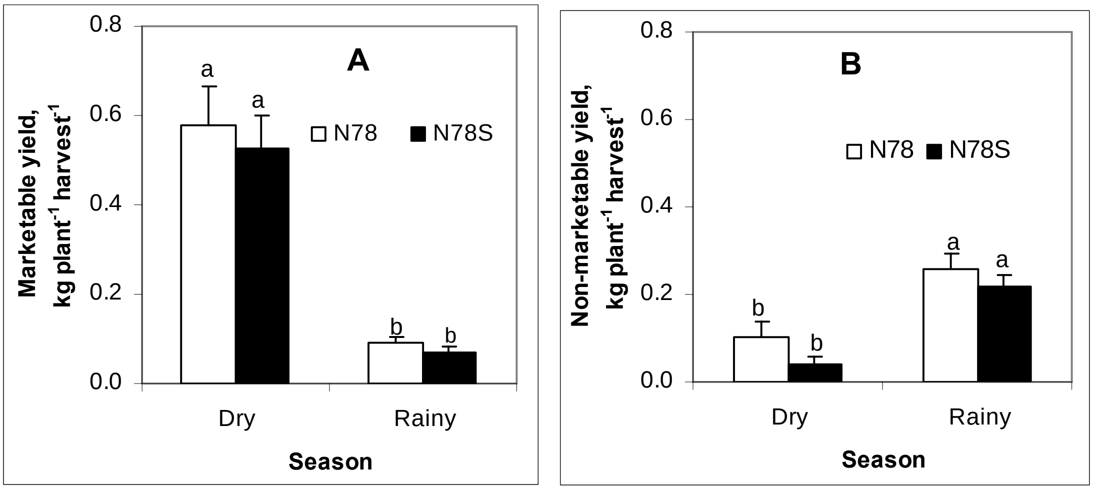


**Figure 4.2.13:** Yield (mean per plant and harvest ± SE) of tomato plants grown in naturally ventilated greenhouses with (N78S) or without (N78) the shading paint with NIR-reflecting pigment on the roof during the (A): the dry season 2005/2006 and (B): the rainy season 2006 in central Thailand. (Significant differences between greenhouse types are indicated by different letters within the columns, student's t-test, α<0.05).

Compared to the dry season, marketable yields during the rainy season were very low. One third (by weight) of the total harvested fruits was marketable with 0.641 kg plant$^{-1}$ and 0.493 kg plant$^{-1}$ in N78 and N78S, respectively. Total non-marketable yield harvested during the same period was 0.738 kg plant$^{-1}$ and 0.665 kg plant$^{-1}$ in N78 and N78S, respectively with most of the fruits being undersize and mostly parthenocarpic. Total yield from 7 harvests, was 2.431 kg plant$^{-1}$ (36.465 t ha$^{-1}$) and 2.003 kg plant$^{-1}$ (30.045 t ha$^{-1}$) in N78 and N78S, respectively.

Generally, shading reduced the quantity of non-marketable yield by 9.9 % and 15.6 %, during the dry and rainy season, respectively (Table 4.2.7). Shading reduced the quantity of blossom-end rot (BER) affected fruits by 42.3 % and 29.9 % all through the dry and rainy seasons, respectively, though the differences were not statistically significant. Undersized fruits were reduced by 7.6 % and 17.9 % during the dry and rainy season, respectively. However, the number of cracked fruits increased by 16.3% and 43.1 % during the same time frame.

**Table 4.2.7**: Non-marketable yield fractions i.e. blossom end rot (BER), undersize and cracked fruits of tomato plants grown in naturally ventilated greenhouses with (N78S) or without (N78) the shading paint with NIR-reflecting pigment during the dry season 2005/2006 and the rainy season 2006 in central Thailand.

| **Defect,** | **Dry Season** | | **Rainy Season** | |
|---|---|---|---|---|
| Number harvest$^{-1}$ | N78 | N78S | N78 | N78S |
| BER | 14.3a | 28.1a | 19.3a | 13.7a |
| Cracking | 16.9a | 19.6a | 42.1a | 60.3a |
| Undersize | 434.8a | 401.6a | 2996.1a | 2460.4a |

Means under the same main column (season) followed by the same letter do not differ significantly according to Student's t-test at $\alpha = 0.05$

#### 4.2.2.6 Fruit quality

During the dry season average brix value of tomato fruits from in N78 was lower (4.67 °) than in N78S (4.89 °), although the difference was not significant. However, for the duration of the rainy season, brix values were significantly higher in N78S (4.90 °) compared to N78 (4.51 °). Shading increased the pH value of the tomato fruits in the dry season, while the reverse was observed in the rainy season. Mean pH values were 4.25 and 4.49 on N78 and N78S during the dry season, and 4.48 and 4.37 during the rainy season in N78 and N78S, respectively.

#### 4.2.2.7 Plant water consumption

Plant water consumption increased with time in both greenhouses during both seasons, (Fig. 4.2.14). Mean water consumption between 4 and 17 WAT was equivalent to 1.45 L plant$^{-1}$ day$^{-1}$ and 1.36 L plant$^{-1}$ day$^{-1}$ for N78 and N78S, respectively during the dry season. An average of 1.57 L plant$^{-1}$ day$^{-1}$ and 1.43 L plant$^{-1}$ day$^{-1}$ was recorded for N78 and N78S, respectively, through the rainy season. During the dry season, water consumption was significantly higher in N78 than N78S at 6 WAT. It is surprising that plant water consumption was significantly higher in N78 than N78S at 13, 14 and 16 WAT during the rainy season.

Cumulative water consumption was 22.01 L plant$^{-1}$ and 20.07 L plant$^{-1}$ in N78 and N78S, respectively, during the rainy season. Shading 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 (calculated as the total yield per plant divided by the total water used between 4 and 17 WAT) was 0.328 kg L$^{-1}$ and 0.339 kg L$^{-1}$ during the dry season, and 0.110 kg L$^{-1}$ and 0.100 kg L$^{-1}$ during the rainy season in N78 and N78S, respectively. Furthermore, shading reduced electric power consumption of the “emergency” ventilation fans by 15.1 % during the rainy season. Fans in N78 and N78S used 451 kWh and 383 KWh, respectively.

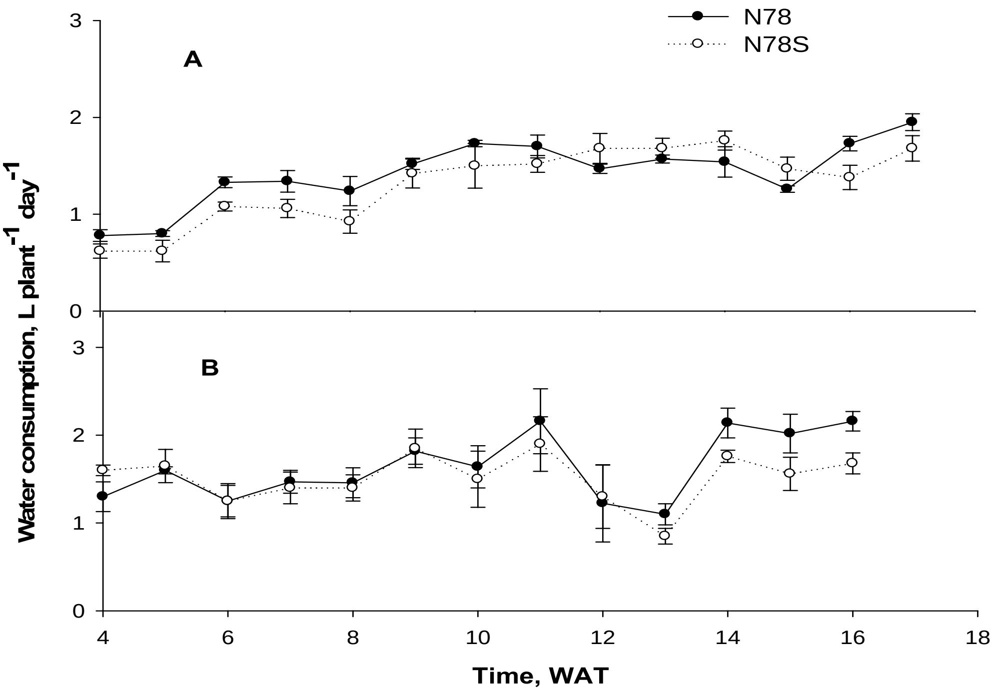


**Figure 4.2.14:** Mean daily water consumption (L plant$^{-1}$ day$^{-1}$) of tomato plants grown in naturally ventilated greenhouses with (N78S) or without (N78) the shading paint with NIR-reflecting pigment during the (A): the dry season 2005/2006 and (B): the rainy season 2006 in central Thailand.

## 4.3 Effect of Natural Ventilation and Evaporative Cooling on Microclimate and Plant Growth

### 4.3.1 Microclimate

#### 4.3.1.1 Global radiation

The intensity of ***G*** inside FAP was significantly higher than in N50 (Fig. 4.3.1A). During the dry season, the maximum value of $\boldsymbol{G_d}$ reached was 36.5 W $m^{-2}$ corresponding to 472.2 W $m^{-2}$, 286.6 W $m^{-2}$ and 250.0 W $m^{-2}$ recorded in the ambient, inside FAP and N50, respectively. The mean transmission for global radiation by the greenhouse cover during the dry season was 60.7 % and 54.3 % in FAP and N50, respectively. The lowest intensity of global radiation was recorded at 6 WAT with mean daytime value of 71.8 W $m^{-2}$, 49.5 W $m^{-2}$ and 33.4 W $m^{-2}$ for ambient in FAP and N50, respectively.

The rainy season started with low ***G***, but this increased to reach a peak at 5 WAT (Fig 4.3.1B). Average values for ***G*** were 426.5 W $m^{-2}$, 258.5 W $m^{-2}$ and 232.5 W $m^{-2}$ for ambient, FAP and N50, respectively. This translated to a transmission of 60.8 % and 54.6 % for FAP and N50, respectively, which was comparable to the values recorded during the dry season. Mean and maximum $\boldsymbol{G_d}$ was 25.9 W $m^{-2}$ and 50.0 W $m^{-2}$. On a representative day during the rainy season (04.07.2006), the maximum value for $\boldsymbol{G_d}$ was 121.1 W $m^{-2}$, corresponding to an ambient ***G*** of 868.3 W $m^{-2}$ recorded at 13:10 h (Fig. 4.3.2).

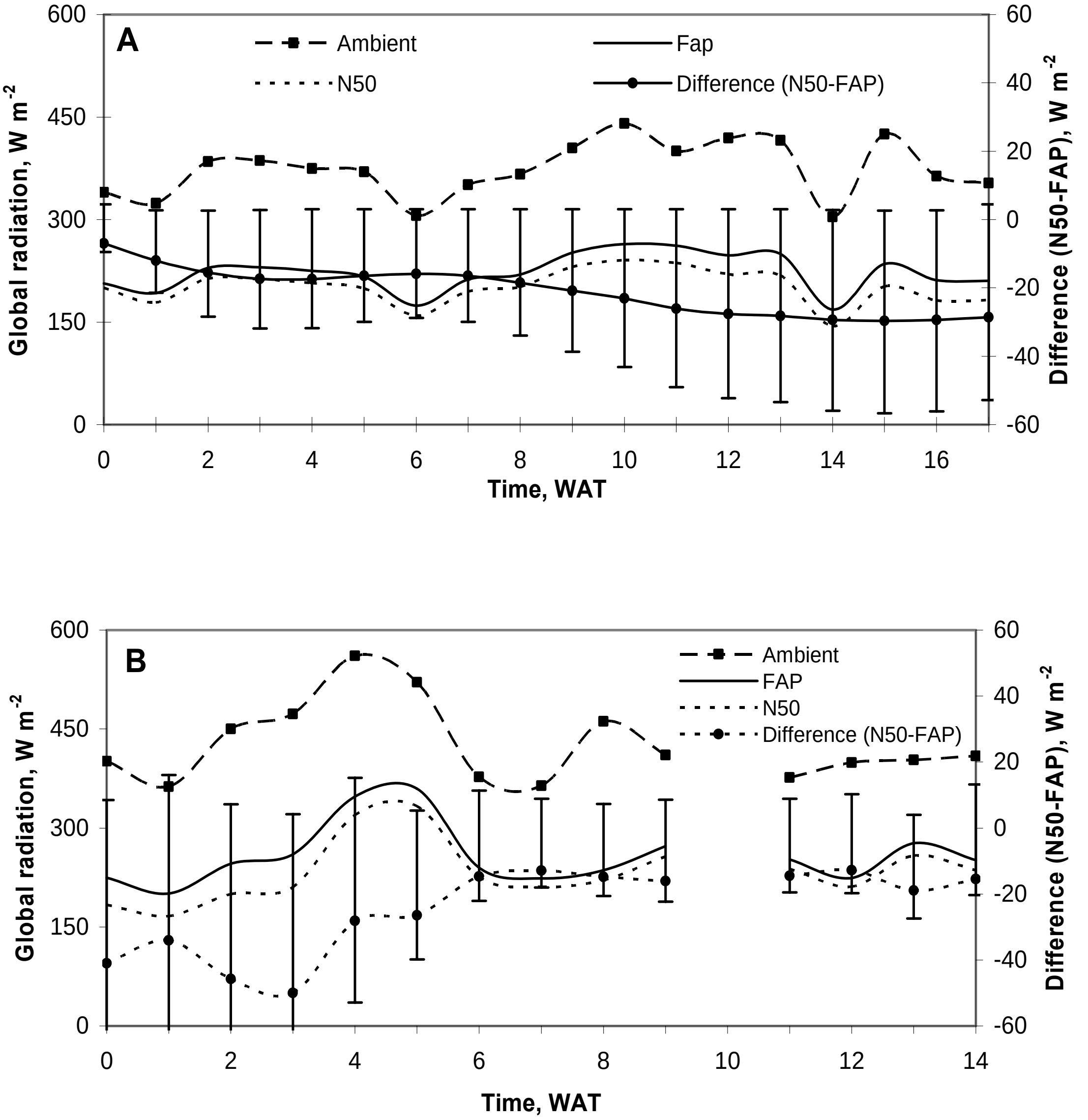


**Figure 4.3.1:** Daytime intensity of global radiation (weekly average) recorded outside (ambient) and in the naturally ventilated (N50) or evaporative cooled (FAP) and the difference between the two greenhouses (N50-FAP) during the dry season 2005/2006 (A) or the rainy season 2005/2006 (B) season in central Thailand.

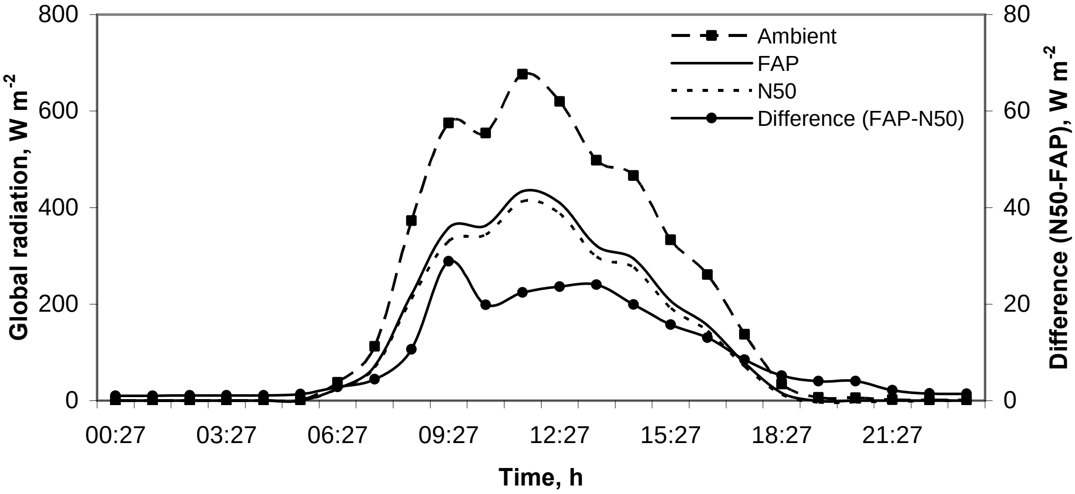


**Figure 4.3.2:** Profile of the intensity of global radiation recorded inside and outside the evaporative cooled (FAP) or the naturally ventilated (N50) greenhouses on a typical day (04.07.2006) during the rainy season 2006 in central Thailand.

### 4.3.1.2 Photosynthetic active radiation

Transmission of PAR on the 1st and 2nd sampling days during the dry season was 48.1 % and 52.6 % in FAP and 47.4 % and 50.0 % for N50, respectively (Table 4.3.1). PAR transmission was slightly higher during the rainy season being 64.0 % and 65.0 % for N50 and 64.1 % and 59.5 % for FAP on the 3rd and 4th sampling dates, respectively. Interception of PAR on a representative day during the dry season (14.12.2005) was 69.9 % and 85.7 % in FAP and N50, respectively.

**Table 4.3.1:** Intensity of photosynthetic active radiation, PAR (µmol $m^{-2}$ $s^{-1}$) recorded outside and inside the evaporative cooled (FAP) and naturally ventilated (N50) greenhouses on selected days during the dry season 2005/2006 and the rainy season 2006 in central Thailand.

| Date | Ambient | FAP | N50 |
|---|---|---|---|
| 14.12.2005 | 1184.0a | 569.2b | 561.4b |
| 31.12.2005 | 1220.8a | 642.0b | 610.4b |
| 07.06.2006 | 1475.5a | 946.30b | 953.2b |
| 29.07.2006 | 1510.6a | 898.7b | 981.8b |

*Means in the same row followed by the same letter are significantly different according to SNK-test at α = 5 %.

### 4.3.1.3 Air temperature

The air temperature (***$T_a$***) inside the greenhouses followed the same trend as the ambient (Fig. 4.3.3A). In both seasons, ***$T_a$*** in FAP was lower than ambient in N50. During the dry season, ***$T_a$*** was similar to that inside N50 during the first days of the experiment. Lowest ***$T_a$*** during the dry season was 23.4 °C, 20.7 °C and 23.1 °C for ambient, FAP and N50, respectively, at 6 WAT. Seasonal mean values for daytime ***$T_a$*** were 27.8 °C, 24.2 °C and 27.4 °C for ambient, FAP and N50, respectively.

During the rainy season, the trend of the mean daytime ***$T_a$*** inside and outside FAP and N50 was as shown in Fig. 4.3.3B. The mean value for the season was 31.4 °C, 27.9 °C, and 30.6 °C for ambient, FAP and N50, respectively. The ***$T_a$*** in N50 was significantly higher than in N50 with an average ***$T_d$*** of 2.7 °C for the season. On a representative sunny day during the rainy season (04.07.2006), ***$T_a$*** increased with increase in ***$G$*** to reach a maximum of 31.3 °C, 29.0 °C, and 32.1 °C for ambient, FAP and N50, respectively. Mean and maximum values for ***$T_d$*** were 2.2 °C and 3.5 °C, respectively. Temperature gradients were observed in FAP with ***$T_a$*** increasing from the pad to the fans (Fig. 4.3.7A). Mean temperature difference from the pad to the fans was 5.1 °C. The mean values for microclimate recorded at night during the dry and rainy seasons are displayed in table 4.3.3 and 4.3.4, respectively.

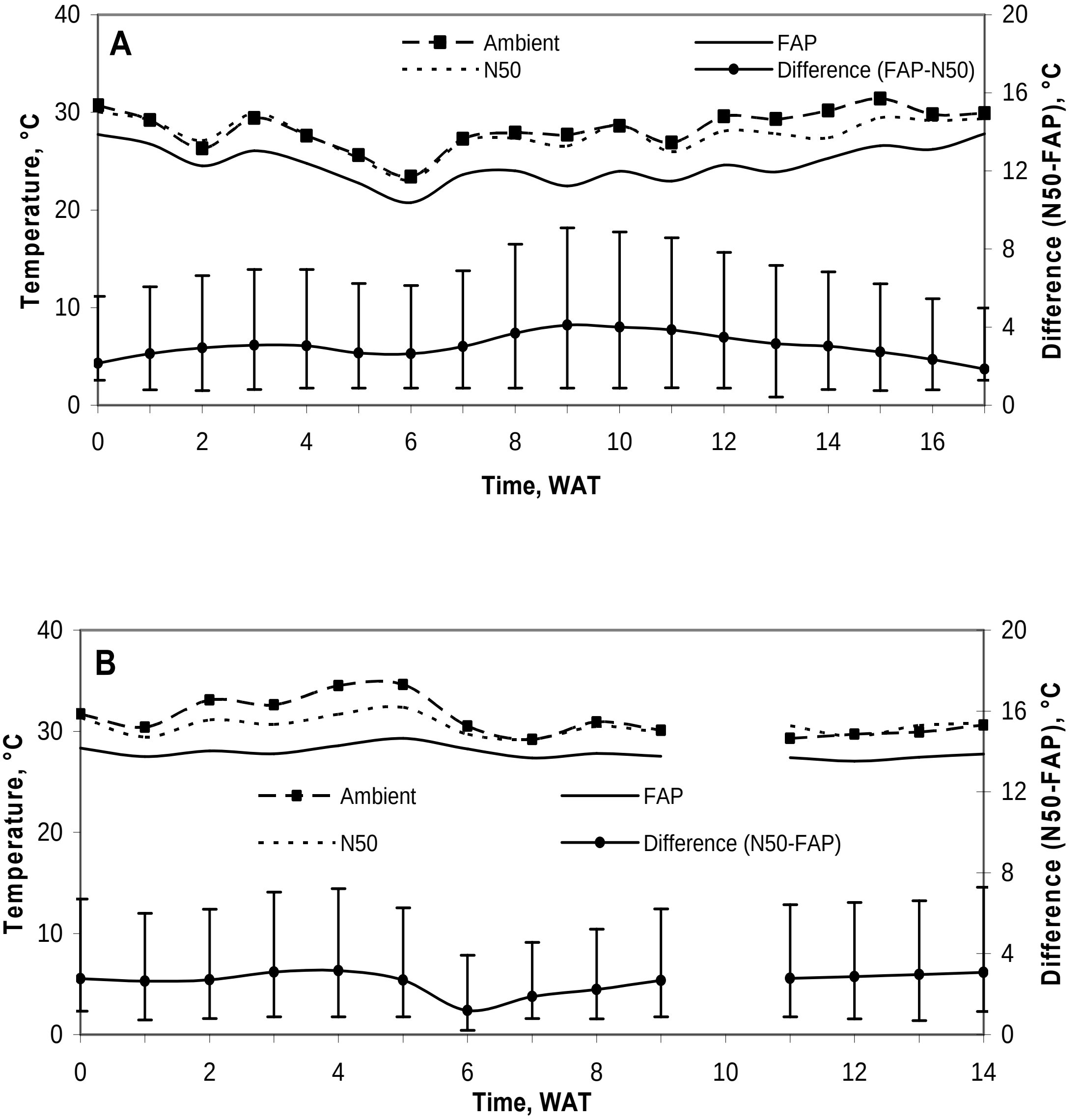


**Figure 4.3.3:** Daytime air temperature profile (weekly average) recorded outside (ambient), in the naturally ventilated (N50) and evaporative cooled (FAP) greenhouses and the difference between the two greenhouses (N50-FAP) during (A): the dry season 2005/2006 (B): the rainy season 2006 (B) season in central Thailand.

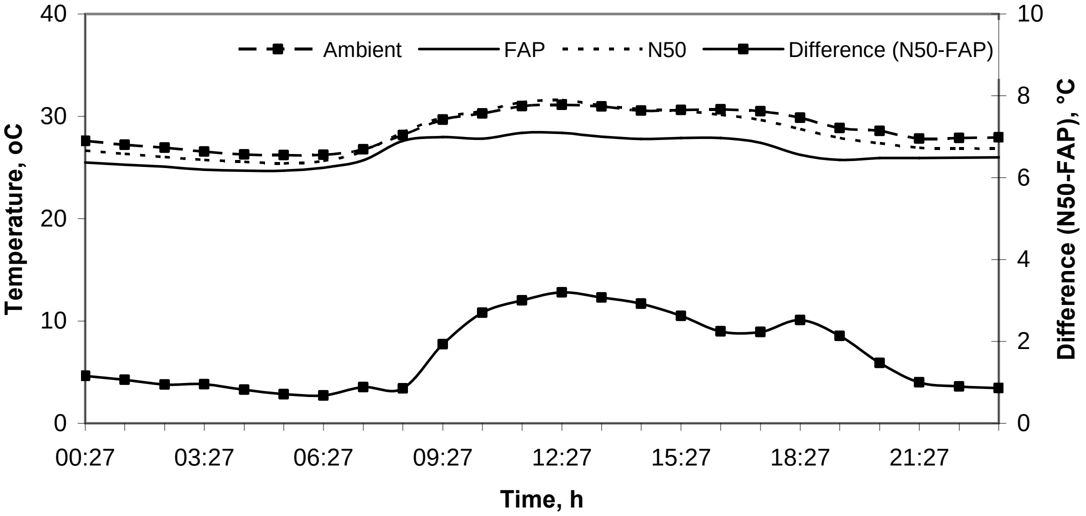


**Figure 4.3.4:** Diurnal temperature profile recorded inside and outside the evaporative cooled (FAP) and the naturally ventilated (N50) greenhouse on a representative sunny day (04.07.2006) during the rainy season 2006 in central Thailand.

### 4.3.1.4 Cooling efficiency of the evaporative cooling system

The efficiency of the evaporative cooling system (η) was determined using the equation:

$$\eta = \frac{T_{db,o} - T_{db,i}}{T_{db,o} - T_{wb,o}}$$

Where η = Efficiency of the fan and pad cooling system, %

$T_{db,\,o}$ = dry bulb temperature of outside air, °C

$T_{db,\,i}$= dry bulb temperature of greenhouse air, °C

$T_{wb,\,o}$= wet bulb temperature of outside air, °C

The mean η attained on a chosen day (22.06.2006) between 09:00 h and 17:00 h was 81.5 % (Fig. 4.3.5). It fluctuated with changes in ambient weather conditions (Table 4.3.2). The lowest η (50.9 %) corresponded to the day when the highest ***rH*** (91.9 %) inside the greenhouse was recorded, while the highest η did not correspond to the lowest ***rH***.

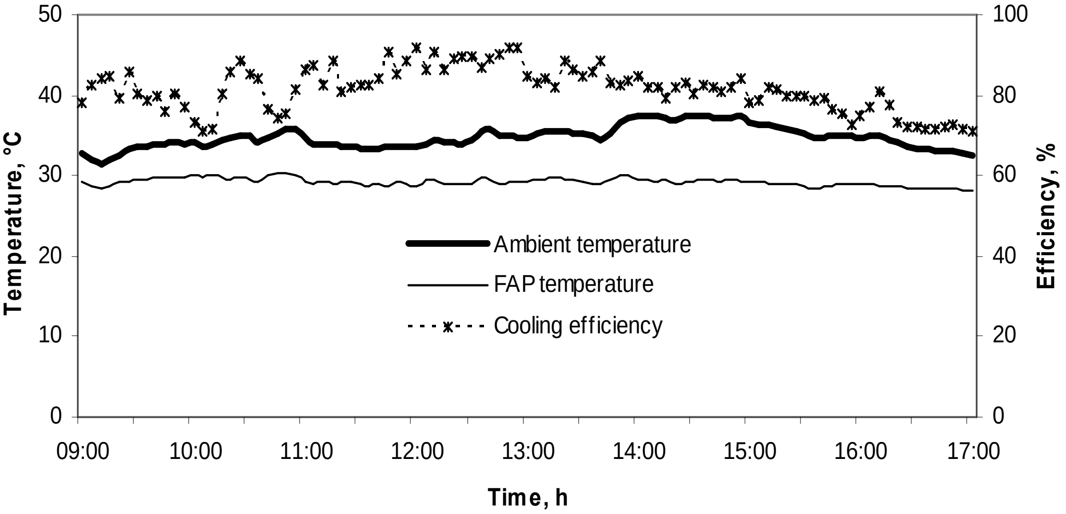


**Figure 4.3.5**: Profile of air temperature outside and in the evaporative cooled greenhouse together with the cooling efficiency of the fan and pad system on a typical sunny day (22.06.2005) during the rainy season 2006 in central Thailand.

**Table 4.3.2:** Mean air temperature and relative humidity recorded in the ambient and in the evaporative cooled greenhouse, and the efficiency of the fan and pad cooling system on some selected days between 09:00 h to 17:00 h during the rainy season 2006 in central Thailand.

| Date | **Mean ambient** Temperature, °C | Relative humidity, % | **Mean greenhouse** Temperature, °C? | Relative humidity, % | **Efficiency,** η, % |
|---|---|---|---|---|---|
| 23.05.2006 | 32.4 | 62.2 | 28.2 | 86.9 | 68.1 |
| 07.06.2005 | 35.1 | 53.7 | 29.7 | 80.9 | 66.5 |
| 14.06.2006 | 38.1 | 53.6 | 29.7 | 81.3 | 75.6 |
| 22.06.2006 | 34.7 | 60.3 | 29.2 | 83.6 | 81.5 |
| 04.07.2006 | 30.2 | 71.8 | 28.0 | 91.9 | 50.9 |
| 30.07.2006 | 32.1 | 64.7 | 28.1 | 80.9 | 70.5 |
| 12.08.2006 | 33.0 | 57.5 | 28.0 | 83.3 | 70.8 |

#### 4.3.1.5 Water content of the air

In the first six weeks of the experiment during the dry season, ***x*** was higher in FAP compared to N50 (Fig. 4.3.6A). However after 7 WAT, the difference between ***x*** in FAP and N50 decreased significantly with ***x*** in the greenhouses remaining above the ambient. Mean values for ***x*** during the dry season were 15.7 g $kg^{-1}$, 18.5 g $kg^{-1}$ and 17.0 g $kg^{-1}$ for ambient, FAP and N50, respectively. The lowest ***x*** values both for ambient, FAP and N50 were 16.0 g $kg^{-1}$, 16.3 g $kg^{-1}$ and 12.4 g $kg^{-1}$, respectively at 6 WAT, corresponding to the week with the lowest $\boldsymbol{T_a}$. The largest difference of ***x*** between N50 and FAP was 3.8 g $kg^{-1}$ at 5 WAT.

During the rainy season, the trend of ***x*** was similar to that of the dry season, with higher ***x*** values in FAP during the first half of the experiment (Fig. 4.3.6B). In some weeks, the ambient ***x*** was above that inside the greenhouses corresponding to the time when there was rainfall. Difference between FAP and N50 was significant most of the time except from 6 to 12 WAT. Mean values for ***x*** recorded during the second half of the experiment was higher than in the first half with 19.7 g $kg^{-1}$, 20.6 g $kg^{-1}$ and 20.8 g $kg^{-1}$ recorded for ambient, FAP and N50, respectively.

As with air temperature, relative humidity of the air was highest near the cooling pad (95.1 %) and lowest near the exit (76.8 %) with a value of 90.5 % being recorded near the centre of the greenhouse (Fig. 4.3.6B).

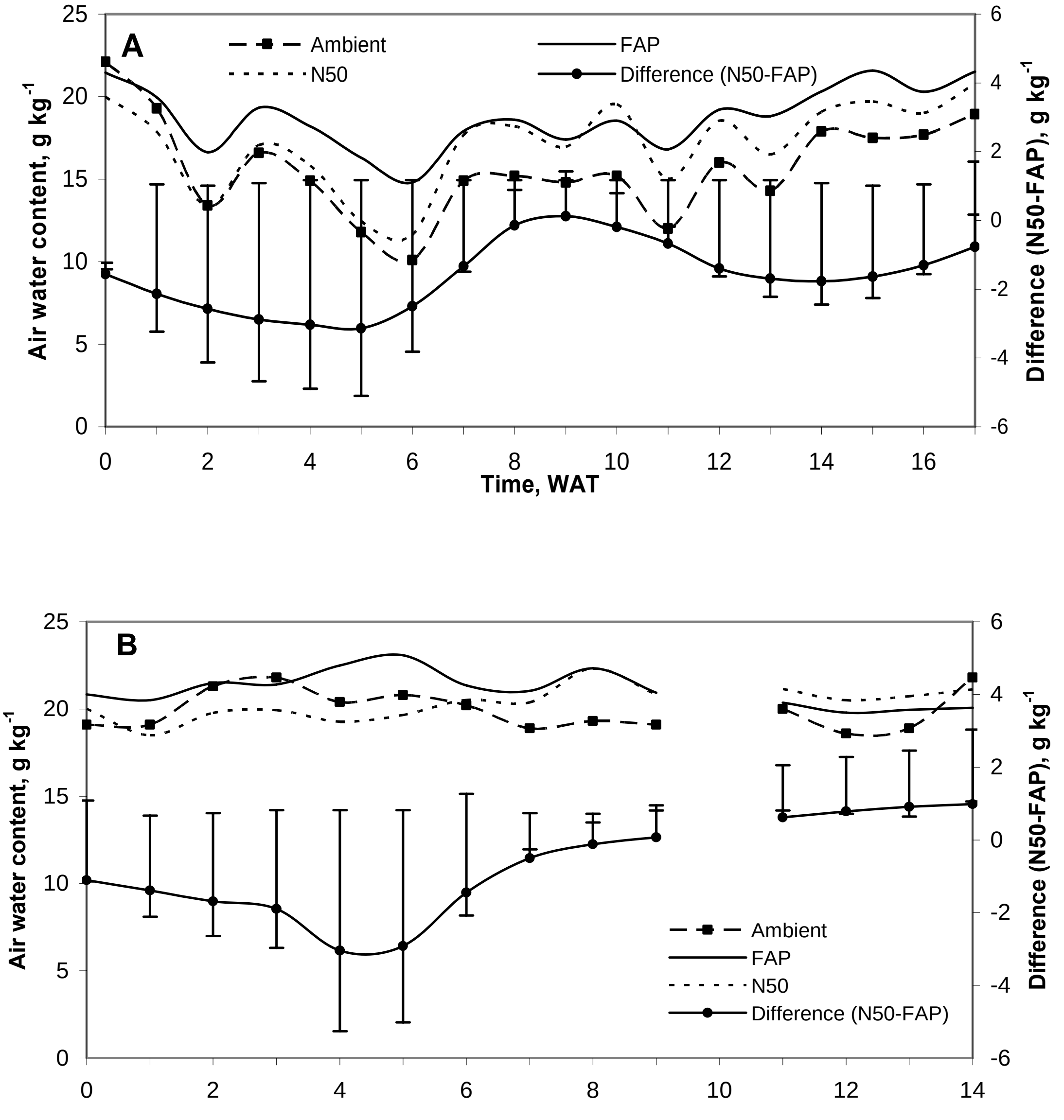


**Figure 4.3.6:** Daytime air water content profile (weekly average) recorded outside (ambient) and in the naturally ventilated (N50) or evaporative cooled (FAP) greenhouses and the difference between the two greenhouses (N50-FAP) during (A): the dry season 2005/2006 (B) the rainy season 2006 in central Thailand.

#### 4.3.1.6 Air vapour pressure deficit

The average ***VPD*** was significantly higher in N50 and ambient compared to FAP (Fig. 4.3.8). In FAP, ***VPD*** was below 0.5 kPa most of the time during the experiment in the dry season. At the beginning of the experiment, ***VPD*** in N50 was similar to the ambient especially during the first 6 WAT, after which the ambient ***VPD*** increased. Average ***VPD*** value for the season was 1.4 kPa, 0.2 kPa, and 1.0 kPa for ambient, FAP and N50, respectively. Maximum value for ***VPD*** during the dry season was 1.9 kPa, 0.5 kPa and 1.7 kPa for ambient, FAP and N50, respectively. The difference in ***VPD*** between FAP and N50 was observed in two peaks at 3 to 5 WAT and 11 to 15 WAT, respectively, which corresponded to the peaks of ***G*** and $T_a$.

During the rainy season, ***VPD*** was below 2 kPa most of the time. The mean value for ***VPD*** in the rainy season was 1.3 kPa, 0.4 kPa and 1.2 kPa, for ambient, FAP and N50, respectively.

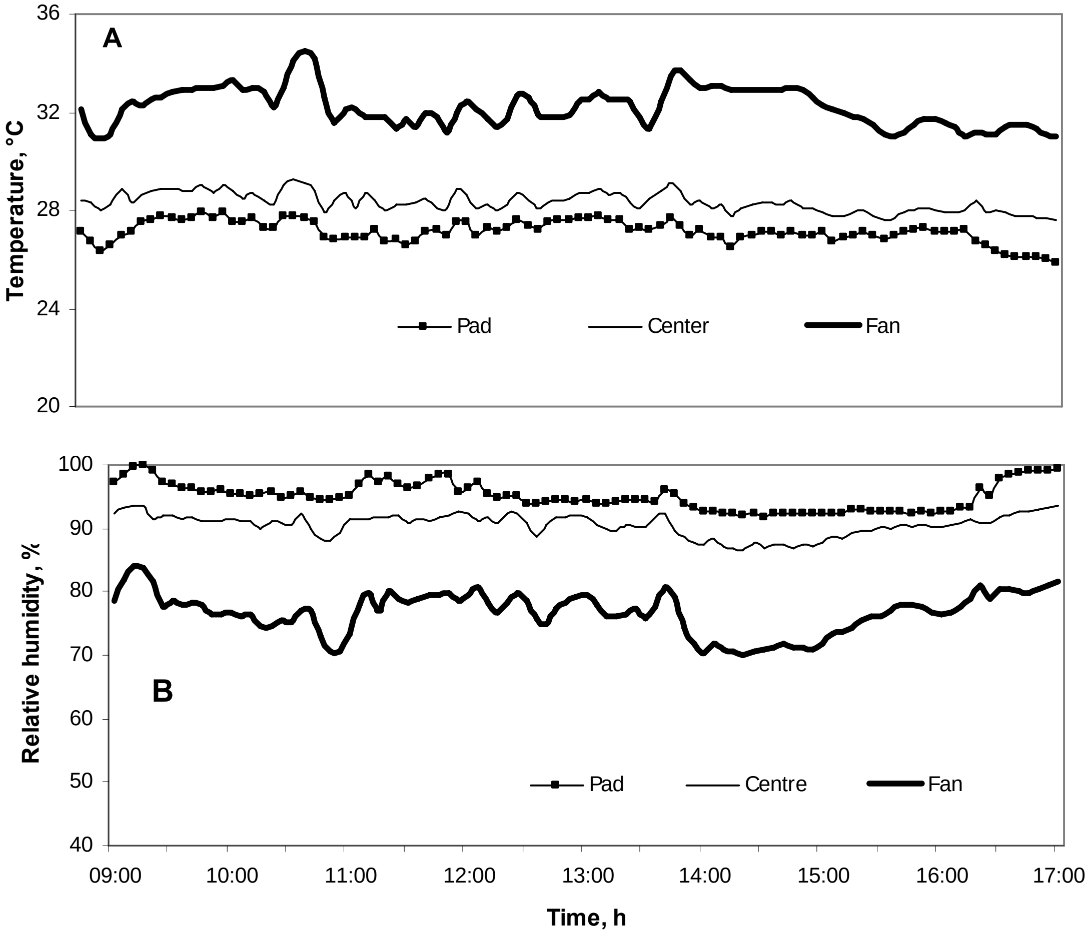


**Figure 4.3.7:** Air temperature (A) and relative humidity (B) profiles measured near the wet pad (Pad), at the middle (Centre) and near the exhaust fans (Fan) inside the evaporative cooled greenhouse on a typical sunny day (22.06.2006) during the rainy season 2006 in central Thailand.

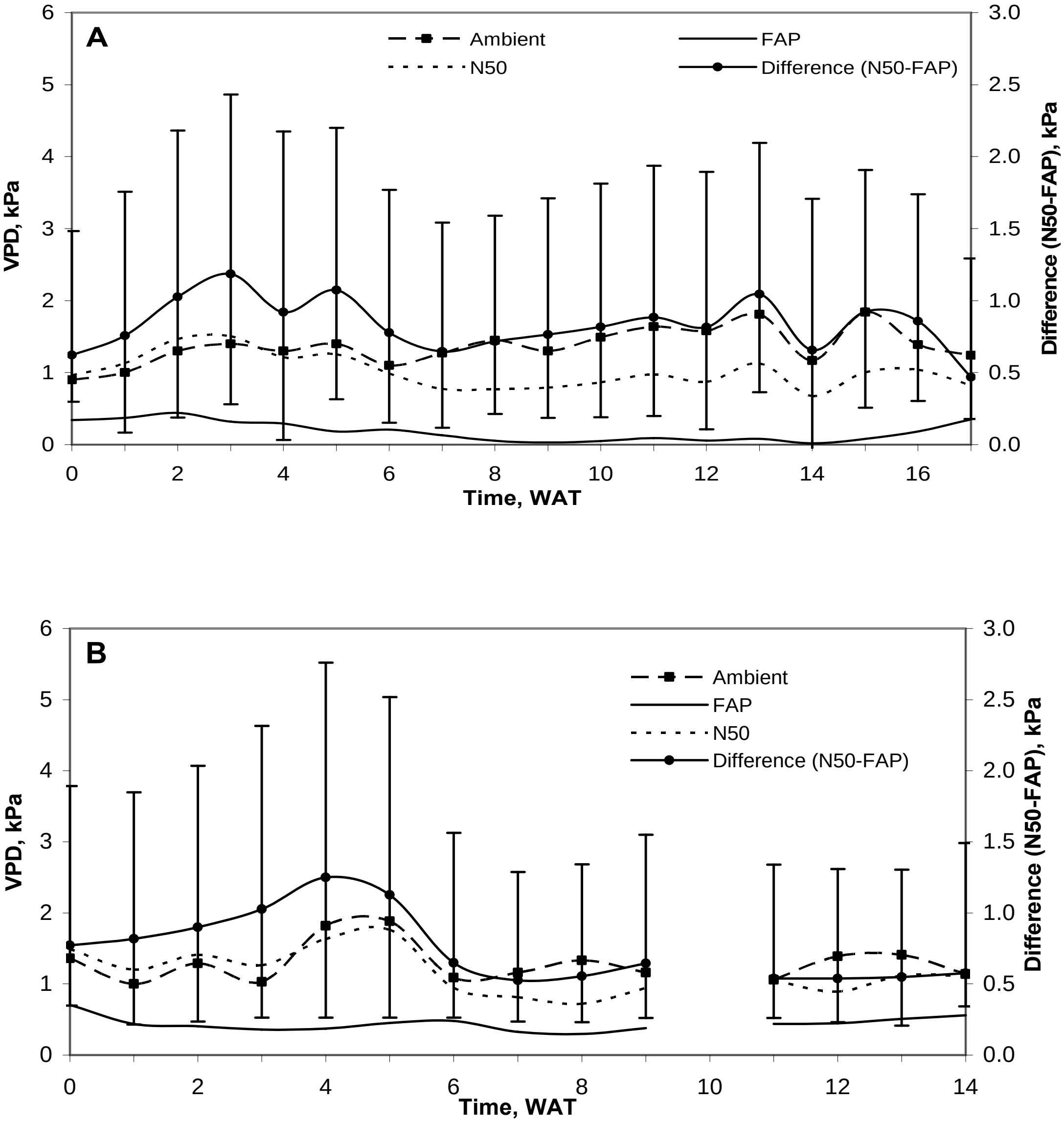


**Figure 4.3.8:** Vapour pressure difference (VPD) measured inside the evaporative cooled (FAP) and naturally ventilated (N50) greenhouse during the 2005/2006 dry (A) or 2006 rainy (B) season in central Thailand. Error bars represent the upper and lower confidence intervals of the difference between the two greenhouses.

**Table 4.3.3:** Mean weekly night-time air temperature, °C, air water content, g kg$^{-1}$, air vapour pressure deficit, kPa, and mean 24 h ambient wind speed, m s$^{-1}$, recorded outside and in the naturally ventilated (N50) or the evaporative cooled (FAP) greenhouses during the dry season 2005/2006 in central Thailand.

| **WAT** | **Temperature, °C** | | | **Humidity ratio, g kg$^{-1}$** | | | **VPD, kPa** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Ambient | FAP | N50 | Ambient | FAP | N50 | Ambient | FAP | N50 |
| 0 | 25.9a | 25.1b | 25.4b | 19.3a | 20.0a | 19.6ab | 0.29a | 0.03b | 0.14b |
| 1 | 26.4a | 25.0c | 25.7b | 18.9a | 19.3a | 17.8a | 0.44a | 0.11b | 0.47a |
| 2 | 23.7a | 22.9b | 23.2a | 14.0a | 16.7a | 13.5b | 0.74a | 0.15b | 0.69a |
| 3 | 25.9a | 24.5c | 25.9a | 17.5a | 18.9a | 17.7b | 0.57a | 0.07c | 0.39b |
| 4 | 24.9a | 23.1b | 23.7b | 15.8a | 17.6a | 15.8a | 0.66a | 0.04c | 0.43b |
| 5 | 24.3a | 21.9b | 22.5b | 12.9a | 16.4a | 11.7b | 0.97a | 0.03b | 0.88a |
| 6 | 20.4a | 20.2a | 20.4a | 9.5a | 14.4a | 10.7b | 0.88a | 0.07c | 0.68b |
| 7 | 23.2a | 21.8b | 22.4b | 15.6a | 16.2a | 15.9a | 0.36a | 0.05c | 0.16b |
| 8 | 25.5a | 22.5b | 23.5b | 16.7a | 16.9a | 16.7a | 0.53a | 0.06c | 0.25b |
| 9 | 21.6a | 20.1b | 21.1ab | 13.9b | 14.4a | 14.3a | 0.36a | 0.04c | 0.23b |
| 10 | 23.4a | 20.9b | 22.3a | 15.1a | 15.2a | 15.3a | 0.47a | 0.05c | 0.27b |
| 11 | 22.4a | 20.6b | 21.4ab | 13.1a | 14.9a | 13.3a | 0.63a | 0.06c | 0.43b |
| 12 | 24.5a | 22.8b | 23.5ab | 16.3a | 17.2a | 16.8a | 0.49a | 0.06c | 0.22b |
| 13 | 24.6a | 22.9b | 23.5b | 14.9a | 17.1a | 15.1b | 0.72a | 0.07a | 0.07a |
| 14 | 25.5a | 23.7a | 24.7a | 16.9a | 17.9a | 17.2a | 0.61a | 0.08c | 0.39b |
| 15 | 26.5a | 23.6c | 25.2b | 18.0b | 17.6a | 18.2a | 0.65a | 0.07c | 0.32b |
| 16 | 26.9a | 22.6c | 25.9b | 18.1b | 16.7b | 18.3a | 0.65a | 0.08c | 0.45b |

**Table 4.3.4:** Mean weekly night-time air temperature, °C, air water content, g kg$^{-1}$, air vapour pressure deficit, kPa, and mean 24 h ambient wind speed, m s$^{-1}$, recorded outside and in the naturally ventilated (N50) or the evaporative cooled (FAP) greenhouses during the rainy season 2006 in central Thailand.

| **WAT** | **Temperature, °C** | | | **Water Content, g kg$^{-1}$** | | | **VPD, kPa** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Ambient | FAP | N50 | Ambient | FAP | N50 | Ambient | FAP | N50 |
| 0 | 26.7a | 26.6a | 27.1a | 19.2a | 19.9a | 19.4a | 0.47a | 0.33b | 0.52a |
| 1 | 25.9a | 26.4a | 26.0a | 18.6b | 20.0a | 18.5b | 0.37a | 0.27a | 0.50a |
| 2 | 27.3a | 26.6a | 27.0a | 20.1b | 20.7a | 19.6b | 0.46a | 0.21b | 0.46a |
| 3 | 26.6a | 26.1a | 26.6a | 20.2ab | 20.6a | 19.5b | 0.29a | 0.11b | 0.42a |
| 4 | 26.9a | 26.0a | 26.6a | 19.2b | 21.1a | 18.9c | 0.52a | 0.03b | 0.50a |
| 5 | 28.6a | 26.8a | 28.5a | 19.7b | 21.2a | 18.4a | 0.82a | 0.21b | 1.00a |
| 6 | 26.4a | 25.4b | 26.2a | 19.8a | 20.0a | 20.2a | 0.30a | 0.10b | 0.24a |
| 7 | 26.6a | 26.4a | 25.5b | 18.5b | 20.3a | 19.3ab | 0.57a | 0.07c | 0.39b |
| 8 | 27.2a | 25.8b | 26.7a | 19.3b | 20.3a | 19.8ab | 0.55a | 0.13c | 0.35b |
| 9 | 27.5a | 25.8a | 27.0a | 18.7a | 20.2a | 19.7a | 0.71a | 0.14c | 0.46b |
| 10 | - | - | - | - | - | - | - | - | - |
| 11 | 27.2a | 25.2b | 26.8a | 18.9a | 19.7a | 19.6a | 0.61a | 0.12b | 0.42a |
| 12 | 27.2a | 24.9c | 27.1b | 17.9b | 19.3a | 18.3b | 0.77a | 0.09b | 0.61a |
| 13 | 27.3a | 25.3b | 26.9a | 18.7b | 19.8a | 19.2ab | 0.68a | 0.09b | 0.53a |
| 14 | 28.0a | 25.6c | 27.1b | 20.3a | 19.9a | 19.6a | 0.54a | 0.16b | 0.53a |

## 4.3.2 Plant Growth and Production

### 4.3.2.1 Plant Height

During the first 3 WAT during the dry season, plants gained height almost at an equal rate but from 4 WAT, plants in FAP were significantly shorter than in N50 (Fig. 4.3.9). The maximum height attained by the plants during the dry season was 359.5 cm and 389.5 cm in FAP and N50, respectively at 18 WAT. The mean height gain per plant was higher in N50 (22.1 cm week$^{-1}$) than in FAP (20.3 cm week$^{-1}$). Therefore, the average height plant$^{-1}$ week$^{-1}$ was significantly lower in FAP (160.8 cm) than N50 (183.3 cm) from 1 WAT to 18 WAT (n = 429, t = -3.01, *P* = 0.003).

During the rainy season, plants in FAP were significantly shorter than in N50, at 6, 8, 10, 11, 15 and 16 WAT. Maximum height at 16 WAT during the rainy season was 295.3 cm and 321.2 cm in FAP and N50, respectively. Moreover, height gain per week in both greenhouses was smaller during the rainy than the dry season. The mean height gain per plant during the rainy season was 18.5 cm week$^{-1}$ and 20.3 cm week$^{-1}$ in FAP and N50, respectively. However, at 16 WAT, the plants were 36.8 cm and 38.2 cm shorter in FAP and N50 during the rainy than the dry season, respectively.

### 4.3.2.2 Plant flowering

Cooling method did not influence the number of trusses on the plants during the initial weeks in either of the seasons (Fig. 4.3.10A). However, this changed after 6 WAT with significantly more trusses in N50 than in FAP during both seasons. During the dry season, the mean number of trusses plant$^{-1}$ week$^{-1}$ was significantly lower in FAP than in N50 (n = 271, t = -3.35, *P* = 0.0009) from 5 to 16 WAT. Total number of trusses during the dry season was 23.3 and 25.5 trusses plant$^{-1}$ in FAP and N50, respectively.

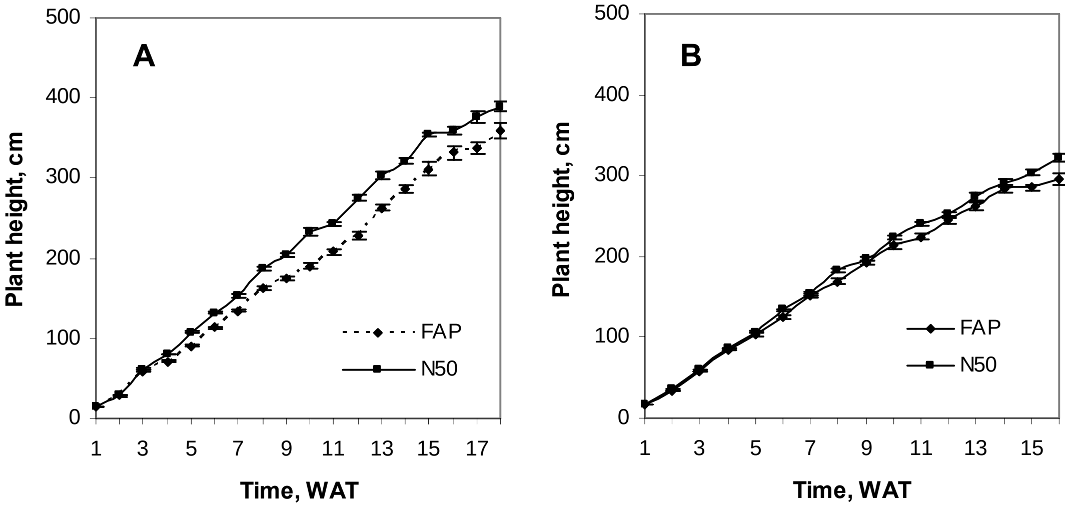


**Figure 4.3.9**: Mean weekly height of tomato plants (mean ± SE) grown inside the evaporative cooled (FAP) and naturally ventilated (N50) greenhouse during (A): the dry season 2005/2006 and (B): the rainy season 2006 in central Thailand.

The plants had more trusses during the rainy than during the dry season (Fig. 4.3.10B). After 6 WAT during the rainy season, the number of trusses increased faster in N50 than in FAP. In N50, at least 2 more trusses plant$^{-1}$ were observed each week compared to 1 in FAP. Consequently, the mean number of trusses plant$^{-1}$ week$^{-1}$ from 4 WAT to 15 WAT, in FAP was significantly lower than in N50 (n = 303, t = -4.53, $P < 0.001$). The total number of trusses on the plants at the end of 15 WAT during the rainy season was 15.0 and 22.6 in FAP and N50, respectively. Flower abortion or death after infection by fungus was high in FAP thus, reducing the number of flowers maturing in to fruits.

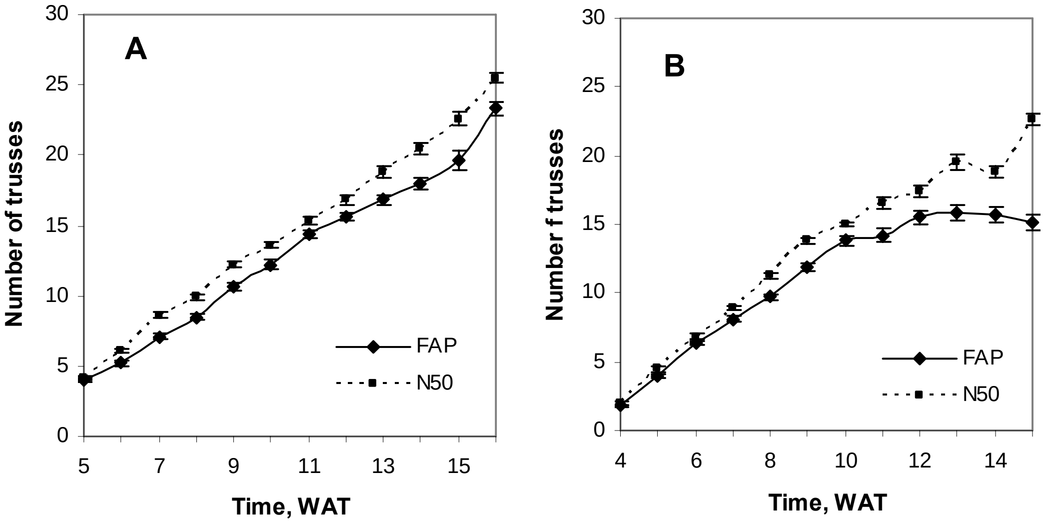


**Figure 4.3.10:** Number of trusses on tomato plants (mean ± SE) grown inside the evaporative cooled (FAP) and naturally ventilated (N50) greenhouses during (A): the dry season 2005/2006 (B) the rainy season 2006 in central Thailand.

### 4.3.2.3 Dry Matter Partitioning

***Leaves***

The average proportion of dry matter (***DM***) allocated to leaves ($\boldsymbol{DM_L}$) was significantly lower in FAP than in N50 (n = 18, t = -3.78, *P* = 0.0006). During both seasons, the $\boldsymbol{DM_L}$ was similar in both greenhouses at 2nd and 4th WAT (Fig. 4.3.11A). During the dry season, a constant weight was noted between 6 and 12 WAT though this was not the case during the rainy season. Peak $\boldsymbol{DM_L}$ during the dry season was 100.2 g plant$^{-1}$ and 100.1 g plant$^{-1}$ in FAP and N50, respectively at 10 WAT. During the rainy season, maximum $\boldsymbol{DM_L}$ was 159.9 g plant$^{-1}$ and 134.9 g plant$^{-1}$ in FAP and N50, respectively at 12 WAT. Furthermore, during both seasons, the proportion of $\boldsymbol{DM_L}$ allocated to the leaves decreased with time. For instance, the proportion of ***DM*** allocated to the leaves during the rainy season decreased from 80 % to 17 % at 2 and 16 WAT.

### *Stems*

There was no significant difference in the $\boldsymbol{DM_S}$ in the first 4 weeks during both seasons (Fig. 4.3.11B). In both greenhouses $\boldsymbol{DM_S}$ was higher during the rainy than the dry season. As shown in table 4.3.5, the proportion of ***DM*** allocated to the stems was almost constant between 4 and 10 WAT (table 4.3.5). After 12 WAT, the proportion ***DM*** allocated to the stems increased in both greenhouses. However, there was no significant difference in the proportion of ***DM*** allocated to stems between 4 and 14 WAT during the rainy season (n = 18, t = -0.12, *P* = 0.91).

### *Fruits*

Plants allocated significantly more ***DM*** to fruits and fruiting parts ($\boldsymbol{DM_F}$) in FAP than in N50 (N= 18, t = 2.78, P = 0.009) during the rainy season. Maximum $\boldsymbol{DM_F}$ in N50 was attained at 10 WAT when 108.7 g plant$^{-1}$ and 73.9 g plant$^{-1}$ (corresponding to 42.3 % and 29.2 % during the dry and rainy season, respectively) during the dry and rainy season, respectively. The highest $\boldsymbol{DM_F}$ content of the fruits in N50 during the rainy season was observed at 12 WAT, which was 22.9 % of the total ***DM*** content of the plants and thus lower than the 29.2 %, recorded at 10 WAT. Maximum $\boldsymbol{DM_F}$ in FAP was realized 12 WAT during both seasons with 111.8 g plant$^{-1}$ (44.6 %) and 242.5 g plant$^{-1}$ (47.5 %) during the dry and rainy season, respectively.

Plants had a higher ***DM*** content during the rainy as opposed to the dry season (Fig. 4.3.11D). Maximum ***DM*** content during the dry season was 250.9 g plant$^{-1}$ and 276.2 g plant$^{-1}$ in FAP and N50, respectively. However, during the rainy season the maximum *DM* was 508.2 g plant$^{-1}$ and 385.2 g plant$^{-1}$ in FAP and N50, respectively.

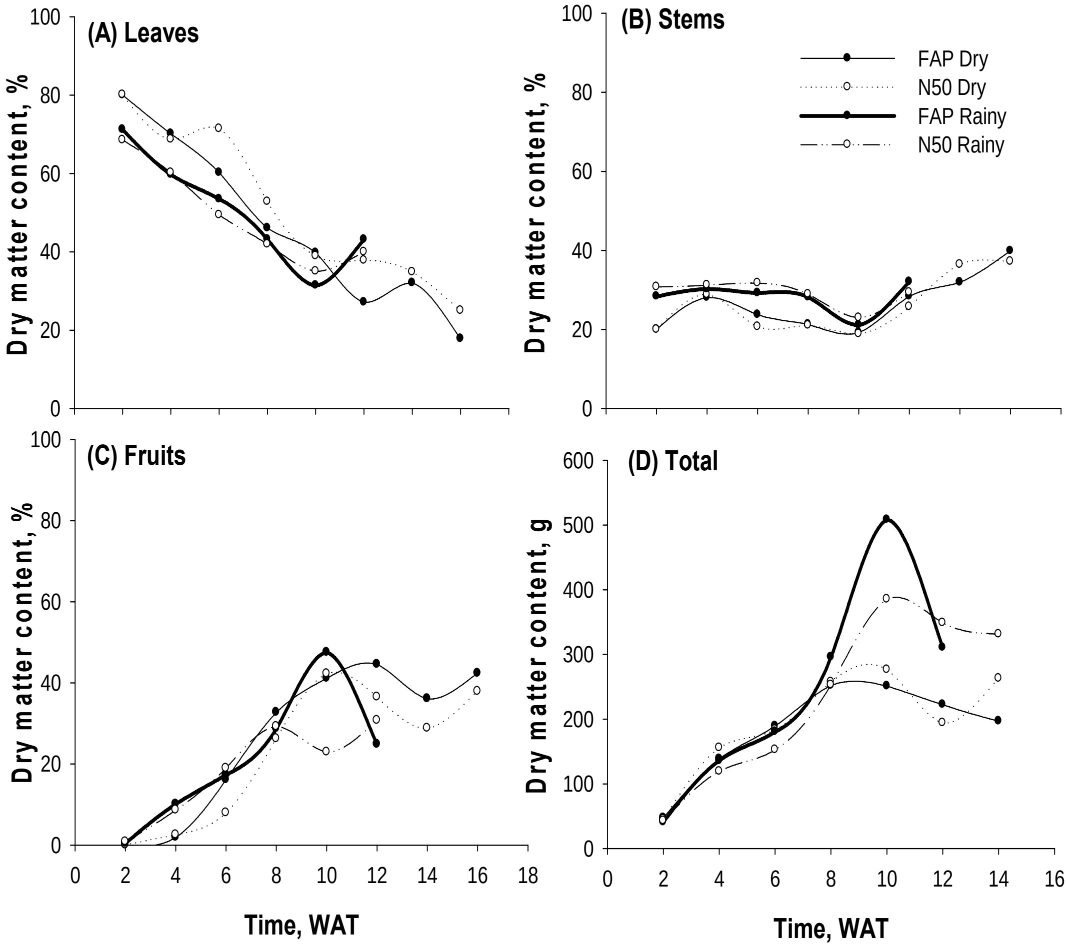


**Figure 4.3.11:** Dry matter content of leaves (A), stems (B) and fruits (C), expressed as proportion, %, of the total dry matter (D) in the plant, for tomatoes grown inside the evaporative cooled (FAP) and naturally ventilated (N50) greenhouses during (A): the dry season 2005/2006 and (B): the rainy season in central Thailand.

**Table 4.3.5:** Mean dry matter content, g plant$^{-1}$, for leaves, stems and trusses (fruits) of tomato plants grown inside the naturally ventilated (N50) and in the evaporative cooled greenhouses during the dry season 2005/2006 and the rainy season 2006 in central Thailand.

| Time, | **Leaves** | | | | **Stems** | | | | **Fruits** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WAT | **Dry season** | | **Rainy season** | | **Dry season** | | **Rainy season** | | **Dry season** | | **Rainy season** | |
| | FAP | N50 | FAP | N50 | FAP | N50 | FAP | N50 | FAP | N50 | FAP | N50 |
| 2 | 2.35 | 2.72 | 1.8 | 2.1 | 0.59 | 0.68 | 0.5 | 0.4 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4 | 33.31 | 30.95 | 29.3* | 29.3* | 13.31 | 12.97 | 11.7a | 13.1a | 0.89 | 1.13 | 0.2* | 0.3* |
| 6 | 83.48 | 111.14 | 81.1* | 71.8* | 32.84 | 32.11 | 40.9 | 37.2 | 22.34 | 12.38 | 13.7* | 10.3* |
| 8 | 87.27 | 96.87 | 96.5* | 75.3* | 40.22 | 38.52 | 52.7 | 48.3 | 61.96 | 48.17 | 31.3 | 28.9 |
| 10 | 100.21 | 100.12 | 127.7* | 105.9* | 48.28 | 48.45 | 83.3* | 72.9* | 103.66 | 108.74 | 84.8* | 73.9* |
| 12 | 68.03 | 104.40 | 159.5* | 134.9* | 71.04 | 71.04 | 107.1* | 88.3* | 111.83 | 100.83 | 241.6* | 161.9* |
| 14 | 71.23 | 67.47 | 133.8* | 139.3* | 70.88 | 70.57 | 99.4* | 102.3* | 80.21 | 55.85 | 77.1* | 107.1* |
| 16 | 35.04 | 65.61 | - | - | 78.31 | 97.60 | - | - | 83.37 | 99.53 | - | - |

Under the same main column, means in the same row under the same season followed by an asterisk (*) show significant differences in the proportion (%) of resources allocation (Student's t-test at $\alpha = 5\%$

#### 4.3.2.4 Leaf area

Plants in FAP had significantly lower ***LAI*** than in N50 during the dry season (N = 24, t = -2.06, P = 0.045) (table 4.3.6). A significantly lower ***LAI*** was recorded in FAP than N50 at 8 WAT and 12 WAT during the dry season. In the first 4 WAT, ***LAI*** in both greenhouses was similar during both seasons. Maximum ***LAI*** attained during the dry season was 1.99 $m^2$ $m^{-2}$ at 10 WAT in FAP and 2.94 $m^2$ $m^{-2}$ at 12 WAT in N50. During the rainy season, ***LAI*** was lower in N50 than in FAP although the difference was not significant. However, during the rainy season, ***LAI*** in both greenhouses was almost 50 % lower than that recorded during the dry season. The maximum ***LAI*** during the rainy season was 1.17 $m^2$ $m^{-2}$ at 12 WAT in FAP, and 1.03 $m^2$ $m^{-2}$ at 10 WAT in N50.

**Table 4.3.6:** Leaf area indices (leaf area per unit ground area), $m^2$ $m^{-2}$**,** of tomato plants grown inside the evaporative cooled (FAP) and naturally ventilated (N50) greenhouses during the dry season 2005/2006 or the rainy season 2006 in central Thailand.

| Time, | **Dry Season** | | **Rainy Season** | |
|---|---|---|---|---|
| WAT | FAP | N50 | FAP | N50 |
| 2 | 0.07a | 0.09a | 0.09a | 0.10a |
| 4 | 0.50a | 0.57a | 0.50a | 0.51a |
| 6 | 1.14a | 1.67a | 1.03a | 0.85ab |
| 8 | 1.56a | 2.09b | 1.06a | 0.92a |
| 10 | 1.99a | 2.67a | 1.07a | 0.97a |
| 12 | 1.50a | 2.94b | 1.17a | 1.03a |
| 14 | 1.52a | 1.66a | - | - |
| 16 | 0.76a | 1.34a | - | - |

*Under the same season, means on the same row followed by different letters differ significantly according to student's t-test at α = 5 %.

#### 4.3.2.5 Yield

Total yield per plant during the dry season was 5.5 kg and 5.7 kg (equivalent to 106.2 t $ha^{-1}$ and 103.7 t $ha^{-1}$) recorded in FAP and N50, respectively. The average marketable yield (M) per plant and harvest during the rainy season was 0.459 kg and 0.471 kg in FAP and N50, respectively and did not differ significantly (n = 12, t = -0.11, *P* = 0.91) (Fig. 4.3.12A). Similarly, the average non marketable yield (NM) per plant and harvest during the dry season was not significantly different (n = 12, t = 1.05, *P* = 0.30) with 0.13 kg and 0.11 kg recorded in FAP and N50, respectively. The total yield per plant during the rainy season was low at 1.9 kg (28.8 t $ha^{-1}$) and 2.2 kg (33.3 t $ha^{-1}$) in FAP and N50, respectively. The average M yield per plant and harvest during the rainy season was lower in N50 (0.035 kg) than in FAP (0.108 kg) but the difference was not significant (n = 7, t = 1.77, *P* = 0.101). On the contrary, average NM yield per plant and harvest during the rainy season was significantly (n = 7, t = -1.38, *P* = 0.192) higher in N50 (0.281 kg) than in FAP (0.209 kg). During both seasons, yield had an oscillating pattern with a big yield followed by a smaller yield.

#### 4.3.2.6 Fruit quality

Brix value in FAP (4.56 °) did not differ significantly from that in N50 (4.68 °) during the dry season (n = 25, t = -1.04, *P* = 0.30) (Table 4.3.7). Although rainy season the brix value in N50 (4.77 °) was higher than in FAP (4.56 °) during the rainy season, no significant difference was observed (n= 20, t = -1.10, *P* = 0.28).

There was no significant difference in pH during neither the dry (n= 25, t = -0.63, *P* = 0.53) nor the rainy season (n = 20, t = -0.67, *P* = 0.51) (Table 4.3.7). The pH value during the dry season averaged 4.33 and 4.37 in FAP and N50, respectively while during the rainy season it was 4.34 and 4.40 in FAP and N50, respectively.

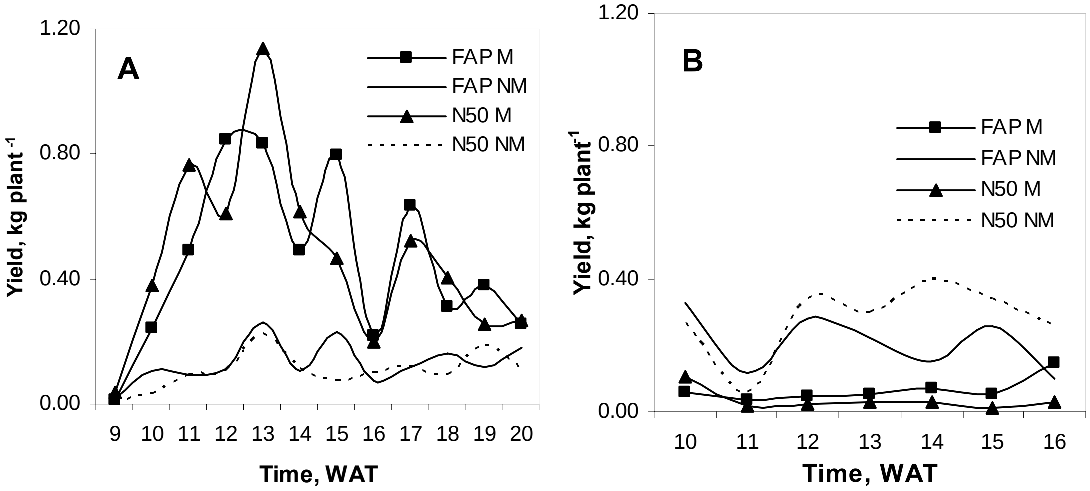


**Figure 4.3.12:** Profile of marketable (M) and non-marketable (NM) yield (kg plant$^{-1}$) harvested from tomato plants grown in evaporative cooled (FAP) or the naturally ventilated (N50) greenhouse during (A): the dry season 2005/2006 (B): the rainy season 2006 in central Thailand.

**Table 4.3.7:** Brix values and pH of tomato fruits from plants grown inside evaporative cooled (FAP) or naturally ventilated (N50) greenhouses during the dry season 2005/2006 and the rainy season 2006 in central Thailand.

| Season | Brix | | pH | |
|---|---|---|---|---|
| | FAP | N50 | FAP | N50 |
| Dry | 4.56 ± 0.11a | 4.68 ± 0.06a | 4.34 ± 0.05a | 4.37 ± 0.04a |
| Rainy | 4.56 ± 0.12a | 4.77 ± 0.06a | 4.34 ± 0.06a | 4.40 ± 0.05a |

*Means under the same main column and season followed by the same letter are not significantly different (Student's t-test, α = 0.05)

#### 4.3.2.7 Plant water consumption

Plant water consumption was significantly higher in N50 than in FAP during the dry ($n = 71$, $t = -05.38$, $P < 0.0001$) and rainy ($n = 55$, $t = -10.83$, $P < 0.0001$) seasons (Fig. 4.3.13). The average water requirement by the plants in FAP was 1.0 L $day^{-1}$ during both seasons. However in N50, plant water consumption was higher during the rainy (1.82 L $plant^{-1}$ $day^{-1}$) than the dry season (1.30 L $plant^{-1}$ $day^{-1}$).

Cumulative water requirement for the plants from 4 to 16 WAT during the dry season was 13.10 L $plant^{-1}$ and 17.60 L $plant^{-1}$ in FAP and N50, respectively. However during the rainy season, cumulative water consumption in N50 from 4 WAT to 16 WAT was almost double (24.90 L $plant^{-1}$) that in FAP (13.40 L $plant^{-1}$). Peak plant water consumption was realized when plants were 14 weeks old during both seasons after which, there was a decrease in water demand.

During both seasons, plants in FAP had a better WUE compared to those in N50. Calculated on the total harvested yield and cumulative water consumption between 4 WAT to 16 WAT, WUE by the plants was 0.553 and 0.349 kg $L^{-1}$ in FAP and N50, respectively during the dry season, and 0.147 kg $L^{-1}$ and 0.094 kg $L^{-1}$ in FAP and N50 during the rainy season, respectively.

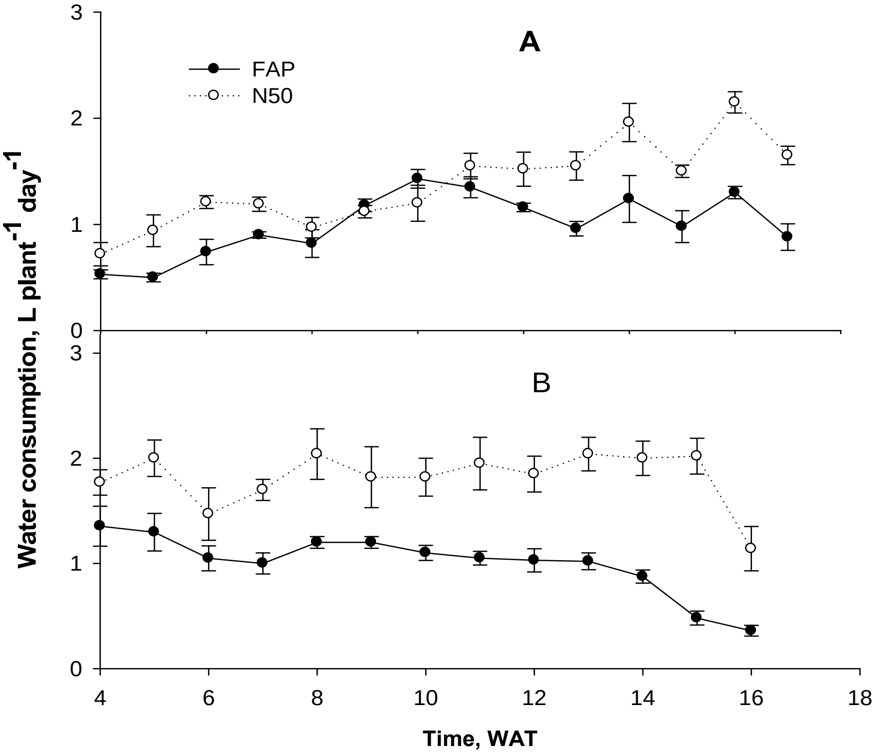


**Figure 4.3.13:** Average water consumption (mean ± SE) of tomato plants grown inside evaporative cooled (FAP) and naturally ventilated (N50) greenhouses during (A): the dry season 2005/2006 and (B): the rainy season 2006 in central Thailand.

## 4.4 Plant Response to Different Greenhouse Cooling Methods

### 4.4.1 Canopy microclimate

In N78 and N78S, both $T_a$ and leaf temperature ($T_L$) were lowest in the early morning hours but increased steadily with increasing intensity of $G$ to reach a maximum around midday. In the afternoon, $T_L$ was higher in N78S than N78. In both greenhouses, the concentration of $CO_2$ in the air dropped from 466 µmol mol$^{-1}$ at 06:00 h to 260 µmol mol$^{-1}$ at 12:55 h but the difference between N78 and N78S was not significant (Fig 4.4.1).

As mentioned in section 4.3.1, the intensity of $G$ was higher in FAP, but both $T_a$ and $T_L$ were lower compared to N50 (Fig. 4.4.2). A slight increase in $T_a$ was realized in the evening after the fans were switched off (Fig. 4.4.2A). High and low air exchange during the day and night, respectively, led to a higher concentration of $CO_2$ in FAP. Maximum $CO_2$ concentration was 687 µmol mol$^{-1}$ and 445 µmol mol$^{-1}$ in FAP and N50 respectively, recorded before daybreak (Fig. 4.4.2B). Slightly higher intensity of global radiation and air exchange in FAP resulted in a higher $E$ hence lower leaf temperature. Moreover, net photosynthesis was significantly higher in FAP, with peak values being almost 2 times higher than in N50.

Surprisingly, $CO_2$ concentration dropped below 300 µmol mol$^{-1}$ on most days at around midday. Furthermore, no significant difference was realized in the $CO_2$ concentration between N50 and N78 (Fig. 4.4.3). Mesh size had a slight influence on the infiltration of $CO_2$ in to the greenhouses (Fig. 4.4.4). The maximum difference in $CO_2$ concentration between ambient air and either N50 or N78 was 30 µmol mol$^{-1}$ recorded when $P_N$ was maximum. Air temperature was 1 °C higher in N50 than in N78 around midday although the difference in the intensity of $G$ was not significant. During the day, leaves were cooler in N78 with a maximum difference of 2 °C recorded at midday (Fig. 4.4.4D). In addition, net photosynthesis was higher in N78 reaching a maximum value of

3.6 µmol $m^2$ $s^{-1}$ compared to 3.0 µmol $m^2$ $s^{-1}$ in N50. However, in the evening (after 17:00 h) ***E*** was higher in N78 than N50.

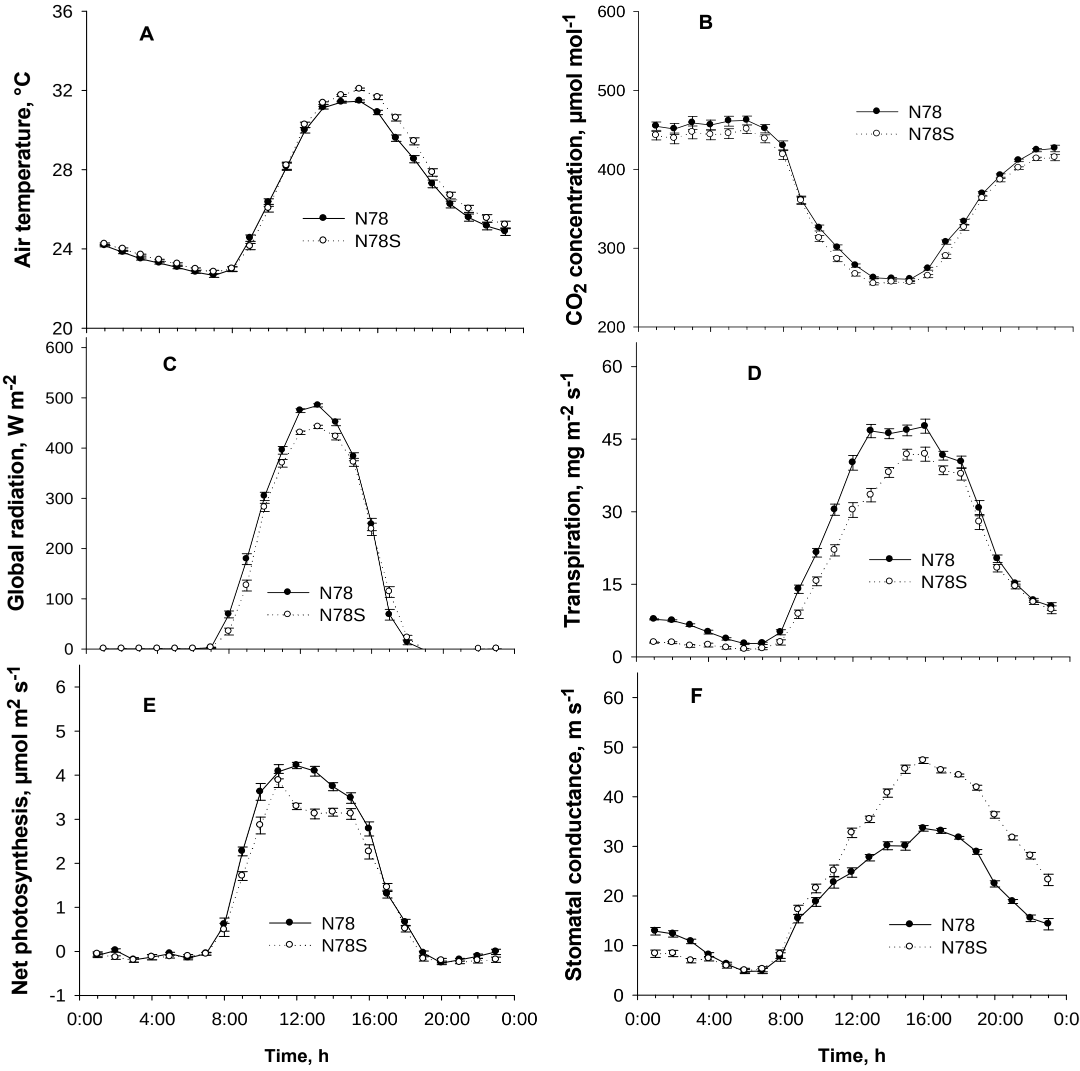


**Figure 4.4.1:** Profiles (mean ± SE) of diurnal air temperature (A), $CO_2$ concentration (B), intensity of global radiation (C), leaf transpiration (D), net photosynthesis (E) and stomata conductance (F) of tomato plants recorded in the naturally ventilated greenhouses with (N78S) or without (N78) the shading paint with NIR-reflecting pigment. Data were collected on 3 sunny days (52 to 54 DAT) during the dry season 2005/2006 in central Thailand.

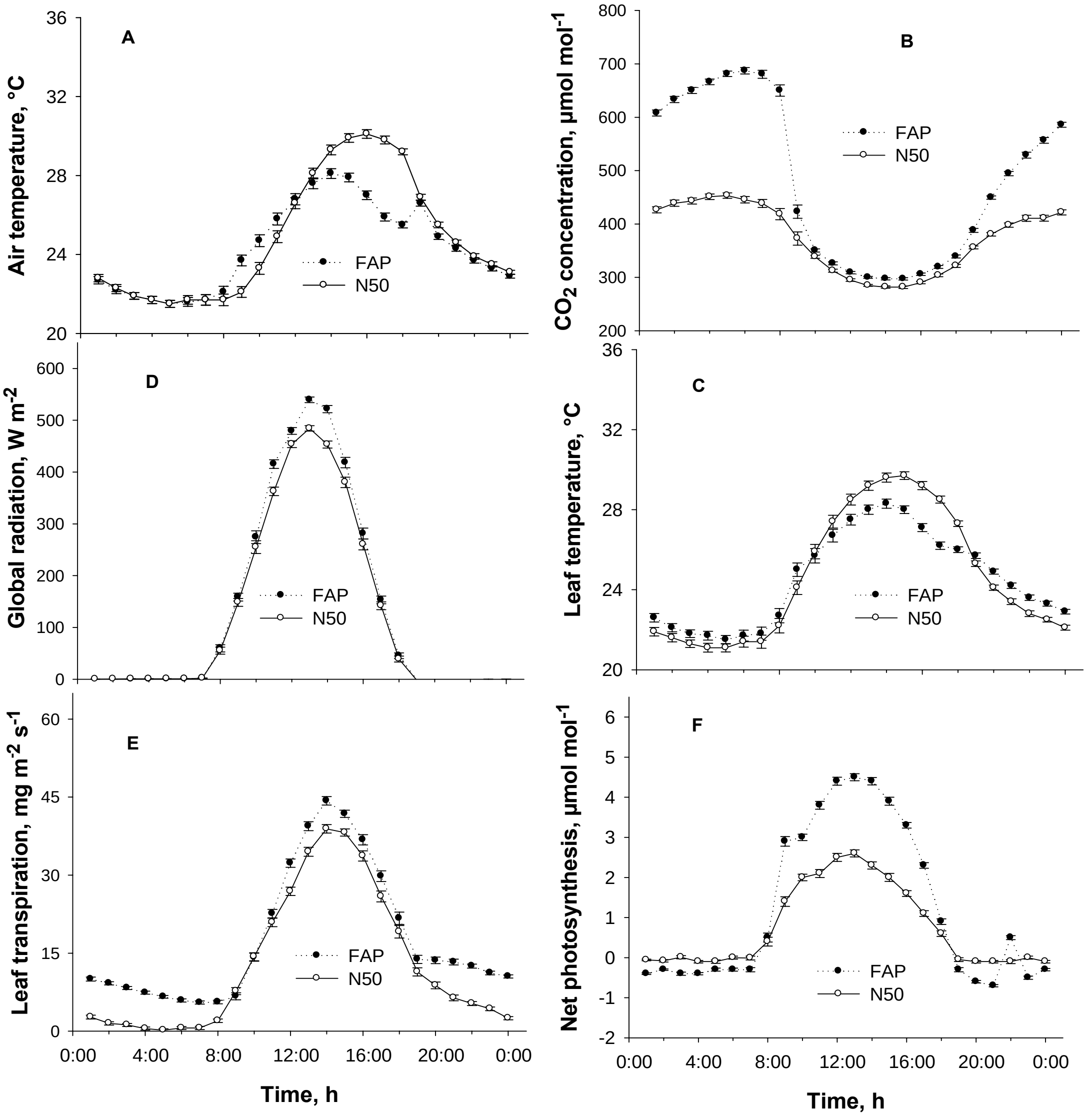


**Figure 4.4.2:** Profiles (mean ± SE) of diurnal air temperature (A), $CO_2$ concentration (B), leaf transpiration (C), intensity of global radiation (D), stomata conductance (E) and net photosynthesis (F) of tomato plants recorded on sunny days (73 to 80 DAT) in the evaporative cooled (FAP) and naturally ventilated (N50) greenhouses during the dry season 2005/2006 in central Thailand.

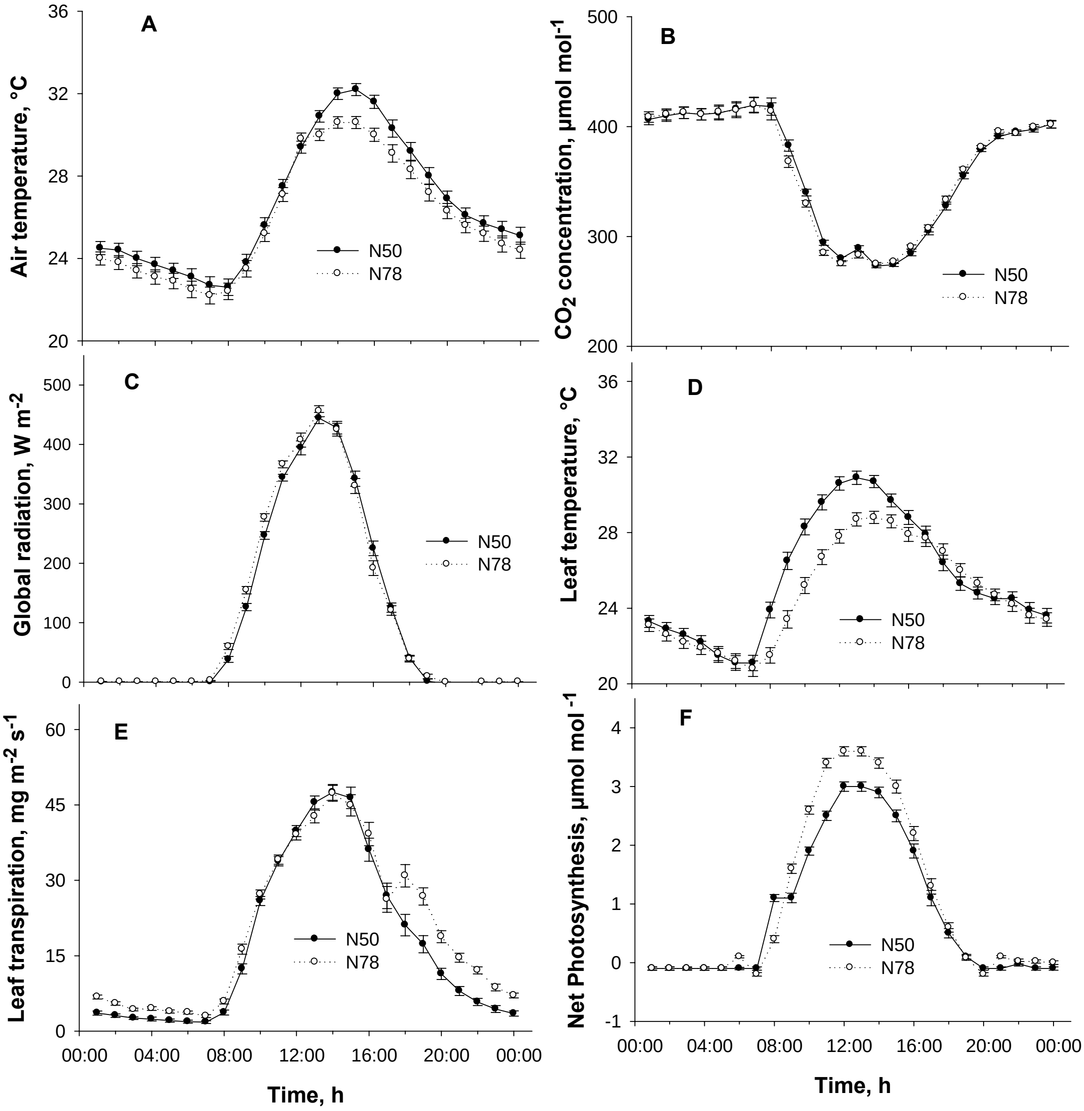


**Figure 4.4.3:** Profiles (mean ± SE) of diurnal air temperature (A), $CO_2$ concentration (B), intensity of global radiation (C), leaf temperature (D), leaf transpiration (E) and net photosynthesis (F) of tomato plants in the naturally ventilated greenhouses covered with 78-mesh (N78) or 50-mesh (N50) insect-proof nets on the sidewalls. Data were collected for 5 sunny days (39 to 43 DAT) during the dry season 2005/2006 in central Thailand.

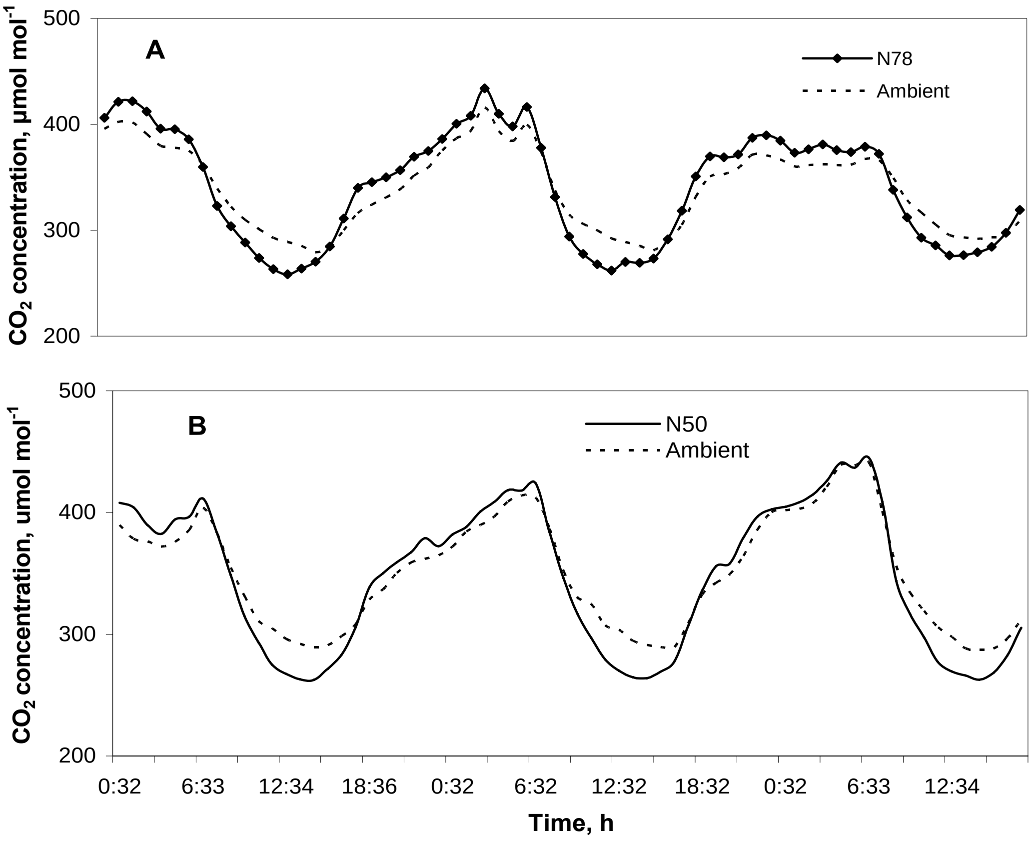


**Figure 4.4.4:** Profiles $CO_2$ concentration (mean ± SE) outside and inside the greenhouses covered with (A): the 78-mesh (N78), and (B): the 50-mesh (N50) insect-proof net on the sidewalls. Measurements were taken simultaneously using 2 gas exchange systems placed in a ventilated housing from 25 - 27.10.2006 (A) and 28 to 30.10.2006 (B) during the dry season in central Thailand. Plants were 43-47 and 48-49 DAT in A and B, respectively.

### 4.4.2 Leaf transpiration

In all greenhouses leaf transpiration (***E***) increased with increasing ***G***. However, ***E*** reached its peak earlier than ***G*** (Fig. 4.4.1, 4.4.2 & 4.4.3). However, after sunset plants continued transpiring for almost 4 hours indicating the influence of other factors mainly temperature and possibly wind on ***E***. Higher stomata conductance ($\boldsymbol{S_c}$) did not necessarily result in higher ***E***. In all greenhouses, ***E*** was linearly correlated to vapour concentration difference (***VCD***). The relation took the form:

$$y = y_0 + ax \qquad \text{Equation 5}$$

Moreover, ***E*** and $\boldsymbol{S_c}$, had a quadratic polynomial relationship as shown below:

$$y = y_0 + ax + bx^2 \qquad \text{Equation 6}$$

The values of different parameters of the relationship are displayed in the tables 4.4.1 and 4.4.2. The parameter $\boldsymbol{y_o}$ indicates that plants continue transpiring even at low ***VCD*** otherwise condensation occurs on the leaves (negative sign), while ***a*** indicates the rate of increase of transpiration with either ***VCD*** or $\boldsymbol{S_c}$.

Data from online measurements showed that shading significantly reduced the intensity of ***G***, $\boldsymbol{T_a}$ and ***VCD*** (plant aged between 48 to 54 DAT) (Fig. 4.4.1). This resulted in the reduction of ***E*** by 6 mg $m^{-2}$ $s^{-1}$ and a one hour delay to the time at which maximum ***E*** was recorded (Fig 4.4.1D). Plants in both greenhouse types continued transpiring for almost 4 hours after sunset i.e. at low intensities of ***G*** (Fig. 4.4.5A). A high correlation ($r^2 = 0.9$) between ***E*** and ***VCD*** was observed in both greenhouses (Table 4.4.1). Moreover, for the plants in N78, $\boldsymbol{S_c}$ stagnated at around 35 m $s^{-1}$ while values as high as 50 m $s^{-1}$ were recorded in N78S.

**Table 4.4.1:** Parameters for the relationship between leaf transpiration and vapour concentration difference (leaf-air), VCD, measured in the evaporative cooled (FAP), or naturally ventilated greenhouses (N50, N78 or N78S) during the dry season in central Thailand.

| Parameter | N78 versus N78S | | FAP versus N50 | | N50 versus N78 | |
|---|---|---|---|---|---|---|
| | N78 | N78S | FAP | N50 | N50 | N78 |
| N | 540 | 298 | 539 | 540 | 298 | 539 |
| $R^2$ | 0.90 | 0.92 | 0.77 | 0.81 | 0.79 | 0.70 |
| a | 4.2 | 5.7 | 6.2 | 4.5 | 5.8 | 4.5 |
| $y_0$ | -13.9 | 18.4 | -15.2 | -15.2 | -19.2 | -18.1 |
| SE | 6.1 | 7.5 | 6.8 | 6.0 | 7.6 | 9.6 |

N is the number of measurements (points) used for the calculation

**Table 4.4.2:** Parameters for the relationship between leaf transpiration and stomata conductance of tomato plants grown in the evaporative cooled (FAP), and naturally ventilated greenhouses (N50, N78 or N78S) during the dry season 2005/2006 in central Thailand.

| Parameter | N78 versus N78S | | FAP versus N50 | | N50 versus N78 | |
|---|---|---|---|---|---|---|
| | N78 | N78S | FAP | N50 | N50 | N78 |
| $R^2$ | 0.81 | 0.85 | 0.88 | 0.94 | 0.84 | 0.89 |
| a | 1.3 | 1.1 | 0.8 | 0.80 | 0.54 | 1.30 |
| b | 0.002 | 0.002 | 0.006 | 0.013 | 0.016 | 0.004 |
| $E_0$ | -4.2 | -3.8 | -4.2 | -1.1 | -0.46 | -2.9 |
| SE | 6.5 | 6.6 | 5.0 | 3.5 | 6.6 | 5.8 |

The values for number of measurements (N) remain the same as shown in table 4.4.1 above.

For plants aged between 73 to 76 DAT, both ***G*** and ***E*** were higher in FAP than N50 (Fig. 4.4.2). Consequently, $\boldsymbol{T_a}$ and $\boldsymbol{T_L}$ were lower in the FAP. Astonishingly, higher ***E*** was recorded in FAP even at low VCD. In both greenhouses, higher ***E*** was recorded in the evening (sunset) than in the morning (daybreak). At almost similar levels of VCD, plants in FAP transpired more than those in N50 (Fig. 4.4.5D). A high correlation was noted between ***E*** and ***VCD*** in both greenhouses (Table 4.4.2). Moreover, higher $\boldsymbol{S_c}$ was recorded in FAP than N50 and a good agreement was obtained between ***E*** and $\boldsymbol{S_c}$.

As the difference in the intensity of ***G*** between N50 and N78 was not significant, ***E*** was similar between both greenhouses except in the evening (measurements done from 39 to 43 DAT). Slightly higher ***E*** was recorded in N78 in the afternoon (Fig. 4.4.3E). Similar to the plants in other greenhouses, hysteresis was evident in the relation between ***E*** and ***G*** (Fig. 4.4.5C). Higher VCD was recorded in N78 than N50. In both greenhouses, a high correlation was found between ***E*** and ***G*** (Table 4.4.1).

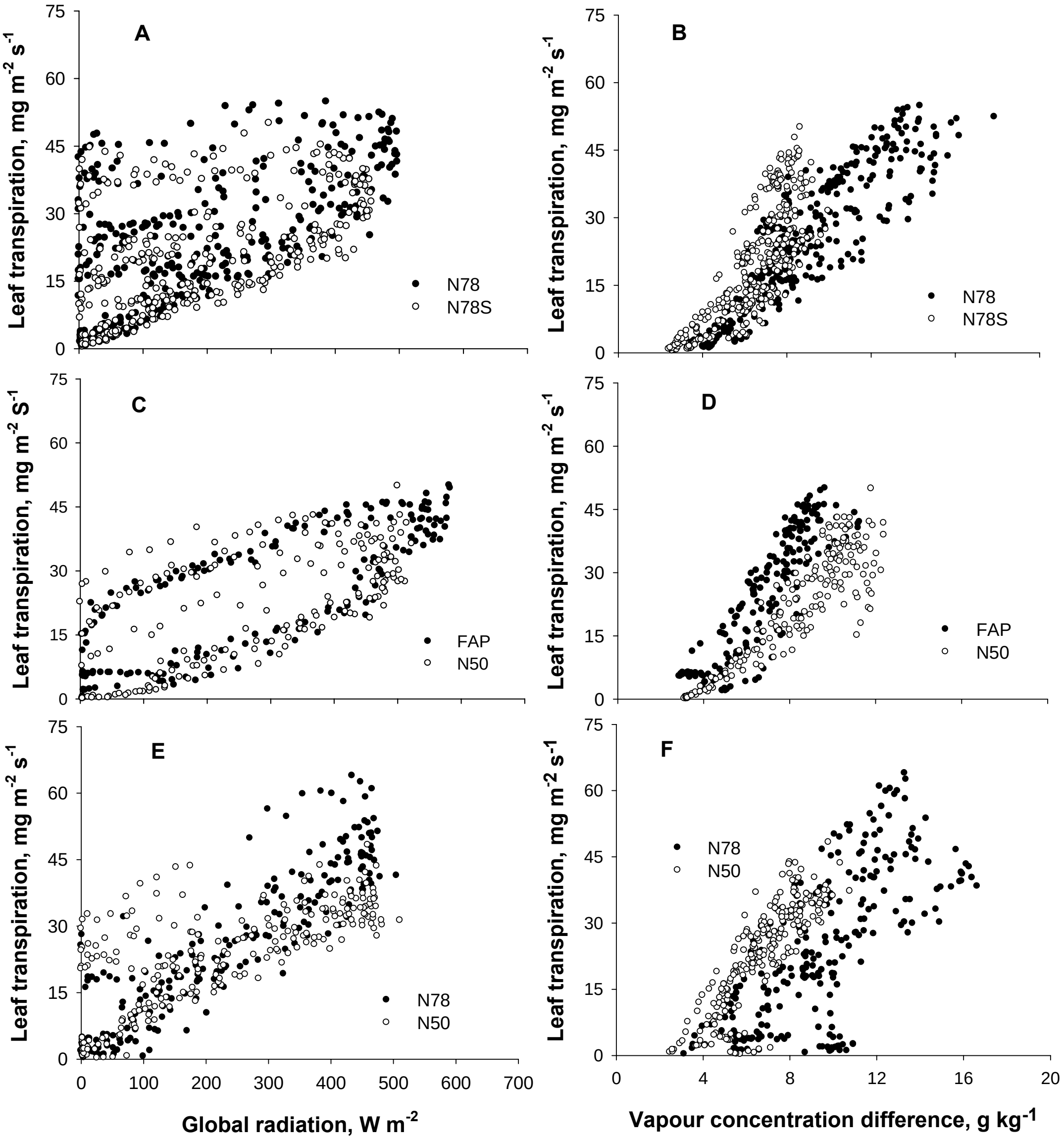


**Figure 4.4.5:** Dependence of leaf transpiration of tomato plants on global radiation and vapour concentration difference (leaf-air) measured by simultaneous phytomonitoring in paired greenhouses. The greenhouses were either evaporative cooled (FAP), naturally ventilated with 50-mesh (N50) or 78-mesh (N78) insect-proof net on the sidewalls or 78-mesh insect proof net on the sidewalls and a shading paint with NIR-reflecting pigment on the roof (N78S).

### 4.4.3 Net photosynthesis

In all greenhouses, net photosynthesis (***$P_N$***) increased with increase in ***G*** to reach a maximum just before midday (Fig. 4.4.1 to 4.4.3). In general ***$P_N$*** was saturated when ***G*** exceeded 300 W $m^{-2}$ and $CO_2$ concentration dropped below 300 µmol $mol^{-1}$. A logarithmic relationship, similar to a rectangular hyperbola with shape parameter between 0 and 0.5, was obtained between ***$P_N$*** and ***G*** (Equation 7).

$$y = y_0 + a\ln\left|(x + x_0)\right| \text{ Valid if } (x - x_0) > 0 \qquad \text{Equation 7}$$

The values of the various parameters of equation 7 are displayed in the table 4.4.3.

**Table 4.4.3:** Parameters for the relationship between net photosynthesis and global radiation intensity measured in the evaporative cooled (FAP) or in the naturally ventilated greenhouses (N50, N78 and N78S) during the dry season 2005/2006 in central Thailand.

| | **Greenhouse combination** | | | | | |
|---|---|---|---|---|---|---|
| **Parameter** | **FAP versus N50** | | **N78 versus N78S** | | **N50 versus N78** | |
| | FAP | N50 | N78 | N78S | N50 | N78 |
| $R^2$ | 0.91 | 0.84 | 0.70 | 0.80 | 0.91 | 0.81 |
| a | 1.72 | 1.05 | 2.43 | 1.48 | 2.75 | 2.66 |
| $x_0$ | -36.36 | -61.62 | -133.43 | -38.17 | -171.84 | -225.44 |
| $y_0$ | -6.78 | -4.37 | -11.74 | -5.70 | -14.35 | -14.62 |
| SE | 0.91 | 0.34 | 0.69 | 0.48 | 0.38 | 0.49 |

The best fit (between $\boldsymbol{P_N}$ and $\boldsymbol{G}$) was obtained in FAP ($\boldsymbol{r^2}$ = 0.91) from 73 to 76 DAT. This model (equation 7) was evaluated by fitting it to data measured from 79 – 80 DAT for plants grown in FAP (Fig. 4.4.6). A good fit was obtained (Fig. 4.4.7A). The model so developed was used to simulate $\boldsymbol{P_N}$ for mature plants in the other greenhouses using a different data set (Fig. 4.4.7B and 4.4.7C). The effect of $\boldsymbol{G}$, $CO_2$, $\boldsymbol{T_a}$ and ***VPD*** on $\boldsymbol{P_N}$ was evaluated by plotting the residuals against each parameter. However, none showed a significant influence independently since the effects were coupled.

Shading significantly reduced $\boldsymbol{P_N}$ (Fig. 4.4.1). Besides, for the plants in N78S $\boldsymbol{P_N}$ lagged behind those in N78 by 30 minutes. The highest mean value of $\boldsymbol{P_N}$ was 4.3 µmol $m^{-2}$ $s^{-1}$ and 3.8 µmol $m^{-2}$ $s^{-1}$ for N78 and N78S, respectively. A lower $R^2$ value was obtained between $\boldsymbol{P_N}$ and $\boldsymbol{G}$ for N78 than N78S (Fig. 4.4.6B, Appendix Table 6.3). Moreover, $\boldsymbol{S_c}$ was significantly lower in N78 than N78S. The plot between $\boldsymbol{P_N}$ and $\boldsymbol{S_c}$ showed a lot of scattering especially at $\boldsymbol{S_c}$ values above 10 m $s^{-1}$.

In FAP $\boldsymbol{P_N}$, $\boldsymbol{G}$ and $CO_2$ concentrations were higher than in N50 (Fig. 4.4.2). Moreover, $\boldsymbol{P_N}$ increased constantly with $\boldsymbol{G}$, although hysteresis was evident in FAP (Fig. 4.4.9). Light compensation point (morning) occurred at the same time in the two greenhouses. After exceeding the light compensation point, $CO_2$ decreased by 165 µmol $mol^{-1}$ and 382 µmol $mol^{-1}$ in N50 and FAP, respectively, by the time $\boldsymbol{P_N}$ saturation occurred. Saturation occurred at almost similar intensities of $\boldsymbol{G}$ (between 200 and 300 W $m^{-2}$) but different $\boldsymbol{P_N}$ levels (2 µmol $m^{-2}$ $s^{-1}$ and 3 µmol $m^{-2}$ $s^{-1}$ for N50 and FAP, respectively) (Fig. 4.4.7A). Although $\boldsymbol{S_C}$ was higher in FAP, the correlation with $\boldsymbol{P_N}$ was better in N50.

Mean $CO_2$ concentration, in N78 was lower than in N50 in the morning but $\boldsymbol{P_N}$ was significantly higher in N78 compared to N50 (Fig. 4.4.3). Mean and maximum $\boldsymbol{P_N}$ was 3.6 µmol $m^{-2}$ $s^{-1}$ and 3.0 µmol $m^{-2}$ $s^{-1}$, in N50 and N78 respectively. The correlation for $\boldsymbol{P_N}$ and $\boldsymbol{G}$ was better in N50 (0.84) than in N78 (0.60) (Fig. 4.4.7C).

### 4.4.4 Stomata conductance

Generally, stomata conductance $S_C$ increased with increasing $G$ (Fig. 4.4.9 A, C & E). Reduction of $G$ through shading increased $S_C$. Due to the influence of other environmental and plant factors, there was hysteresis in the relationship between $G$ and $S_C$ (Fig. 4.4.9). In all greenhouses, the relationship between $S_C$ with absolute humidity was not clear (Fig. 4.3.8 B, D & F) as stomata remained either open or closed. However the stomata remained open during most of the day.

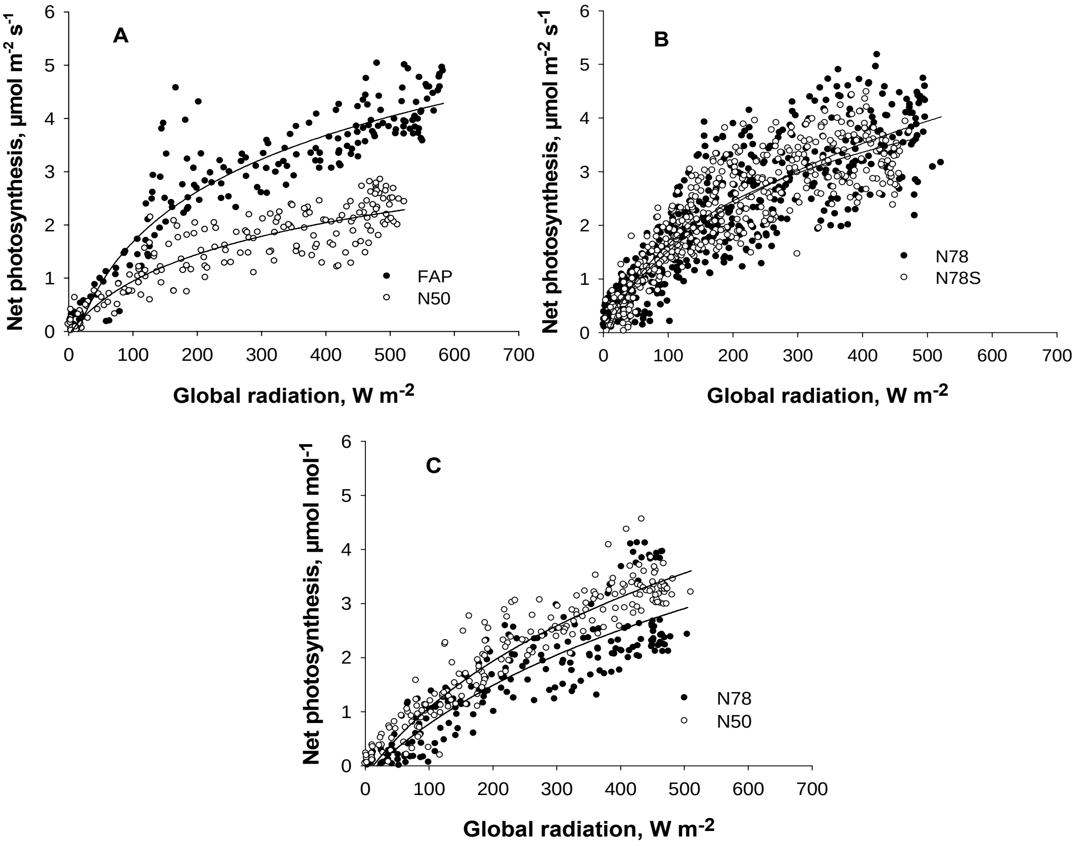


**Figure 4.4.6:** Dependence of net photosynthesis of young tomato plants on global radiation measured through simultaneous phytomonitoring in paired greenhouses during the dry season 2005/2006 in central Thailand. (A) In evaporative cooled (FAP) versus naturally ventilated with 50-mesh insect-proof net (N50), (B): Naturally ventilated with (N78S) versus without (N78) shading paint on the roof and, (C): Naturally ventilated greenhouses N50 versus N78.

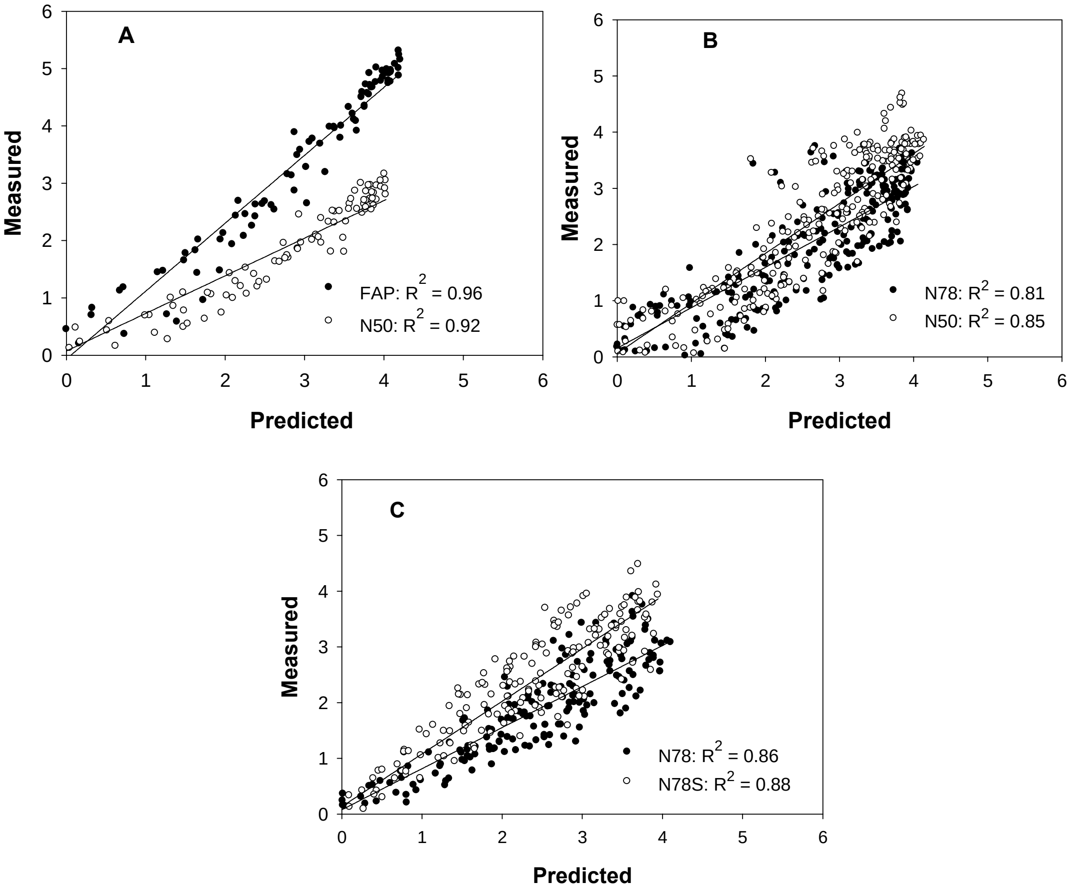


**Figure 4.4.7:** Measured versus predicted net photosynthesis for tomato plants grown in evaporative cooled (FAP) or a shaded-naturally ventilated (N78S) or naturally ventilated greenhouses in central Thailand. Data were collected 79-80 (A), 92-96 (B) or 100 – 104 (C) days after transplanting.

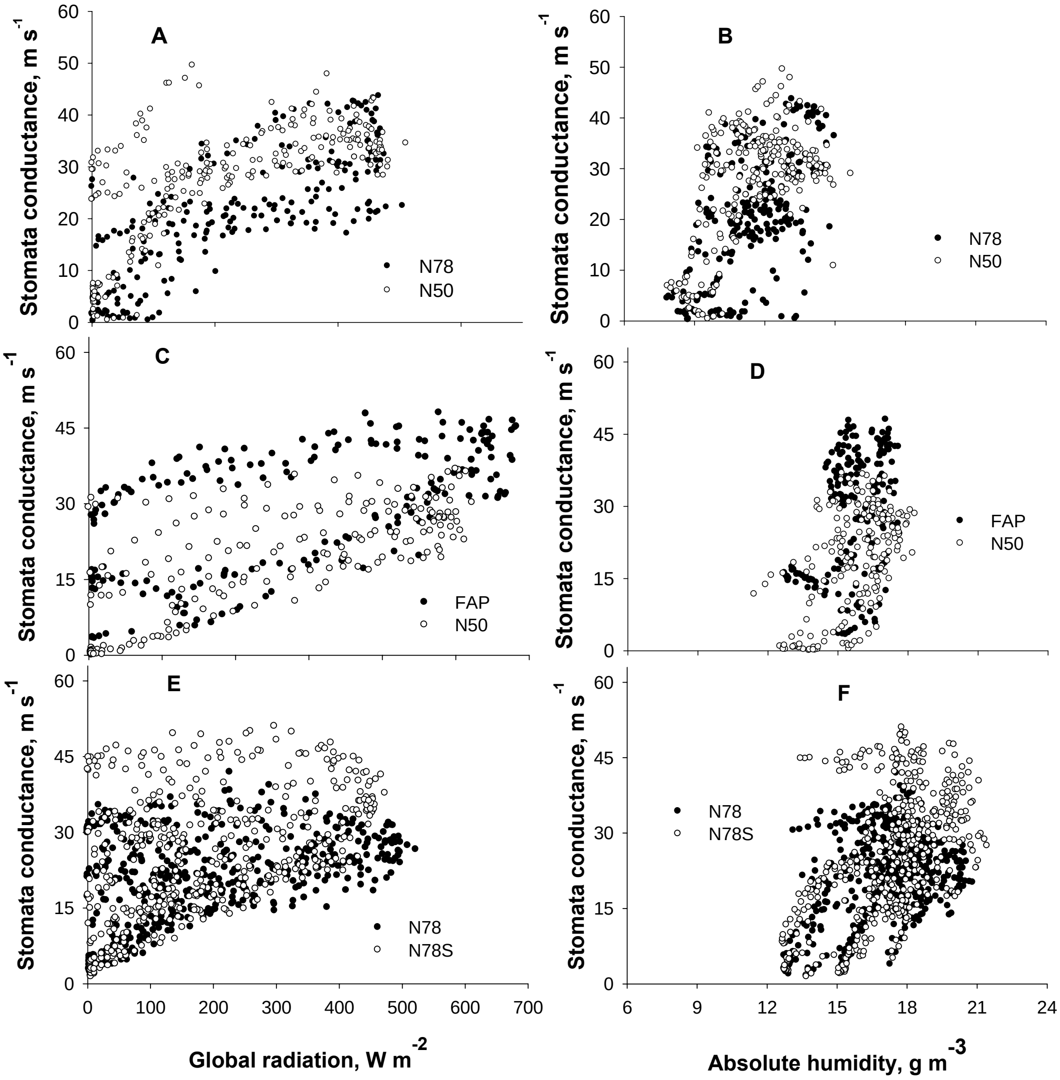


**Figure 4.4.8:** Dependence of stomata conductance of tomato plants on global radiation and absolute humidity measured through simultaneous online measurements in paired greenhouses during the dry season 2005/2006 in central Thailand. The greenhouses were either evaporative cooled (FAP), naturally ventilated with 50-mesh (N50) or 78-mesh (N78) insect-proof net on the sidewalls or 78-mesh insect proof net on the sidewalls and a shading paint with NIR-reflecting pigment on the roof (N78S).

# 5 DISCUSSION

One of the objectives of this research and the preceding works was the development of a greenhouse for the sustainable vegetable production in the tropics. It was envisaged that the greenhouse developed must support integrated plant protection and improve resource use efficiency hence yield (in terms of both quality and quantity). Moreover, the ultimate greenhouse had to meet the structural requirements of the region (strong to withstand monsoons), be affordable and support agronomic requirements of the crops especially during periods when weather is considered to be too harsh, pest pressure too high or both.

The research was split into four main parts. The first part of this research dealt with the investigation of the physical and spectral properties of various polyethylene films and insect-proof nets for covering greenhouse or use as mulches. This was followed by an investigation of the effects of the application of shading paints with NIR-reflecting pigment on the greenhouse roof on the microclimate and plant growth. The effects of natural ventilation, and fan and pad greenhouse cooling methods on microclimate and plant growth were investigated. On the last part, the plant response to greenhouse cooling method was studied using the phytomonitoring method. Tomato *S. lycopersicum* cv. FMTT260, was used as a model crop in all experiments. The findings from these studies are hereby discussed.

For covering the roof of the greenhouse, a PE film with additives for reducing the transmission of UV and NIR without reducing that of PAR was sought. In addition, for the greenhouse cover, a quality product was sought in order to avoid the problems associated with aging and subsequent negative effect on crop production. As mentioned by Briassoulis et al. (1999a), none of the roof covering materials evaluated offered all the required characteristics on its own. The PE film selected offered low and high transmission of UV and PAR, respectively, but could not block NIR. Thus an alternative, the application of shading paint with NIR-reflecting pigments, was adopted. The significance of the spectral properties of glass and PE greenhouse cover materials, especially PAR transmission, on plant growth is well understood and widely documented (Giacomelli and Roberts, 1993; Kittas and Baille, 1998).

For covering the sidewalls, several insect-proof nets were evaluated. Results show that pressure drop increased with approach velocity although the increment was higher for the finer net. The newly developed Spider net had the highest pressure drop at all measured velocities while Econet-T (78-mesh) offered a slightly lower pressure drop than the combination of 2 layers of BioNet (50-mesh). To physically exclude small insect pests like thrips that are common in the experimental area, the 78-mesh insect-proof net was chosen (Bethke, 1994), although it offered a high resistance to air flow. The 50-mesh insect proof net can physically block the entry of insect pests larger than whiteflies into the greenhouse (Bethke, 1994). As insect-proof nets have been shown to influence quantity of light inside a greenhouse (Klose and Tantau, 2004), the UV-absorbing 50 mesh insect-proof net (BioNet) met the requirements as a cladding material for the sidewalls. The other insect-proof nets investigated were not selected because they either offered too much resistance to air flow, were not UV-absorbing or had a large porosity. Due to high restriction of air flow as shown by the results from wind tunnel measurements, covering a greenhouse with two layers of the 50-mesh insect-proof net was not a suitable option.

Within the context of IPP, blocking the transmission of UV radiation has been shown to enhance non-chemical plant protection measures by influencing their visual behaviour (Antignus et al., 1998; Mellor et al., 1997). This lowers the invasion, penetration, dispersion and consequently the population of some insect pests inside greenhouses (Mutwiwa et al., 2005 a & b; Kumar and Poehling, 2006; Doukas and Payne, 2007). The efficacy of UV-absorbing PE films on plant protection was not investigated in this research but had been done previously (Mutwiwa, 2004; Kumar, 2005) while further investigations were been undertaken (Nguyen, 2007, unpublished results). Furthermore, during the ongoing investigations, results showed a reduced infestation by thrips and whiteflies in the central experimental greenhouses which were covered with UV-absorbing PE film on the roof and UV-absorbing insect-proof nets on the sidewalls (Max, 2006, personal communication).

The reduction of global radiation through shading is a common practice in the Mediterranean region since it reduces the greenhouse heat load (Baille et al., 2001). However in this research, the shading paint used not only reduced the intensity of ***G*** transmitted into the greenhouse but also modified the spectral distribution (quality). Laboratory results show that the shading paint reduced the intensity of NIR inside the greenhouse in two ways; firstly, by reducing its transmission, and secondly, by increasing its reflection. This implies that there was less energy absorbed by the surfaces inside the greenhouse hence less thermal energy was emitted. Consequently, air temperature was lower in the shaded greenhouse. Similar results were obtained by von Elsner and Xie (2003).

Results show that the shading applied for this study had the disadvantage of reducing the transmission of PAR and increasing that of UV inside the greenhouses. The reduction in PAR transmission, although minor during the dry season, was unwelcome since it lowered the amount of energy available for assimilation. This is in agreement with the results of other researchers (Hemming et al., 2005, 2006; von Elsner and Xie, 2003). In this experiment, a new layer of the shading paint was applied on top of the previous one. This is contrary to the usual practice whereby the old layer would have to be removed using a special solution (ReduClean). It is speculated that the binding agent (carrier) from the previous application of the shading paint was more responsible for the reduction in PAR transmission than the NIR-reflecting pigment itself. This is based on the fact that the reduction in PAR intensity became more pronounced after the second application of the shading paint. Another reason for the reduction of PAR intensity recorded from the instantaneous measurements is obstruction by construction parts and the dynamic weather conditions especially clouds between sampling in one greenhouse and the next.

Results of spectral measurement indicated an increase in the transmission of UV radiation by the PE film after the application of the shading paint. Although the reason behind this is unclear, it is speculated that there was a reaction between the active ingredient responsible for NIR-reflection and that for UV-absorption. The active ingredient responsible for NIR reflection might have migrated from the surface (point of application) to the lower layers of the PE film where the UV-absorbing additives are located. This increase in UV transmission caused by the shading paint with NIR-reflecting pigment might lower the ability of UV-absorbing PE films to protect plants from certain pests and diseases. Partial or complete absorption of UV radiation interrupts the lifecycle of fungal pathogens and alters the visual ability of many insects (Raviv and Antignus, 2004), while an increase in UV might cause damages at the molecular level (Roberts and Paul, 2006). During both dry and rainy season, plants grown in N78S were found to have a more severe infection by black leaf mould, *Pseudocercospora fuligena,* than those in N78. Since the two greenhouses were covered by similar insect-proof nets on the sidewalls, air exchange was similar. Thus it is speculated that an increase in UV intensity inside N78S might have increased sporulation and spread of the fungal infection, corroborating Reuveni and Raviv (1992).

The durability of the shading paint was found to be slightly less than 6 months after the date of application. Degradation of the NIR-reflecting pigment by UV and erosion by heavy rains seem to be responsible for this short service life. The small differences in $\boldsymbol{G}$ and $\boldsymbol{T_a}$ between N78 and N78S, recorded 6 months after the initial application for the shading paint support this argument. Visual inspection showed that the roof of N78 had more dirt than that of N78S. In addition during the first half of the rainy season, i.e. before the re-application, the mean value for $\boldsymbol{G_d}$ (N78-N78S) was negative i.e.-8.8 $Wm^{-2}$. This suggests that the shading paint prevented dust particles from adhering onto the surface of the PE film. Besides erosion of the shading paint, the angle of the sun in relation to the greenhouse could have influenced the intensity of radiation entering the greenhouses. When the sun rays strike the greenhouse from an angle, more radiation was transmitted through the sidewalls (insect-proof nets) as opposed to the roof. Furthermore, the spectral properties of the film were taken using a direct beam while in the field the sun strikes at an angle hence some differences are expected.

Lack of uniformity in the distribution of the shading paint on the roof surface due to the absence of a suitable application method may have lowered its efficiency in reducing the heat load and influenced the distribution of light in greenhouses (Kittas et al., 1999). The magnitude of temperature reduction by the shading paint was dependent on the ambient weather conditions especially the intensity of ***G*** and possibly wind speed. This corroborates the 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. During this research, the maximum temperature difference between N78 and N78S was found to be 2.7 °C which is higher than that simulated by Hemming et al. (2006). However, the intensity of ***G*** and method of application of the filtering agent are different between Dutch and Thailand conditions. Garcia-Alonso et al. (2006) reported a maximum temperature difference of 4.3 °C during the month of June in Spain. According to Sonneveld et al. (2006) a NIR-reflecting film reduces the heat load inside a greenhouse by a factor of two, and when combined with evaporative cooling, the water consumption is halved while the energy consumption is reduced by a factor of ten.

In addition, greenhouse type and cropping system may also influence the absolute temperature reduction by a NIR-filtering material (Hemming et al., 2006). The large ventilation openings of the naturally ventilated greenhouses used in this research influenced air exchange rate thus may have lowered the magnitude of temperature reduction. Furthermore, the position and distance of the greenhouse in relation to the others also influenced temperature reduction. For instance, the distance between N78S and the adjacent greenhouse was only 5 m. Since the fans were positioned on the Eastern gable of all greenhouses, it is believed that hot air was forced into the adjacent greenhouse. This was evident since the western wall of N78S was sagging and fluttering when the fans in the adjacent greenhouse were running. Late application of the shading paint and transpiration cooling effect of the plants and higher ambient wind speeds (Table 3.3.4) are responsible for the low average $T_d$ (N78-N78S) during the rainy season.

In this research, $T_s$ profile was similar in N78 and N78S with an almost constant difference observed from 2 WAT to the end of the experiment. Lower intensity of $G$ inside N78S led to slightly lower $T_s$ compared to N78. The lack of response in $T_s$ after the re-application of the shading paint is possibly due to the prevention of the global radiation from directly striking the substrate surface by the crop canopy. Thus the increase in $T_s$ was a result of radiation that managed to penetrate the canopy. This was however small since penetration of light in to a canopy decreases exponentially from top to bottom (Ross, 1975). Furthermore, the effect of the shading paint on $T_s$ was minimal since the leaves and mulch also reflected NIR.

The small difference in the calculated air ***VPD*** and $x$ between the two greenhouses could be ascribed to the dependence of the two parameters on the ambient conditions. The difference between the ambient $x$ and that inside N78 was similar to that reported by Harmanto (2005). In this study, the occurrence of water stress was minimal as irrigation was based either on a timer (early morning and late evening) or on the integral of solar radiation with a 25% over drain. These frequent irrigation cycles coupled with the ambient high air humidity, increased $x$ and maintained ***VPD*** levels below 2 kPa, the value beyond which stress sets in (Baille et al., 2001). However this might increase the likelihood of fungal diseases as water may condensate on the leaves and lowered transpiration (Ajwang, 2005) thereby influencing uptake of nutrients by plants (Max 2006, personal communication). Baille et al. (2001) reported a reduction in air VPD by 1-

2 kPa following the application of shading paint in a glasshouse filled with rose crop in Greece. Greenhouse cover material, size of ventilation openings, cropping system and geographical location is attributed to the difference between the observations of Baille et al. (2001) and the result from these experiments. Lorenzo et al. (2006) reported a reduction by 3.5 °C and 0.7 kPa in air temperature and ***VPD***, respectively when mobile shading screens were used under Mediterranean climatic conditions. Although the operation of mobile shading screens depends on the ambient climatic conditions, they are costly to install and operate. Their effectiveness may be improved by equipping them with a NIR-filtering agent (Hemming et al., 2006).

The performance of the fan and pad cooling system was described in section 3.3.2. In comparison with N50, $\boldsymbol{T_a}$ was lower in FAP during both dry and rainy seasons. This is attributed to the operation of the fan and pad cooling system and corroborates the results of various researchers (Cohen et al., 1983; Arbel et al., 1999; Willits, 2000a; Katsoulas et al., 2001). Ambient climatic conditions had a higher influence on the microclimate in N50 than FAP, possibly due to the large ventilation opening. Thus on days with low ambient $\boldsymbol{T_a}$, the difference in air temperature or $\boldsymbol{T_d}$ (N50-FAP) was negative. For instance on 14.05.2006 and 18.05.2006, ambient $\boldsymbol{T_a}$ was 29.6 °C and 28.0 °C, while that in FAP was 27.4 °C and 26.9 °C and in N50 was 27.1 and 25.5 °C, respectively. The prevalence of strong winds around this time might have contributed to high air exchange in N50 thereby increasing transpiration by the plants and consequently transpiration cooling.

It is already established that the main drawback of evaporative cooling systems (based on cooling pads and extracting fans) in greenhouses is the development of a thermal gradient developed along the direction of the airflow (Kittas et al., 2003b). In this experiment, temperature differences as high as 5 °C were recorded between the wet pad and the exhaust fan sides of the greenhouse. As a result of temperature gradients, the required (set point) temperature could only be achieved at the centre of the greenhouse. These gradients in the microclimate from the wet pad to the exhaust fans, can markedly affect plant growth, thus several modifications in design need to be incorporated. Arbel et al. (2003) modified the arrangement of the fans (by adding 2 extra fans on the sidewalls of a greenhouse) and obtained uniform conditions (lengthwise) inside evaporatively cooled greenhouses. Kittas et al. (2003b) investigated the combination of fan and pad cooling method with shading. They found that the combination of high ventilation rates and shading contributed to reducing thermal gradients. Sabeh et al. (2006) concluded that temperature gradients in a fan and pad cooled greenhouse could be decreased by increasing the air exchange rate of the greenhouse although this decreased the efficiency of the system. Using models Willits (2000a&b) found that increasing canopy size was more influential in reducing air temperatures.

During both dry and rainy season, ***x*** was significantly higher in FAP than N50 due to the addition of humid air when the fan and pad cooling system was operated a result likewise reported by Shen and Yu (2002) and Fuchs et al. (2006). Cooling obtained with an evaporative wet pad at the air inlet lowered the ***VPD*** in the greenhouse corroborating the findings of Liu et al. (2006) and Fuchs et al. (2006). For days with moderate evaporative demand, the difference in ***VPD*** between FAP and N50 was lower than 1.45 kPa which is in agreement with the results of Liu et al. (2006).

The cooling efficiency of the system in FAP was not constant but fluctuated with changes in ambient weather conditions. The highest value for cooling efficiency (81.5 %) was achieved on the hottest day. Several factors could have contributed to this observation: Firstly, ambient relative humidity was relatively low (60.7 %), the plants were not very tall (1.25 m) perhaps a better air exchange and finally the greenhouse was not too big (only 20 m long × 10 m wide). On the other hand, the lowest $\eta$ (50.9 %) corresponded to the day when the highest relative humidity (91.9 %) inside the greenhouse was recorded. According to Sabeh et al. (2006) lower cooling efficiency of fan and pad systems at higher ventilation rates causes a reduction in cooling. On cool days, the lower ventilation rates limited air exchange and effectively reduced cooling. Furthermore, dry portions, possibly caused by the precipitation of salts on the surface of the pads lowered the efficiency of the system further.

Light affects all aspects of growth and development, as a primary requirement for plant fitness is optimization of light harvesting for photoautotrophic growth (Roberts and Paul, 2006). The use of photo-selective films and specifically changing the ratio of red to far red radiation has been reported as one of the non-chemical ways of controlling plant height (Li, et al., 2000; Rajapakse et al., 2001). It is possible, that the differences in plant height between N78 and N78S resulted from alterations in light quality. Moreover, a small difference between the day and night air temperature decreases stem elongation hence overall plant height (Erwin et al., 1994). Thus the potential of the shading paint used in this research to control plant height (replace growth regulators) should be investigated.

The lack of uniformity in the distribution of the shading paint on the roof may have led to uneven distribution of light inside the greenhouse. Consequently plants in areas of higher illumination grew taller than those in darker areas (photo-mapping), thereby reducing the difference in plant height between N78 and N78S. Low temperature and possibly high humidity reduced plant height in FAP compared to N50. Moreover the difference between daytime and night-time temperature influences plant height. The number of trusses was directly related to plant height, it is implied that lower yields in N78S and FAP could be due to slightly shorter plants. This contradicts the findings of Hemming et al. (2006b) and Fletcher et al. (2003) who reported lack of correlation between vegetative growth parameters and fruit production, e.g. *Fragaria x ananassa* ‘Elsanta’. More so, the ratio of red to far red radiation has a significant effect on the partitioning of resources (Crotser et al., 2003).

In agreement with Heuvelink (1995 a & b) temperature reduction by both shading and evaporative cooling did not appear to influence ***DM*** partitioning significantly. During the rainy season, total ***DM*** was double that recorded in the dry season. This suggests that more than one climatic parameter (not just temperature) influenced ***DM*** allocation. Lowering $\boldsymbol{T_a}$ by shading or using fan and pad cooling increased the water content of plant organs but not dry matter. Hemming et al., (2006b) reported insignificant differences in the vegetative growth parameters of *Fragaria x ananassa* 'Elsanta' grown under newly developed fluorescent films, which supports our findings.

Leaf area obtained during the rainy season was half that recorded during the dry season. Plants reacted to heat stress by decreasing leaf size. Besides, during the rainy season, many leaves were thin, spike-shaped and curled inwards, to possibly reduce the area exposed to direct radiation thereby minimise transpiration. This is similar to observations in rose flowers which adapt to high ***VPD*** by adjusting the leaf area for maintaining high sap flow rate per unit area (Liu et al., 2006). During the rainy season, an increase in ***LAI*** was observed in N78S after the re-application of the shading paint, showing that plants recovered from heat stress. Higher LAI were reported for tomato in similar greenhouses by Harmanto (2006). This author reported LAI of 3 $m^2\ m^{-2}$ for FMTT260, while a maximum of 2.9 $m^2\ m^{-2}$ in this research. These differences between the results of Harmanto (2006) and from this research could be due to a higher crop density. Season of the year influenced LAI differently, For instance; during the dry season, plants in the N50 and N78 increased their LAI compared to those in N78S and FAP. On the contrary, plants FAP and N78S had a slightly higher LAI during the rainy season. Increasing LAI by increasing the planting density and maintaining 2-stems per pot may increase temperature reduction by the cooling effect by the transpiring crop (Kleinhenz et al., 2006). Moreover, LAI influenced the temperature reduction caused by transpiration cooling (Katsoulas et al., 2001).

Yield is a manifestation of various physiological processes occurring in plants which may be influenced /or modified by the imposed management practices (Gill and Narang 1993). For instance, through pruning (removal of side shoots and lower leaves), a good balance between fruits and leaves was maintained, while an efficient ventilation system controls the microclimate. In the experimental greenhouses, 10 flowers per truss were maintained as recommended by Chen and Lal (1999), while all leaves below the first fully harvested truss were removed. This diverted nutrients to flower clusters and fruits on the main stem and improved air circulation (Chen and Lal, 1999). Thus the low marketable yield despite favourable temperature in FAP (mainly caused by an increase in the number of cracked fruits) could be improved by having more flowers per truss. This may increase the sinks for water and assimilates thereby producing many fruits of an average size minimising fruit cracking. According to Ho (1989) the ability of sink to attract assimilates depends on sink activity and size.

In general higher yields, both marketable and non-marketable categories, were recorded in N78 and N50 compared to FAP and N78S. Shading lowered photosynthesis and the proportion of resources allocated to fruits, hence consequently yield. On the other hand, fan and pad cooling increased both photosynthesis and proportion of resources allocated to fruits but this did not result in increased yields, due to higher losses through fruit cracking and infection of flowers by fungal diseases.

The reduction in BER by the shading paint with NIR-reflecting pigment is attributed to the reduction in transpiration of the plants in response to the microclimate improvement. The fact, that typical symptoms of Ca-deficiency such as contorted growth, tip die back and curled leaves were less frequently observed in N78S is corroborating this interpretation. Since fertigation was the same in both greenhouses, the variations in moisture of the substrate in N78S was lower compared to N78 thus reducing leaf transpiration and consequently the deficiency of Ca on the mature fruit by enhancing Ca-transport to fruits (Ho et al., 1993). High irradiance enhances leave transpiration thus $Ca^{2+}$ absorbed by the roots is predominantly transported towards the leaves rather than to the fruits thereby increasing BER (Saure, 2001). Relatively high irradiance and high temperatures are likely to be responsible for the increased number of BER affected fruits in the rainy season. High temperature stimulates cell enlargement (greater rate of fruit enlargement) thus without an increase in supply of calcium on the distal end of the fruit, BER occurs (Ho et al., 1993). Reducing the VPD may affect fruit growth by improving the leaf water status (Stirzaker et al., 1997) which increases leaf conductance and hence $CO_2$-assimilation (Bakker, 1990) and decreases fruit transpiration (Leonardi et al., 2000).

One of the reasons for the increased number of cracked fruits in N78S could be seen in the reduced transpiration possibly entailing an increased water influx into the fruits (Guichard et al., 2001; Dorais et al., 2007). Peet and Willits (1995) reported a clear relationship between excess water availability to plants and tomato fruit cracking, although this increased the fresh weight of total yield. Moreover high day and night temperature drastically impede tomato flowering (Dane et al., 1991), pollination (Adams et al., 2001) and fruit set (Dane et al., 1991; Peet et al., 1997) resulting in increased numbers of parthenocarpic fruits and hence lower marketable yields (Kleinhenz et al., 2006). According to Peet et al. (1997), the optimal mean daily temperatures for tomato are between 21 and 24 °C which were below the mean $T_a$ during this experiment. Depending on developmental stage and temperatures only a few degrees above optimal can reduce fruit production and seed set (Peet et al., 1997).

The results indicate that none of the cooling methods influenced the brix and pH contents of the fruits. The measured values were found to be close to each other although fruits from ***FAP*** were more succulent. This contradicts Bertin et al. (2000), that reducing ***VPD*** dilutes both the dry matter and sugar content of tomato fruits.

Through photosynthesis, light controls much of the biochemical activity within plant tissues. In this research, plants grew in a constantly evolving greenhouse environment. Generally, this is a very complex process involving the interaction of various parameters. Through phytomonitoring, $\boldsymbol{P_N}$ and $\boldsymbol{E}$ were measured under natural conditions inside different greenhouses. In all the greenhouses, $\boldsymbol{P_N}$ increased with $\boldsymbol{G}$, although saturation point is not clear, similar to the findings of Tartachnyk and Blanke (2007). This is attributed to the fact that all measurements were conducted on the upper most actively growing leaves which have maximum $\boldsymbol{P_N}$ to meet the needs of the whole plant. According to Acock et al. (1978) the upper most layers assimilate as high as 66 % of the net $CO_2$ fixed by the canopy. Thus the leaves selected for the measurements during this experiment might have worked more than the average leaf in order to meet the demand for the whole plant. In agreement with the results of Ayari et al. (2000), $\boldsymbol{P_N}$ were maximal early in the morning and then markedly declined during the day even though the incident light was still rising**.** As light and water were not limiting, it is speculated that $\boldsymbol{P_N}$ was limited by $CO_2$ concentration and air temperature.

Due to the nature of the greenhouses it was not possible to independently investigate the effect of each environmental factor on any of the plants physiological processes. It is surprising that the $CO_2$ concentration both in and outside of the greenhouses dropped below the known ambient e.g. 350 µmol mol$^{-1}$ (Bunce, 2000). During previous experiments, Indriasari (2005) recorded minimum values for $CO_2$ concentration between 210 µmol mol$^{-1}$ and 265 µmol mol$^{-1}$. Actively growing vegetation and water masses around the experimental site may have contributed to this rather low ambient $CO_2$ levels. Although the porosity of an insect-proof net influences greenhouse air exchange rate (Harmanto, 2006; Fatnassi et al., 2002; Teitel, 2007), the infiltration of $CO_2$ from ambient into the N50 and N78 was not significantly reduced. The large ventilation openings (and forced ventilation in FAP) maintained equilibrium between $CO_2$ concentration in the ambient and inside the greenhouses. Dark respiration increased $CO_2$ concentration in all greenhouses during the night although the maximum values were below those reported by Tartachnyk and Blanke (2007). Although the difference in ***G*** and $\boldsymbol{T_a}$ between N50 and N78 was not significant, $\boldsymbol{T_L}$ and $\boldsymbol{P_N}$ were higher in the former. The reasons for the higher $\boldsymbol{P_N}$ recorded in ***N78*** are not clear. However it is speculated that this could be as a result of lower $\boldsymbol{T_L}$ (due to high ***E***) and lower wind speed (due to low porosity).

The results of the effects of shading on ***G*** were described in section. 4.2.1. By reducing the intensity of ***G*** inside N78S, $\boldsymbol{P_N}$ was significantly reduced. In general, the results of higher stomata conductance with increasing light flux density and temperature agree with Kozlowski (1976). However the fact the measured $\boldsymbol{S_C}$ was higher in ***N78S*** than ***N78*** seems to contradict this theory. The non-uniform spread of the shading paint in ***N78S*** might have created varying light condition inside the greenhouses. Under such conditions, in one mesophyll region the stomata are open and there is a correspondingly high photosynthetic rate, whereas in an immediately adjacent region the stomata are partially closed and the mesophyll has a low photosynthetic rate (Terashima, 1983). This phenomenon, termed patchy stomata, might arise under low illumination, or when leaves are stressed. Although patchy stomata may reflect normal interactions between stomata and leaf mesophyll (Siebke and Weis, 1995), patchiness can lead to inaccurate determinations of $\boldsymbol{P_N}$.

Extreme high temperature during the rainy season could not allow for the online measurements of plant response (e.g. dying of leaves inside cuvettes). The lower yield in N78S corresponds to the low $\boldsymbol{P_N}$ recorded. Shading reduced ***E*** during both seasons corroborating the findings of Sonneveld et al. (2006). Simulation results from Kittas et al. (2003) showed that stronger shading reduces the transpiration demand, but proportionally reduces photosynthetic rate and, consequently, the expected yield. This corroborates the findings of Baille et al. (2001) and Lorenzo et al. (2006). Thus increasing the concentration of the shading paint applied onto the roof may not be useful as this may significantly reduce yield.

The relation between ***E*** and ***$S_C$*** in the shaded greenhouse is puzzling. Compared to N78, shading increased ***$S_c$*** but this did not necessarily increase ***E***. Since plants were not subjected to water stress (frequent irrigation cycles) this suggests that the stomata were responding to other factors within the plant and not just the environmental factors (Kozlowiski, 1976). For instance, stomata may also close in response to hormonal signal (abscissic acid) from roots that are subjected to stress other than water deficiency (Zhang and Davies, 1990). Besides, stomata closure in N78 could have been induced by restriction in water transport due to the long stem (plants were taller in N78) or an older less efficient root system unable to absorb water to meet transpiration demand even though irrigation was adequate (Ayari et al., 2000). The high ***E*** recorded in FAP compared to N50 is attributed to higher air exchange (in FAP) induced by the operation of the exhaust fans inside the greenhouse. Operation of the fans in FAP resulted in an almost immediate reduction in $CO_2$ concentration. However, there was a delay (almost 45 minutes) between the time when the reduction in $CO_2$ concentration occurred (i.e. time when fans start operating) and when the corresponding reduction in photosynthesis was recorded.

However, every technique has limitations. In this research, online measurements were taken from few leaves on 4 plants per greenhouse. Extrapolating these results to a whole greenhouse (300 plants) may result in errors (over or under estimation) since there are variations/gradients in the microclimate inside a greenhouse. Problems might arise when some stomata are closed and others are open, especially in leaves in which discrete regions of mesophyll are sealed off from each other by leaf veins. Moreover, the effect of temperature above the specifications of the ***GES***, even it lasts only for a short duration, and may influence its accuracy. For instance, some leaves inside cuvettes died from scorching due to high temperatures during the rainy season. This could imply that depending on the intensity of ***G***, the conditions inside the leaf cuvette could be different from those in the greenhouse environment. Furthermore, the duration of the interaction between the air sucked through the cuvette and the leaf depends on the speed of the diaphragm pump which could be higher than ambient wind speed. In addition, the equations used in the ***GES*** model assume uniform stomata behaviour across the leaf surface, which might not be the case in reality as plants are either amphistomatous or hypostomatous. Besides, data from plant response measurements were continuously collected. Hence, errors resulting from disturbances of sensors e.g. increased $CO_2$ concentration due to the presence of personnel in the proximity of the GES, movement of leaf temperature sensor or leaf in cuvette during pruning etc can not be accounted for. Sensor location, for instance intensity of ***G*** reaching the leaf and recorded by the solarimeter (roof), could also have contributed to inaccurate interpretation of $\boldsymbol{P_N}$ especially due to shadows. Condensation of water in the pipes connecting the leave cuvettes and the mixing chamber may have led to errors in the measurement of transpiration. Moreover, cropping systems and greenhouse position in relation to the others could have influenced the results. For instance; in N50, although measurements were conducted from plants receiving similar treatments as those in N78, plants in the adjacent rows received a different fertigation (extra irrigation) at night. This influenced among other things, the air humidity inside the greenhouse which may trigger different response from the stomata, than in uniform cropping system. In addition, in-order to fill the area inside the cuvette, 2 or 3 leaves were occasionally used. Thus overlapping of leaves could not be avoided. Since, tomatoes have stomata on both surfaces (amphistomatous) it is not clear how this influenced the $CO_2$ depletion since the airflow rate through the cuvette was not adjusted.

# 6 CONCLUSIONS AND RECOMMENDATIONS

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 mesh size significantly influenced the resistance to air flow across insect-proof nets. When an insect-proof net is fixed in front of ventilation openings both mesh size and spectral characteristics should be considered especially when the objective is pest exclusion.

Results from spectral measurements show that newly applied shading paint with NIR-reflecting pigment doubled the transmission of UV radiation and decreased that of PAR and NIR-A by 17.7 % and 26.5 %. Moreover the efficiency of the shading paint decreased with time, being almost ineffective 6 months after application. In addition, this shading paint protected the film from ageing especially by improving the film's anti-dust characteristics. The application of shading paint with NIR-reflecting pigment on the greenhouse roof reduced air and substrate temperatures by a maximum of 2.8 °C and 3.5 °C, respectively during the dry season. The magnitude of the temperature reduction was influenced by the time of application in relation to stage of plant growth. Air water content was reduced by 1.6 g $kg^{-1}$ and 0.4 g $kg^{-1}$ during the dry and rainy seasons, respectively. Leaf transpiration was lower in the greenhouse with shaded compared to control. Consequently, cumulative water consumption between 4 and 17 WAT was reduced by 8.8 % and 6.2 % during the dry and rainy season, respectively. However, this did not significantly influence water use efficiency (calculated as the total yield per plant divided by the total water used between 4 and 17 WAT).

Compared to control, shading reduced the number of BER affected fruits by 43 % and 30 %, during the dry and rainy seasons, respectively. As a result, the proportion of non-marketable yield in N78S was reduced by 59.0 % and 16.0 %, during the same time period. The reduction in BER is attributed to the reduction in transpiration of the plants in response to the microclimate improvement. However, shading increased the number of cracked fruits by 16.1 % and 43.1 % during dry and rainy season, respectively. The reduction in total yield in the shaded greenhouse (though not statistically significant) was as a result of the reduction in net photosynthesis due to a reduction in the intensity of PAR. Moreover, shading had a slight influence on plant height, number of trusses, improved leaf area index and dry matter partitioning. Besides, by selecting the colour of plastic film to coat the near-infrared reflection layer, the concepts of using spectral filters to regulate plant growth can also be easily applied.

Fan and pad cooling system reduced air temperature by 3.0 °C and 2.7 °C, during the dry and rainy seasons, respectively, compared to a naturally ventilated greenhouse with 50-mesh insect-proof net on the sidewalls. However, this was accompanied by an increase in air water content by 1.6 g $kg^{-1}$ and 0.8 g $kg^{-1}$ during dry and rainy seasons, respectively. Air ***VPD*** was lowered by 0.8 kPa during both seasons. Air temperature and humidity gradient was observed in the greenhouse equipped with a fan and pad cooling system. Temperature differences as high as 5 °C was recorded between the pads and the fan side. In addition, the efficiency of the fan and pad cooling system was dependent on the ambient weather conditions. Disease incidence (especially fungal infections) and nutrient deficiencies were higher in the greenhouse equipped with the fan and pad system compared to the naturally ventilated one. Moreover, crop water requirement water use efficiency was higher and lower, respectively, in the naturally ventilated greenhouse.

Results from online measurement of plant response show that shading reduces leaf transpiration but it also lowers net photosynthesis and consequently yield. On the other hand, evaporative cooling enhances net photosynthesis due to two factors: (1) lowers air and leaf temperature and (2) higher air exchange maintains a balance between ambient $CO_2$ concentration and that inside the greenhouse. Although decoupling of other environmental factors was not possible, the results suggest that mesh size significantly influences both photosynthesis and leaf transpiration. Low porosity of the mesh size reduces wind speed (higher resistance to air flow) and thus leaf transpiration. Moreover, results from FAP and N50, show that there is a time delay between when changes occur in the greenhouse microclimate and when the plants respond.

Thus the cooling system, which consists of ventilation fans with covering materials having near-infrared reflection capability, may provide the best cooling methods among others. This cooling method has advantages such as heat load are lowered by reducing the near-infrared portion of incident solar energy, excessively high humid conditions are avoided, undue loss of photosynthetic active radiation is minimal, and light quality may also be controlled by selecting the colour of covering materials. Due to the vertical gradients in air temperature (highest at the top) increasing the greenhouse height by a few meters could beneficial several ways:- improving the chimney effect, shifting the high temperature to beyond the canopy and uniformity of light distribution (minimising the effect of shadows from construction parts). Installation of extra fans on the greenhouse roof may improve air circulation within the greenhouse. If and when a fan and pad cooling system is to be used, then it should be modified e.g. adding more exhaust fans on all sides and above the canopy so as to minimise temperature and humidity gradients. However this may increase wind induced transpiration.

The reduction in marketable yield (though statistically insignificant) corresponds with the reduction in PAR transmission into the greenhouse. The reduction in income could be compensated by the savings from resource use mainly water and power.

To avoid warm air from adjacent greenhouses the distance between 2 adjacent greenhouses ought to be put into consideration. The shading paint should be applied just before the plants are transplanted in to the greenhouse and re-applied as necessary (after 4 to 6 months for Thailand). A high leaf area index should be maintained in order to cool the greenhouse further. However, the use of NIR-filtering materials should be discouraged during periods of low irradiation (winter) as this may result in an unwanted temperature and light reduction. Further research is necessary in order to improve the performance of the gas exchange system especially when the environment is harsh. In addition, the effect of the shading paint on plant growth should be investigated further. Due to the incidences of fungal infection and fruit cracking fan and pad cooling systems appear to be not recommendable for semi-humid and humid areas in the tropics, unless distinct technical modifications, which could improve its performance, are introduced.

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