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An Adjustable LED Lighting System for Plant Seedling Production in Controlled Environment Systems

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Abstract: The use of light emitting diode (LED) assimilation lighting can become an important player in greenhouse horticulture if energy efficient LEDs can increase production. However, before LEDs can be broadly applied in horticulture, more knowledge is necessary on the effects of LEDs on crops. In this research, a flexible LED light source was developed suitable for the research on photobiological responses of plantlets in greenhouses and growth chambers for research and the young plant production. The LED lamp allows the difference wavelength, light intensity and light quality to be controlled as automatic via computer. The components of the LED lamp device include super bright Cool White (6500 K), Red (620-630 nm), Blue (465-485 nm) and UV-A (390-410 nm), LED group mounting fixture and drivers. In each LED group, there are 160 Cool White, 192 red, 32 blue and 16 UV-A LEDs. According to the experimental results of LED lamp at 20 cm distance maximum photosynthetically active radiation (PAR) values of 824.5, 967.7, 173.3, 38.2, 1129.3, 1141.3, 1784.5 $\mu mol.m^{-2}.s^{-1}$ were obtained for Cool White, Red, Blue, UV-A, Red-Blue, Red-Blue-UV-A and total of LED groups, respectively.
Key words: Light emitting diode, horticulture, photosynthetically active radiation, growth chamber

INTRODUCTION

Although traditional artificial light sources contribute to the plant production in terms of meeting the missing Photosynthetic Active Radiation (PAR) energy, they also have some disadvantages stemming from their structural properties. Especially in tissue culture applications, plant growing chambers and greenhouses, LED lamps with higher light flux may be sufficient in producing effective light (Yeh and Chung, 2009).

Berkovich et al. (2005) used LED light sources in different wavelengths and light densities in their studies, and since the LEDs can give light in narrow bandwidths, they reported that these are the most suitable light sources in determining the reactions of the plants in different lighting conditions. On the other hand, Yeh and Chung (2009) stated that chlorophyll molecules absorb the blue and red wavelengths better than green and yellow wavelengths. This situation means that plants may be limited in terms of wavelengths of the light, and may be grown with white light as well. As a conclusion, since LEDs are capable of giving only the desired wavelengths, they reduce the required power supply by eliminating the use of the wavelengths that are not needed for photosynthesis.

Many factors, such as lighting conditions, nutrient availability, humidity, temperature, and many others regulate plant growth and development. When designing an enclosed system for plant growth, whether it be a commercial greenhouse or a system situated in more challenging environments such as northern settlements, underground, it is vital that the system be optimized to the requirements of whatever plant species is being produced. In this study, a prototype LED lighting system has been designed and applied to provide the PAR energy necessary in greenhouses, in plant growing chambers and in tissue culture applications. In LED lamp, the LED series giving red, blue and ultraviolet lights are efficient in increasing the photosynthesis rate. In addition, the LED series which give cool white daylight (6500 K) with a 400-700 nm value to all PAR region in the spectrum are together. After the Lighting Automation System is completed, it was subjected to various lighting tests, and especially the lamp performance was examined and the results were discussed.

MATERIALS and METHOD

The Lighting Automation System consists of three parts: LED lamp, sensors and control software. The general chart of the Lighting Automation System is given in Figure 1.

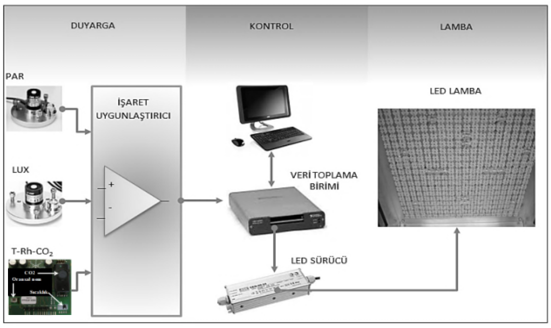

Figure 1. General schema of the lighting automation system

The red (620-630 nm), blue (465-485 nm), ultraviolet (UV-A, 390-410 nm) and cool white (6500 K) high flux light 350 mA, 1 W LEDs (XLamp XP-C, Cree Inc.) were used in the LED lamp. LEDs were produced with SMD (Surface Mount Device) Technology and were placed on star type coolers. The mechanical dimensions of the LEDs are given in Figure 2, and their technical specifications and their numbers are given in Table 1.

Constant current LED drivers (Mean Well HLG-185-30) with switch mode in 30 V_{dc}, 6.2 A and 186 W for each LED group were used. In the Automation System sensors, for radiation measurement, LI-190 (LICOR inc.) PAR quantum sensor (0-2000 μmol.m^{-2}.s^{-1}; 400 - 700 nm; 5 - 10 μA/1000 μmol.m^{-2}.s^{-1}); for luminous intensity measurement, LI-210SA sensor (0 - 100 klx; 400 - 700 nm; 30 μA/100 klx); for temperature, relative humidity and CO_2 measurement, EE80 (E+E Electronics Gmbh) integrated sensor (Temperature: -20 - 60°C ±0.7°C; Relative humidity: 10 - 90% ±%3, CO_2: 0 – 2000 ±50 ppm) were used.

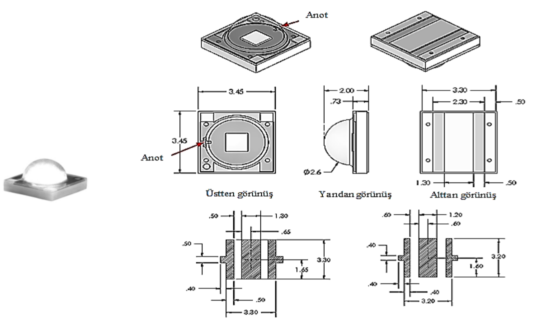

Figure 2. The mechanical dimensions of LEDs (XLamp XP-C, Cree inc.).

Table 1. Technical specifications of LEDs

Technical specification	LEDs			
	Cool White	Red	Blue	Ultraviolet (UV-A)
Color temperature (K)	6500	-	-	-
Wavelength (nm)	400-700	620-630	465-485	390-410
Luminous flux	100 lm	45.7 lm	23.5 lm	528 mW
Color rendering index (CRI)	70	-	-	-
DC forward current (A)	0.35	0.35	0.35	0.70
DC forward Voltage (V)	3.2 - 3.9	2.2 - 2.5	3.3 - 3.9	3.4
Power (W)	1	1	1	3
Max. junction temperature (°C)	150	150	150	125
Thermal resistance (°C W^{-1})	12	10	12	15
Viewing angle (°)	115	125	125	120
Temp. coefficient of voltage (mV.°C^{-1})	- 4	- 2	- 4	- 2
Quantity in LED Lamp	160	192	32	16
Package type	Surface Mount Device (SMD)			

A Data Acquisition (DAQ) unit was used to collect the analogous and numerical data from the sensors and send them to the computer and to provide the lighting control in the LED groups within the LED lamp. The Data Acquisition Unit (USB-6363, National Instruments inc.) has 16-bit 32 analogue channels.

LED Lamp Design

LED series should be formed in order to obtain light intensity equal to traditional light sources used in growing plants. For this purpose, separate LED series have been formed for each light wavelength. The control of each LED series can be performed independently from each other.

The light sources used in artificial lighting need to be in a proper height to ensure homogenous light on the plants. The distance between the lamp and the plant may be calculated with the Inverse Square Law. According to this law, if the LED is considered as the light source point, the surface area of the LED to be lit is five times less than the size of the LED series (Figure 3).

Figure 3. Inverse Square Law (O'Nolan, 2012).

According to the Inverse Square Law, the brightness on the object is reversely proportional with the square value of the distance between the light source and the object. For example, if the distance is far away from the source twice the source, then the lighting value decreases to ¼. This situation can be explained with the Equation (1):

$$E=\frac{1}{r^{2}} \tag{1}$$

In the formula, *E* is the light value on the object (lx), *r* is the distance from the light source (m). The diffusion of the light in space for LEDs with high brightness value is obtained with the Equation (2);

$$I_{e}(\alpha)=I_{eo}\cos\alpha \tag{2}$$

Here $I_e(\alpha)$ is the angular light value of the LED which has an α angle with the vertical platform, I_{eo} is the light value coming with vertical line to the horizontal platform. On a horizontal platform, the angular brightness at a point which is in *d* distance from a LED is calculated with the following equation:

$$E_{e}(\alpha)=\frac{I_{eo}}{d^{2}}\cos\alpha \tag{3}$$

The brightness value can be converted into Photon Flow Value ($mol.m^{-2}.s^{-1}$) with the following equation:

$$E_{p}(\alpha)=\frac{\lambda_{peak}\times I_{eo}}{N_{A}\times h\times c\times d^{2}}\times\cos\alpha \tag{4}$$

Here, N_A is the Avogadro number ($6.022x10^{23}$), h is the Planck stable ($6.626x10^{-34}$ J.s), c is the speed of light in space ($2.998x10^{8}$ $m.s^{-1}$) and λ_{peak} is the peak point of the LED light wave (O'Nolan, 2012).

LEDs have a semi-isotropical spatial diffusion that diffuses the light in a certain direction. However, some of the photons from the LED are diffused is the area nearby the defined direction and with a wide viewing angle. For this reason, the mounting height is very important for right diffusion and lighting. The light diffusion on the plant must be homogenous when the LED groups in the LED lamp are on. For this reason, different LED orders have been tried in vitro and the light diffusion on the horizontal plane has been examined. As a result, the most suitable LED order, in which four LED groups can be on together at the same time, has been determined. The LED lamp has an aluminium case in the size of 450x450 mm^2 in Figure 4. The LED order in the LED lamp is given in Figure 5.

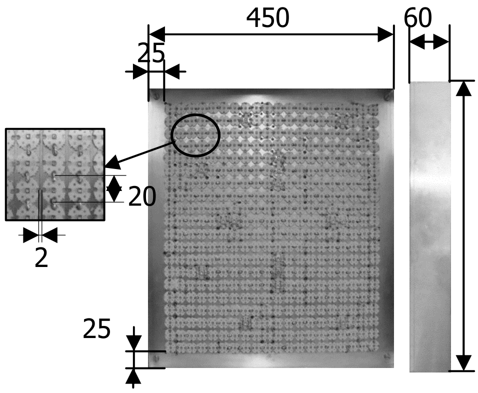

Figure 4. LED lamp

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K
2	K	B	K	B	K	M	M	M	K	B	K	B	K	M	M	M	K	B	K	B
3	K	B	K	B	K	B	M	B	K	B	K	B	K	B	M	B	K	B	K	B
4	K	B	K	B	K	B	U	B	K	B	K	B	K	B	U	B	K	B	K	B
5	K	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B
6	K	B	K	B	K	B	K	B	K	B	U	B	K	B	K	B	K	B	K	B
7	K	B	K	B	K	B	K	B	K	M	U	M	K	B	K	B	K	B	K	B
8	K	B	U	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B	U	B
9	K	B	M	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B	M	B
10	K	M	M	M	K	B	K	B	K	B	K	B	K	B	K	B	K	M	M	M
11	K	B	K	B	K	U	U	U	K	B	K	B	K	U	U	U	K	B	K	B
12	K	B	K	B	K	B	M	B	K	B	K	B	K	B	M	B	K	B	K	B
13	K	B	K	B	K	B	M	B	K	B	K	B	K	B	M	B	K	B	K	B
14	K	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B
15	K	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B
16	K	B	K	B	K	B	K	B	K	M	U	M	K	B	K	B	K	B	K	B
17	K	B	U	B	K	B	K	B	K	B	U	B	K	B	K	B	K	B	U	B
18	K	B	M	B	K	B	K	B	K	B	K	B	K	B	K	B	K	B	M	B
19	K	M	M	M	K	B	K	B	K	B	K	B	K	B	K	B	K	M	M	M
20	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K

Figure 5. The LED order in the LED lamp

The control software of the Lighting Automation System has been performed in LabVIEW. LabVIEW is the environment which has been developed for measurement and automation in high-performance scientific and engineering applications and works with the G programming language (Bishop, 2006).

The Lighting Automation System is controlled with an automation software. The software performs some basic functions such as automatically turning on the LED groups in the lamp according to the defined reference values and adjusting the light intensity. In addition to these functions, it also enables collecting data such as lighting values, heat, relative humidity and CO_2, logical calculations, registry jobs and data analysis from the vegetable production environment. The Lighting Automation System can operate in two different modes; full artificial closed environment and greenhouse lighting. The "Manual" mode can be chosen for plant production cabins and tissue culture chambers where full artificial lighting is required, and the "Automatic" mode can be chosen for greenhouses to obtain additional lighting. In automatic mode, in a greenhouse where extra lighting is used, the incoming light amount (PAR) is measured and the missing lighting amount can be covered by the LED lamp. For the PAR value, the adjustable upper limit is 2000 $\mu mol.m^{-2}.s^{-1}$ and for lighting intensity. Each color light level can be adjusted between 0-100% with 1% intervals. The interface of The Lighting Automation System is given in Figure 6.

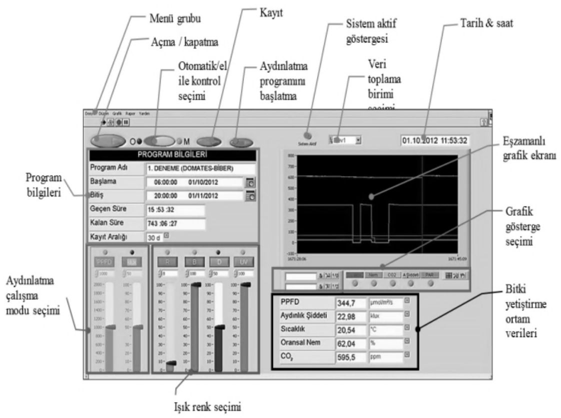

Figure 6. The interface of the lighting automation system

Lighting programs according to the different lighting demands may be prepared in the software and the data obtained from the sensors may be recorded with 1, 5, 15, 30 or 60 minutes intervals. In addition to this, the data can be observed simultaneously with the help of the graphic screen and can be transferred to MS Excel. The system enables the applications such as Day Extension, Dividing the Night, Dividing the Night in Intervals. The photo-periodical application views are given in Figure 7.

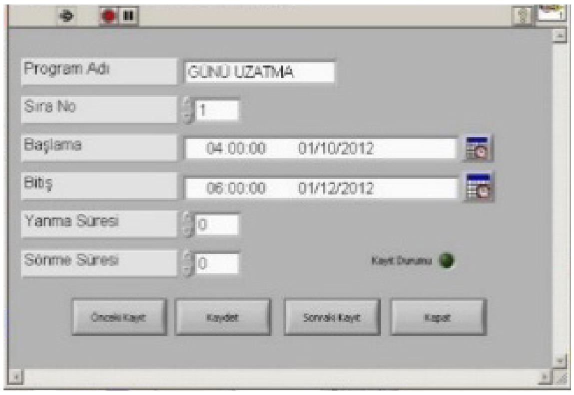

Figure 7. The photo-periodical applications

RESULTS and DISCUSSION

In order to obtain the lighting data of the LED lamp on the surface area, the linear LED order was used and the measurements were performed in vitro and 20, 40, 60, 75 and 90 cm over the ground level. The measurements were performed while the LED group light levels were full on and in full dark non-reflecting environment. When the results are considered, in addition, radiating lighting values decreased from the center to the circumference. It was also observed that, while the lighting level was homogenous in most of the surface area, there were differences only in corners of the square shape. The measured light values are given in Table 2. According to Table 2, the highest PAR value in single colors (20 cm height) was given by the red LEDs with a value of 967.7 $\mu mol.m^{-2}.s^{-1}$; the highest lighting level was given by the Cool White (CW) LEDs with a value of 57210 lx and 6500 K.

When all the LEDs are on in the lamp, the PAR and lighting intensity values are 1784.5 $\mu mol.m^{-2}.s^{-1}$ and 82620 lx respectively 20 cm over the ground level. There is a reverse proportion between the radiation amount of the LED groups in the lamp and the lamp height. According to the values obtained, the best relationship between the radiation and lamp height in single LED group is obtained in blue LED group with R^2=0.8620 (Figure 8); while the worst is obtained in UV-A (R^2=0.7997). The best relationship in the mixture of different lights (Figure 9) from different wavelengths is obtained in all color mixture with R^2=0.8606; and the worst is obtained when the red and blue groups are on together (R^2=0.8538). According to the results obtained, the relationships between the lamp height and the radiation values of the red, blue and cool white lights in single LED groups are close to each other; and only the UV-A is different. In mixed LED groups no significant difference was observed.

Table 2. The measured light values

Lamp height (cm)	Light level (%)	CW		R		B		R+B		R+B+UV		CW+R+B+UV	
		PAR (µmol m^{-2} s^{-1})	Light intensity (lx)	PAR (µmol m^{-2} s^{-1})	Light intensity (lx)	PAR (µmol m^{-2} s^{-1})	Light intensity (lx)	PAR (µmol m^{-2} s^{-1})	Light intensity (lx)	PAR (µmol m^{-2} s^{-1})	Light intensity (lx)	PAR (µmol m^{-2} s^{-1})	Light intensity (lx)
20	25	259.7	18590	233.5	7862	67.7	777	303.7	9047	314.7	8965	583.7	28380
	50	478.1	34240	490.1	15260	106.9	1260	602.1	17010	605.3	15790	1083.7	51450
	100	824.5	57210	967.7	29660	173.3	1992	1129.3	31110	1141.3	30300	1784.5	82620
40	25	130.9	9495	118.9	4005	35.7	477,2	153.3	4438	159.6	4596	295.7	15150
	50	241.3	16170	246.9	8252	56.5	724	301.3	8033	313.3	9206	562.1	28240
	100	415.7	28420	489.3	14530	90.1	941	578.1	15490	590.1	15160	941.1	43950
60	25	84.4	6071	77.2	2557	24.4	318,6	102.8	3031	104.4	2995	189.3	9760
	50	154	9820	160.4	5337	38	484	201.2	6129	203.6	5935	362.9	18350
	100	267.6	17920	316.4	8830	60.4	732,3	378.1	9790	387.6	9870	626.9	29150
75	25	66.3	5023	60.6	2170	19	259	80.6	2520	82.2	2494	149.3	7484
	50	122.3	9140	126.2	4410	29.4	392	159	5012	161.4	4911	283.7	14230
	100	210.2	15820	251	8250	47	592	298.2	8420	302.2	8510	493.4	23200
90	25	55.7	4270	50.9	1850	15.7	190	66.1	2080	68.5	2110	121.3	6210
	50	102.9	7780	106.1	3800	24.5	310	130.1	4120	134.1	4200	230.1	11500
	100	172.5	13020	210.1	7190	38.9	480	250.1	7760	254.1	7680	419.7	20250

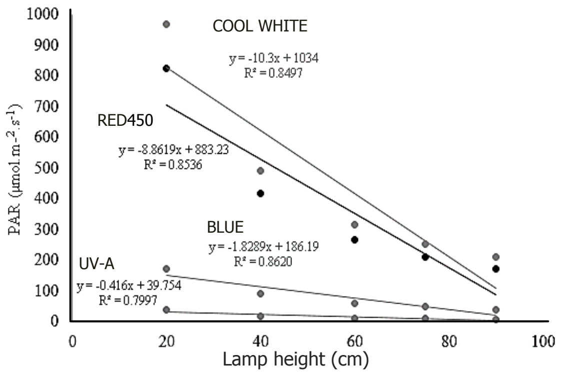

Figure 8. Relationship between the radiation and lamp height in single LED groups

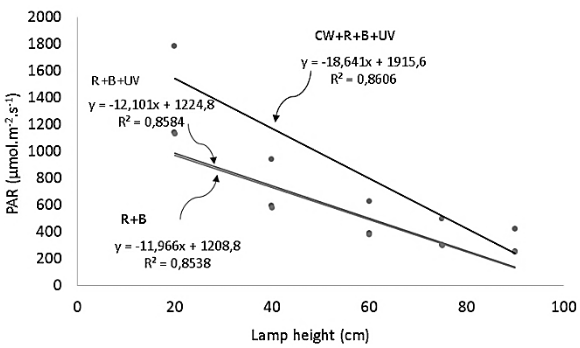

Figure 9. Relationship between the radiation and lamp height in the mixture LED groups

CONCLUSIONS

While traditional light sources such as the arc used in artificial lighting, fluorescent and white-hot lamps diffuse the whole of the visible part of the electromagnetic spectrum and a small part of the light near infrared and ultraviolet areas, LED lamps diffuse only one colour, such as only red or blue light.

Red and blue lights have the greatest impact on plant growth because they are the major energy sources for photosynthetic CO_2 assimilation in plants. Past studies examined the action spectra for photosynthesis of higher plants. It is well known that action spectra have action maxima in the B and R ranges. Combined R+B LED lights were proven to be an effective lighting source for producing many plant species in controlled environments.

This system has significant advantages when compared to the traditional artificial lighting sources in plant growing chambers and tissue culture applications, because the electric energy is converted into light energy with a small loss. Therefore, the main advantage appears to be the decrease in the energy use in plant growing environments.

The Lighting Automation System makes it possible for the researchers to use light in different wavelengths and intensity levels in photoperiodic and photosynthetic applications.

ACKNOWLEDGEMENT

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