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Full Length Research Paper

Study of high power light emitting diode (LED) lighting system in accelerating the growth rate of *Lactuca sativa* for indoor cultivation

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The experimental study of indoor cultivation using high power light emitting diode (LED) lighting system to accelerate the growth rate of *Lactuca sativa* plant is presented in this article. A novel high power LED lighting system with the use of aluminum indium gallium phosphide (AlInGaP) and indium gallium nitrate (InGaN) LEDs to produce photosynthetically active radiation (PAR) light source required for photosynthesis process of plant has been constructed. This study has verified that high power LED lighting system can accelerate the growth rate of *L. sativa* when compared with those plants cultivated under normal solar irradiance.

Key words: *Lactuca sativa*, high power LED, AlInGaP, InGaN, photosynthetically active radiation, indoor plant cultivation, Solar irradiance.

INTRODUCTION

Light emitting diode (LED) lighting is a promising artificial light source that is getting more attention for indoor plant cultivation. This is because the LED lighting can provide advantages including lower energy consumption, less heat generation and least insecticide used as compared to the conventional lighting, such as vapor sodium, metal halide or fluorescent lamp. Overall, the LEDs can be grouped into low power LED with current rating ranging from 1 to 20 mA, medium power LED with current rating around 100 mA and high power LED with current rating from hundreds of mA to more than an ampere.

In the early development, the only available type of LED was made from gallium arsenide (GaAs) material with illumination ranging from infrared to red. Advances in material science had then made possible the production of devices with ever-shorter wavelengths to produce light in a variety of colors (Yeh and Chung, 2009). In late 1960s, the first practical LED was invented by Nick Holonyak, Jr using gallium arsenide phosphide (GaAsP) material to provide a 655 nm red light with low brightness levels of approximately 1 to 10 mcd at 20 mA. As LED technology progressed through the 1970s, additional colors and wavelengths became available, such as GaP for green and red lights, GaAsP for orange and high efficient red light, and GaAsP for yellow light, etc., (Yeh and Chung, 2009). In 1980s, a new material gallium aluminum arsenide (GaAlAs) was developed to provide superior performance over previously available LEDs with a minor improvement in brightness and efficiency. In the late 1980s, LED designers started to produce high-brightness and high reliability LEDs. This has led to the development of indium gallium aluminum phosphide (InGaAlP) LEDs that can have different color output via adjusting the energy bandgap.

The studies of indoor plant cultivation using low and medium power LED can be listed in the following. Schuerger and Brown (2004) applied LED arrays with different spectral qualities to determine the effect of light on the development of tomato mosaic virus in peppers and powdery mildew on cucumbers. Matthijs et al. (1996) used LED as sole light source in continuous culture of green algae. Goins et al. (1997) used plenty of LED

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arrays to study the wheat plants grown in Kennedy Space Center. Okamoto et al. (1997) used LED to study the lettuce seedling growth and morphogenesis. Strawberry micro-propagation study using LED as a light source was carried out by Nhut et al. (2000). Jao and Fang (2004) studied different frequency and duty ratio on the growth of potato plantlets *in vitro* by using LED light source. All these studies had to use a lot of normal low power LED or customized LED array to produce sufficient photosynthetically active radiation (PAR), which is not cost effective solution for commercial or mass agricultural production purpose.

Since year 2009, LED technology has been developing into a much more energy efficient with power conversion efficiency as high as 14.9% at 25°C temperature with the use new base materials, that is, aluminum indium gallium phosphide (AlInGaP), indium gallium nitrate (InGaN), etc. These base materials can produce much higher radiant flux at high operating current of 700 mA and operating temperature of 135°C for AlInGaP, while at 1000 mA of operating current and 150°C of operating temperature for InGaN (Philips Lumileds, 2011). These types of LEDs are also called high power LED because it consumes electrical energy power of 1 W or higher. A single AlInGaP LED (model LXML-PD01-0030 from Philips Lumileds) can produce a typical of 62 lumens of radiant flux at the dominant wavelength of 627 nm with the input current and forward voltage of 700 mA and 3.60 V, respectively at 25°C (Philips Lumileds, 2011). A normal type of low power LED, such as 5 mm cylindrical package LED from Avago Technology only produces typical of 1 lumen of radiant flux with 20 mA, which is a much lower flux production than that of a high power LED (Avago Technologies, 2009). The AlInGaP and InGaN LEDs produce the irradiance in the wavelengths of 620 to 645 nm and 440 to 490 nm, respectively, which are within the useful range of PAR of most plants' chlorophyll for photosynthesis process to produce glucose (Photosynthesis Timeline, 2008).

In this paper, the use of novel high power LEDs in accelerating the growth rate of plants for indoor cultivation has been studied. High energy efficient solid state lamp (SSL) has been designed and constructed using high power LEDs that consist of Luxeon Rebel Red (model LXML-PD01) and Luxeon Rebel Royal Blue (model LXML-PR01) LEDs by Philips Lumileds to produce high photosynthesis photon flux (PPF). In this study, low light *Lactuca sativa* (Romanian Lettuce) was chosen as test specimen in the experiment, because of its high commercial value, short test cycle and easy to grow under normal condition.

METHODOLOGY

The high power LED lighting system that was designed and constructed for indoor plant cultivation can be divided into three main components: LED module, alloy fixture of LED lamp and LED driver.

LED module and alloy fixture

AlInGaP LED as red radiation source (wavelength ranging from 620 to 645 nm) and InGaN LED as blue radiation source (wavelength ranging from 440 to 460 nm) in which both are supplied by Philips Lumileds under the product range of Luxeon Rebel have been employed.

Luxeon Rebel LED is in a bare emitter form and it is required to be mounted on printed circuit board (PCB) for electrical connection to the power supply. A hexagonal PCB with 20 mm in diameter was fabricated by printing the footprint layout on a raw ceramic substrate of PCB that contains both the anode and cathode pads where the bare emitter can be mounted on. PCB with ceramic based substrate was selected, because of both its good thermal conductivity and high electrical resistivity. The Luxeon Rebel LED was then soldered to the PCB using a hot plate soldering machine to form a LED module as shown in Figure 1.

During the process of assembling the LED module, special care was required to avoid touching on the Luxeon Rebel dome lens that could lead to defects in the LED as it is a fragile material. From the manufacturer specification of PCB, PCB with ceramic substrate has thermal resistance of 0.12°C/W (Hokuriku, 2009). Luxeon Rebel Red (AlInGaP) and Blue (InGaN) LEDs have thermal resistances of 12 and 10°C/W, respectively (Philips Lumileds, 2011) and therefore, the total thermal resistance of Luxeon Rebel Red and Blue LED modules can be obtained as 12.12 and 10.12°C/W, respectively. The completed LED modules were then installed to an alloy fixture.

In the preparation of LED module assembly, an open-ended pyramidal reflector with two different slope angles of 25 and 52° supplied by Diffractive Optics was mounted on each of the LED module using high temperature grade thermal adhesive in order to produce collimated light with reasonably uniform illumination onto the young *L. sativa*. Figure 2 shows the photo taken for the open-ended pyramidal reflector (Diffractive Optics, 2009).

Two units of Luxeon Rebel Red LED panel and two units of Luxeon Rebel Blue LED module assembly have been constructed in this study. Each LED panel consists of an array of 4 × 2 units of Luxeon Rebel Red LED module assembly fixed to the alloy fixture. Each LED module assembly consists of the LED module and the open-ended pyramidal reflector. Figure 3 shows the flow diagram of how the LED panel was constructed.

The attachment of the Luxeon Rebel Red LED modules to the alloy fixture was done with the use of Dow Corning SE4486 adhesive, which has a good thermal conductivity of 1.53 W/mK (Dow Corning, 2012). The thermal resistance contributed by the adhesive is as low as 0.4°C/W when 0.2 mm maximum thickness of adhesive was applied to bond the LED module to the inner part of alloy fixture. On the other hand, Luxeon Rebel Blue LED modules were attached to 20 × 20 mm aluminum sheet to assist heat dissipation and were placed at both sides of the alloy fixture. Since the efficiency of AlInGaP LED is dependent on temperature, thermal management is important to ensure Luxeon Rebel Red LED operating in the optimal performance, and hence, Philips Lumileds's thermal management concept was adopted in this case. The high power LED modules that are attached to the alloy fixture with thermal resistance of 0.8°C/W could create temperature as high as 80.4°C at the LED junction when the LED is driven by constant input current of 700 mA at ambient temperature of 25°C. The eight Luxeon Rebel Red LED modules in the panel were connected in series with the maximum forward voltage of 3.51 V each to form the total voltage of 28.08 V for each panel.

The calculation of total input electrical power of each panel can be shown as follow:

$$P_{tot\_LED} = V_f \times I = 28.08\text{ V} \times 0.7\text{ A} = 19.66\text{ W} \qquad (1)$$

where V_f is the total maximum forward voltage of Luxeon Rebel Red LED panel.

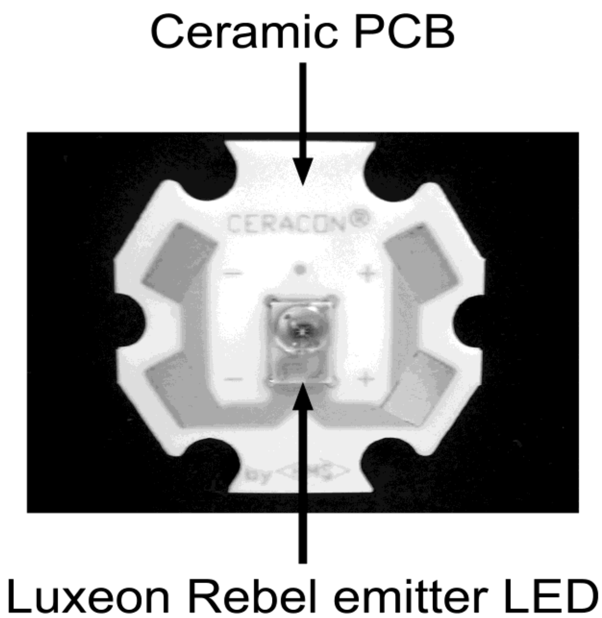

Figure 1. Luxeon Rebel LED module in which a Luxeon Rebel LED is mounted at the centre of a hexagonal ceramic PCB where positive and negative pads are printed on the surface.

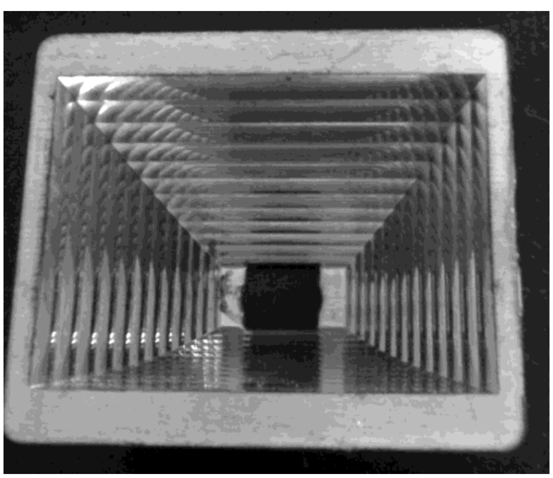

Figure 2. An open-ended pyramidal reflector with two different slope angles of 25 and 52º to be supplied by diffractive optics and it is mounted on each of the LED module using high temperature grade thermal adhesive in order to produce collimated light with reasonably uniform illumination.

The calculation of the LED temperature in the panel:

$$Tj\text{-}a = P_{tot\_LED} \times (R\Theta_{LED\_module})/8 \quad (2)$$

$$Tj\text{-}a = 19.66 \times [(12 + 0.12 + 0.4 + 0.8) \times 3.51\times 0.7]/8 = 80.4°C \quad (3)$$

where

$$R\Theta_{LED\_module} = R\Theta_j + R\Theta_{pcb} + R\theta_{ads} + R\Theta_f \quad (4)$$

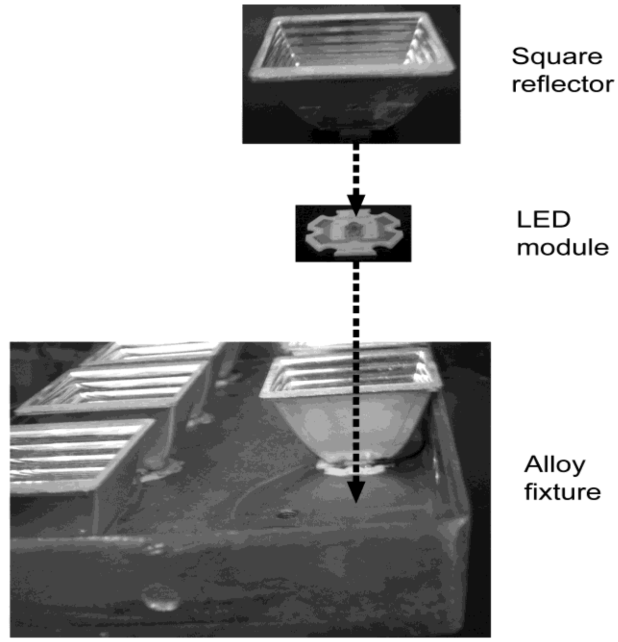

Figure 3. Flow diagram to indicate how the LED panel was constructed: it was started with mounting the open-ended pyramidal reflector to the LED module and is then followed by fixing them into an alloy fixture.

provided that thermal resistance of LED die junction-slug, $R\Theta_j$ = 12°C/W; thermal resistance of PCB with ceramic substrate, $R\Theta_{pcb}$ = 0.12°C/W; thermal resistance of silicone adhesive with 0.2 mm thickness, $R\Theta_{ads}$ = 0.4°C/W; thermal resistance of alloy fixture, $R\Theta_f$ = 0.8°C/W; where solder has extremely low thermal resistance less than 0.001°C/W and has been ignored in the calculation (Bai et al., 2004).

Temperature at outer surface of the alloy fixture was measured as 53°C. By using the system thermal resistance model of Philips Lumileds AB05 (Philips Lumileds, 2006), the temperature of LED junction should be 53°C + (12 + 0.12 + 0.4 + 0.8)°C/W $\times$ (3.51$\times$ 0.7) W = 85.7°C, which was quite close to the calculated temperature value, and it is still well below the maximum operating temperature of 135°C. In fact, these values are based on the maximum forward voltage to provide safety margin for the operation of the LED panel.

LED driver

The LED driver must deliver a DC output voltage greater than 28.1 V in order to forward bias all the Luxeon Rebel Red in the LED panel and is also capable of supplying constant current of up to 700 mA as shown in Figure 4. National semiconductor LM3404IC (2010) was used in the buck LED driver design due to its simplicity and capability to support a current up to 1.0 A, which was enough for the driving specification. Surface mounted device (SMD) resistors were chosen to sense and to feedback the output current for the purpose of regulating and delivering sufficient current to drive the LED circuit. In this design, two SMD resistors with the resistance of 0.68 Ω each were connected in parallel to have a total resistance of 0.34 Ω and total power rating of 0.25 W. Two resistors instead of one were used to increase the heat dissipation capacity when high current pass through them. A step down transformer was used to convert the AC voltage from 240 to 24 V and before it is supplied to the LED driver as shown in Figure 4. The overall efficiency of the LED driver is about 85%.

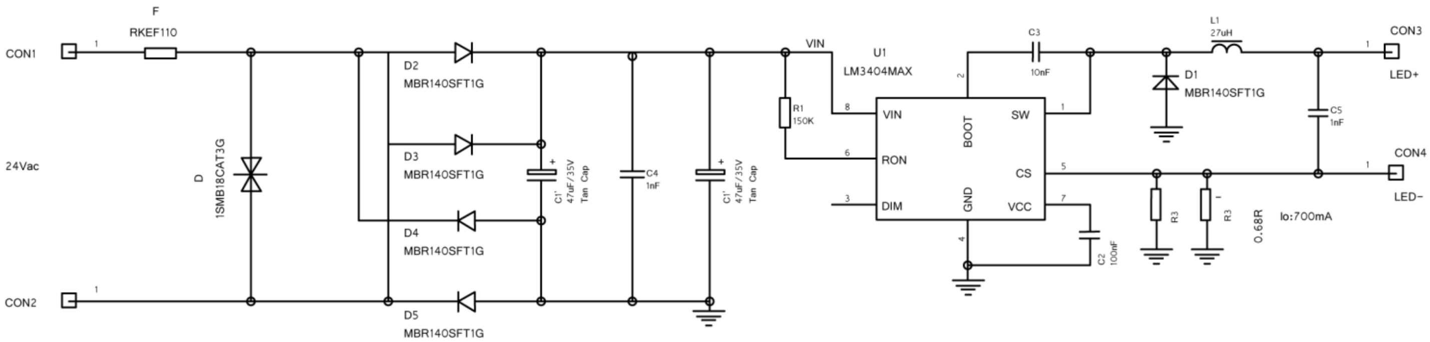

Figure 4. Circuit diagram to show a 24 V AC input LED driver that is capable of supplying constant output current of 700 mA and DC output voltage greater than 28.1 V in order to drive a maximum of eight Luxeon Rebel LEDs in series.

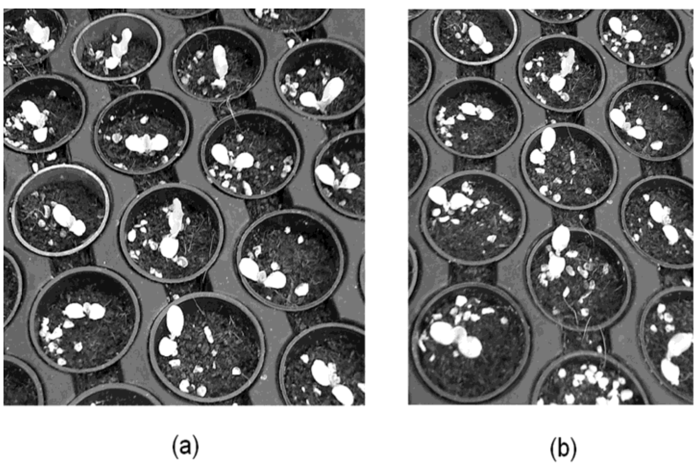

Figure 5. The Photos to show two pallets of germinated young *L. sativa* that were prepared as test specimen plants for cultivation under two different illumination conditions: (a) solar irradiance and (b) high power LED lighting system.

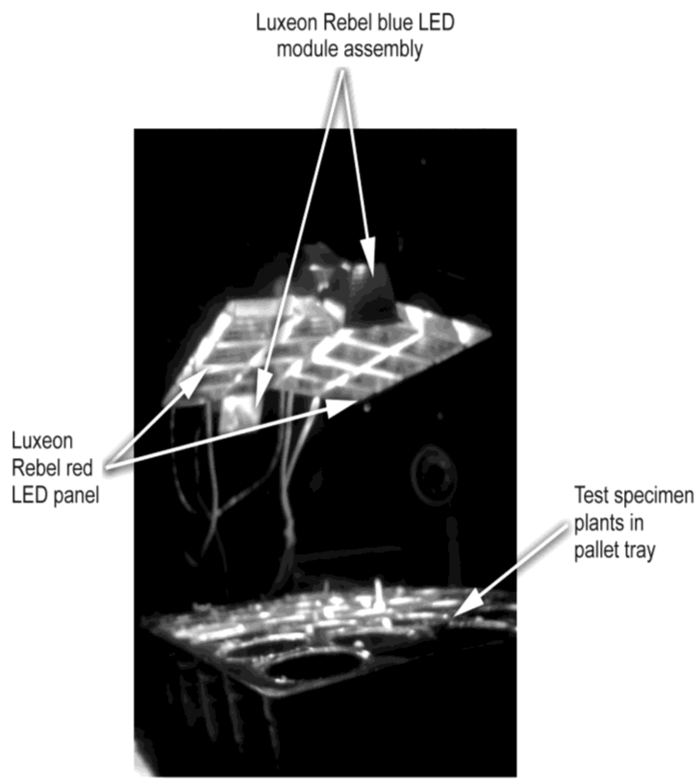

Figure 6. Picture to show the experimental setup in a dark room where the high power LED lighting system is placed at 20 cm above the test specimen plant where the high power LED lighting system was switched on for 16 h per day from 8 to 12 am throughout the whole experiment.

Experimental set-up

The young *L. sativa* plants were prepared in a pallet tray and the experiment only started after it appeared to have two pieces of leafs fully expanded and germinated from the seeds as shown in Figure 5a and b. Each pallet contained thirty three pots of germinated young *L. sativa*.

These experiments were carried out in a green house of lettuce farm at Kampung Raja, Cameron Highland in Malaysia with altitude of 1311 m, latitude of 4.57°N and longitude of 101.40°E which lies entirely in the equatorial region. In these experiments, there were two pallets of young *L. sativa* plants to be cultivated under two different illumination conditions for a comparison study: one pallet was placed inside a dark room equipped with high power LED lighting system and another pallet was placed outside the dark room to be exposed to normal solar irradiance. One pallet of young *L. sativa* was well aligned under the LED lamp that was hung at the height of 20 cm above the plants so that the light cone that irradiated from high power LED will just be sufficient to cover all the plants as shown in Figure 6. The ambient temperature was recorded ranging from 18 to 26°C during the testing period in which the lowest temperature happened in the midnight whilst the highest temperature happened in the sunny afternoon. The high power LED lighting system was powered up by a 24 V AC and the operating time was set from 8.00 to 12.00 am (or 16 h of photo-period) per day with the use of a timer. The young *L. sativa* plants cultivated in the dark room were watered twice daily, that is, in the morning and in the afternoon, with the same timing as those young *L. sativa* plants grown under the normal solar irradiance. It was continued for a period of 11 days in the first experiment and the same procedure was also repeated in the second experiment for a period of 8 days. The whole cultivation process had been monitored and recorded by CCD cameras for the purpose of tracing the development of *L. sativa*.

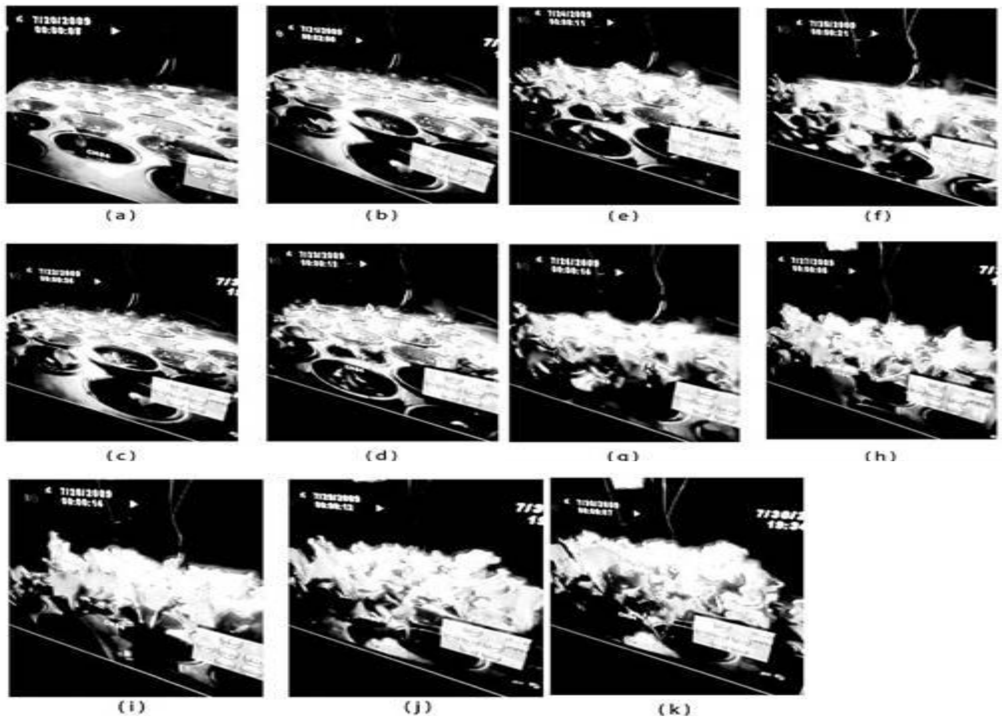

Figure 7. A series of photos taken with CCD video camera for 11 days starting from 20th to 30th July in experiment 1 to show the progress of plant growth under high power LED light system in the dark room: (a) Day 1, (b) Day 2, (c) Day 3, (d) Day 4, (e) Day 5, (f) Day 6, (g) Day 7, (h) Day 8, (i) Day 9, (j) Day 10 and (k) Day 11.

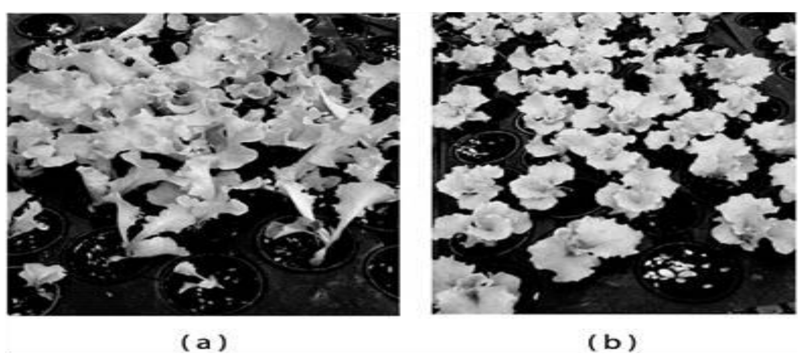

Figure 8. The Pictures to show the comparisons of final results for cultivating the *L. sativa* plants under the solar irradiance and high power LED lighting system in the experiments 1 and 2: (a) *L. sativa* plants cultivated under high power LED in experiment 1 and (b) *L. sativa* plants cultivated under solar irradiance in experiment 1

RESULTS AND DISCUSSION

To ensure the repeatability of the experimental result, two experiments were successfully conducted for different periods of growing time, that is, eleven days for experiment 1 and eight days for experiment 2. From the physical observation, the specimens of young *L. sativa* plants cultivated under high power LED lighting system had shown faster growth rate than that of the specimens cultivated under normal solar irradiance. From the recorded video, Figure 7a to k shows the photos of specimen plants taken from day 1 to day 11 for the experiment 1. In the overall results as shown in Figure 8, the young *L. sativa* plants cultivated under high power LED lighting system have been observed to have larger leaf area and taller stem than those of the young *L. sativa*

Table 1. Measurement result of total leaf area index per plant, plant fresh weight and leaf width of the ten selected samples in Experiment 1.

Plant sample	Experiment 1 (11 days of plant)					
	Total leaf area index per plant (mm^2)		Plant fresh weight (g)		Leaf width (mm)	
	High power LED	Solar irradiance	High power LED	Solar irradiance	High power LED	Solar irradiance
S1	1515	502	3.0	0.8	36, 33, 28, 24, 10	22, 20, 19, 11, 6
S2	1479	487	2.8	0.7	34, 28, 26, 25, 10	22, 20, 18, 10, 5
S3	1423	485	2.5	0.7	30, 27, 26, 18, 9	22, 19, 18, 10, 6
S4	1202	463	1.7	0.6	29, 24, 16, 8, 8	21, 18, 17, 9, 5
S5	1487	445	2.7	0.6	32, 27, 27, 24, 10	19, 17, 15, 8, 5
S6	1265	435	1.8	0.6	29, 24, 18, 10, 9	18, 16, 13, 8, 5
S7	1390	470	2.2	0.7	29, 27, 19, 17, 9	21, 20, 18, 9, 5
S8	1338	486	2.0	0.7	29, 25, 20, 14, 8	21, 20, 18, 10, 6
S9	1476	412	2.8	0.5	33, 30, 26, 24, 10	16, 14, 12, 8, 5
S10	1426	403	2.4	0.5	30, 28, 23, 18, 10	15, 14, 12, 7, 5
Average	1400.1	458.8	2.39	0.64	21.8	13.6
Max	1515	502	3.0	0.8	36	22
Min	1202	403	1.7	0.5	8	5

Table 2. Measurement result of total leaf area index per plant, plant fresh weight and leaf width of the ten selected samples in Experiment 2.

Plant sample	Experiment 2 (8 days of plant)					
	Total leaf area index per plant (mm^2)		Plant fresh weight (g)		Leaf width (mm)	
	High power LED	Solar irradiance	High power LED	Solar irradiance	High power LED	Solar irradiance
S1	294	386	0.3	0.4	17, 4, 4	18, 16, 7, 6
S2	908	341	1.2	0.4	28, 24, 7, 6	16, 12, 4, 4
S3	587	335	0.8	0.4	24, 20, 5, 5	15, 14, 5, 4
S4	718	342	0.9	0.4	24, 24, 5, 5	16, 10, 6, 5
S5	667	330	0.8	0.3	23, 20, 6	14, 14, 4, 4
S6	868	359	1.1	0.4	28, 23, 5, 6	15, 14, 5, 4
S7	844	338	1.0	0.4	23, 25, 6, 6	16, 12, 5, 4
S8	550	343	0.6	0.4	18, 22, 5, 5	15, 14, 5, 5
S9	340	327	0.4	0.3	20, 14, 6	21, 7, 4
S10	479	316	0.5	0.3	10, 21, 5, 6	17, 6, 6
Average	625.5	341.7	0.76	0.37	13.7	9.7
Max	908	386	1.2	0.4	28	21
Min	294	316	0.3	0.3	4	4

plants cultivated under normal solar irradiance in the same period of time.

To compare the results of plant cultivation under the two different illumination conditions quantitatively, ten samples of specimen plants were selected from each pallet to perform a series of measurement in the last day of each experiment, such as leaf width, total leaf area index per plant and plant fresh weight. The measurement results were listed in Tables 1 and 2 for experiments 1 and 2, respectively. As a summary of experiment 1, most of the specimen plants cultivated under high power LED lighting system grew up with four big leafs with average leaf width of 21.8 mm, average total leaf area index per plant of 1400.1 mm^2 and average plant fresh weight of 2.39 g as compared to plants cultivated under solar irradiance with average leaf width of 13.6 mm, average total leaf area index per plant of 458.8 mm^2 and average plant fresh weight of 0.64 g. As a summary of experiment 2, the specimen plants cultivated under high power LED lighting system grew up with two big leafs with average

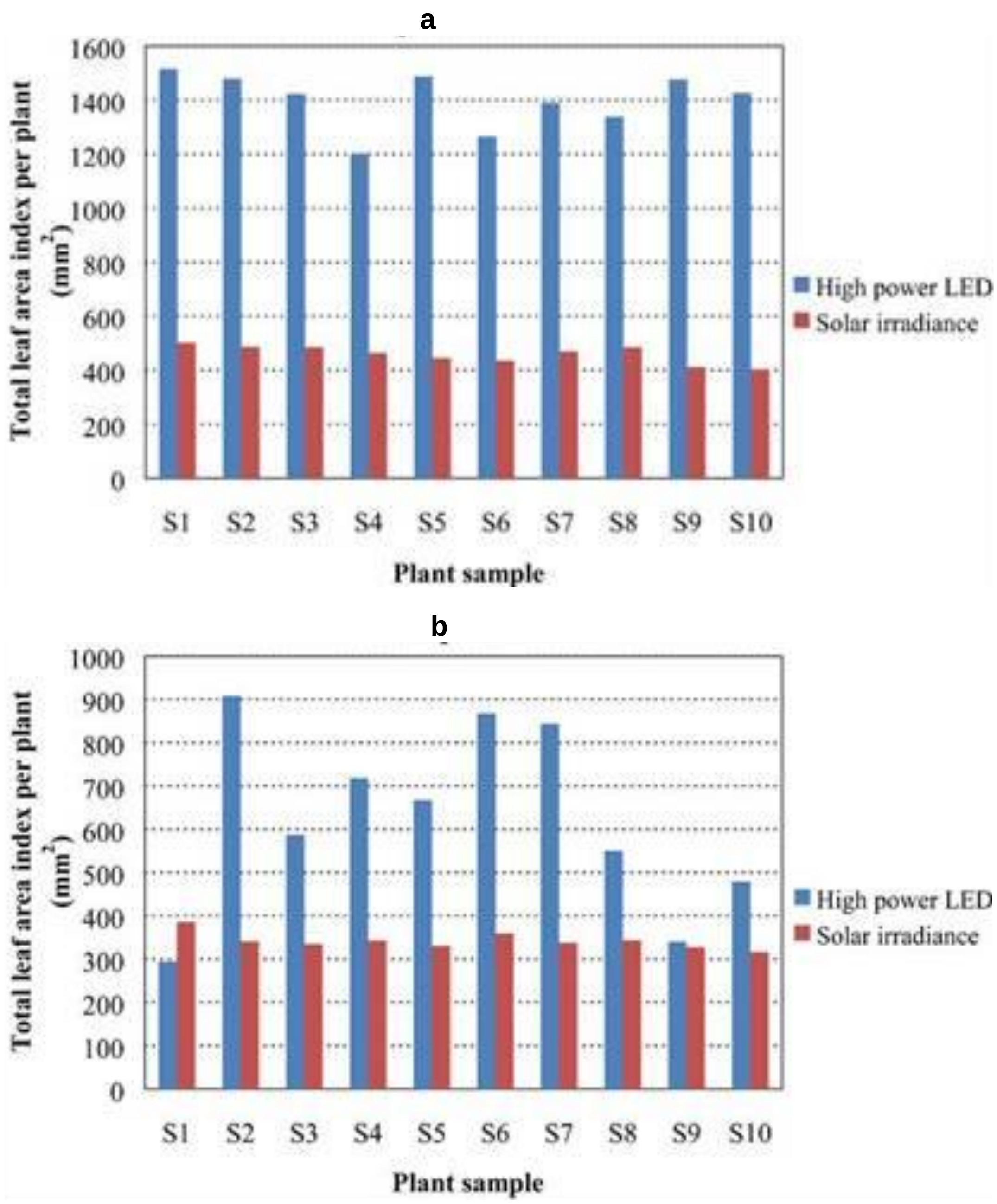

Figure 9. The Bar charts to show the total leaf area index per plant that were measured from 10 selected pots in the last day of the whole experiment for a comparison of *L. sativa* plants cultivated under solar irradiance and high power LED lighting system. (a) Experiment 1 and (b) Experiment 2.

leaf width of 13.7 mm, average total leafs area index per plant of 625.5 mm^2 and average plant fresh weight of 0.76 g whilst the specimen plants cultivated under solar irradiance grew up with average leaf width of 9.7 mm, average total leafs area index per plant of 341.7 mm^2 and average plant fresh weight of 0.37 g. For the comparison of the leaf size and plant fresh weight of the test specimen plants as shown in Figures 9 to 11, the *L. sativa* plants cultivated under high power LED lighting system have shown a faster growth rate than that of plants cultivated under solar irradiance.

Conclusion

The high power LED lighting system that consists of the AlInGaP and InGaN LEDs has been successfully designed and constructed. The young *L. sativa* plants

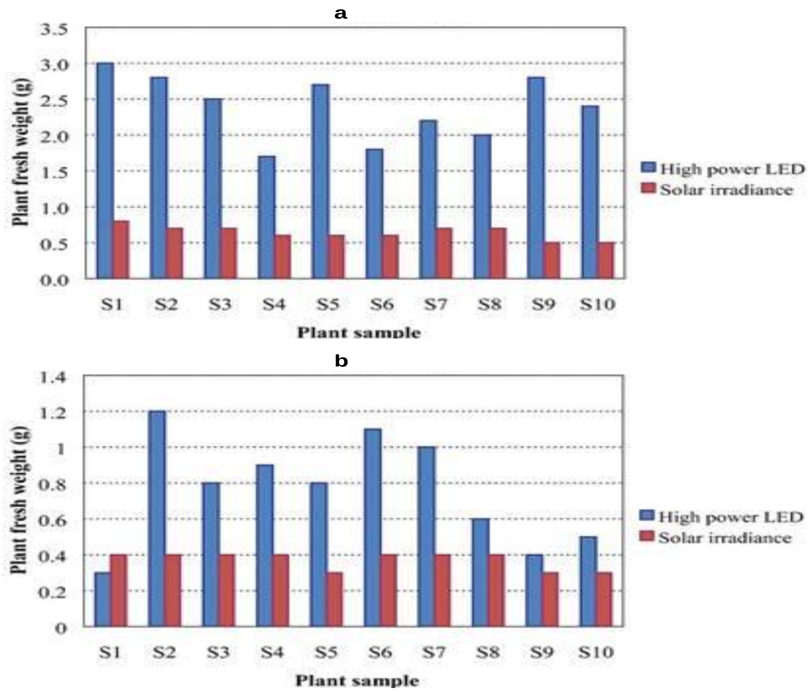

Figure 10. Bar charts to show the fresh weight that were measured from 10 selected pots in the last day of the whole experiment for a comparison of *L. sativa* plants cultivated under solar irradiance and high power LED lighting system (a) Experiment 1 and (b) Experiment 2.

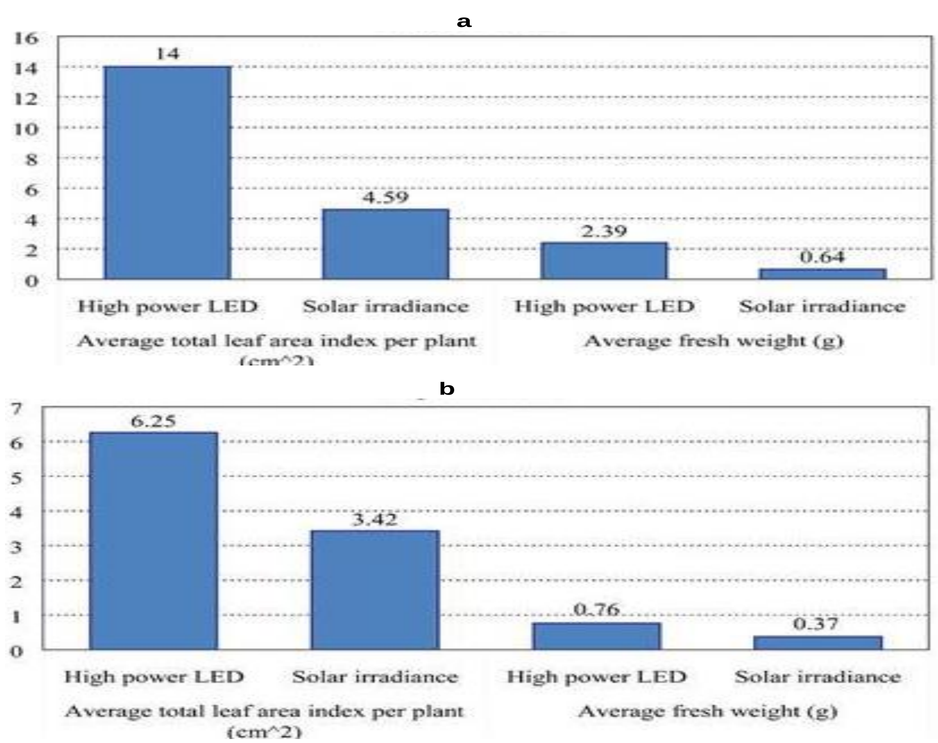

Figure 11. The Bar charts to show the average values of both total leaf area index per plant and fresh weight that were measured from 10 selected pots in the last day of the whole experiment for a comparison of *L. sativa* plants cultivated under solar irradiance and high power LED lighting system (a) Experiment 1 and (b) Experiment 2.

cultivated under the high power LED lighting system have higher growth rate when compared with plants cultivated under normal solar irradiance in terms of total leaf area index per plant, average fresh weight, etc.

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