Int. Agrophysics, 2005, 19, 329-336

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Spatial variability of air-humidity inside naturally ventilated tropical greenhouse**

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Received March 1, 2005; accepted June 16, 2005

A b s t r a c t. Research was conducted in four net-greenhouses with tomato crop inside, to study the spatial distribution of air-humidity under naturally ventilated conditions. Both, absolute and relative stress-gradients of air-humidity were observed for vertical (z) and horizontal (x and y) directions with x as semi-minor axis of 3 m x 6 m greenhouse structure. Four greenhouses with 53, 34, 33 and 19% porosity HDPE nets were used with two plant maturity stages and two plant density levels. Shorter plants occupied 5% of gutter height while taller stature 50%; plant density doubled from 1.7 to 3.3 plants m^{-2} with three and five rows kept parallel to y axis respectively. It was observed that specific humidity gradients in vertical (z) direction increased by 30% with vegetation. Lowering porosity increased vertical humidity gradient. Horizontal (x) locations exhibited 25% humidity gradients that increased with vegetation. However, it decreased with less porous nets. About 30% horizontal (y) humidity gradient was noted, which decreased with vegetation but lowering porosity increased it from 10 to 25%. Horizontal gradients responded considerably slowly towards plant density, rather they were found to be more sensitive to plant height. Plant density, on the other hand, altered their peak absolute values. With matured plants inside, less porous greenhouses evidenced lesser evapotranspiration values.

K e y w o r d s: greenhouses, air-humidity, microclimate, ventilation, tomato

INTRODUCTION

Greenhouse vegetable production is greatly influenced by the environmental stresses mainly due to humidity and temperature. High relative humidity levels, in tropics, are considered to be the major environmental limiting factor offering favourable conditions for development of fungal diseases. Greenhouse microclimate mainly depends on cladding properties, and ultimately governs the plant quality, production and amount of input resources. Influence of such nets on inside air temperature and humidity is not well-known and needed to be investigated. Greenhouse covering material selection is very important to protect against insects' entry inside. Also, it affects greenhouse microclimate by influencing temperature and humidity distribution within the greenhouse. Humidity inside greenhouse is usually higher than outside due to evapotranspiration of vegetation canopy, but it can be lowered by proper ventilation. Horizontal air movement is found to be beneficial for minimizing the possibility of temperature or humidity gradient build up inside the greenhouse. This movement is also desired to remove moisture from the lower part of the greenhouse *ie* under the foliage, and to distribute moisture in the rest of the house (Arbel *et al.*, 1999; Baptista *et al.*, 2001; Giacomelli, 2002; Shilom *et al.*, 2004; Tantau and Zabeltitz, 2003; Zhang, 2002). In automated greenhouses, microclimate is controlled using pre-set or real-time threshold values of key parameters, which can sometime mislead as they may not be the true representation of each coordinate. Knowing the spatial variability pattern of air humidity under naturally ventilated condition could serve a basis for proper fan mounting under forced ventilation, and humidifier/dehumidifier installation under automated control systems, with an aim at providing minimum variation of microclimate.

Snyder (2003) advocated the importance of having constant air movement within the greenhouse to maintain uniform environment by avoiding pockets of high or low

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**This paper was done under Protected Cultivation collaborative research project between Hannover University, Germany, and Asian Institute of Technology, Thailand.

temperature and humidity. Zhao *et al*. (2001) concluded that temperature and humidity distribution in greenhouse are among those factors that influence the uniformity of crop growth. Humidity distribution inside greenhouse, with respect to height above the ground, varied with solar radiation intensity. Either too high or too low humidity can stress plants. Lower values hinder transpiration while higher levels cause water stress. Vapour pressure deficit (VPD) could be used as an indicator to identify disease-causing climatic conditions. VPD has also been reported to steer plants into generative or vegetative growth habit. The acceptable range of humidity deficit is 3-7 g m^{-3} for tomatoes and cucumbers (Anonymous, 1994; Anonony-mous, 2003; Gaffen, 2003; Hand, 1988; Mohyuddin, 1994).

This research was conducted with different porosity high density polyethylene (HDPE) insect-nets with tomato crop inside to investigate the effects of insect-net porosity on spatial variability of air-humidity in naturally ventilated greenhouse (Soni, 2003).

EXPERIMENTS AND METHODS

Experiments were carried out at the greenhouse complex of Asian Institute of Technology (AIT), Bangkok (Thailand). Four greenhouses, erected East-West, were named as A, B, C and D. The structures had EW dimension of 6 m (length), NS dimension of 3 m (breadth). Total vertical height was 3.2 m with gutter stood at 2.2 m height from the ground. The greenhouses, throughout their roof length (*ie* 6 m), were provided with two-way roof openings (ridge-vents) with 40 cm wide air passage. All four green-houses were covered at roof with low density polyethylene (LDPE) sheet, from top of the roof to gutter height. A 40-mesh HDPE insect net was used to cover the two-way roof opening vents, protecting the greenhouses against direct insect/pest infusion. Insect nets of 32, 40, 50 and 78-mesh were used for cladding. The Eastern-most greenhouse 'A' was covered with 32-mesh and, successively in the sequen-ce, the Western-most was covered with 78-mesh HDPE net (Table 1).

Outside climatic data including wind velocity, wind direction, rainfall, light intensity and outside solar radiation were recorded. Data logging system of the four greenhouses comprised thermocouple sensors (TC), multiplexer boards (Campbell AM416 relay multiplexer), data loggers (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 colour-coded, Copper-Constantan (Type-TX, ANSI standard) thermocouple extension wires were used to measure temperature at various locations.

Both dry and wet bulb TC sensors were mounted on bamboo sticks erected inside the greenhouses. Figure 1 depicts the mounting of dry and wet bulb TC sensors at various locations along vertical and two horizontal axes in the greenhouses. The 'common' point location was common for all three axes. Thermocouple locations were numbered as 1-5 in the vertical direction, 0.5 m apart. In the horizontal direction they were numbered as 6-12, all 0.5 m above the 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.

Dry and wet bulb temperatures were used to compute absolute humidity (AH or specific humidity or humidity ratio) for each location. Psychrometric equations developed by United States Water Conservation Laboratory (Barnes, 2003) were used for the calculations. AH was expressed in kg of water vapour per kg of dry air.

Tomato seeds were sown in multi-trays. The atmos-pheric conditions were 28°C average daily temperature and 81% average RH. Four weeks after sowing, seedlings were transplanted into plastic pots containing 4 kg (oven dried weight) of soil substrate. Automatic drip irrigation and fertigation systems were used to irrigate tomato plants in all four greenhouses, attributed to soil temperature and solar radiation for automatic actuation. Drippers of 2 l h^{-1} capacities were connected to lateral pipes for individual plants. Irrigation duration was set at 10 min per application during young plant stage, while it was increased to 14 min at matured plant stage. Depending on climatic conditions, irrigation frequencies of 6 to 8 times a day were used.

Two plant densities, single and double, were used for this study. A plant density of 1.7 plants m^{-2} was considered as single density (S), which was obtained by placing three rows of 10 plants each. Rows were placed lengthwise *ie* EW. For double plant density (D) of 3.3 plants m^{-2}, 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.

Table 1. Properties of insect screens used

Insect screen	Material[1]	Mesh[1]	Wire diameter[2] (μm)	Opening size[2, 3] (μm x μm)	Opening area (nm^2)	Percent opening (%)
A	HDPE	32	285	780 x 755	589	53
B	HDPE	40	245	355 x 330	117	34
C	HDPE	50	265	785 x 210	165	33
D	HDPE	78	175	135 x 135	18	19

[1]as claimed by supplier, [2]measured with profile projector, average of three repetitions, [3]opening size: inside to inside dimensions of hole.

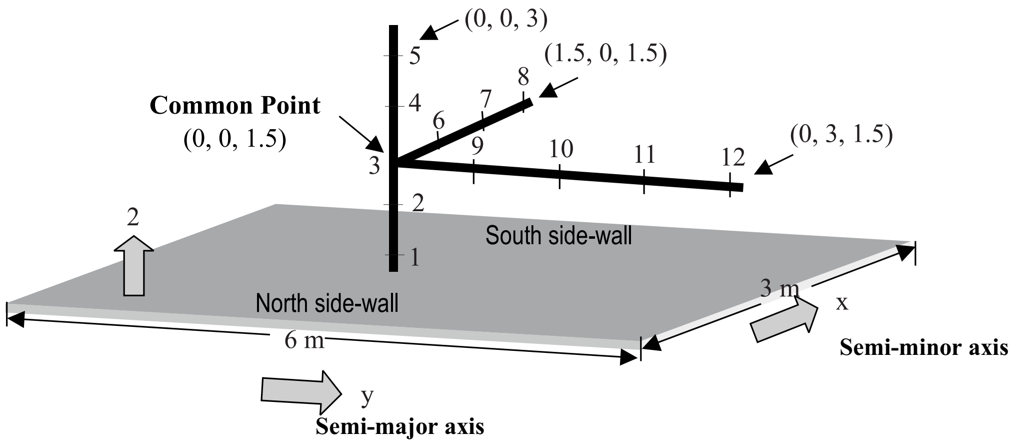

Fig. 1. Arrangement of TC sensors on bamboo sticks inside greenhouse, horizontal axes (x and y) are coordinated with origin at floor central plane (Figure not to scale).

RESULTS AND DISCUSSION

Vertical gradients

Absolute humidity values in the vertical-z direction were the highest (0.030-0.034 kg kg^{-1}) at the highest vertical location near the gutter. The point of the lowest AH (0.023-0.025 kg kg^{-1}) shifted from location-4 for young plants to location-2 for taller plants (Fig. 2). This might be due to the height of the plant canopy. With shorter plants, humidity build-up was well above the canopy, but with taller plants the upper surface of the canopy exhibited higher AH (this AH was trapped by surrounding cladding) and thus the point of lower AH was forced down below the canopy.

The less porous insect screen exhibited high AH values (0.029-0.034 kg kg^{-1}), while the more porous screen showed lower values of AH (0.022-0.026 kg kg^{-1}). Variation of AH with vegetative condition was different for vertical locations but still location-5 (gutter height) exhibited the highest AH

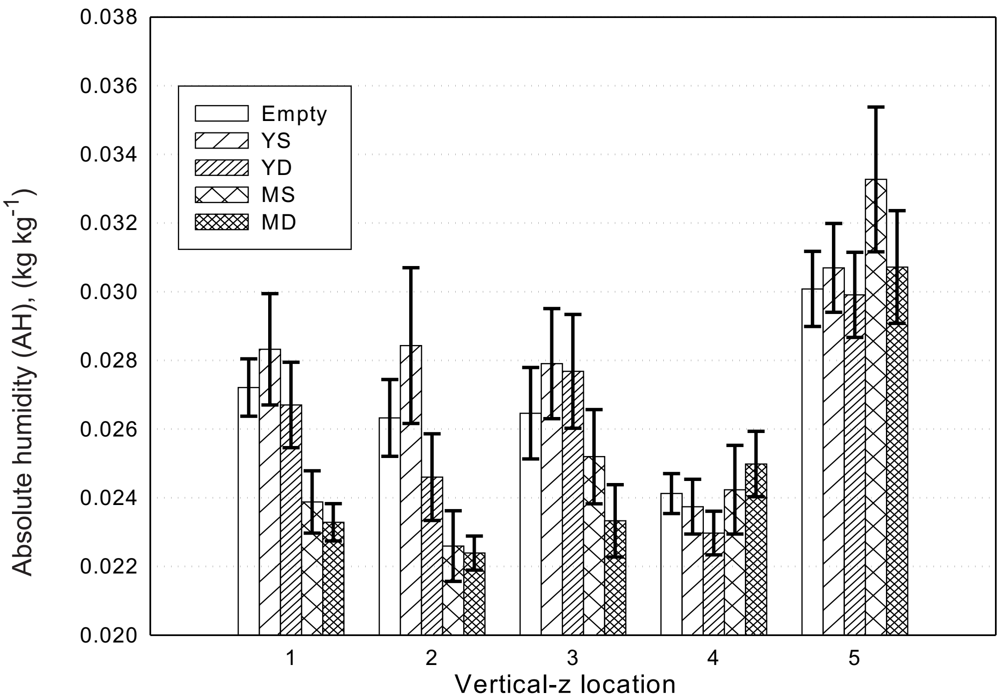

Fig. 2. Average absolute humidity for vertical-z locations with: Empty (without plants), YS (young plant single density), YD (young plant double density), MS (matured plant single density) and MD (matured plant double density) conditions outside and inside of all greenhouses.

values. Percent humidity gradients among different vertical locations were calculated in fraction, after normalizing AH values with respect to the maximum. With shorter plants, 20-25% vertical AH gradients were observed at around 80% height (Location-4) (Fig. 3a and b), while 25-30% vertical AH gradients were noted nearer 20% height (Location-2) for taller plants. Obviously, 5% higher vertical AH gradients were exhibited by taller plants than shorter ones.

0.035 kg kg^{-1}) at the greenhouse centre (Fig. 4). Due to the adherence of nearby air-layer with the sidewall, AH values probably could not circulate freely and thus the air could not lose its moisture. Air-humidity then further tended to decrease but again increased nearer to the sidewall. This was probably due to inside heat-envelope and possibly the adherence of nearby air layer with the screen did not allow adhered air-mass to freely circulate and lose its moisture.

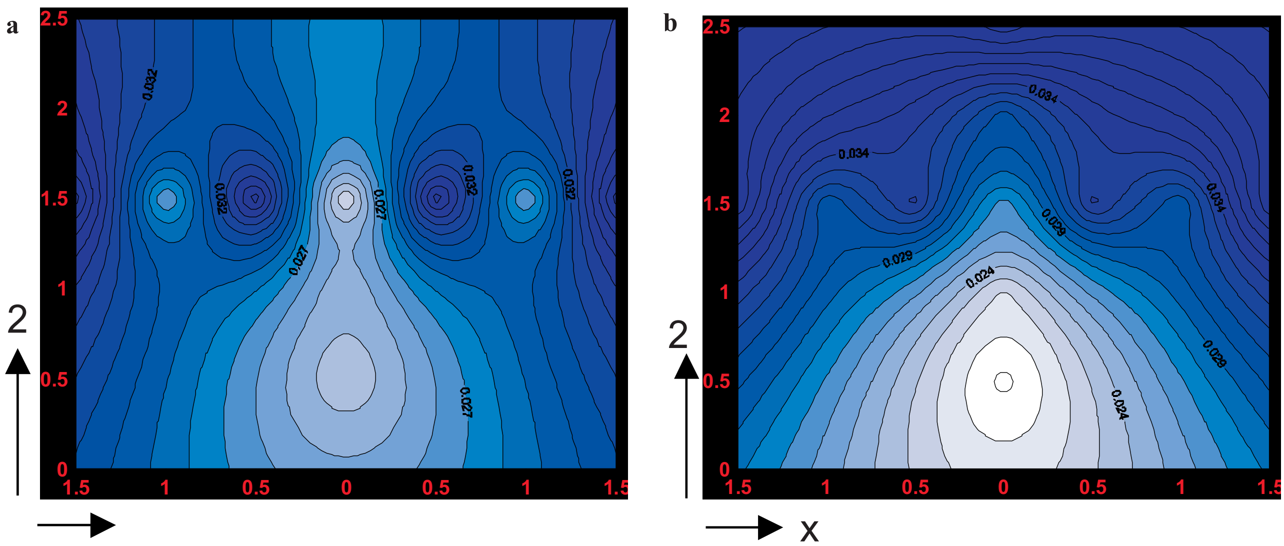

Fig. 3. Front view of absolute humidity distribution inside greenhouses vertical gradients in: a) GH-B and b) GH-D; with matured plant double density.

Vertical AH gradients were found to be sensitive to plant height only; plant density did not affect them significantly. Greenhouses with the less-porous insect screen revealed higher AH gradients (10-15%). Similarly, less-porous screens exhibited higher values of AH.

The numerical difference between the maximum and minimum values of AH is presented as ΔAH, which was higher in less-porous greenhouse. Taller plants showed larger ΔAH with less-porous screen (0.02 kg kg^{-1}) with numerical AH gradient of 0.0067 kg kg$^{-1}_{dryair}$ m^{-1} than in porous screen greenhouses (0.006 kg kg^{-1}) with numerical AH gradient of 0.002 kg kg$^{-1}_{dryair}$ m^{-1}. Also, shorter plants exhibited larger differences between the maximum and minimum humidity values in less-porous screen (0.012 kg kg^{-1}) than in porous (0.008 kg kg^{-1}). Thus again the taller plants turned up with higher AH vertical gradient values than shorter plants.

Horizontal-x gradients

In horizontal-x direction or minor axis of the greenhouse structure, AH values were found to be the highest (0.030-0.035 kg kg^{-1}) at location-6 (at 33% distance from the greenhouse centre) and were the lowest (0.027-

Also, that air layer near to the insect screen received more opportunity for vapour exchange with outside air. Increasing plant height widened the gap between the minimum and the maximum AH, whilst increasing plant density lowered the AH values.

Horizontal-x location near to greenhouse centre (33% from centre) and nearer to the net (67% from centre) showed the highest horizontal-x AH gradient of 15-25% (25-30% was in vertical-z) by sharing 75-85% AH values of the maximum horizontal-x humidity.

Taller plants (22%) showed higher AH gradients than shorter plants (15%), probably due to higher interception, which offered higher resistance to the free circulation of air masses within the greenhouse. Figure 4 revealed that the porous-greenhouse experienced higher horizontal-x humidity gradients (12-20%). Similarly, it exhibited larger differences between the maximum and minimum humidity values, ΔAH (0.010-0.014 kg kg^{-1}) with numerical AH gradient of 0.0067-0.0093 kg kg$^{-1}_{dryair}$ m^{-1} than less-porous screened greenhouses (0.004-0.008 kg kg^{-1}) with numerical AH gradient of 0.0027-0.0053 kg kg$^{-1}_{dryair}$ m^{-1}. Humidity gradients were found to be more affected by plant height than by plant density.

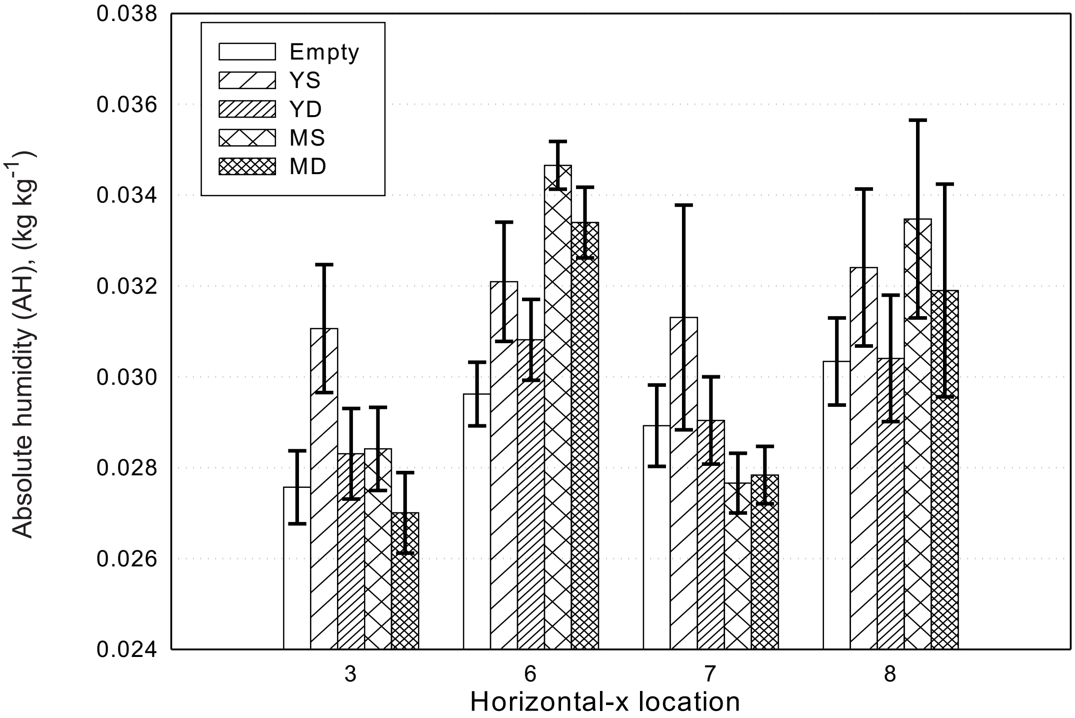

Fig. 4. Average absolute humidity for horizontal-x locations (minor axis) with: Empty (without plants), YS (young plant single density), YD (young plant double density), MS (matured plant single density) and MD (matured plant double density) conditions outside and inside of all greenhouses.

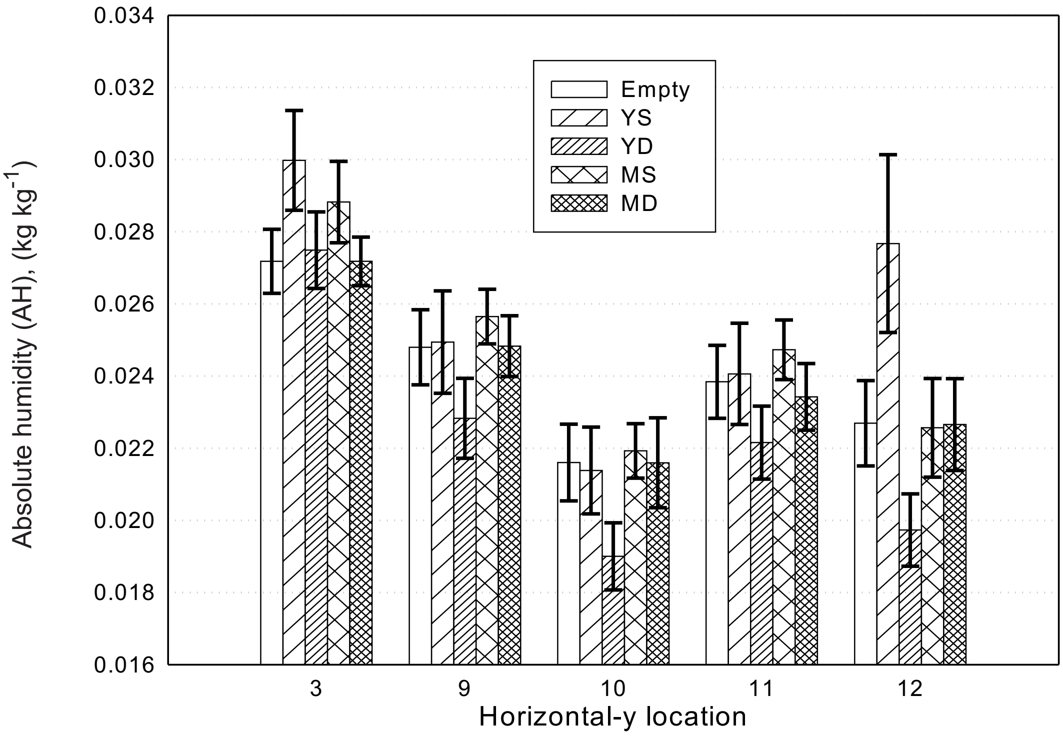

Fig. 5. Average absolute humidity for horizontal-y locations (major axis) with: Empty (without plants), YS (young plant single density), YD (young plant double density), MS (matured plant single density) and MD (matured plant double density) conditions outside and inside of all greenhouses.

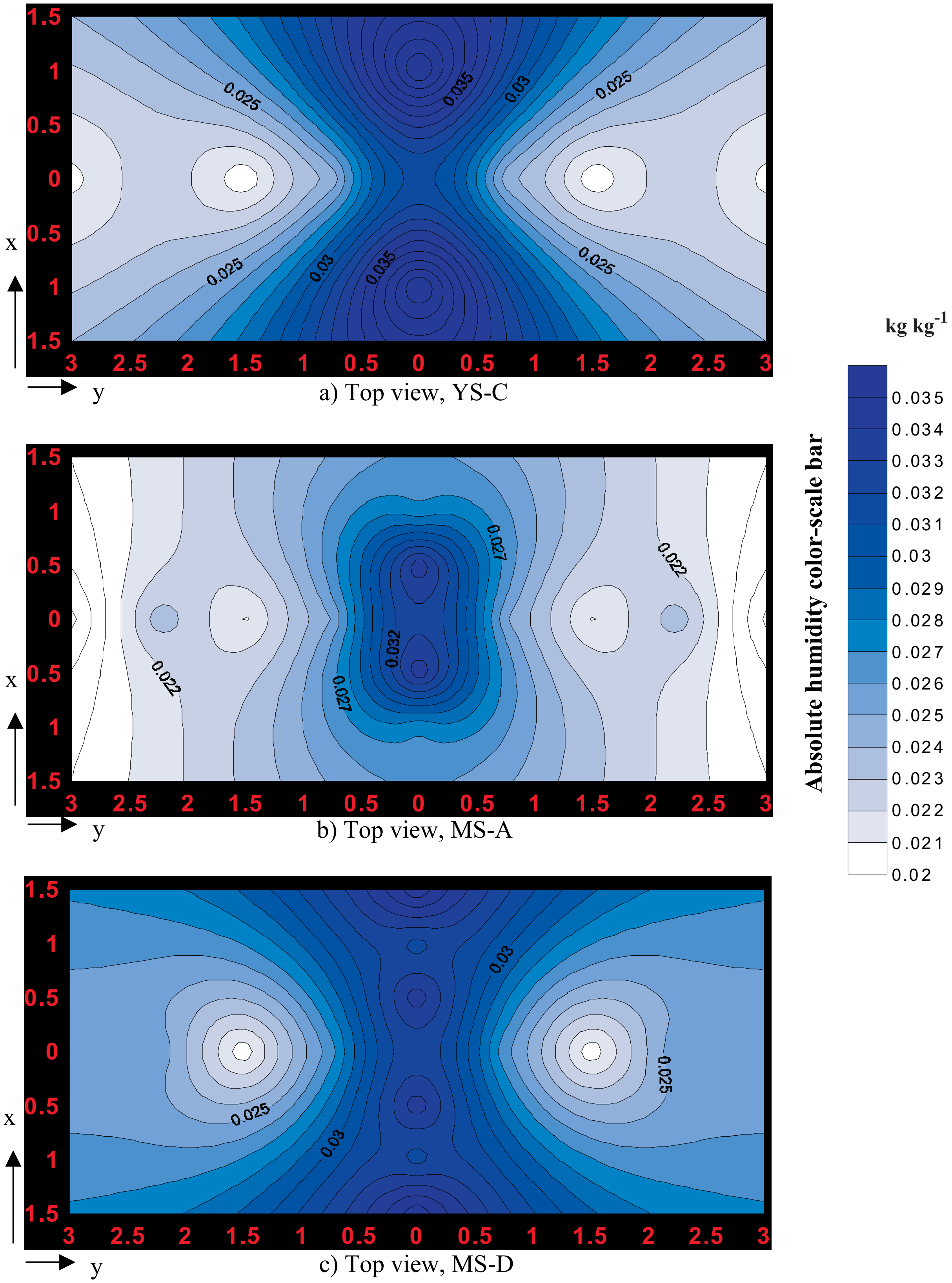

Fig. 6. Top view of absolute humidity distribution inside greenhouses horizontal gradients in: a) GH-C with young plant single density, b) GH-A with matured plant single density, and c) GH-D with matured plant single density.

Horizontal-y gradients

Horizontal-y or major-axis humidity values were maximum (0.027-0.031 kg kg^{-1}) at the greenhouse centre and decreased to minimum (0.019-0.022 kg kg^{-1}) at midway between greenhouse centre to the back wall (Fig. 5). This might be due to the adhered air layer with back wall that could not participate in free circulation with the rest of the air masses in the greenhouse. The variation in air-humidity was probably due to combined effect of channelling of rows and inside heat envelope (Fig. 6).

The midway between greenhouse centre and back wall showed the highest horizontal-y gradient (20-30%) among major-axis locations by sharing 75% of maximum horizontal-y humidity values.

Horizontal-y AH gradients were sensitive towards plant maturity. Shorter plants revealed higher gradients (30%) than taller plants (20%) (Fig. 6). The gradients were found to be affected significantly by plant height rather than density. This was again, perhaps, due to the channelling of plant rows, which tried to maintain status-quo condition between the channels of rows parallel to it. The phenomenon could be compared with the results by Fernandez and Bailey (1994) who investigated the daytime three-dimensional distribution of air velocities, temperatures, humidity and carbon dioxide in a greenhouse planted with rows of tomatoes. They observed that the tall crop moderated the air speeds in the upper greenhouse space, which is quite similar to the behaviour observed in the present research.

For taller plants, less-porous-greenhouses exhibited higher horizontal-y AH gradient (20-25%) than porous-greenhouses (5-10%). Similarly, less-porous-greenhouses showed higher ΔAH in horizontal-y direction (0.012 kg kg^{-1}) with numerical AH gradient of 0.004 kg kg$^{-1}_{dryair}$ m^{-1} than porous-greenhouses (0.002-0.006 kg kg^{-1}) with numerical AH gradient of 0.0006-0.002 kg kg$^{-1}_{dryair}$ m^{-1} (Fig. 6).

CONCLUSIONS

1. Higher altitudes reflected higher values of absolute humidity in the vertical-z direction. No significant difference in absolute humidity between GH-B and GH-C, having almost similar porosity but with different aperture dimensions, was found. The less porous insect screens (19% porosity) resulted in accumulation of moisture within the house and exhibited high AH values. With shorter plants, 20-25% vertical AH gradients were observed, while 25-30% vertical AH gradients were noted with taller plants. Greenhouses with less-porous insect screen represented higher AH gradients (10-15%) and a large difference between the maximum and minimum humidity values. A similar trend was observed in horizontal-x and horizontal-y directions.

2. In the minor axis of greenhouse, air-humidity values were the highest at 33% distance from the greenhouse centre and were the lowest at the greenhouse centre. The horizontal-x AH gradients were 15-25%.

3. Horizontal-y AH values were maximum at greenhouse centre. The highest horizontal-y gradients were between 20-30%. Shorter plants claimed higher gradients (30%) than taller plants (20%).

4. Results from the research can be used to develop an efficient and optimised misting/fogging system. Further, the knowledge of air-humidity stress gradients might facilitate the existing measures of maintaining greenhouse-micro-climate uniformity under tropical conditions, where high humidity is the major cause of plant diseases.

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ABBREVIATIONS

ΔAH - numerical difference between maximum and minimum AH
AH - absolute humidity, kg of water vapour per kg of dry air
AIT - Asian Institute of Technology
GH - greenhouse
GH-A - greenhouse with 53% porosity insect screen
GH-B - greenhouse with 34% porosity insect screen
GH-C - greenhouse with 33% porosity insect screen
GH-D - greenhouse with 19% porosity insect screen
HDPE - high density polyethylene
LDPE - low density polyethylene
$l\ h^{-1}$ - liter per hour
MD - matured plant stage with double density
MS - matured plant stage with single density
RH - relative humidity, %
TC - thermocouple
VPD - vapour pressure deficit
YD - young plant stage with double density
YS - young plant stage with single density