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Hybrid Lighting System for Indoor Crop Production

Anton Louise P. de Ocampo* and Divina Gracia D. Ronquillo
Department of Electronics Engineering
Batangas State University
Batangas City, 4200 Philippines
**antonlouise.deocampo@g.batstate-u.edu.ph*

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Abstract

Lighting systems for indoor crop production facilities face consistency, quality of lighting, and energy efficiency challenges. In this work, these challenges were addressed by developing a natural light collection system that allows sunlight to be concentrated and transmitted via optical conduits into the growing areas of an indoor crop production facility and supplementing it with artificial lighting. The daily light integral (DLI) estimator measures the natural light received while the supplemental lighting provides the additional photosynthetic photon flux to achieve the crop's lighting requirements. Lux meter and spectrometer characterized the light sensors used to ensure accurate light measurements. The proposed system obtained a mean relative error of 1.78% between the DLI estimator and light instruments. In one testing activity, the system had collected 13.64 mol·m^{-2}·d^{-1}, while the artificial lighting supplemented 6.53 mol·m^{-2}·d^{-1}. The proposed system is vital in maintaining the DLI required by crops throughout the day.

***Keywords**:* daily light integral, indoor crop production, LED lighting, natural light illumination system, optical fiber lighting

1. Introduction

The world population's rapid increase brings forth challenges to the agricultural sector to increase production by 70% to suffice the food demand (Beecham Research, 2014). The shrinkage of global arable land, which accounts for about 40% of conversion to industrial use, intensifies food security (Wu *et al*., 2018). For this reason, governments and universities worldwide have recognized the benefits of indoor crop production and created programs to implement it. Aside from the smaller footprint, the environmental conditions in an indoor crop production facility can be controlled and optimized for the efficient use of crop inputs such as fertilizers and nutrient solutions (Lee *et al*., 2017). With the integration of current technologies, agriculture placed indoors increases the yield and maintains the quality of produce by protecting the crops from climate disturbances (Marcelis *et al.*, 2017). A survey verified the effect of climate change on crops. Long-term variations in precipitation and temperature, altering the planting seasons, would mean crop losses if not carefully addressed (Rudinas *et al.*, 2013). Protected agriculture might be the solution for the season shift and the threat of pests and plant diseases. However, just putting crop production indoors does not solve the problem of the need for increased yield. The proper provision of the requirements of plants for growth (media and nutrition, temperature, relative humidity and lighting) is another challenge (Lak *et al.*, 2019; Hopper *et al.*, 2017). Lighting systems for indoor crop production must optimize the photosynthetic photon flux (PPF) generated by artificial lighting to mimic the photosynthetic active radiation (PAR) produced by the sun. This can be accomplished by measuring the daily light integral (DLI) that has been received by plants at any time of the day (Morgan, 2013).

Several ways of lighting indoor crop production facilities have been proposed which include either bringing natural light indoors or by the use of artificial lighting. The main component for bringing sunlight inside to any desired point in the room is the sunlight collector. There is a multitude of research that proposes methods of sunlight collection. However, most of them are for photo-thermal conversion applications (Khamooshi, *et al.*, 2014; Zhang *et al.*, 2012; Mozumder *et al.*, 2014; Zheng *et al.*, 2014). Only a few are specific about collecting visible sunlight for indoor illumination.

Muhs (2000a, 2000b) proposed using the reflective parabolic solar collector to concentrate sunlight into the optical conduit. One company in Japan named La Forêt Engineering Co., Ltd. (2006) developed a natural lighting system that uses Fresnel lenses as sunlight concentrators. Wang *et al.* (2014) used a heliostat composed of turning mirrors for redirecting sunlight to a predetermined collection point. Couture *et al.* (2011) made some improvements to passive sunlight collector which uses an assembly of parabolic and hyperbolic mirrors as concentrators. The collection of sunlight is one thing but the coupling of sunlight to the distribution media is another important concern. To transfer the collected sunlight into the distribution media, Whang *et al.* (2014) proposed the use of bi-layered planes as light guides and a light compressor before transmission through optical conduits. After collection, the distribution of sunlight is another challenge. Chia *et al.* (2014) proposed redirecting the natural light to anywhere in an indoor facility by using light distributors which can be tuned to desired configurations. In separate works by Muhs (2000b) and Lee *et al.* (2008), optical fibers were used as distribution media for light into an indoor facility. Other methods used for the distribution of sunlight indoors are the use of reflective tunnels (SG ECO Industries Inc., 2016), tunnel lighting (Chen *et al*., 2020), a network of mirrors (Latter, 1981) and tunable distributors (Chia *et al*., 2014).

Indoor crop production facilities are usually lighted artificially. The recommended lighting for supplementing natural light must be within the range of 100-200 $umol \cdot m^{-2} \cdot s^{-1}$ at the plant's canopy level (Paz *et al*. 2019). Lighting for indoor crop production facilities depends heavily on efficient lights to replace or supplement sunlight. Modern LEDs have leveled with other lighting devices in terms of intensity and outrun others in terms of efficiency (Mitchell *et al*., 2012). Because LEDs are becoming more affordable and have inherent benefits, farmers use LEDs in indoor crop production (Singh *et al*., 2015). However, electric lamps and LEDs must mimic the spectral composition of light needed by plants for photosynthesis (Newbean Capital, 2015). In addition, for a lighting system using only artificial lights, the energy consumption adds up significantly to the operational cost of the indoor crop production facility.

This study developed a hybrid lighting system where natural light is allowed to enter the indoor crop production facility through optical fibers while supplemented with artificial lighting. DLI required by plants is still maintained at a specific level even if sunlight is unavailable. In addition, the composition of light can be altered to provide the optimum proportions of red and blue lights needed by plants. The developed system can also manage photoperiod or the time that plants receive PPF within the day. Photoperiod must also be considered in lighting for plants to synchronize their growth and development with the variation in seasons (Currey *et al*. 2013).

2. Methodology

2.1 Sensor Development for DLI Measurements

Maintaining the proper amount of light in terms of the DLI requires quantifying the photosynthetically active (or available) radiation (PAR) region that, fortunately, is in the same spectrum as visible light or 400 to 700 nm (Tripathy *et al*., 2013). In this work, the DLI estimator used illumination and spectral radiation in approximating the amount of light. The light-dependent resistor was used as the light sensor cell for the DLI estimator because it is more sensitive to the PAR region other than its diode and transistor counterparts. Figure 1 shows the spectral response of light sensor cells and Si-based light sensors. The sensitivity of the light sensor cell is highest at the center of the visual spectrum at 540-550 nm while Si sensitivity is highest at 1,000-1,100 nm. The LDR is more sensitive in the PAR region than silicon sensors (Scofield, 2009; Sunrom Technologies, 2008). The actual light measurements from natural and artificial sources were acquired using the lux meter (LX-1010B, MaxTech, India) and spectrometer (C-700, Sekonic, Japan). The measurements characterized the response of the light sensors used in the ATmega2560-based data logger.

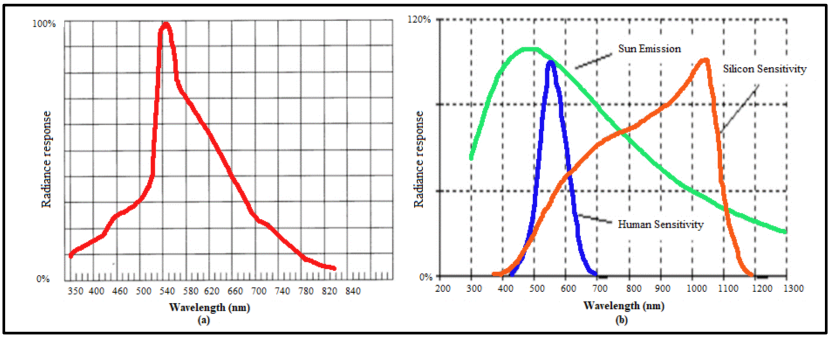


Figure 1. Radiance response of light sensor cell (a) and Si-based light sensor (b) (Young *et al*., 2018)

2.2 Characterizing Light Transducer

The response of the light sensor cell is logarithmically decreasing as the illumination increases. Figure 2 shows the characteristic curve of the light sensor cell used in the DLI estimator where resistance (y-axis) is described as a function of illumination (x-axis) in lux.

Based on the characteristic curve of the light sensor cell, the relationship of resistance to illumination can be described using Equation 1 where I_{lux} is the illumination (in lux) received and R is the resistance in kΩ.

$$R_{k\Omega} = 10^{-0.7993\log(I_{lux})+2} \tag{1}$$

For estimating the DLI produced by artificial lighting, the pixels of the images of spectral irradiances measured using a spectrometer were translated into a quantum unit for irradiance. In Figure 3, the spectral irradiances of the blue and red lights from a single LED module containing three diodes are shown. The number of pixels was used to quantize the spectral energy that each discrete wavelength had. Each pixel included in a column represented the amount of irradiance per unit wavelength. The integral of the distribution of spectral irradiances for each wavelength corresponded to the irradiance (W/m^2/nm) received from the light source.

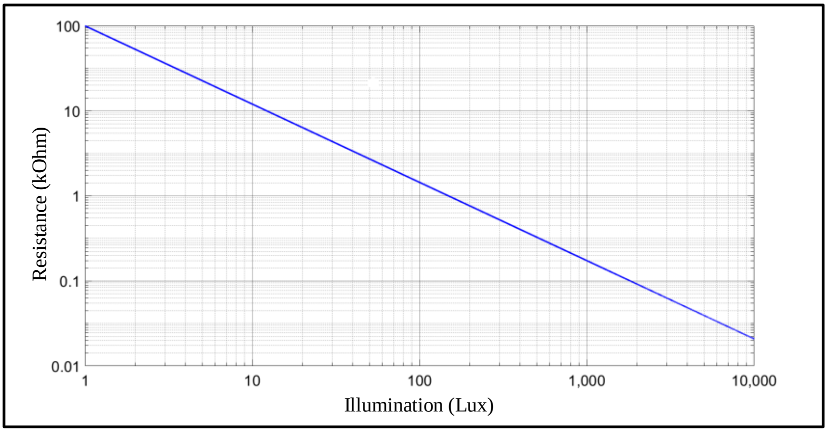


Figure 2. Light Sensor cell resistance as a function of illumination

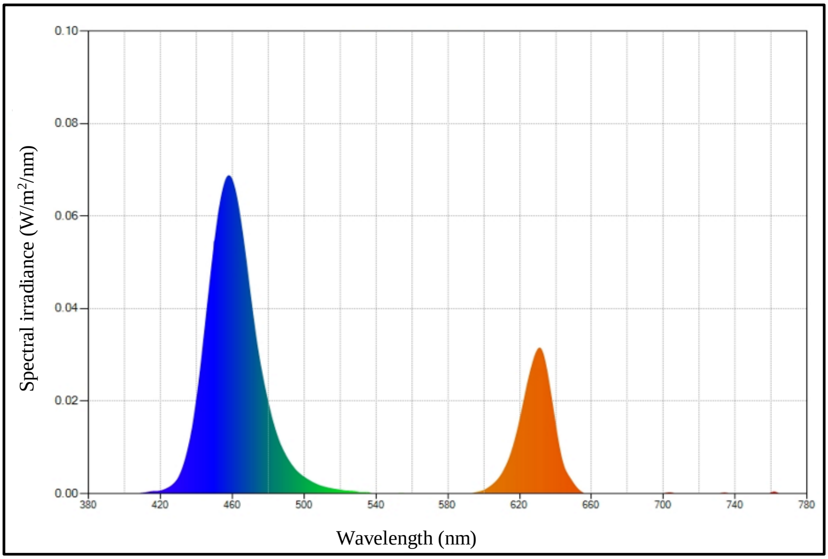


Figure 3. Spectral irradiance (W·m^{-2}·nm^{-1}) of blue and red LED modules as measured using a spectrometer

The estimate for the PPF produced using the artificial lighting is calculated with Equation 2 where W_{λ_d} is the spectral irradiance in watts per sq. meter per nanometre, λ_d is the wavelength in nanometre, $\Delta\lambda$ is the resolution and h, c and A_v correspond to Planck's constant, speed of light and Avogadro's number, respectively (de Ocampo, 2017). The single module can provide an estimated PPF of 11.82 umol·m^{-2}·s^{-1} based on the image specimen of the spectral irradiance of the LED.

$$PPF \approx \sum_{\lambda_d = 400\,nm}^{\lambda_d = 700nm} \frac{W_{\lambda_d}\lambda_d \Delta\lambda}{hcA_v} \tag{2}$$

2.3 Development of Natural Light Collection System

The natural light collection system consisted of concentrating lenses and optical fibers attached to a metal frame with a solar tracker installed. The focal length of Fresnel lenses on visible light was measured by allowing collimated light to pass through the lens while taking note of the distance from the lens when the light converges. The optical fiber receptor was placed in the focus or the convergence point where only the visible part of the solar spectrum permeates the optical fiber distribution network that leads to the growing media in the indoor crop production facility as described in Figure 4.

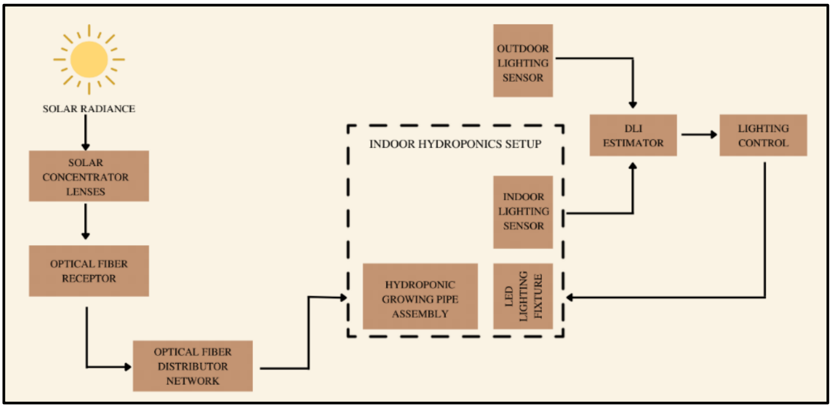


Figure 4. Block diagram for the hybrid lighting system

2.4 Artificial Lighting System

The natural sunlight collected was supplemented with artificial lighting composed of blue and red LEDs arranged in a lighting fixture. The blue and red lights of the PAR region have the most effect on plants in photosynthesis (Yadav, 2018). In the experiments conducted by Li *et al*. (2013), plants subjected to LED radiation treatment showed a significant increase in growth than those subjected to fluorescent lamps. LEDs supplement natural light during the low available sunlight to suffice the DLI requirements of the plants in the indoor crop production facility. An ATmega 328-based controller defines the required red and blue light proportions, and a 100-W solar station supplied the required power to the whole system. Both the indoor and outdoor lighting were measured to compute the DLI and how much light was needed for the artificial lighting to supplement. The calculations were done in the DLI estimator and measurements were fed to the lighting control (Figure 4).

2.5 Validation and Testing

Natural light collection system with artificial lighting ran in a whole day operation (8:00 AM to 6:00 PM). The required DLI is configured to 20 $mol \cdot m^{-2} \cdot d^{-1}$ with a maximum photoperiod of 16 hours. Light measurements using both the lux meter and spectrometer were compared with the measurements of the DLI estimator. Statistical measures on central tendencies and dispersions of the data collected using the light instruments were compared to that of the DLI estimator.

3. Results and Discussion

3.1 Natural Light Collection System

The natural light collection system included the Fresnel lenses, optical fibers, light sensor, sun-tracking controller, gears, motor and a battery (Figure 5). The visual focal length of the Fresnel lens was 22 cm at which the terminal of the optical fiber was directly placed. This ensured that only the radiation of the visual spectrum strikes the optical fiber terminal surface. Ultraviolet and infrared rays were offset several centimeters from the entry of the optical fiber to ascertain that UV and IR did not traverse the optical conduit. Because of how a concentrator worked, a solar tracker was required to maintain the optimal position of the natural light collector concerning the sun. The solar tracker used was the only single axis; hence, the panel was several degrees tilted to the axis perpendicular to the locus of the sun.

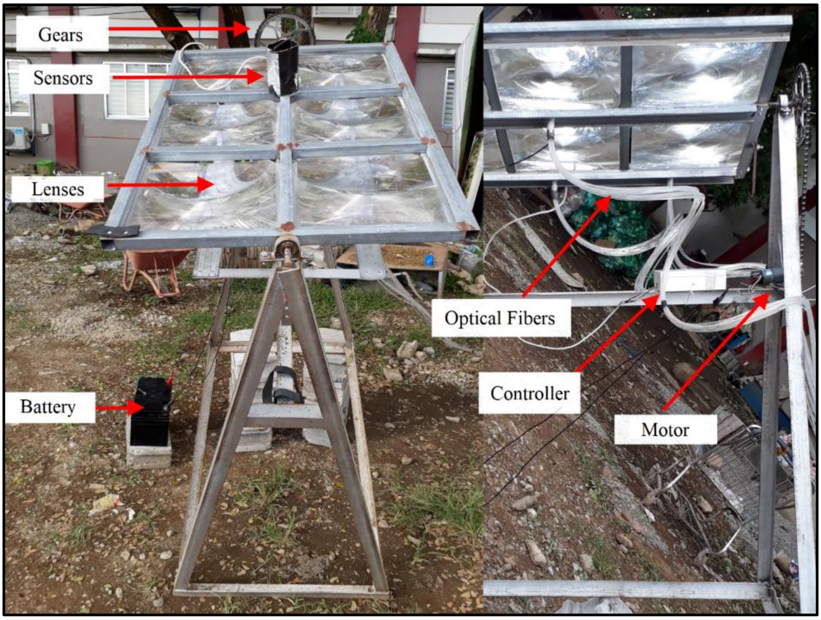


Figure 5. Natural light collection system

Using the natural light collection system, PPF delivered to an indoor crop production facility was measured at the exit end of one group of optical fibers (Figure 6). The measured DLI was 1.41 mol·m^{-2}·d^{-1} for 6 h.

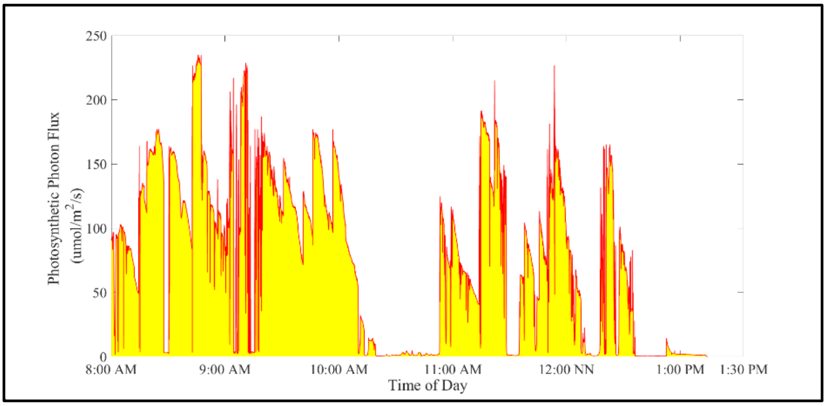


Figure 6. Datalog of the collected natural light in terms of PPF

3.2 Validation and Testing Results

The DLI Estimator was configured to measure illumination to compare its measurements with that of a commercially available lux meter. The red circle markers in Figure 7 represent the lux meter measurements while the blue line signifies the illumination readings using the DLI estimator. The mean error between the DLI estimator and the lux meter was 1.78%.

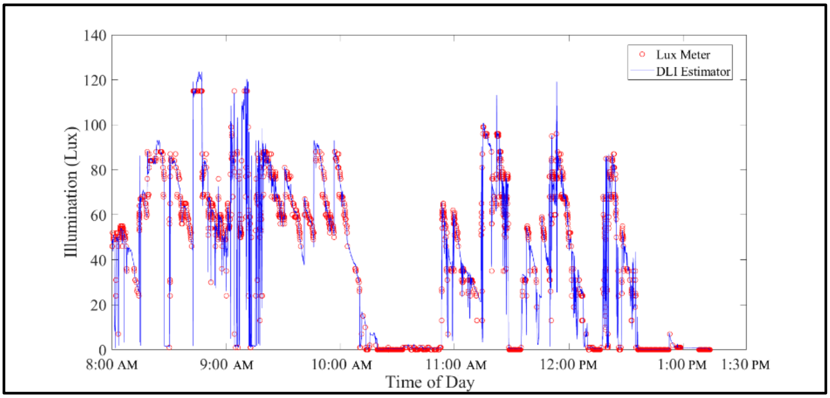


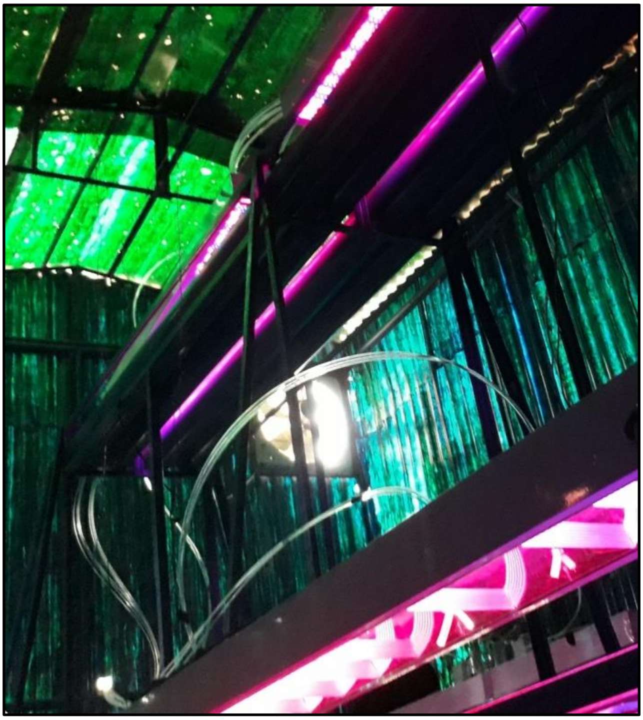
Figure 7. Comparison of the illumination measured using lux meter (red circles) and the DLI estimator (blue lines)

Error analysis suggested that the lighting measurement made by the proposed system was at par with that of the commercially available instruments (lux meter and spectrometer). Table 1 shows the centrality and dispersion of the measurements obtained using the proposed system.

Table 1. Statistical measures of the available lighting (in lux) acquired using lux meter and spectrometer versus the proposed system

	Light measuring instruments	Proposed system
Min.	0	0.0259
Max.	115	123.5
Mean	32.723	39.46
Median	25	41.14
Mode	0	0.2087
Std	34.7556	33.7836
Range	115	123.47

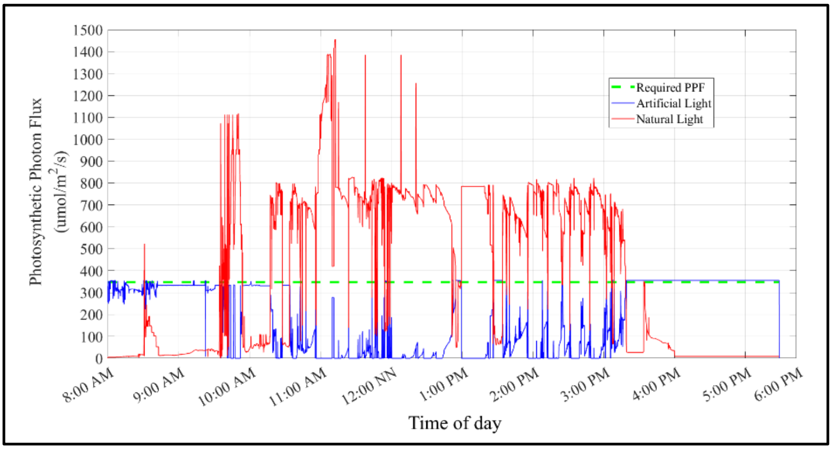
The optical fibers were distributed inside the crop production facility toward the growing areas. The collected natural light passed through the fibers and was delivered to the luminaires above the growing area. The sunlight was restricted to enter the production facility to simulate an indoor system. The supplemental artificial lighting adapted to the amount of collected sunlight (Figure 8).



The lighting system was placed atop the growing area.

Figure 8. Vertical growing area inside the crop production facility

Figure 8 shows the received natural light and the supplement provided by artificial lighting. In another test, the total natural light collected for that day was 13.64 $mol \cdot m^{-2} \cdot d^{-1}$ while the artificial lighting had supplemented with 6.53 $mol \cdot m^{-2} \cdot d^{-1}$. The PPF from natural sunlight is described as the red lines on the figure while the PPF from artificial lighting is shown by the blue lines. A significant observation should be derived from Figure 9 – that is, the artificial lighting can provide the level of DLI required by plants with no sunlight available. In addition, there is a possibility that the intensity of sunlight is high enough to cover all the DLI requirements of the indoor crops. In those instances that sunlight flowing into the indoor crop production facility is sufficient, the artificial lighting would not be activated.



Red lines were measured natural light while the blue lines were the supplemented light from artificial lighting.

Figure 9. Received natural and artificial light in terms of PPF

4. Conclusion and Recommendation

The proposed system for collecting natural light using concentrator lenses and optical fibers was successfully validated for day-long operation and was able to provide the necessary DLI for plant growth. Although the system was not implemented in real plants growing indoors, the commercially available instruments validated the quality of light that the proposed system provided. In general, concentrators and optical fibers can be used to distribute sunlight in an indoor crop production facility but must be installed with an artificial lighting system to ensure that proper lighting is provided even sunlight is unavailable. For future work, the effect of the hybrid lighting system on the growth of indoor crops can be evaluated.

5. Acknowledgement

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