Evaluation and Enhanced Use of Light Emitting Diodes for Hydroponics

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Abstract: Hydroponic farming is a viable and economical farming method, which can produce safe and healthy greens and vegetables conveniently and at a relatively low cost. It is essential to provide supplemental lighting for crops grown in greenhouses to meet the daily light requirement, Daily Light Integral (DLI). The present paper investigates how effectively and efficiently LEDs can be used as a light source in hydroponics. It is important for a hydroponic grower to assess the requirement of photosynthetically active radiation (PAR) or the Photosynthetic Photon Flux Density (PPFD), in a greenhouse, and adjust the quality and quantity of supplemental lighting accordingly. A Quantum sensor (or PAR sensor) can measure PAR more accurately than a digital light meter, which measures the light intensity or illuminance in the SI unit Lux, but a PAR sensor is relatively expensive and normally not affordable by an ordinary farmer. Therefore, based on the present investigation and experimental results, a very simple way to convert light intensity measured with a Lux meter into PAR is proposed, using a simple conversion factor (41.75 according to the present work). This allows a small-scale hydroponic farmer to use a simple and inexpensive technique to assess the day to day DLI values of PAR in a greenhouse accurately using just an inexpensive light meter. The present paper also proposes a more efficient way of using LED light panels in a hydroponic system. By moving the LED light panels closer to the crop, LED light source can use a fewer number of LEDs to produce the same required daily light requirement and can increase the efficiency of the power usage to more than 80%. Specifically, the present work has determined that it is important to design more efficient vertically movable LED light panels with capabilities of switching individual LEDs on and off, for the use in greenhouses. This allows a user to control the number of LEDs that can be lit at a particular time, as required. By doing so it is possible to increase the efficiency of a LED lighting system by reducing its cost of the electricity usage.

Key words: Hydroponics; Grow lights; Light Emitting Diodes (LEDs); Photosynthesis; Photosynthetic Active Radiation (PAR); Photosynthetic Photon Flux Density (PPFD); HPS (High Pressure Sodium); HID (High Intensity Discharge); Daily Light Integral (DLI); Quantum Sensor; Digital Light Meter (Lux meter)

1 Introduction

Hydroponic farming is a very efficient farming method and can be a simple partial solution to meet the food requirement in the world as it is a convenient method that does not require much land. Hydroponics is a subset of hydroculture, which is a method of growing plants in aqueous nutrient solutions instead of soil, in a greenhouse or in a confined space with controlled environment[1]. Hydroponically grown agricultural products are free of weedicides, pesticides and bacteria such as Salmonella and *E.coli*, which are quite harmful to humans. Hydroponics can supply healthy greens and vegetables to humans, year-round, and can contribute to saving the environment from toxic pollutants. The basic components of a hydroponic system are a grow chamber, nutrient reservoir, submersible pump, delivery system, and grow lights (Fig. 1).

Light is a very important factor that controls the growth andthe yield of a plant, and therefore, it can be manipulated to increase the yield and the quality of crop plants [2-3]. Plants use part of the radiant energy emitted by the sun for photosynthesis, which is the most vital metabolic process of plants. The intensity and the quality of light is important for the efficiency of photosynthesis. Photosynthetically active radiation (PAR) is the light with wavelength between 400 to 700 nm [4]. Increasing the energy in the PAR range increases the plant photosynthesis [4].

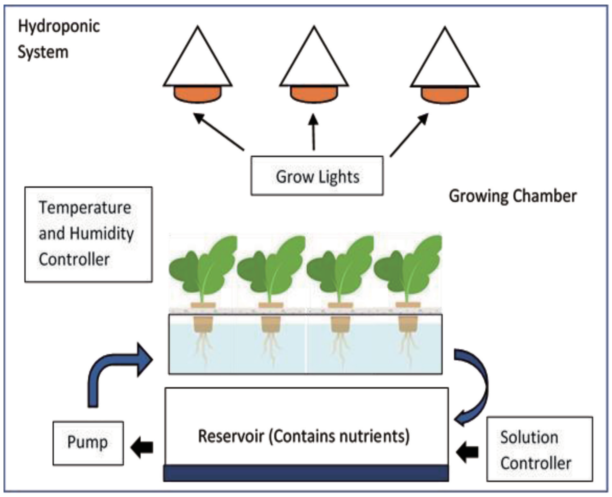

Fig. 1 Components of a Hydroponic System.

The most common units for measuring lightintensity are the foot-candle (lumens per square-foot) and Lux (lumens per square-meter). Horticultural workers typically measure the instantaneous light in micromoles per square meter per second, or PAR [μmol m^{-2} s^{-1}]. This "quantum" unit quantifies the number of photons (individual particles of energy) used in photosynthesis that fall on a square meter in a second [5]. Apart from the PAR values, the Daily Light Integral (DLI) is considered an important factor for greenhouse farming systems including hydroponics because DLI measures the amount of PAR received during a day[6-7]. The DLI is an important variable to measure in a greenhouse because it influences the plant growth, development, yield, and quality. This is especially applicable for growers in northern latitudes who grow crops in greenhouses during the winter season, from December to March. During this period, the naturally occurring outdoor DLI values are between 5 to 30 mol · m^{-2} · d^{-1}[6, 8].

Plant biologists often quantify PAR using the number of photons in the 400-700 nm range received by a surface in a specified period of time, or the Photosynthetic Photon Flux Density (PPFD), which is normally expressed in mol m^{-2} s^{-1}[8-9]. DLI can be measured using a quantum sensor connected to a data logger or a computer, measuring instantaneous light intensity (preferably in μmol · m^{-2} · d^{-1}) in some defined time period such as once every 15 to 60 seconds, which can then be used to calculate DLI[5]. Even though quantum sensors can accurately measure PAR, they are rather expensive compared to light meters.

Crops with a DLI requirement of 3 to 6 mol · m^{-2} · d^{-1} are considered low-light crops, 6 to 12 mol · m^{-2} · d^{-1} are medium-light crops, 12 to 18 mol · m^{-2} · d^{-1} are high-light crops, and those requiring more than 18 mol · m^{-2} · d^{-1} are considered very highlight crops [7, 10]. Providing supplemental lighting is essential for greenhouse crops that often receive insufficient light, especially in the winter in the northern half of the globe[6]. Indoor hydroponic systems also require a continuous supply of supplemental artificial light. In practice, artificial light is generally provided by high pressure sodium (HPS) lamps or metal halide lamps, which typically provide light intensities between 250 and 750 foot-candles (33 to 98 μmol · m^{-2} · s^{-1}). HPS lamps that deliver 400 foot-candles (52 μmol · m^{-2} · s^{-1}) for 12 hours provide a DLI of 2.3 mol · m^{-2} · d^{-1}. This is a relatively small amount of light compared to the DLI provided by the sun[5]. The perceived drawbacks of using HID lamps for supplemental lighting include heavy ballasts and high energy consumption. Light emitting diodes (LEDs) have a huge potential as a supplemental or main source of light for hydroponic plants. These are small in size, durability, longevity, capability of spectral composition control, high level of radiation at low thermal radiation, low energy consumption, and low cost of installation are considerable advantages as lighting sources [11].

It is commonly known that photosynthetic pigments of plants absorb red and blue light most effectively for photosynthesis. Most of the experiments conducted up to date have studied the influence of these two light wavelengths on plant growth. Such research has been done on lettuce [12-14] and other plant species[15]. It has been observed from studies that supplementing 10-30% blue light, about 5% of green light or white light with red light, can increase the growth of plants, when compared to providing exclusively either white light or blue light and red light [11-12].

In addition to the light quality, the position of the light sources relative to the photosynthetic surfaces of plants has a significant effect on the crop productivity. Because the radiation energy intercepted by a surface from a point source is related to the inverse square of the distance between them [16], reducing that distance will have a large impact on the incident light level. Compared with scorching hot, high-intensity discharge emitters, cooler LED emitters can be brought much closer to the plant tissue. LEDs, therefore, can be operated at much lower energy levels to give the same incident PPF at the photosynthetic surface [11]. Another issue that the LED technology raises in hydroponics concerns the development of metrics for quantification of the light source. New techniques, software calibrations, and hardware must be developed to accurately quantify PPF for LEDs, and the light absorbed by crops. Additional metrics of radiation capture may have to be considered for parameters such as canopy volume or total energy use (cost). In the future, light emitting diodes (LEDs) may entirely replace HID lamps because the former are more energy-efficient, reduce energy cost, provide more options for the control of crop characteristics, are safer to operate, and reduce the light pollution. However, the use of LEDs for supplemental lighting must be extensively investigated in order to improve their efficiency.

The key objective of the present study is to evaluate the efficiency of blue and red-light emitting diodes (LEDs) for providing the required PAR and DLI amounts for hydroponically grown crop plants in a controlled environment.

2 Materials and Methods

2.1 Materials

The experimental setup in the present work consists of components such as light source, power supply, light intensity measuring sensors and a multimeter. Seven different types of light emitting diodes (LEDs), which are mainly used in horticultural applications were selected for the present study. For more generalization, two types of LEDs, "surface mount device (SMD)" and "Pin-Through Hole (PTH)" with different viewing angles and operating voltages were used. The specifications of the LEDs used are listed in the Table 1. LEDs with different wavelengths were selected in such a way that they represent areas that are sensitive to the photosynthetic activity of the plants (Fig. 2).

Table 1 Specifications of Light Emitting Diodes

Model Number /Color	Voltage [V]			Wave length [nm]	View Angle (Deg)	Type
	Min	Typ.	Max			
1672-1131-ND	2.7	2.8	3.2	451	120	SMD
1497-1005-ND	3.3	-	4	470	130	PTH
1672-1127-ND	2.7	3	3.4	450	130	SMD
754-2141-ND	2	-	2.8	640	130	PTH
732-5013-ND	-	2	2.6	628	60	PTH
732-5021-ND	-	1.9	2.6	631	60	PTH
1672-1129-ND	1.8	2.1	2.6	660	130	SMD

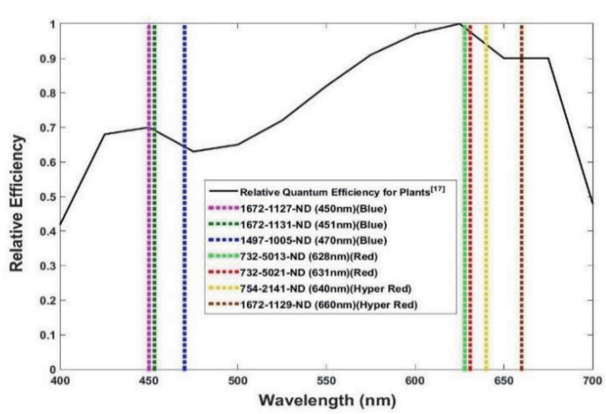

Fig. 2 Wavelengths of the Selected LEDs.

For measuring the light intensity emitted from

LEDs, two type of sensors, a general digital light meter (Lux meter) and an industrial grade quantum sensor were used. Fig. 3, shows the Digital light meter and the quantum sensors

Technical specifications of used sensors are as indicated in Table 2. Both sensors have data logging capabilities. When compared to a digital light meter, a quantum sensor can measure photosynthetically active radiation (PAR) more accurately.

Even though a quantum sensor is more accurate in measuring PAR values, quantum sensors are generally much more expensive than ordinary digital light meters. The source voltage controlled by the DC power supply, and the applied voltage and the current flow across the light source were measured using a Fluke multimeter. The key specifications of the equipment used in the present study are given in Table 2.

Table 2 The Specifications of the Equipment.

Equipment	Technical Specification	Value	Unit
DC Power Supply (Sorensen XPH42-10)	Voltage	0-42	V
	Current	0-10	A
	Resolution	10	mV
		10	mA
Multimeter (Fluke 87V)	Voltage (Max)	1000	V
	Voltage resolution	10	μV
	Voltage accuracy	±(0.05%+1)	
	Current (Max)	10	A
	Current resolution	0.01	μA
	Current accuracy	±(0.2%+2)	
Digital Light Meter (EXTECH LT300)	Lux (Max)	400	Klux
	Lux (Min)	40	Lux
	Accuracy	±(5% Rdg + 0.5% Full Scale)	
Quantum Sensor (Full spectrum quantum meter MQ-501)	Measurement Range	0-4000	μmol m^{-2} s^{-1}
	Accuracy	±5%	
	Spectral range	389-692	nm
	Field of View	180	^{0}

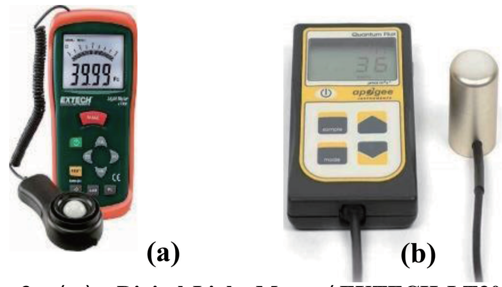

Fig. 3 (a): Digital Light Meter (EXTECH LT300), (b): Quantum Sensor (MQ-501).

2.2 Experimental Setup

In order to measure the intensity ofthe light emitted from the tested LEDs, a cylindrical light measuring chamber was set up as shown in Fig. 4. External light interferences and internal light reflections in the measuring chamber were minimized by covering the inner sides, including the bottom and the top of the cylindrical chamber using thick black sheets of paper.

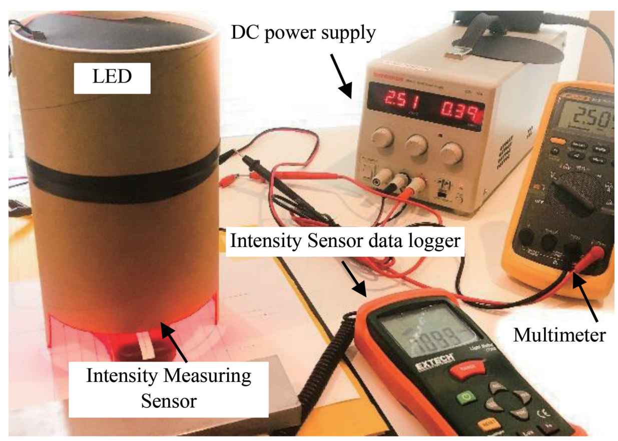

Fig. 4 Experimental Setup.

The sensor was placed at the bottom of the chamber. To measure the light intensities emitted from the tested LEDs, each LED was placed in the chamber at different heights: 9cm, 18cm and 27cm, away from the sensor, by moving the light source vertically to the required height. With this improvised setup, it was possible to maintain the acceptable initial conditions (PPF = 0, Lux = 0.1 and Temperature = 25°C). In order to avoid any horizontal misalignment or tilting between the LED sources and the sensor, several repeated readings were taken, and the system was adjusted accordingly so that the maximum effective light intensity was captured by the sensor. A laboratory power supply was used to control the voltage of the light source. A Fluke multimeter was used to measure the current and the voltage applied to the LED. Diagrammatic view of complete measuring set up is given in Fig. 5.

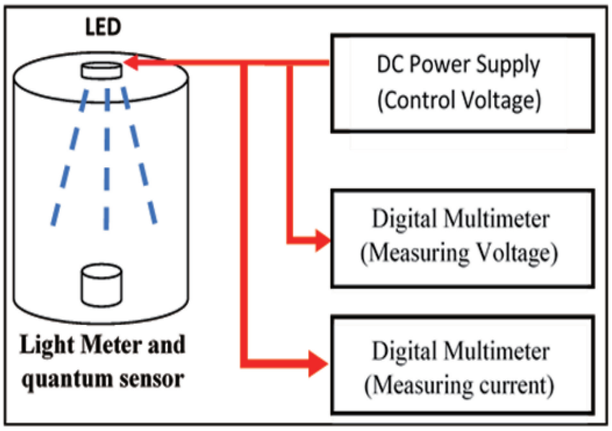

Fig. 5 Diagrammatic View of the Experimental Setup.

2.3 Light Intensity Measurements

The intensity of the light emitted from the light source, was measured using two different sensors, a digital light meter and a quantum meter. Initially, the light source (LED) was placed at a height of 9 cm above the digital sensor (Lux meter) or the Quantum sensor, in the center of the setup, as shown in Fig. 5.

Then the intensity of light emitted from each LED was measured using the sensor by supplying different voltages, starting from minimum to maximum, as per the data sheet applicable for the tested LED. Minimum and maximum voltage data are specified in the data sheets and given in Table 1. Different voltages were supplied using a laboratory DC power supply (Table 2). Intensity measurements were taken in triplicate for each tested LED, at 3 different heights (9cm, 18cm and 27cm). The same procedure was used to measure the intensity of light emitting from different LEDs at different heights, using the Quantum sensor MQ - 501. Seven different blue and red LEDs with different light emitting properties (see Table 1) were evaluated.

3 Results and Discussion

3.1 Relationship between Intensity Measurements from Lux Meter and Quantum Sensor

The intensity of light emitted from seven blue and red LEDs (Table 1) was measured with two different sensors, Digital light meter and Quantum meter, by supplying different voltage levels to each LED at different heights. Results obtained for a representative LED sample (P/N: 1672-1131-ND) are presented in Table 3.

Table 3 Intensity Measurements of Blue LED, (P/N: 1672-1131-ND) using Digital Lux Meter and Quantum Meter.

Blue (451nm) (P/N : 1672-1131-ND)					
voltage [V]		2.8	2.9	3	3.1
Average Current[mA]		158.89	276.11	403.33	538.33
Sensor	Height, [cm]	LightIntensity (Lux)			
Digital Light Meter	9	1,933	3,179	4,437	5,670
	18	472	782	1,096	1,402
	27	287	473	662	850
		LightIntensity (PAR), μmol m^{-2} s^{-1}			
Quantum Meter, MQ-501	9	58	95	132	168
	18	11	19	27	35
	27	6	10	15	19

Results presented as a plot in Fig. 6, show the relationship between the light intensity emitted from the LED with respect to the voltage supplied, and the distance of light source from the sensor. It is observed from the results, that by changing the voltage applied to the LED light source and its placement relative to the sensor, i.e., height, can change the intensity of the light source, and higher intensity values can be obtained at lower heights.

Measurement of the light Intensity using a Quantum sensor gives more accurate values of photosynthetically active radiation (PAR) than by using a Lux meter. However, a small-scale hydroponic grower may not be able to use a quantum sensor to measure PAR values in a greenhouse, because of it high cost when compared to a Lux meter. Therefore, the present study has sought to establish a relationship between the intensity readings taken by both a Lux meter and a Quantum sensor, to establish a conversion factor to convert the Lux intensity data into PAR values. The results obtained are presented as a plot in Fig. 7, which shows the distribution of the calculated ratios of conversion.

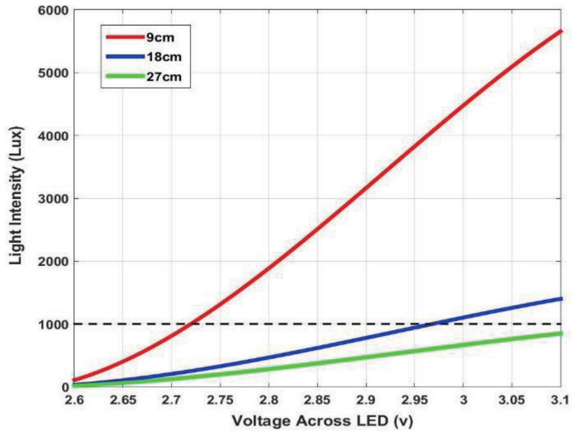

Fig. 6 Light Intensity versus Voltage and Height.

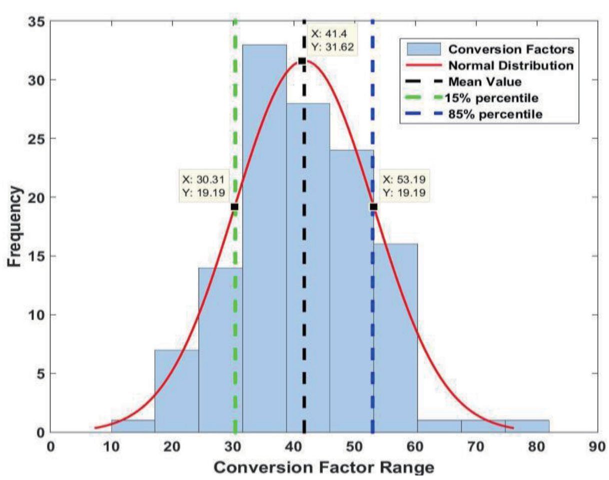

Fig. 7 Ratio Distribution of the Conversion Factors.

The red line represents the normal distribution of the dataset (ratios), and the intersection of the black dotted line and the red line gives the mean value of the distribution. The calculated ratios were subjected to analysis of variance (ANOVA), to check the relationship between the independent variables and the dependent variables. In this experiment, applied voltage and the height are the independent variables and the calculated ratio is the dependent variable. ANOVA of the data shows that the *P* values for height and voltage as 0.054 and 0.067 respectively. Since these values are greater than 0.05, it can be concluded that a relationship does not exist between the dependent and independent variables.

In addition, it is observed that 71% of the calculated factors are distributed within the values 30.31 and 53.19. Therefore, a single mean value can be selected from the calculated ratios and this mean value, 41.75, can be considered as a suitable conversion factor for the present application. Then, it is possible for a small-scale hydroponic grower to use this conversion factor to convert the Lux light intensity values measured using a Lux meter into more accurate PAR values without using an expensive quantum sensor.

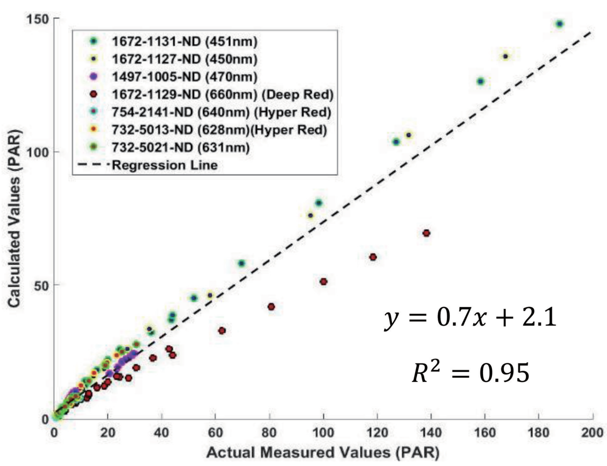

Fig. 8 Correlation between Measured PAR values and Calculated PAR values.

To test the present hypothesis, PAR values are computed using the Lux values measured using a digital light and applied the proposed correction factor (41.75). The results obtained in this manner demonstrate that the calculated PAR values using Lux values measured with a LUX meter and PAR values measured directly with a Quantum sensor are not significantly different. Specifically, a statistical analysis of the data shows that there is no significant difference between measured and calculated PAR values. The relationship between the measured and the calculated PAR values was tested, and the results are shown in Fig. 8. It can be observed from these results that a high positive correlation of (r = 0.95) exists between the measured and the calculated PAR values.

3.2 Efficient Use of LEDs to Provide Daily Light Intensity (DLI) requirements in a Hydroponic System

Data obtained for the light intensity values and the height of LED placement were plotted against the power consumed by the LED light source, as shown in Fig. 9. It is observed that in order to produce the same light intensity of 800 Lux, the light source placed at a height of 18 cm required a power consumption of 823 mW, and it was drastically reduced to 169 mW by lowering the light source to a height of 9 cm, which is approximately a fivefold decrease.

Accordingly, it can be concluded that by moving the light source vertically closer to the grown plants in a hydroponic system, it is possible to use a fewer number of LEDs while providing the same light intensity. This feature can be easily implemented in a LED light panel by simply switching the LEDs on or off as required. This can eliminate the need of an additional voltage controller for the LED light source, which also will reduce the cost of the light source.

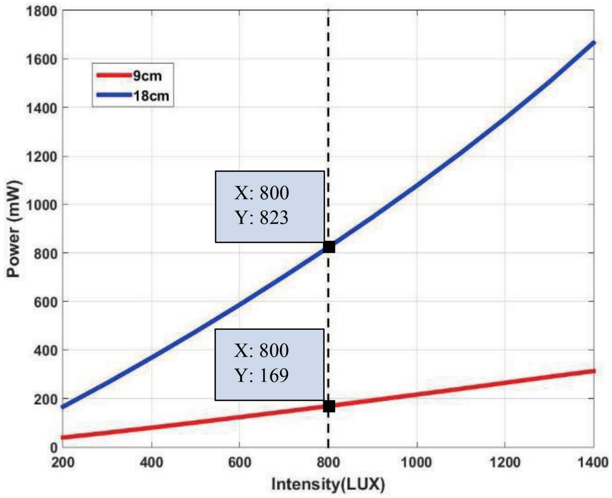

Fig. 9 Light Intensity versus LED Power Requirement.

In order to practically test this hypothesis, the maximum PAR value requirement was calculated using the daily light integral (DLI) values recommended by horticulturists [7, 10]. For this purpose, the maximum PAR values were calculated for each tested LED using an average DLI value of 20 mol · m^{-2} d^{-1} or ~ 232 μmol · $m^{-2}s^{-1}$. The obtained results are presented in Table 4.

Table 4 Economical use of LEDs to Produce Daily Light Integral (DLI).

LED model	Maximum PAR (μmol m^{-2} s^{-1})			Number of LED			Total Power [W]			Power Efficiency Relative to 27cm	
	Height										
	9cm	18cm	27cm	9cm	18cm	27cm	9cm	18cm	27cm	9cm	18cm
1672-1131-ND	168	35	19	2	7	13	3.3	11.7	21.7	85%	46%
1497-1005-ND	30	8	4	8	29	58	3.1	11.1	22.1	86%	50%
1672-1127-ND	188	52	24	2	5	10	4.2	10.5	21.0	80%	50%
732-5013-ND	23	9	3	11	26	78	1.3	3.1	9.4	86%	67%
732-5021-ND	31	8	4	8	29	58	1.0	3.5	7.0	86%	50%

Using these PAR values, the number of LEDs and the total power requirement essential to provide the targeted light intensity in PAR were calculated as well. The required number of LEDs was calculated by dividing the average DLI (232μmol $m^{-2}s^{-1}$) value by the maximum PAR value. The total power requirement for each LED was calculated using the current and the voltage applied to each LED.

It is observed from the results in Table 4, that by vertically moving the LED light source from a higher level (27 cm) to a lower level (9 cm), it is possible to use a fewer number of LEDs for providing the required amount of PAR. It is also observed that by moving the light source closer to the sensor, the efficiency of power usage has increased to more than 80%.

This study confirms that it is desirable to design LED light panels for hydroponic systems with the capability of switching on off when required. This will allow a hydroponic grower to cut down the cost of electricity usage by regulating the number of illuminated LEDs depending on the light intensity requirement.

The other advantage of using LEDs as the light source for a hydroponic system is that they are cooler and produce negligible amount of heat when compared to halide lighting systems, which become extremely hot during operation. Therefore, LED light panels can be easily moved closer to the crop plants in a hydroponic system without causing leaf damage due to heat, which has been observed with halide light panels [13]. Notably, this allows a hydroponic grower to regulate the number of LEDs illuminated to suit the light intensity requirement for optimum plant growth, and this added feature will reduce the cost of electricity usage.

4 Conclusion

Light is an important factor that affects photosynthetic activity of plants and can be manipulated to increase the yield and the quality of crops grown in a hydroponic system. Light intensity requirements for photosynthesis is measured as photosynthetic active radiation (PAR), which is an important fraction of the visible light required for photosynthetic activity of crop plants. PAR intensities can be accurately measured using a Quantum sensor. However, small-scale hydroponic growers may not be able to use it because of its high cost, and hence they normally opt for inexpensive digital light meters to measure the light intensities in Lux, which however is less accurate than PAR.

As a solution to this problem, this paper proposed a simple way to convert the light intensity measured in Lux into PAR values, using a conversion factor (estimated as 41.75). This would help a small-scale hydroponic farmer in using an ordinary Lux meter to measure the day to day DLI values in a green house in Lux and convert them into PAR values using the proposed inexpensive technique.

In addition, an efficient way of using LED light panels in a hydroponic system was proposed. By vertically moving the LED light source towards the crop plant, it was found that the light intensity emitted by the LED light source could be significantly increased. Hence, it would be possible to use a fewer number of LEDs in the light panel to produce the same light requirement. This could increase the efficiency of power usage to more than 80%.

In this manner, it is possible to design an efficient vertically movable LED light panel with the capability of switching the individual LEDs on and off as required, for low-cost and efficient operation.

These findings will have a direct impact on improving the efficiency and the quality of a hydroponic farming system. The present work studied only seven LED models, and it is useful to expand the scope of the investigation further by including more LED models, in order to identify more suitable LEDs that can be used for hydroponics lighting systems.

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