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Root-Zone Cooling in Tropical Greenhouse: a Review

A G Niam¹ and H Suhardiyanto¹

¹ Department of Mechanical and Biosystem Engineering, Bogor Agricultural University.

* Email: ghautsun@apps.ipb.ac.id

Abstract. To prevent the decrease of vegetable production during the rainy season in a tropical region, it is important that cultivation is carried out in greenhouses. However, air temperature inside the greenhouse tends to be very high during the daytime in clear days. To overcome these problems, root zone cooling system has been developed as an energy efficient cooling system for tropical greenhouses. In this paper, performances of the root zone cooling system for tropical greenhouse are described. The application of the root zone cooling system for plant production in tropical greenhouses is still very potential to be developed. This is because the most significant temperature influencing plant growth of some plants was the root-zone temperature. It is important to evaluate the application of root zone cooling in tropical greenhouse for protected plant production in the tropics. It has been shown that CFD simulations analysis are able to visualize the temperature distribution in a tropical greenhouse equipped during root zone cooling. This has a positive potential for improving performance analysis, design, construction with more careful attention to environmental climate factors, type of screen, dimensions, arrangement of plant layout, and types of plants produced.

1. Introduction

Air temperature in the greenhouse during sunny days in the tropics tends to be too high for the growth of plants inside the greenhouse. Cooling the greenhouse as a whole requires very large amount of energy. It has been proven that cooling load to reduce the air temperature inside the greenhouse as a whole to 6 °C below the outside air temperature can reach 0.32 MJ m⁻² h⁻¹ in the summer at night [1]. Therefore, root zone cooling system has been developed as energy efficient cooling system for tropical greenhouse.

2. Root zone temperature and plant response

Research on plant response due to differences in temperature in roots began in the late 70s, where the roots of tomato plants warmed around 23-26 °C in winter (night air temperature around 9 °C) had the best growth compared to roots without heat [2]. The same thing has also been tested on potatoes in vitro, where at 28/13 °C day/night the potato plants can produce a significantly higher zeatin riboside hormone as compared to potato plants which are given a temperature treatment of 30/28 °C day/night [3]. In addition, effects of root-zone and shoot-zone temperature have also been tested on lettuce plants that are cultivated in floating



hydroponic. The most significant temperature influencing the biomass growth of lettuce was the root-zone temperature, where from a temperature variation between 12 °C to 31 °C, the best temperature was around 24 °C [4]. All of the above evidences occur in the subtropical region, and have a positive impact on the quality and productivity of plants. The development of root zone cooling system for plant production in tropical greenhouse still remain a big challenge.

3. Tropical greenhouse

Tropical greenhouse has its characteristic to allow natural ventilation at maximum level. Natural ventilation occurs due to the existence of two factors that trigger the mechanism of fluid movement. The first trigger factor is caused by thermal buoyancy, which is often referred to as the stack effect, where the temperature difference that occurs in the fluid inside the greenhouse comes from the heat convection process, solar radiation flux and metabolism of organisms in the greenhouse [3]. Heated air will reduce its density so that the air mass gets lighter and with the influence of gravity can cause air parcels that are getting lighter. The air then tends to move up or float. The second trigger factor is the presence of wind which causes a difference in pressure on the walls and cover of the greenhouse building because of the pressure drop that forces the air inside the greenhouse to move through the gap of the vent openings [4]. Therefore, thermal factors play a dominant role when the air velocity is low, resulting in air movement due to differences in temperature and air density inside and outside the greenhouse.

The wind speed limit where thermal factors can still play a dominant role is 1 ms⁻¹ [5], whereas when the air velocity is more than 1.8 ms⁻¹ the thermal effect on the ventilation rate can be ignored [5,6]. If the wind speed outside the greenhouse is quite high and the difference in air temperature inside and outside the greenhouse is small, then the dominant wind factor and the influence of thermal factors can be ignored. The minimum ventilation openings area is 20% of the greenhouse floor area so that the temperature in the greenhouse can approach ambient temperatures outside the greenhouse [5]. However, if the area of ventilation openings is more than 40% of the area of the greenhouse, then the rate of natural ventilation is quite good and can avoid extreme temperature increases in tropical greenhouses [3]. Therefore, the use of screens as a cover for ventilation openings helps to reduce the number of disturbing pest attacks into the greenhouse, but their use will reduce the rate of ventilation and increase the air temperature in the greenhouse.

4. Simulation of temperature distribution in the root zone

It is important to predict temperature distribution in the root zone. One method for describing the temperature distribution pattern in the plant root zone is a numerical simulation approach. Today many numerical simulations are approached based on the finite volume method. The numerical calculation is solved by a computational approach that has considered three main aspects of physics, namely in the form of mass, momentum and energy equilibrium. Then, this is known as Computational Fluid Dynamics (CFD) [7]. CFD is a field of science that studies ways to predict fluid flow, heat transfer, chemical reactions, and other phenomena by solving mathematical and physical equations, so that this can be a design tool as well as research tools [8].

Temperature distribution in tropical greenhouses equipped with refrigerated NFT hydroponic systems has been simulated using CFD-based software. Root zone cooling was applied through

nutrient solution which was channeled into NFT gutters in the greenhouse and used for tomato cultivation (Figure 1.a). Through an experimental approach and reliability test, the simulation results of the distribution of temperature in the greenhouse have a maximum error of 8.06% with a temperature distribution of around 31.3 °C to 32.0 °C (Figure 1.b). In addition, the value of the uniformity coefficient obtained was around 98.2%. The simulation results show that root zone cooling through nutrient solution also gives rise to the cold effect on the air around nutrient gutters in Figure 1.b. Therefore, the concept of zone cooling, in addition to reducing energy consumption, can also have a positive effect on the leaf zone around the cooled area.

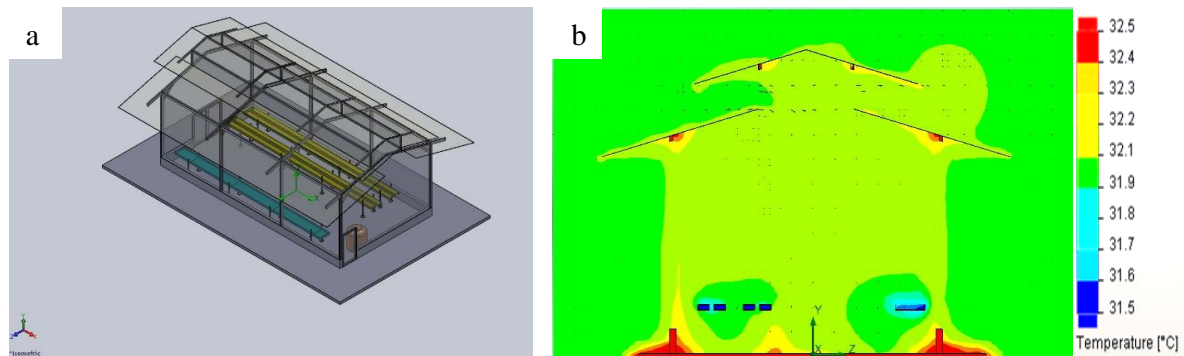


Figure 1. a) greenhouse geometry, b) cut plot temperature distribution at the front view

5. Root zone cooling on leaf vegetable cultivation

Lettuce and capsicum have been successfully grown in the tropical greenhouse in Singapore, by applying the root zone cooling system between 15-25 °C while their shoots were maintained at hot ambient temperatures ranging from 26-42 °C [9]. The results of this study prove that the treatment of root zone cooling at 25 °C yields a yield of 37.7% higher than the treatment temperature of 30 °C, and 61.4% higher than without root zone cooling treatment. The interaction of root zone cooling application and P-induction can increase the average growth rate by about 31% [9]. Similar results have also been proven in the hydroponic nutrient film technique (NFT) in tropical climate regions of Brazil, for lettuce plants. The plants were tested at root zone temperature around 24-30 °C and interact with the addition of nutrient solution concentrations from 1 to 3 dS m⁻¹. The test results concluded that cooling the root zone around 26 °C was the optimum temperature for the growth of lettuce in tropical climate regions. However, the addition of EC to nutrient from 1 to 3 dSm⁻¹, cause reduction in growth of lettuce [10]. In addition, the butterhead lettuce plant also shows photosynthetic CO₂ assimilation, stomatal conductance, relatively mid-content midday leaf higher at constant rooting temperatures of around 20 °C, compared to rooting temperatures which are allowed to follow fluctuations in ambient air temperature of 23-40 °C [11].

6. Root Zone Cooling on Tuber Plants Cultivation

Root zone cooling for the cultivation of tuber plants has been carried out also for shallots. With a floating hydroponic system, the temperature distribution around plant holes is simulated using CFD. Root zone cooling in shallots is intended to accelerate flowering initiation as occurred in the highlands. The application of root zone cooling on shallots was adopted from the vernalization process, where the bulb of shallots is stored first at a temperature of around 10 °C for 40 days before being planted on the ground. This can accelerate flower induction. The cooling process is carried out in line with the tubers planted. A study has reviewed the root

zone cooling effect on hydroponic floating for the production of shallot seeds in tropical lowland greenhouses. The study was carried out at three root temperature set points, namely low (8-10 °C), medium (13-15 °C) and ambient (23-26 °C), where the ambient air temperature fluctuated around 32-38 °C [12]. The results of the study showed that the onion plant had not been able to produce flower initiation at the temperature setting variation. However, another response appears in the form of multiplication of tubers (figure 2). Root zone cooling on hydroponic floating was able to increase the number of tubers almost 2 times more than ambient conditions, namely 12 tubers per clump at low temperatures, 9 tubers per clump at medium temperatures, and 5 tubers per clump at ambient temperatures. The same as true for aeroponic systems in tropical lowlands, the results obtained for each set of low, medium and ambient temperature points are 5.00, 4.50, and 1.50 cloves per clump, respectively [13].

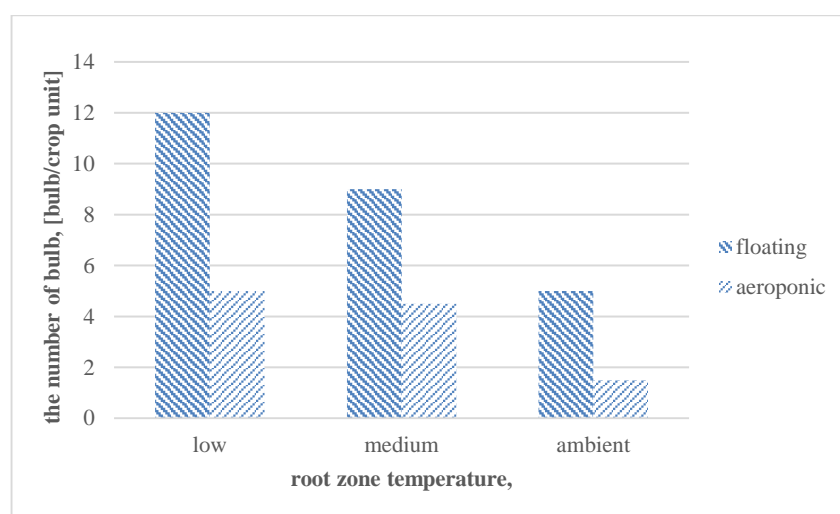


Figure 2. The number of shallot bulbs produced on floating and aeroponic systems with root zone cooling.

Root zone cooling has also been applied to aeroponic systems for mini potato seed production [14]. The set temperature points in the chamber for root cooling were 10 °C, 15 °C, 20 °C, and ambient fluctuation (30.3-32.6 °C). The best tuber production was obtained in the aeroponic system with 10 °C zone cooling which included average productivity (579 tubers m⁻²), average tuber number (14.85 tubers per plant), and average tuber weight (409.15 mg per tuber). Zone cooling with a temperature of 15 °C produced 55 tubers m⁻² with an average number of tubers 1.67 tubers per plant, tuber weight 205.44 mg per tuber. The number of tubers per plants at zone cooling 20 °C was not significantly different from 15 °C zone cooling. Potato plants at non-cooling temperatures (30.3-32.6 °C) did not produce tubers.

7. Root zone cooling on fruiting plants cultivation

Amaliah (2018) conducted a study on cooling the root zone for hydroponic curly chili cultivation using cooling elements in the form of water flowed through galvanized pipes with a set point temperature of 14 °C and the temperature of the planting medium reached below 26.9 °C. Chili plants grown in hydroponic systems with cooling zones produce higher fruit weights per plant than plants without zone cooling treatment. Chili plants with zone cooling

have a fruit weight per plant of 873.6 g and chili plants without zone cooling have a fruit weight per plant of 546 g.

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