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Development of a Cylindrical Hydroponics System for Vertical Farming

Chow Kheong Keat[1] and Chithrameenal Kannan[2]

1. School of Life Sciences and Chemical Technology, Ngee Ann Polytechnic, 599489, Singapore

2. Centre for Plant Breeding and Genetics, Tamil Nadu Agricultural University, Coimbatore 641003, India

Abstract: The study aimed to develop a vertical crop cultivation system for leafy plants based on cylindrical hydroponics and light emitting diode (LED) technology. Investigations were conducted on growing lettuce (*Lactuca sativa* cv. “Rex”, “Nanda” and “Canasta”) indoors in a rotary system and Chinese cabbage (*Brassica chinensis*) in a multi-tier cylindrical hydroponics system under red and blue (RB) LED lightings. Light intensity from different light sources have an influence on the yield and growth behaviour of indoor lettuce. Photosynthetically active radiation (PAR) levels at 63 μmol/m^2·s produced low fresh weights (FW) and leaf areas of lettuce “Rex” and “Nanda” were grown under rotating conditions. The effect was, however, different on the better developed “Canasta”. Stem etiolation was a common occurrence under such influence. Chlorosis was not observed on all plant types grown under the LEDs. Cultivating Chinese cabbage plants (FW: 28 g/plant) in cylindrical units stacked vertically above another, increased planting density by 47% when compared to the rotary system.

Key words: Chinese cabbage, cylindrical hydroponic system, LED lights, lettuce, rotary system, vertical farming.

1. Introduction

The world population was expected to reach nine billion in 2050. Hence, much emphasis has been placed on land utilization for housing and commercial purposes, such as in Singapore where land space is limited. Thus, there is an urgent need for high-yielding agriculture technology that efficiently utilises land, water, fertilizer and energy without relying on external climatic conditions. Vertical agriculture or farming in the form of indoor cultivation on high-rise buildings is being explored as a potential technology to provide reliable and healthy produce to consumers living in a dense urban environment. Indoor cultivation of vegetables began in Japan in the 1970s and has since progressed to multi-layer cultivation system incorporating special growing lights, such as light emitting diode (LED), and hydroponic systems [1].

Corresponding author: Chow Kheong Keat, M.Sc., research fields: hydroponics, controlled environment agriculture and vertical farming. E-mail: ckk@np.edu.sg.

To improve crop productivity in Singapore’s urban environment, multi-tier hydroponic growing systems equipped with red and blue (RB) LEDs were developed for vertical farming [2]. The combination of RB LED lights was proven to be an effective lighting source for producing many plant species, including lettuce, in controlled environments [3-6]. Earlier work by Smith [7] revealed favourable plant growth and development due to high absorption of RB lights. Massa et al. [8] also reported the relevance of RB LED on leafy and food crops. Successful development of an indoor multi-tier hydroponics system will improve the efficiency of land and water use. This will ensure a stable supply of healthy greens and improve food security, as Singapore imports at least 92% of fruits and vegetable from overseas [9].

The objective of this research was to develop a high-yielding indoor vertical cylindrical hydroponics system for leafy vegetables using LED as a light source. To achieve this, the first phase of the project will evaluate crop growth under LED on the rotary hydroponic system established on various growing media. The second phase will involve the designing of a vertical cylindrical hydroponics system.

2. Materials and Methods

2.1 Cultural Conditions

Lettuce seedlings (*Lactuca sativa*) of butterhead cultivars "Rex", "Nanda" and loose-leaf "Canasta" were raised on 2.5 cm polyurethane cubes and then transferred to two lots of 7 cm 10 days after sowing (DAS), each containing either vermiculite or cocopeat:perlite (2:1). Half-strength modified nutrient solution by Cooper [10] was supplied to the seedlings 7 DAS. The solution was modified by reducing 10% of N, K, Ca and Mg. Potted seedlings were then acclimatized in the greenhouse and transplanted to the two light treatments, i.e., under LED and natural outdoor environment 15 DAS. The electrical conductivity (EC) and pH of the full-strength nutrient solution were maintained at 2 mS and 5.8 to 6.2, respectively, for both treatments during maturing stage. A total of 106 plants per cultivar were harvested 50 DAS for each treatment.

The Chinese cabbage seedlings (*Brassica chinensis*) were propagated and prepared in the same manner as the lettuce seedlings. At 10 DAS, the seedlings were transferred to cocopeat-filled 7 cm pots. After the greenhouse acclimatization, the Chinese cabbage seedlings were transplanted onto the multi-tier cylindrical hydroponics system.

All plant trials involving the light treatments and multi-tier cylindrical hydroponics system were conducted between October 2011 and April 2013 at the School of Life Sciences & Chemical Technology, Ngee Ann Polytechnic.

2.2 Light Treatments

The plants were grown under two light sources—natural outdoor (control) and RB LED. Since plants used the energy of the electromagnetic spectrum from 400-700 nm (photosynthetically active radiation (PAR)), a LI-COR light meter quantum sensor [11] was used to measure the PAR of RB LED and natural outdoor treatments to get an idea of the spectral characteristics. PAR levels were determined at the plant canopy top.

2.3 RB LED Rotary Hydroponics System

In the LED rotary system, equal plant numbers from each cultivar of 40 pots were filled with vermiculite and cocopeat:perlite (2:1). The Volksgarden® rotary hydroponics system [12] consisted of a rotary wheel (1.25 m diameter × 0.75 m deep), and held 80 plants (85 plants/m^2) with a 7 cm root medium. The chain driven wheel which rotated continuously throughout the day, and the plants absorbed nutrient solution at the base of the wheel every 45 min when a rotation was completed. Twelve LED tubes were held in a stainless steel support structure at the inner zone of the rotating wheel (Fig. 1).

Each 26W LED tube with a length of 1.2 m contained 108 red (660 nm) and 36 blue (470 nm) individual diodes. Lighting for the RB LED (ratio 3:1, respectively) was 16 h light/8h dark with PAR at 63 μmol/m^2·s 15 cm away from LED tubes (Fig. 2). Constant PAR levels at the distance of 15 cm were maintained throughout the growth period by adjusting

Fig. 1 Lettuce in the rotary system rotates around the 12 LED tubes held by a support structure.

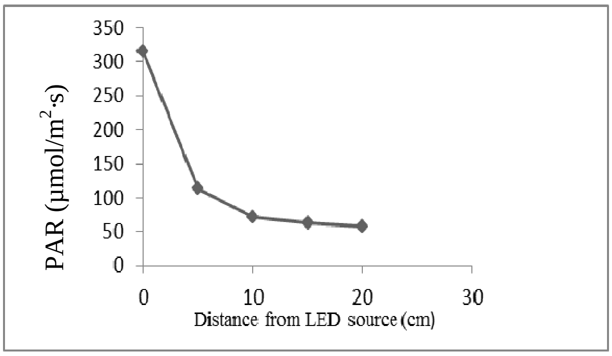

Fig. 2 PAR levels determined at various distances from RB LEDs which were centrally positioned at the rotary hydroponic system.
The data points are averages of a pool of measurements from the 12 LED tubes for each distance.

the LED tubes along the support structure. Indoors temperatures of 21-30 °C and relative humidity (RH) 53%-84% were recorded for the RB LED system.

2.4 Natural Outdoor Conditions

For the natural outdoor treatment, plants of control group were kept outdoors along the 7th level balcony, where daily mean PAR levels of 440 μmol/m^2·s were recorded with ambient temperatures of 22-37 °C and RH 75%-90%. The plants were held in 60 cm × 40 cm trays and sub-irrigated at alternate days with full-strength nutrient solution by Cooper [10].

2.5 Growth Characteristics

Shoot FW and leaf area of lettuce were determined at 50 DAS. Leaf area measurements were made from the largest expanded leaf per plant. Three trials were conducted under RB LED and natural outdoor conditions to accommodate the three lettuce cultivars. A two-tailed *t*-test was performed at 5% level of significance on the growth data to determine the significance of effects of the treatment.

2.6 Multi-Tier Cylindrical Hydroponics System

Six sets of aluminium structures, each containing eight columns of RB LED lights, were uniformly placed around the multi-tier cylindrical hydroponics system (Fig. 3). The lights were turn on for 16 h with PAR at 44 μmol/m^2·s at 25 cm away from the plants. Indoor environment with temperatures of 20-24 °C and RH 70%-82% was measured. The multi-tier cylindrical hydroponics system was made up of two polyvinyl chloride (PVC) cylinders (1.20 m diameter × 0.75 m height) stacked above each other (Fig. 4a). Each cylinder was designed to hold 90 planter boxes (10 cm × 10 cm) with a root depth of 10 cm. At a total height of 1.8 m, the growing system could accommodate 180 plants at a planting density of 125 plants/m^2 (Fig. 4b).

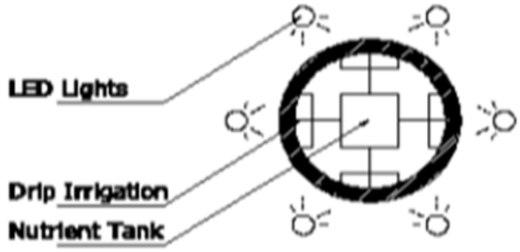

Fig. 3 Top view of schematic diagramme showing the arrangement of six sets of aluminium structures (with LED lights) and nutrient delivery components.

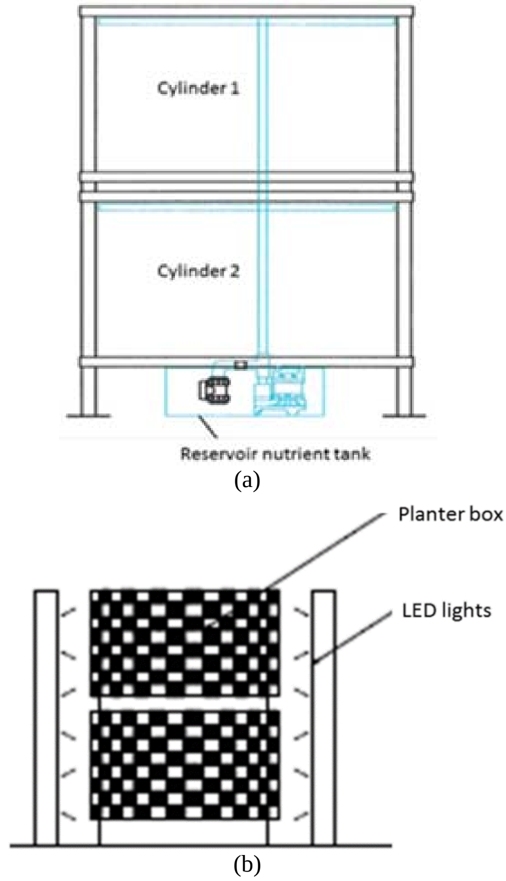

Fig. 4 Side view of schematic diagrammes showing the arrangements of two PVC cylinders (a) and planter boxes (b) in the multi-tier cylindrical hydroponics system.

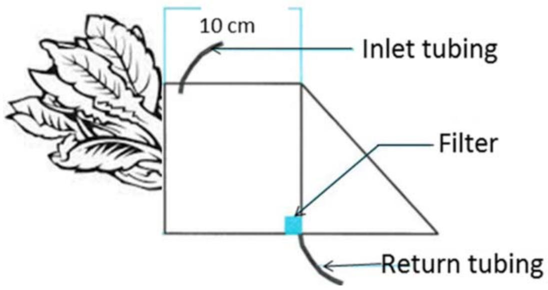

Fig. 5 Plant in the planter box receives nutrient solution from a 5 mm inlet tubing and excess solution returns to the reservoir.

Nutrient solution of EC 2 mS and pH 6 was delivered upwards through 30 mm PVC pipe from the reservoir nutrient tank by a 1 hp submersible pump. The 5 mm flexible plastic tubings were connected to the PVC pipes and then delivered the nutrients to the individual planter box in cylinders 1 and 2. A timer controlled the pump where plants received the nutrient solution half-hourly for 15 min. Excess nutrients from the planter boxes were then channelled back to the reservoir via return tubings (Fig. 5).

3. Results and Discussion

3.1 LED Rotary Hydroponics System

Butterhead lettuce "Rex" and "Nanda" under natural light conditions were able to develop early into a rosette in both vermiculite and cocopeat:perlite (2:1). Shoot FW and leaf area of control lettuce "Rex" and "Nanda" were significantly greater (P = 0.05) than plants grown in LED except for cultivar "Nanda" raised in cocopeat-perlite (Table 1). High PAR levels (440 µmol/m^2·s) available outdoors in the natural environment provided sufficient light energies for growth and development. Although high air temperatures greater than 30 °C were common occurrence, generally the leaves of control plants were able to grow into the head.

The smaller sized leaves from LED rotary were seen to curl with many plants undergoing stem elongation, which indicates a photomorphogenic response to LEDs, and resulted in the lower shoot FW. The decreased growth of RB LED lettuce observed in this study was affected by insufficient PAR levels. Low leaf areas achieved in RB LED compared to the control plants were in contrast to that of Lin et al. [13], who reported that the higher leaf areas were achieved with the use of RB LEDs. However, LED "Canasta" yield was comparable to the loose-leaf type lettuce yield under RB LED by Kim et al. [4]. It could not be confirmed if spectral qualities of the RB LEDs used in this study did enhance LED "Canasta" growth, as the 16 h long growth period may provide greater effect instead. Findings from Yorio et al. [14] and Kim et al. [4] seemed to suggest that red and blue lights alone were sufficient for lettuce growth and development.

Prospects that the higher plant growth rates with the shorter internodes on the rotary system due to gravitational influences [12] were not evident during the trials. The lower lettuce yield from RB LED caused by poor root development was discounted, as root rot incidence was not present. Excess nutrient solution was drained off when each time the plants emerged from the nutrient reservoir at the rotary base to make direct contact with air. Growth comparison of lettuce "Rex" and "Nanda" between the two growing media were similar except for the control lettuce "Nanda" established in vermiculite. Here, the shoot growth was greater than those in cocopeat-perlite media.

There was no significant difference in yield between lettuce "Canasta" grown under LED or natural conditions. Stem etiolation occurred on both control and LED "Canasta" 23 days after transplanting with greater severity on RB LED plants (Fig. 6). Significant reduction of PAR levels encountered indoors could possibly stimulate stem etiolation. However, Dougher et al. [15] and Watanabe [1] contributed this specifically to insufficient blue lights. Unlike low chlorophyll content which may accompany with stem elongation in lettuce [15], leaf chlorosis was not noticed during the trials. Lighting effects on the development of lettuce in greenhouses have been earlier reported by Schippers [16] that winter

Table 1 Influence of light quality on mean shoot fresh weight* (FW) and leaf area of three lettuce cultivars grown in vermiculite and cocopeat:perlite (2:1) at 50 DAS.

Light treatments	Lettuce "Rex"				Lettuce "Nanda"				Lettuce "Canasta"			
	Shoot FW (g)		Leaf area (cm²)		Shoot FW (g)		Leaf area (cm²)		Shoot FW (g)		Leaf area (cm²)	
	Vermiculite	Cocopeat: perlite (2:1)	Vermiculite	Cocopeat: perlite (2:1)	Vermiculite	Cocopeat: perlite (2:1)	Vermiculite	Cocopeat: perlite (2:1)	Vermiculite	Cocopeat: perlite (2:1)	Vermiculite	Cocopeat: perlite (2:1)
RB LED	23^{a}	23.8^{a}	53.3^{a}	51.9^{a}	19^{a}	18.9^{a}	40^{a}	42.9^{a}	30.8^{a}	24.7^{a}	117.9^{a}	103.3^{a}
Natural outdoor	34.8^{b}	31.4^{b}	77.9^{b}	80.5^{b}	26^{b}	17^{a}	69.7^{b}	59.3^{a}	30.5^{a}	33.3^{a}	124.2^{a}	99.3^{a}

$^{a, b}$Mean values of 53 plants followed different letter are significantly different (P = 0.05) according to two-tailed t-test.

(a) (b)

Fig. 6 Mature lettuce "Canasta" growing under two light sources: (a) RB LED and (b) natural outdoor conditions. Stem etiolation was more severe on the lettuce plants grown under RB LED.

Fig. 7 Non-uniformity in growth rates of Chinese cabbage crop in multi-tier cylindrical hydroponics system remained a problem.

varieties adapted to low light requirements were noted to bolt when grown under the stronger light conditions. None of the lettuce cultivars suffer from tip burn occurring either in the young developing leaves of the centre head or on outer leaves. Such symptom normally arises from calcium disorder in hydroponic lettuce [17].

Plant growth could be enhanced if the plants were positioned closer to the light source (i.e., at 10 cm or less), as received significantly higher irradiance without any foliage damage from heat generated from the diodes. However, physical damage to the leafy crops was encountered especially on mature plants, when it brushed against the LED tubes during the wheel rotation.

The close proximity of lights to the plants at 15 cm makes the rotary system a compact plant cultivation system suitable for confining living space. Planting density at 85 plants/m^2 has the potential to be increased several times if the production units are stacked vertically at multiple levels, increasing the productivity over the same floor area. Venter [18] mentioned similar strategy that production area was estimated to increase up to 650% when the rotating units were assembled within a structure and were elevated above the floor.

3.2 Cylindrical Hydroponics System

Moving machineries involving wheels, chains and motors were removed to increase the reliability and efficiency of the growing system. By redesigning and assembling the vertical growing system in a horizontal manner, the new improved growing system is a multi-tier cylindrical hydroponics system equipped with RB LEDs and recirculating drip irrigation system designed to improve productivity. Cultivating the plants in cylindrical manner and stacking them above one another vertically managed to increase the planting density by 47% when compared to the rotary system.

The preliminary study on the multi-tier cylindrical hydroponics system demonstrated that the light energy was adequate to produce Chinese cabbage crops 45 DAS with a mean FW of 28 g/plant and without chlorotic symptoms (Fig. 7). Nonetheless, variation in plant sizes with long green petiole was visually observed on the non-headed plants. Studies have suggested that non-uniformity in growth response was due to the narrow-bandwidth lightings [8, 19]. In this instance, such yield deviation was enhanced by the curved cultivation surface, which created "blind spot", resulting in uneven PAR distribution among the plants. With a current yield of 3.5 kg/m^2, the multi-tier cylindrical hydroponics system has the ability to contribute 13.2% of Singapore's per capita vegetable consumption estimated at 85.7 kg/person/year [20].

Rotary and cylindrical type of hydroponic systems can be adopted for high density crop production and permit leafy vegetables to be grown indoors (e.g., residential buildings) throughout the year without depending on soil and climate. With a close loop, both growing systems enable water and minerals to be efficiently utilized with the elimination of runoff. This study has managed to establish parameters, which are essential in developing efficient and productive vertical farming or plant factory systems. However, more work is warranted to optimise the intensity, spectral quality and combination ratios of the LEDs. Studies on combination of blue, red, far-red and green lights have shown to have an influence on morphogenesis [3] and shoot biomass [4] of fruit and leafy crops. Further trials on variety selection of indoor grown lettuce that is adaptable to cylindrical hydroponics will be necessary to ensure successful crop production in a vertical manner.

4. Conclusions

This study has developed a multi-tier cylindrical hydroponics system as a possible vertical farming technique for tight-spaced high-rise buildings with improved productivity over the rotary system. Although parameters for indoor crop production are established, further work on optimising intensity, spectral quality and combination ratios of the LEDs to maximize plant growth is required.

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