



Effect of net size on horizontal temperature gradients in naturally-ventilated tropical greenhouses

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Abstract

Experiments were conducted in four greenhouses of sizes 3 m x 6 m x 3.2 m (W x L x H) with tomato crop inside, to study the spatial distribution of air-temperature under naturally ventilated condition. HDPE insect-nets of 32, 40, 50 and 78 mesh having 53, 34, 33 and 19% porosity, respectively, were used for greenhouses-cladding. Both absolute and relative stress-gradients of temperature were observed along the central horizontal (x and y) axes of 3 m x 6 m greenhouse structure with x as semi-minor and y as semi-major axes. A real-time comparison was made among greenhouses for young and matured plants and two plant densities, single and double. Younger plants occupied 5% of gutter height while matured stunted 50%; plant density was doubled from average 1.7 plant/m² to 3.3 plants/m² with three and five rows kept lengthwise, respectively. Horizontal (x) locations exhibited 12% temperature gradients that were found insensitive to vegetation but lowering net porosity increased these gradients from 8 to 12%. There was 10% temperature gradient recorded in horizontal (y) locations, which decreased with decreasing vegetation, especially with plant height. It was further noted that horizontal air-temperature gradients responded considerably slower towards plant density; rather they found to be more sensitive against plant height. Plant density, on the other hand, altered their peak absolute values. Doubling plant density reported significantly higher horizontal temperature gradients.

Key words: Greenhouse, insect nets, temperature gradients, microclimate, tomato.

Introduction

Greenhouse microclimate ultimately governs the product quality, production and amount of input resources. Greenhouse microclimate depends on various factors including greenhouse cladding material. Investigation of heat distribution in greenhouses has been of great importance for designing either ventilation, cooling or heating systems. Horizontal air movement helps minimize air temperature gradients, and uniformly distributes moisture and carbon dioxide. The overall optimization of the greenhouse microclimate requires a thorough knowledge of the quantitative (rates) and qualitative (pattern) mechanisms of natural ventilation¹⁻⁴.

The temperature gradients across the greenhouse at plant level are the most important concern and the prediction of such gradients was found to be difficult because the nature and steepness of such gradients is complex⁵. It was concluded that the temperature distribution in greenhouse is one of the factors that influence the uniformity of crop growth and was remarked that not much work has been published on the temperature and humidity distribution within a naturally ventilated greenhouse⁶. The small air-temperature differences could alter the time of first flowering for tomato plants and had a direct effect on the sink strength of individual organs of the plant⁷. It was confirmed that to attain an improved bio-control and to have more insight into response of the plants to microenvironment, one must be well aware of temperature distribution surrounding it⁸. Scientists compared un-shaded, single plastic film clad with no crop and double cladding cover greenhouses and found that the temperature gradient was reduced by 50% when full crop cover was present, a further 45% reduction was observed with 50%

external shading, and using double cladding provided an additional reduction of 20%⁹.

Only a limited control of airflow in the greenhouse can usually be achieved by natural ventilation¹⁰. In natural ventilation, location and type of the greenhouse, location of ventilator openings and climatic characteristics (wind velocity, wind direction and temperature) influence ventilation rates. The main advantage of natural ventilation is its low cost of operation¹¹.

Insect proof nets induce a strong additional pressure drop through the openings, which significantly reduce the ventilation rate and an increase air temperature. Insect screens maintain controlled-climate inside, simultaneously help keeping away the insects/pests and thus eliminating use of harmful chemicals or pesticides¹²⁻¹⁴. Insect screens are available in different opening sizes. Apart from commercial names, the screens are normally described by mesh sizes, which give the number of threads per linear inch in each direction¹⁵. Researchers have suggested screen mesh-size for exclusion of various insects. These nets reduce ventilation through it by offering resistance to air-exchange between inside and outside greenhouse and thus affect the interior climate. The situation becomes more critical under naturally ventilated greenhouses^{16, 17}.

Spatial distribution of temperature has been recognized as important factor influencing crop growth uniformity and it was emphasized by researchers to understand the heat distribution in naturally ventilated greenhouses in order to develop optimal ventilation system. Despite numerous studies have been carried out for insect screens, yet mostly attributed to windows or vents, not much research was devoted towards full insect screened

net-house for tropical climates. Greenhouse covering material selection is very important to suit the insects' exclusion from crop inside. Tropical regions are susceptible to unevenly distributed yearlong rains. It is thus a general practice to use insect screens around sidewalls of a greenhouse while the roof has to be covered with plastic sheet. Effects of cladding materials on temperature distribution pattern in greenhouse microclimate and stress levels in terms of their gradient in horizontal directions were assessed in this study¹⁸.

Materials and Methods

Experiments were carried out at greenhouse complex of Asian Institute of Technology, Bangkok (Thailand) during mid April to late June 2003. Four high density polyethylene (HDPE) nets with 32 (53%), 40 (34%), 50 (33%) and 78 (19%) mesh-sizes (% porosity) coded as A, B, C, D, respectively, were used to clad greenhouses for growing tomato crop. Percent porosity of these nets was calculated by measuring wire diameter with profile-projector. Opening size, inside to inside dimensions of hole ($\mu\text{m} \times \mu\text{m}$) of insect nets A (780x755), B (355x330), C (785x210) and D (135x135) was computed after measuring wire diameter (μm) as 285, 245, 265 and 175, respectively. King Kong-2 tomato seeds were sown in multi-trays in March when the average daily temperature was 28°C and 81% average RH. The trays were kept inside a nursery and watered manually. Four weeks after sowing (WAS) in April, seedlings were transplanted into plastic pots. Each pot was containing approximately 4 kg (oven-dried weight) soil substrate.

Greenhouse construction: Four greenhouse skeletons of GI pipes were erected with East-West orientation. The name 'A' was given to the most Eastern structure and B, C and D to the successive West, respectively. A hinged door was provided on the Eastern side with handle lock. Gravel flooring was used to raise plinth level by 5 cm to prevent surface runoff entrance and reptiles' insurgency. The structures had EW dimension of 6 m (length), and NS dimension of 3 m (breadth). The total vertical height was 3.2 m with gutter stood 2.2 m high from ground. Greenhouses, throughout its roof length (*i.e.* 6 m) were provided two-way roof openings (ridge-vents) with 40 cm wide air passage.

Cladding material: All four greenhouses were covered at roof with LDPE (low density polyethylene) sheet, from top of the roof to gutter height. A 40-mesh HDPE insect net was used to cover two-way roof opening vents, protecting greenhouse against direct insect/pest infusion. Insect nets of 32-, 40-, 50-, and 78-mesh were used for cladding. Eastern-most greenhouse 'A' was covered with 32-mesh and successively in the sequence, the Western-most was cladded by 78-mesh HDPE net.

Irrigation and fertigation system: Automatic drip irrigation and fertigation system was used to irrigate tomato plants in all four greenhouses. The fertigation system was attributed to soil temperature and solar radiation for automatic actuation. Drippers of 2 lit h⁻¹ capacities were connected to lateral pipes for individual plant. Irrigation duration was set 10 minutes per application during young plant stage, while it was increased to 14 minutes at matured plant stage. Depending on climatic conditions irrigation frequencies of 6 to 8 times a day were used.

Instrumentation and accessories: Outside climatic data including wind velocity, wind direction, rainfall, light intensity and outside solar radiation were obtained from the weather station. Data logging system of the four greenhouses mainly comprised of thermocouple (TC) sensors, multiplexer boards (Campbell AM416 relay multiplexer), dataloggers (Campbell CR-21x), storage modules, interface card (Campbell PC 532), personal computer and compatible software. Sixteen-gauge solid alloy, twisted single paired, overall shielded, ANSI color-coded, Copper-Constantan (Type-TX, ANSI standard) thermocouple extension wire was used to measure temperature at various locations. After connecting thermocouples with multiplexer and datalogger, the whole setup was calibrated for 25–50°C operating temperature range in a Memmert water bath using distilled water.

Experimental setup: TC sensors were mounted on bamboo sticks, erected in and outside greenhouses. Fig. 1 depicts mounting TC sensors at various locations along two horizontal axes in the greenhouses. The sensors along South wall represented horizontal 'x' axis with 'zero' mark at 'common' point. Sensors mounted along West wall denoted horizontal 'y' axis with 'zero' mark at 'common' point and increasing Westward. Vertical or 'z' axis had 0.5 m apart five locations, South or semi-minor axis or 'x' axis had 0.5 m apart four locations and West or semi-major axis or 'y' axis had 0.75 m apart five measurement locations. The 'common' point location was the same for all three axes. Thermocouple locations were numbered as 6-12 in horizontal direction, all 0.5 m above ground. Locations 3 and 6-8, on horizontal-x semi-minor axis were 0.5 m apart from each other while Locations 3 and 9-12, on horizontal-y semi-major axis were 0.75 m apart.

Two plant densities, single and double were used for study. A plant density of 1.7 plants/m² was considered as single density (S), which was obtained by placing three rows of 10 plants each. Rows were placed lengthwise *i.e.* East-West. For double plant density (D) of 3.3 plants/m², five rows of 12 plants each were distributed in greenhouses with similar orientation. Temperature inside the greenhouses and ambient air temperatures were simultaneously recorded every minute.

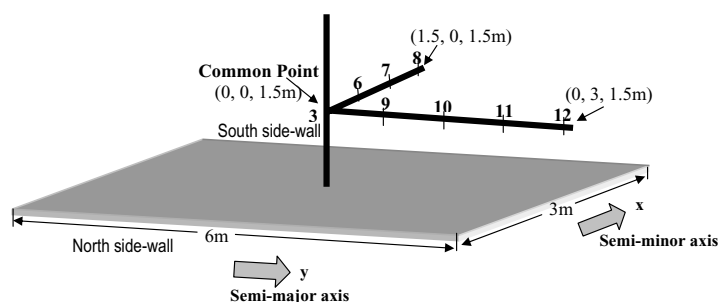


Figure 1. Arrangement of TC sensors on bamboo sticks inside greenhouse, horizontal axes (x and y) are coordinated with origin at floor central plane.

Results and Discussion

Horizontal diurnal variation of air temperature: Temperature gradients were studied for horizontal-x and -y directions (semi-minor and semi-major axes) with the all five configurations (Empty, Ys, Yd, Ms and Md: where Empty stands for empty greenhouse without crop inside; Y and M stand for young and mature plant stages, respectively; s and d represent single and

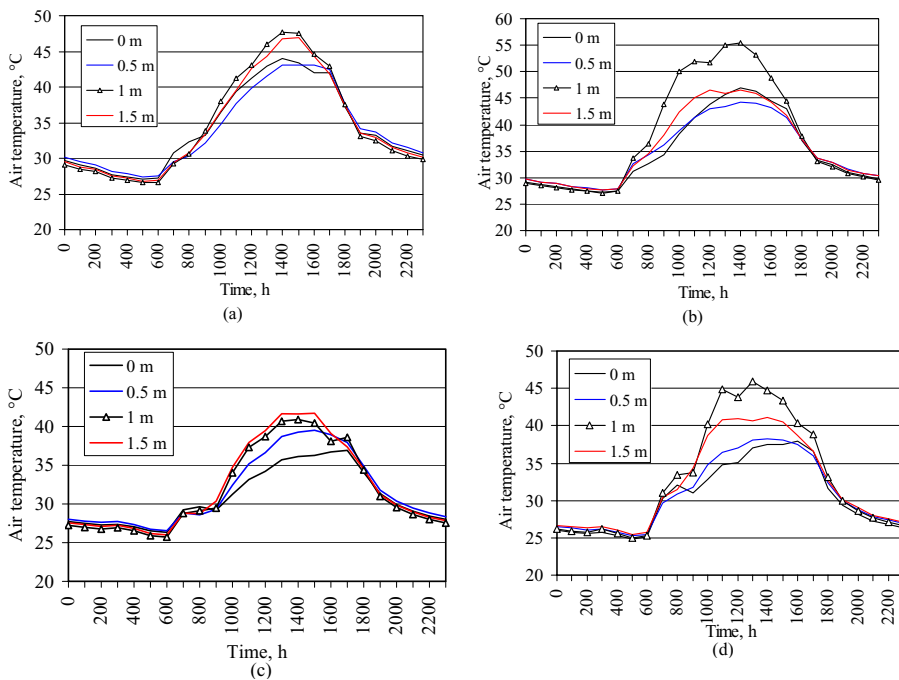


Figure 2. Horizontal-x diurnal variation of greenhouse air temperature, °C (a) Young plant single density -B; (b) Young plant single density -D; (c) Matured plant double density -B; (d) Matured plant double density -D.

double plant densities, respectively). Under all operating conditions, absolute temperature values and gradients varied significantly with the solar radiation. The highest values were found with peak solar hours *i.e.* 1200-1400 h, during bright days. Fig. 2 shows typical diurnal variation of air temperature at different horizontal-x semi-minor locations of greenhouses -B and -D, whilst Fig. 3 shows the similar information for horizontal-y semi-major axis. Results from the study conducted by Zhao et al.⁶ also reconfirmed that the temperature distributions inside a greenhouse

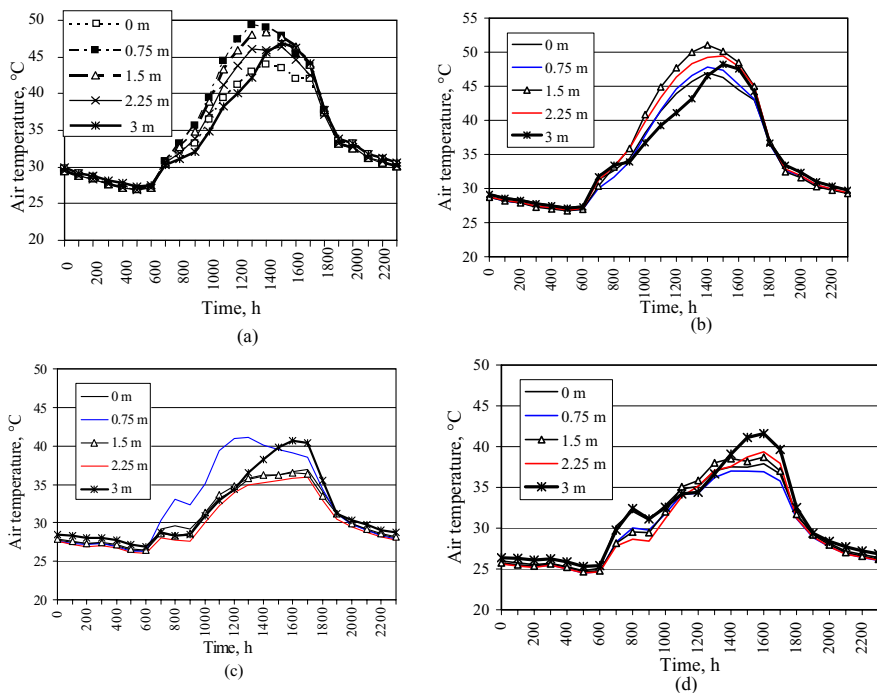


Figure 3. Horizontal-y diurnal variation of greenhouse air temperature, °C (a) Young plant single density -B; (b) Young plant single density -D; (c) Matured plant double density -B; (d) Matured plant double density -D.

varied significantly with the solar radiation intensity. The largest values occurred with the solar radiation peak, around noon.

Horizontal absolute peak air temperature:

The absolute values of horizontal-x peak air temperature during 24 h for four greenhouses (A, B, C and D) at four horizontal-x semi-minor locations (3, 6, 7 and 8) for Empty, Ys, Yd, Ms and Md were measured. Data were corresponding to the average of repetitions for several bright sunny days. As a general trend, location-7 (the two-third distance away from greenhouse-center or one-third distance from side-wall), showed all-time maximum air temperature inside all greenhouses. Figs 4 and 5 demonstrate results for different horizontal-x locations and different greenhouses, respectively. It was also noted that for all greenhouses absolute peak air temperatures were higher than that of the ambient temperature.

For Empty greenhouse condition, a significant temperature difference in greenhouse GH-D and GH-A, -B, -C, -D was observed. Greenhouse GH-D exhibited the highest absolute peak air temperature as compared to the rest and the average difference was 3-5°C. It supported the obvious expectation of occurring less air-transaction through the least porous screen, resulting higher air temperature in corresponding greenhouse. At Ys and Yd configurations there were no significant differences in peak absolute temperatures among greenhouses; shorter plants were hardly able to influence microclimate, while the same was altered with taller plants inside. Statistically significant difference was found in Ms configuration between GH-A and -C; GH-C exhibited the highest absolute peak air temperature as compared to the rest; the difference was 1-2°C. In the Md vegetation configuration, there was significant difference in absolute peak air temperature between GH-C, -D and GH-A, -B; GH-C and GH-D showed higher absolute peak air temperature, which was about 2°C higher than the rest. The location-7 showed the highest absolute peak air temperature, while the location just near to side wall showed a peculiar sudden drop in temperature. The probable reason might be the effect of adhere-ness of air-mass near the walls. Higher number mesh resulted higher peak air temperature, probably due to lesser air-exchange caused by restricted ventilation through smaller porosity apertures. Doubling plant density caused lowering peak air temperature in all greenhouses. These results confirm to those by Anon.¹⁹ who concluded

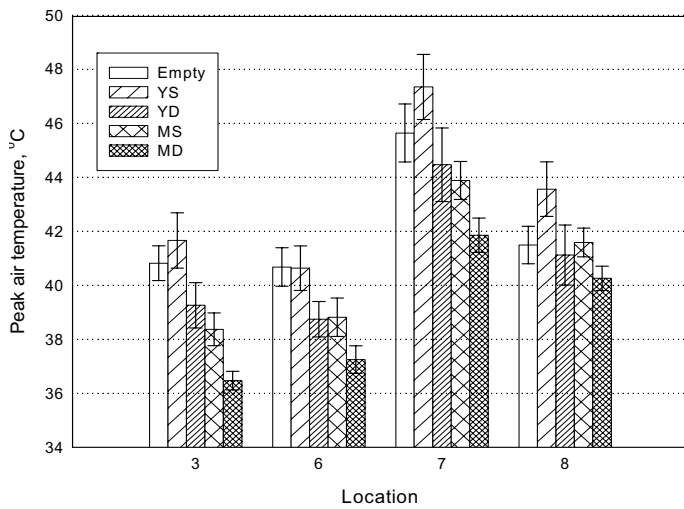


Figure 4. Absolute peak air temperature for different horizontal-x locations.

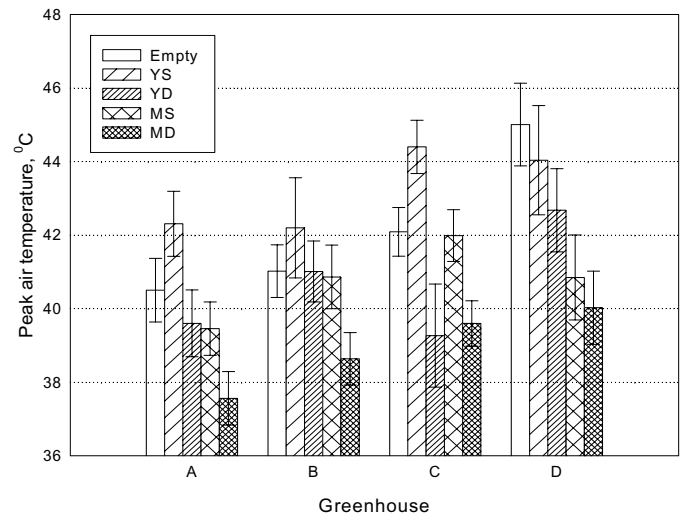


Figure 5. Absolute peak air temperature for different greenhouses [horizontal-x].

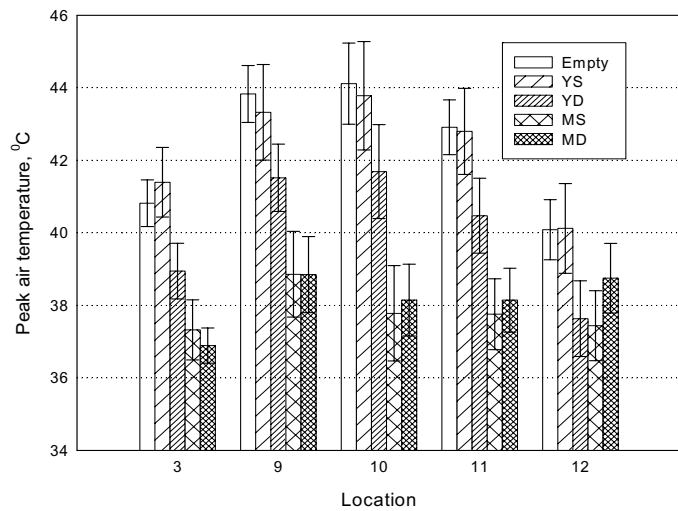


Figure 6. Absolute peak air temperature for different horizontal-y locations.

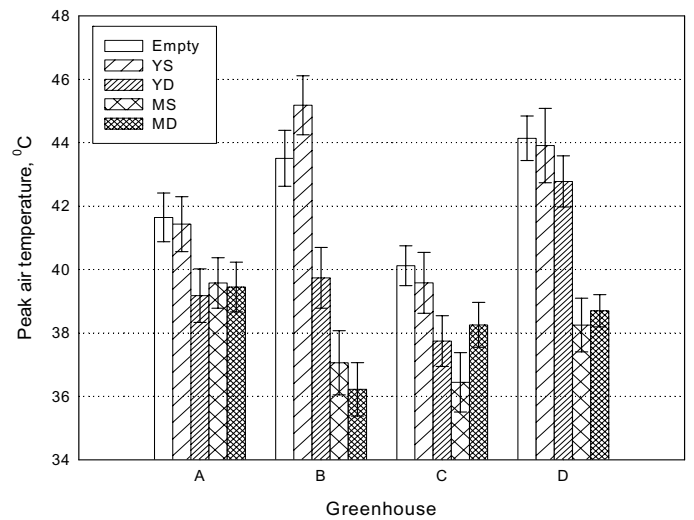


Figure 7. Absolute peak air temperature for different greenhouses [horizontal-y].

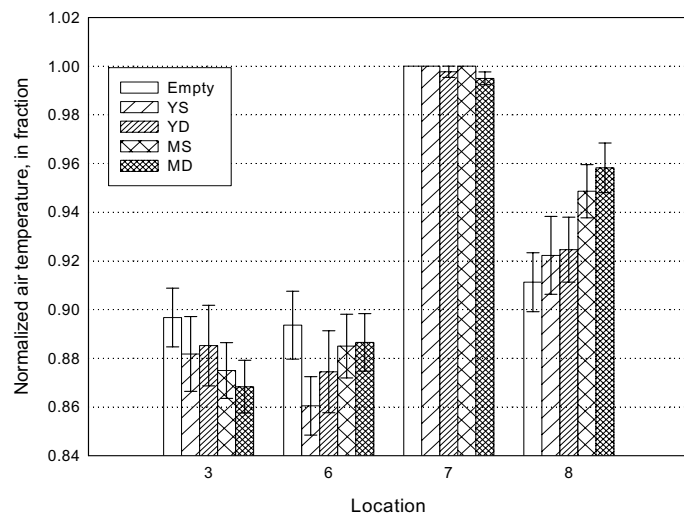


Figure 8. Normalized air temperature for different horizontal-x locations.

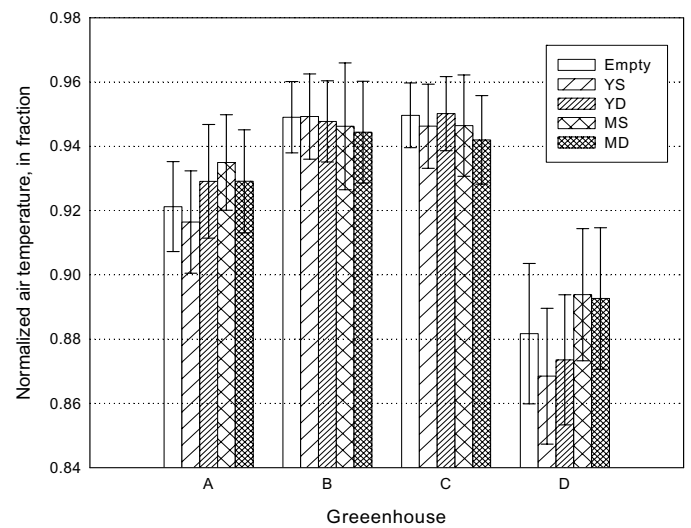


Figure 9. Temperature gradients for different greenhouses [horizontal-x].

that the small-hole screens severely reduce ventilation efficiency due to high resistance to airflow, which caused higher static pressure drops and eventually resulted in higher greenhouse temperatures.

Figs 6 and 7 demonstrate results for different horizontal-y locations and different greenhouses, respectively. Location-12 was found to be with the least temperature. For Empty greenhouse condition, GH-D exhibited the highest absolute peak air temperature as compared to the rests and the average difference was 1-4°C.

Normalized air temperature (gradients): The horizontal-x air temperature values were then normalized with the maximum absolute value among four locations for greenhouses in all five, Empty, Ys, Yd, Ms and Md conditions. Figs 8-10 show normalized air temperature (V_i/V_{max}) for different horizontal-x locations, temperature gradients in various greenhouses, and the absolute values of horizontal-x temperature gradients (maximum difference) for different greenhouses, respectively. Where V_i is the value of temperature at i^{th} location ($i = 3, 6, 7, \text{ and } 8$) and V_{max} is the maximum value among them.

Under Empty (no plants inside) condition there was about 11% temperature gradient noted among horizontal-x locations, the least value was 89% of the maximum corresponding temperature. Greenhouse-D exhibited higher temperature gradients (12%) than greenhouses GH-A and -B (6-8%). There was no significant difference between greenhouse GH-A and -B; and GH-C and -D in terms of horizontal-x temperature gradients. Greenhouse GH-D showed the highest value of absolute gradient (8.7°C) *i.e.* the difference between the maximum and minimum air temperature among all horizontal-x locations was the highest in greenhouse GH-D. Probably lesser porous screen offered less air exchange through it, which resulted in build up of heat stress as the houses were allowed to vent through roof.

Ys (Young plant with single plant density) configuration showed about 14% temperature gradient among horizontal-x locations. The least value was 86% of the corresponding maximum temperature. Greenhouse GH-D exhibited higher temperature gradients (14%) than greenhouses GH-B and -C (6%) while GH-A remained the least. These values were significantly higher in GH-A than -B; GH-C than -D in terms of horizontal-x temperature gradients. GH-D showed the highest value of absolute gradient (10.4°C). Under Yd (Young plant with double plant density) configuration about 13% temperature gradient was noted among horizontal-x locations. GH-D exhibited the highest temperature gradients (13%) than greenhouses GH-A (8%), while GH-B and -C revealed the least (5%). No significant difference existed between GH-A, -B and GH-C in terms of horizontal-x gradients.

About 13% temperature gradient was noted among horizontal-x locations, under MS (Matured plant with single plant density) condition. GH-D showed the highest temperature gradients (11%) than GH-A, -B and -C (6-7%). With MD (Matured plant with double plant density) configuration, about 14% temperature gradient was observed among vertical locations. GH-D exhibited the highest temperature gradients (11%) than GH-A, -B and -C (6-8%). Temperature gradients in horizontal-x direction were not significantly different among GH-A, -B, -C, and -D. GH-D offered the highest value of absolute peak horizontal-x gradient (8.3°C).

The maximum absolute values among five locations were used to compute corresponding normalized values (V_i/V_{max}) of air temperature in horizontal-y direction where V_i was the value of temperature at i^{th} location ($i = 3, 9, 10, 11 \text{ and } 12$) and V_{max} was the maximum value among them. Figs 11-13 show normalized air temperature for different horizontal-y locations, temperature gradients in various greenhouses, and the absolute values of horizontal-y temperature gradients (maximum difference), respectively. Under Empty condition there was about 11% temperature gradient noted among horizontal-y locations, the least value was 89.3% of the maximum corresponding temperature. GH-B exhibited higher temperature gradients (7%) than the rest (4-5%). GH-B showed the highest value of absolute gradient (6.3°C).

Ys configuration showed about 11% temperature gradient among horizontal-y locations. GH-B exhibited the highest temperature gradients (6%) while GH-C revealed the least (4%). GH-B showed the highest value of absolute gradient (5.3°C). Under Yd configuration about 12% temperature gradient was noted among horizontal-y locations. GH-B exhibited the highest temperature gradients (6.2%). No significant difference existed among greenhouses in terms of horizontal-y absolute gradients.

About 11% temperature gradient was noted among horizontal-y locations, under Ms condition. It was observed that with Md configuration, where considerable volume of microclimate was occupied by vegetation, there was no significant horizontal-y gradient existed among all locations.

Fig. 14 shows iso-thermal plots at the central transverse-plane as the horizontal temperature distribution inside greenhouses with insect screens C and D, at different vegetative stages (Ys, Yd, Ms, and Md). Linear dimensions are reported in metre, while iso-thermal lines are plotted to represent gradients. All figures are on the same color-scale; intensity of color shows absolute air-temperature. Horizontal-x peak air temperature was the highest at 67% (two-third) distance from the greenhouse-center and the lowest was at the center. The hottest point was about 7°C warmer. Air layer near the sidewall acted like it was adhered to it thus was not available for free-circulation. Increasing vegetation lowered the peak air temperature, horizontal-x locations were found sensitive to both plant maturity and plant density change. Taller plants exhibited about 2°C lower peak temperatures. This phenomenon could be explained by degree of resistance offered by particular mesh to air exchange. While investigating 3-D distribution of air velocity and temperature, scientists observed similar results that taller crop moderated air speeds in upper greenhouse space²⁰. There existed about 12% temperature gradients among horizontal-x locations within a greenhouse. These gradients were not found sensitive to the vegetation, probably due to the fact that being perpendicular to the plant-rows; all horizontal-x locations had equal effect of plant height increment or density change. Increasing mesh number (decreasing porosity) increased horizontal-x temperature gradients. Lower mesh (larger openings) reported 6-8% gradients while higher mesh numbered screens showed 10-12% gradients in horizontal-x. Absolute air temperature gradients were also higher in smaller-opening mesh (8-10°C) than that in the larger-opening screens (4-6°C).

The highest horizontal-y peak air temperature was observed at mid-way between greenhouse-center and the back-wall. Increasing plant density decreased peak air temperature for smaller plants,

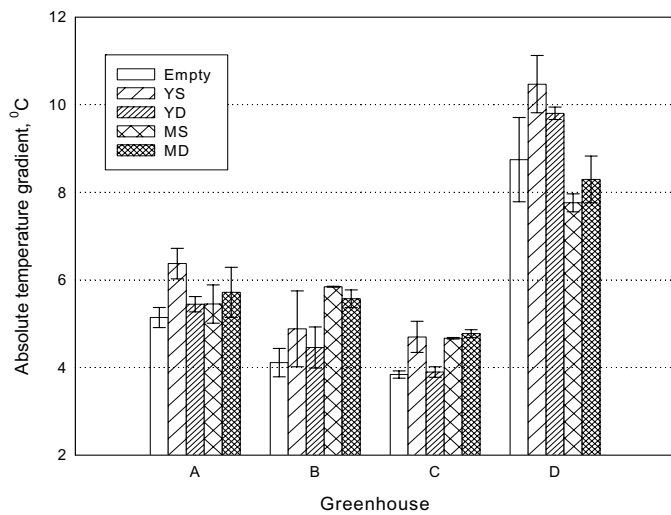


Figure 10. Absolute horizontal-x temperature gradients for different greenhouses.

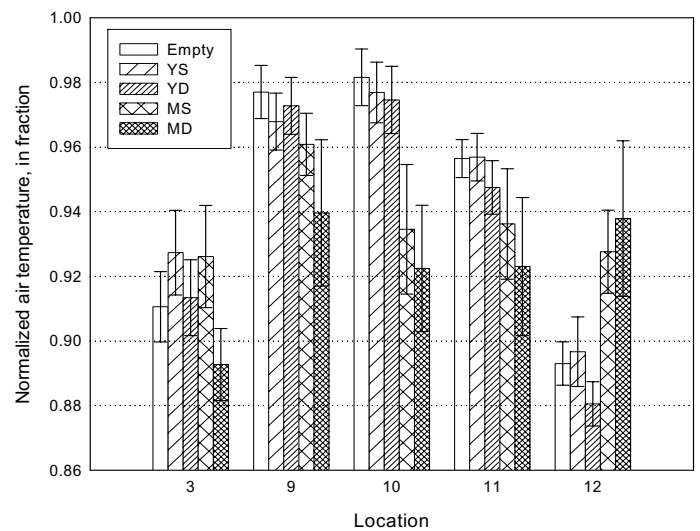


Figure 11. Normalized air temperature for different horizontal-y locations.

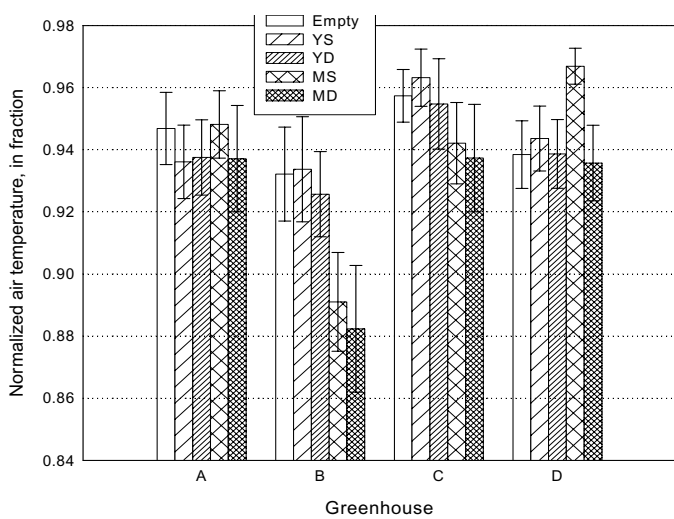


Figure 12. Temperature gradients for different greenhouses [horizontal-y].

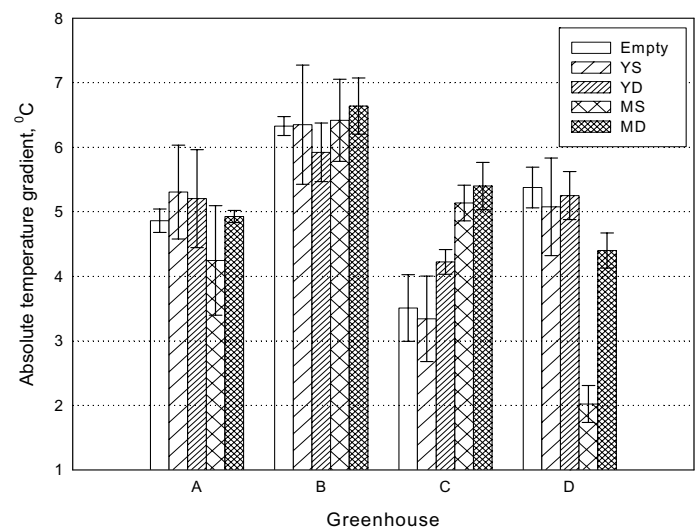


Figure 13. Absolute horizontal-y temperature gradients for different greenhouses.

not with taller plants. Probably due to that the taller plants created a passage parallel to y-axis and thus resulted in air-flow channeling between rows and therefore didn't respond to density increment. Taller plants resulted in about 5°C less air temperatures. About 10% temperature gradients existed among horizontal-y locations. These gradients were found sensitive to only plant height.

Leaf temperature was measured at the central location of all four greenhouses. No significant difference was monitored in leaf-temperatures among greenhouses; still doubling plant density significantly lowered the leaf-temperature. Probably air circulation was hindered by denser plant arrangement that caused this temperature reduction of plant leaves.

Greenhouses –B and –C showed significantly higher per-plant and total yields (934-1,096 kg ha⁻¹) than greenhouses –A and –D (61-457 kg ha⁻¹). This observation reveals that either the extreme of percent-opening of insect-net used caused negative impact on yields. Too high or too low porosities lowered yields because of insect intrusion and extremely high temperature gradients, respectively. However, the calculated yield is obviously much lower than that of practical values with greenhouses, yet these values were fair enough to compare the effect of screen-porosity. The lower values of yields might be due to improper plant-nutrition, which was not under the scope of present study.

Conclusions

In the naturally ventilated greenhouses, there exists strong horizontal air temperature gradient. Horizontal-x locations showed about 12% gradients and horizontal-y locations showed about 10% gradients. These gradients were not found sensitive to the vegetation change. Increasing mesh number (reducing porosity) increased these temperature gradients. Where highly porous greenhouses showed 6-8% gradients, lesser porous greenhouses claimed 10-12%. Results suggest that in addition to the insect screen selection, area and geometry of the greenhouse structure plays an important role in microclimate-governance as through their effects on microclimate uniformity, it significantly causes shifts in heat concentrations. These horizontal gradients suggest the selection of taller or shorter and rare or denser crop varieties inside the greenhouse with the available geometry. During the experiments a peculiar behavior of air-mass near the sidewalls was observed, which apparently doesn't take part in the internal air-circulation. Further studies are thus recommended towards this behavior of insect-screens, which affect greenhouse microclimate due to their adhering characteristics of air-mass close to inside of screen.

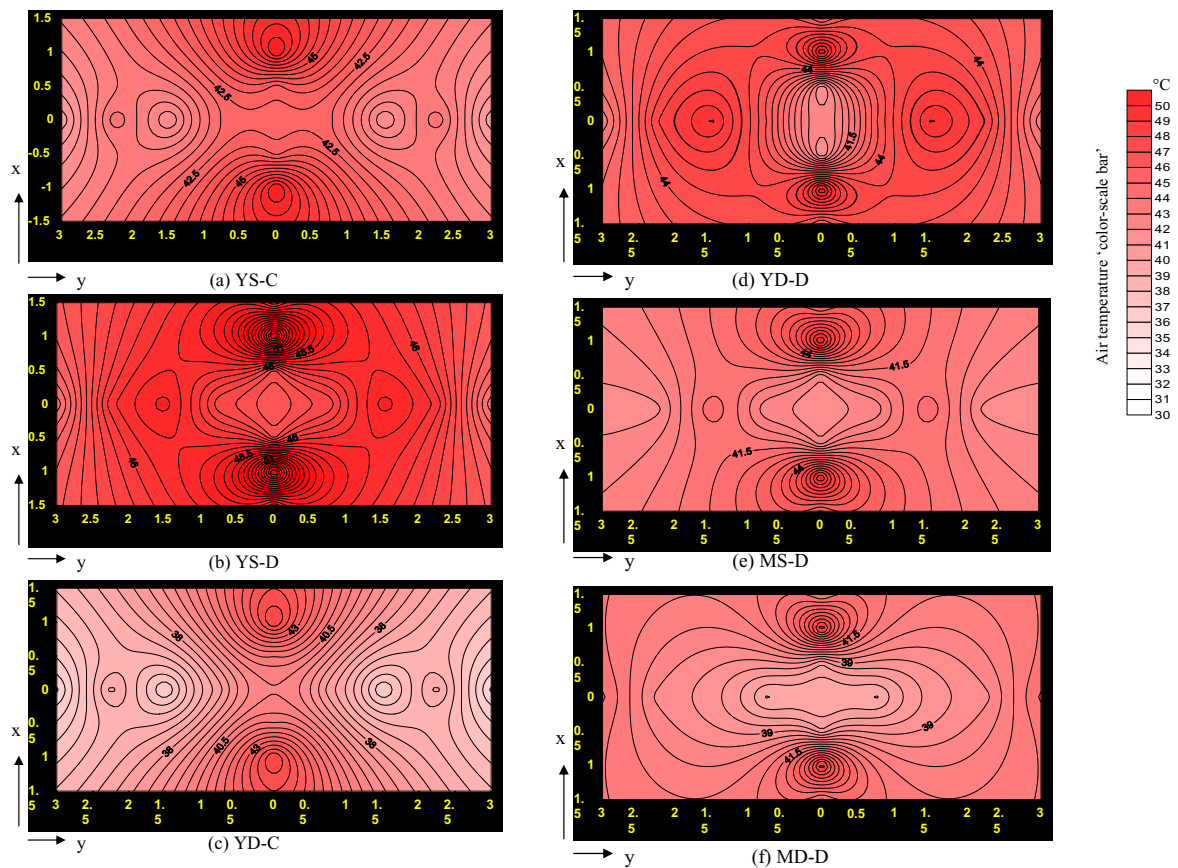


Figure 14. Horizontal temperature distribution inside greenhouses with insect screens C and D, at different vegetative conditions (Isotherm plots, °C): (a) Young plant single density -C; (b) Young plant single density-D; (c) Young plant double density-C; (d) Young plant double density-D; (e) Matured plant single density-D; (f) Matured plant double density-D.

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