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Effect of ground heat exchanger for root-zone cooling on the growth and yield of aeroponically-grown strawberry plant under tropical greenhouse condition

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Effect of ground heat exchanger for root-zone cooling on the growth and yield of aeroponically-grown strawberry plant under tropical greenhouse condition

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Abstract. With the increasing cost of fossil fuel to generate power for cooling purposes, there is a need for alternative methods of cooling system that is sustainable and economically viable in producing high quality crops under tropical condition. This study aimed to investigate the effect of ground heat exchanger (GHE) for root-zone cooling on the growth, yield, and economic returns of aeroponically-grown strawberry plants under tropical greenhouse condition. The experiment had two treatments; the root-zone cooling methods (GHE, Air-conditioning Unit (ACU), and Control – no root-zone cooling) and photoperiods (8-hours, 16-hours, and 12-hours). We observed that the root-zone mean temperature under GHE was maintained at 26.75 °C, which was 2.61°C higher than ACU and 2.17°C lower than the control. The GHE and ACU did not significantly differ in terms of plant's growth with larger and number of leaves, and longer petioles than the control. We found no significant interaction of the treatments on the yield nor difference between GHE and ACU with 181-186 g/plant. Projected benefit cost ratio using GHE is 4.24 and annual return of investment is at 32%. This study underscores the feasibility of GHE application for root-zone cooling under tropical greenhouse condition.

1. Introduction

The ambient tropical condition of high temperature and solar radiation in most Southeast Asian countries like the Philippines has been a major constraint in the production of temperate vegetable crops. In such condition, the growth and development of temperate crops are severely reduced due to poor nutrient and dissolved oxygen root uptake [1]. With ideal temperatures, temperate crops could grow between 20 and 26°C [2]. In the Philippines, the cultivation of temperate crops like strawberry is limited in selected cooler highlands such as La Trinidad, Benguet where lower temperature is experienced [3]. Due to high energy demand for crop production of these types of crops under normal tropical condition, many Filipino farmers are constraint to grow strawberries under greenhouse condition, despite the prospect of high income especially during off season. Hence, there is a need to find ways for alternative methods of cooling system that is sustainable and economically viable for the production of high quality temperate crops (e.g. strawberry) not only in the highlands where lower temperature is prevalent, but also under lowland condition.

The ground heat exchanger (GHE) is a passive cooling system that requires a pipe or a series of pipes buried underground at a certain depth to dissipate heat from the air to the ground surface. Ground has a high heat capacity and thermal inertia that absorbs 46% of the sun's energy and makes temperature



fluctuation of the ground surface penetrate deeper into the ground at an exponential rate [4]. Hence, a time lag occurs between the temperature fluctuations at the surface and in the ground. At sufficient depth, the ground temperature is constant and almost equal to the mean annual air temperature. The use of earth underground as heat exchanger was commonly reported for cooling buildings [5-6] and only a few studies for crop growth purposes such as under greenhouse condition [7]. An experimental study of GHE performance in Burkina Faso reported that ambient air temperature was decreased by 7.6°C [8]. Moreover, while there were studies conducted relating to the root-zone temperature for crop production grown in hydroponics and aeroponics condition, there is a limited research carried out on the use of GHE for root-zone cooling of aeroponically grown strawberry crops in a tropical country like the Philippines. This study aimed to investigate the effect of GHE as root-zone cooling method on the growth, yield, and economic returns of aeroponically and tower-grown strawberry plants under tropical greenhouse condition.

2. Materials and Methods

2.1. Field layout and design

The experimental set-up was established at the College of Engineering Land and Water Field Laboratory, Central Luzon State University, Munoz, Nueva Ecija, The Philippines from September 24, 2017 to March 13, 2018. Statistical analysis was arranged in a strip plot design with root-zone cooling method (GHE; air conditioning unit (ACU); control-without cooling) as the main treatment and photoperiod (8-hr; 16-hr and 12-hr) as the sub-treatment with three replications. The 8-hr day length period was 6AM – 2PM, while the 16-hr and 12-hr were 6AM - 6PM + Artificial light from 6-10 PM, and 6AM - 6PM, respectively. An improvised covering made of black cloth was provided to enclose the 8-hr treatment from 2 PM onwards and remove the cover before 6 AM to expose the plants to sunlight for 8 hours. The 16-hr treatment was also covered with the same material from 6 PM to 10 PM and introduced artificial light within that time to extend the day-length to 16 hours. The artificial light used a 16 watts ECOLUM LED T8 tube and maintained a light level of not less than 40 $\mu\text{mol}/\text{m}^2\text{s}$, which is favorable for photosynthetic activity and to extend the day-length exposure of the plants [9]. A Quantum meter (MQ-100) was used to measure and fix the distance of the lights from the plants at 20 cm.

2.2. Aeroponic towers and ground heat exchangers

A greenhouse which measures 12 x 6 x 3.5m (L x W x H) was used for the experiment. Its top is covered with ultra-violet resistant transparent plastic and its sidings are wrapped with insect net to allow natural ventilation and air circulation, while preventing insect entry. It was covered on top with a 30% light reduction net. A 4-in diameter x 50 m long PVC pipe was buried outside the greenhouse, alongside a 3/4-in x 100 m polyethylene pipe which served as GHE system for air and nutrient solution, respectively. The aeroponic towers were improvised 6-in diameter x 1.5 m length PVC pipes with holes arranged alternately at a distance of 25 cm. A total of 20 holes were made as placement for the plants in one tower. The base of the towers is interconnected with 4-in diameter PVC pipe buried at a depth of 70 cm but separate with each treatment so that nutrient solution returns to the collection tank for re-circulation. Before the pipes were covered with soil, a system test run was done for a few days to ensure the workability of the set-up and identify possible nutrient leaking on the pipe connections. Also, pressure gauge and control valve was installed in each water pump for proper adjustments to avoid break down. A 1-hp re-circulating water pump was used to deliver the nutrient solution into the roots of the plants.

The roots of the strawberry plants were continuously misted with nutrient solution during daytime from 8AM – 5PM and an interval of 15 minutes mist application for every 30 minutes rest at night time using a sprayer nozzle. Each main treatment used a separate water pump. A 200-mesh filter was used to filter impurities and solid materials from entering the system that may clog the mist nozzle. A 4-in diameter fan was also installed to facilitate the evenly distribution of mist particles on the roots of the plants and help dissipate heat accumulation in the root-zone especially during daytime. Figure 1 shows the schematic diagram of the GHE set-up. For ACU, similar set-up was used as in Figure 1, but the pipes

buried at 1.5 meters were eliminated and an air conditioning unit was installed instead of fan to cool the nutrient solution and the mist in the aeroponic tower.

A Hawaiian strawberry variety was used as test crop for this study. An improvised net cups and polyfiber were used as an anchorage for the plants in the tower. A nitrogen-based nutrient solution was used to provide the needed nutrients for vegetative growth, which extended to 2.5 months after transplanting. Prior to that, the newly transplanted strawberry runners were fed with a 0.5 dS/m dosage of nutrient solution for 1-week and gradually increased to 1.0 – 1.8 dS/m afterwards. During the flower initiation, a higher Potassium content fertilizer was used to support the needed nutrient for flower production and prepare the plants for fruit product.

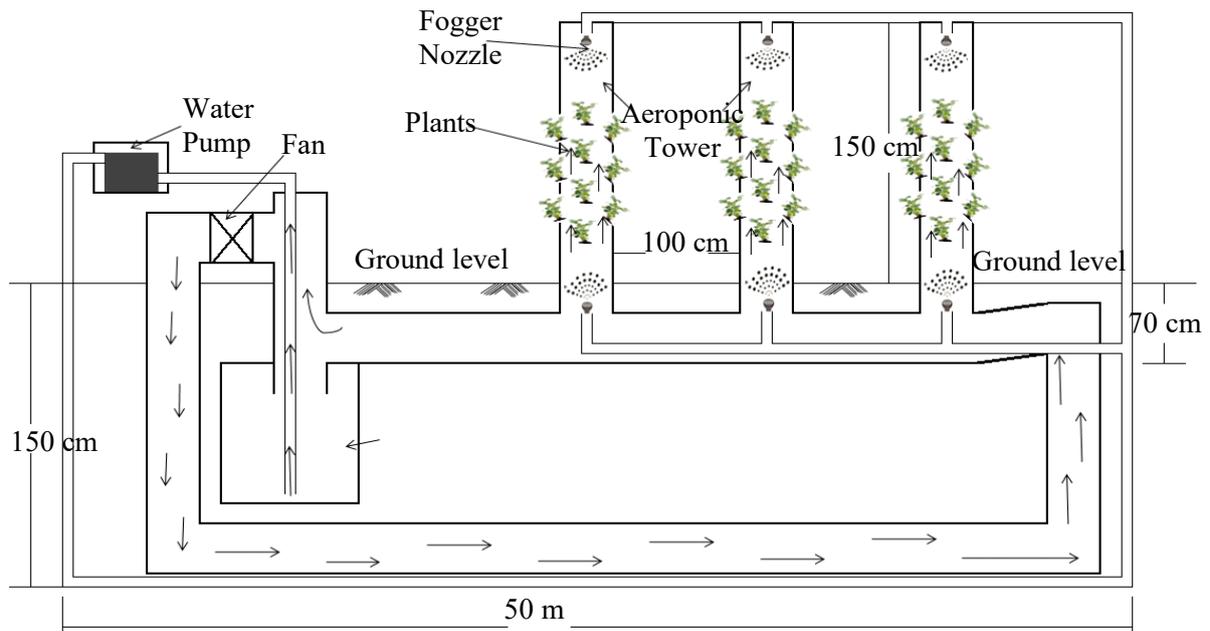


Figure 1. Schematic diagram of the experimental-set up using the ground heat exchanger

2.3. Data collection

The temperature, pH, electrical conductivity (EC) and dissolve oxygen (DO) of the nutrient solution was monitored daily and recorded using a multi-parameter tester (YSI Professional Plus, Model Pro 10102030, USA). A pre-test temperature sampling was done to establish a pattern and to test if the ground heat exchanger is really effective as compared to the control treatment and prevailing ambient and greenhouse temperature.

The relative humidity inside and outside the growing area was measured using a thermo-hygrometer (KTJ, Model TA318, China). Growth and development as indicated by number of leaves, petiole length, and number of stolons, of the strawberry plants were measured every week. Three samples were taken from each replicates (top, middle and bottom plants). The yield was determined for each plants and the average was computed for each treatment. The average yield was computed using the formula:

$$AY = TFW/TNP \quad (1)$$

where:

AY = average yield per plant, grams/plant

TFW = total fruit weight in one treatment, grams

TNP = total number of sample plants in one treatment

2.4. Cost Analysis

The initial investment for the whole system was estimated that includes the tropical greenhouse, vertical towers, nutrient solution, water pump, blower, nutrient delivery system, fogger/mister and installation of ground heat exchanger for root-zone cooling. Annual fixed cost was computed which comprised of depreciation and interest on investment. A fixed cost was based on a 10-year useful life with 20% salvage value and depreciation rate of 10% per year. The forecast on potential income was based on 6-month period of crop production because strawberry plants are seasonal. The benefit cost ratio was 4.24 and the annual return of investment generated was 32%.

2.5. Statistical Analysis

The data collected were analysed using the Statistical Tool for Agricultural Researches (STAR) based on analysis of variance (ANOVA) and Least Significant Difference (LSD) at 5% probability. Results of investigated parameters such as growth and yield from the combination of root-zone cooling methods and photoperiod were analysed in strip plot design.

3. Results and discussion

Figure 2 shows the weekly average temperature during the growing period of the strawberry plants. The average ambient temperature was 28.05°C while inside the greenhouse was more elevated at 35.19°C. The average root-zone temperatures for GHE, ACU and the control were 26.75°C, 24.14°C and 28.92°C, respectively. Extreme fluctuation on the root temperatures were reported to have a negative effect on the growth and development of plants [10]. Few minutes a day of root-zone temperatures of more than 30°C will slow the growth of heat-sensitive crops such as lettuce and parsley [11]. Although the control had an average temperature of 28.92°C, the fluctuation was evident with maximum and minimum temperatures of 33.32°C and 26.00°C, respectively. The root-zone temperature using the ground heat exchanger was more stable with no incidence of rising higher than 30°C which ranged from 24.22°C - 29.50°C.

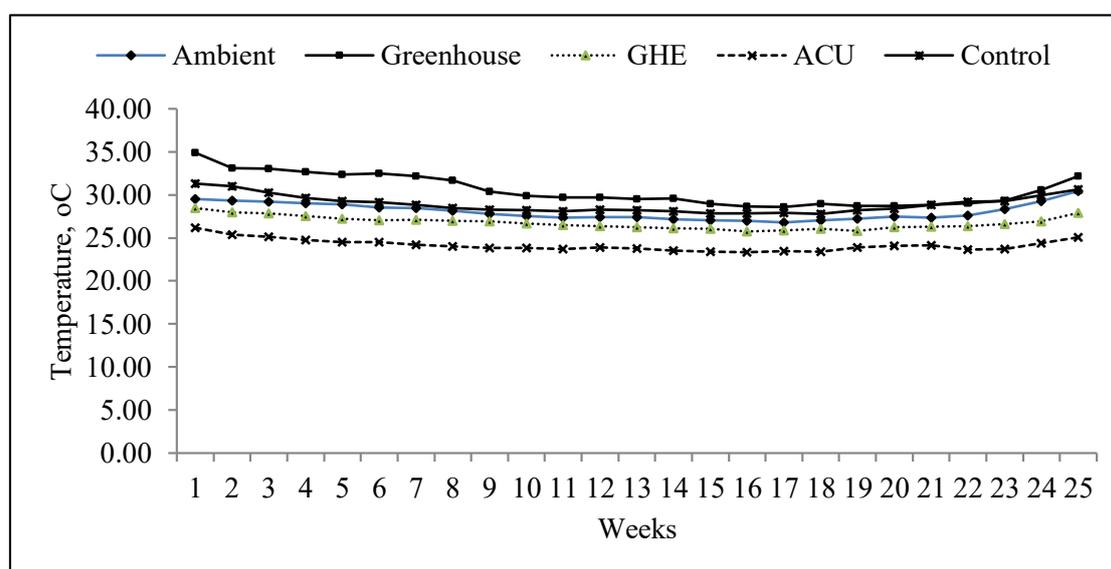


Figure 2. Root-zone, ambient and greenhouse day-temperature during the growing period, °C

The number of leaves per plant was significantly affected ($P < 0.05$) by the interacting effects of the treatments (Table 1). Plants whose roots under ACU and GHE with 16-hr photoperiod were comparable and had the most number of leaves with mean ranged from 76-82 leaves/plant. The number of leaves tend to increase over a period of time with response to temperature [12]. With root-zone cooling, new leaves are increased [13].

Table 1. Average number of leaves with different root-zone cooling methods and photoperiods.

Cooling Methods	Photoperiod		
	8-hr	16-hr	13-hr
GHE	68.67 ^{aAB}	75.33 ^{aA}	64.67 ^{aB}
ACU	70.33 ^{aB}	81.67 ^{aA}	61.67 ^{aB}
Control	28.33 ^{bA}	27.67 ^{bA}	32.67 ^{bA}

Data in columns followed by a different lowercase letters are significantly different at 5% level using LSD. Data in rows followed by different capital letters are significantly different at 5% level using LSD.

The ACU and 8-hr photoperiod, showed a significantly ($P < 0.05$) longer petioles relative to other treatments. While the number of stolons did not differ between ACU and GHE, but both were higher than the control regardless of photoperiods (Table 2). Strawberry yield were comparable between ACU and GHE ranged from 181-186 g/plant, but both were significantly ($P < 0.05$) higher than the control with 31 g/plant. The photoperiod did not affect the yield. Our results were comparable to reported yield of sweet Oso Grande and Camarosa cultivar in Brazil [14].

Table 2. Growth and yield of strawberry plants under different cooling methods and photoperiods.

Treatments	Petiole length, cm	No. of stolons	Yield, g
Cooling methods			
GHE	16.44 ^a	121 ^a	181.44 ^a
ACU	17.92 ^b	125 ^a	186.42 ^a
Control	14.16 ^c	57 ^b	31.31 ^b
Photoperiods (average of 3-treatments)			
8-hr	16.42 ^a	104 ^a	134.04 ^a
16-hr	16.13 ^b	99 ^a	135.50 ^a
13-hr	15.98 ^b	99 ^a	129.64 ^a

Data in columns followed by a different lowercase letters are significantly different at 5% level using LSD.

In terms of economic returns, Table 3 shows the details of cost and return analysis using a 72 m² greenhouse for one cropping cycle. The gross income was projected at \$3,461, while the total production cost was \$2,096. A potential net income of \$ 1,365 per season or \$3.49 per m² could be generated. The break-even yield was computed at 363.33 kg. The break-even yield can still be lowered when the unit price of strawberry fruits would go higher during off season and also when the fruiting season is extended.

Table 3. Cost and return analysis of aeroponically- grown strawberry plants using GHE at 72 m² greenhouse.

Variables	Amount, US \$
Fixed cost	
Average interest on investment	346.15
Depreciation	346.15
<i>Sub-total</i>	<i>692.30</i>
Variable cost	
Seedling	288.46
Nutrient Solution	134.62
Electricity	461.54
Chemicals	38.46
Labor	288.46
Repair and Maintenance	96.15
Miscellaneous	96.15
<i>Sub-total</i>	<i>1403.84</i>
Total Cost	2096.14
Gross income	3461.54
Net income	1365.38
Production cost, \$/kg	3.49
Break-even yield, kg	363.33

4. Conclusion

This study showed that the use of GHE as passive cooling was comparable with the used of air-condition for root-zone cooling in terms of growth and yield of vertically and aeroponically grown strawberry plants. The application of GHE for root-zone cooling under tropical greenhouse condition is economically viable. Also, propagation of planting materials during off-season can be done as a source for additional income.

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