AN ANALYTICAL METHOD OF LED LIGHTING DESIGN FOR GREENHOUSES WITH PHOTOSYNTHETIC FLUX DENSITY PREDICTION

PEDRO L. TAVARES[1], JOSÉ M. S. DUTRA, DÊNIS DE C. PEREIRA[1], ALINE R. SILVA[1], VINÍCIUS M. DE ALBUQUERQUE[1], RAFAEL M. DA S. B. DE SALES[1], HENRIQUE A. C. BRAGA[1], PEDRO S. ALMEIDA[1]

[1]Modern Light Research Group (NIMO), Federal University of Juiz de Fora (UFJF)
University Campus - 5th Platform - 36036-030 - Juiz de Fora, MG - Brazil
E-mails: pedro.laguardia@engenharia.ufjf.br, pedro.almeida@ufjf.edu.br

CRISTIANO F. DE RESENDE[2], PAULO H. P. PEIXOTO[2]

[2]Plant Physiology Laboratory, Botany Department, Federal University of Juiz de Fora (UFJF)
University Campus - 3th Platform - 36036-030 - Juiz de Fora, MG - Brazil
E-mails: cristianoig2004@hotmail.com, paulo.peixoto@ufjf.edu.br

Abstract— This paper bases on photosynthetic radiation concepts to propose an analytical method to identify Yield Photon Flux Density (YPFD) needed for proper growth of different plants species and calculate its correlated Yield Photon Flux (YPF) according to certain distance between plant canopy and lighting source. The studies have been applied considering the *Humulus lúpulos* (Hop) as the object of research under High Flux Chip-On-Board (COB) Light-Emitting Diode (LED) to perform the radiation source for experiments and validation of calculus proposed. The design includes, firstly, the flux density amount and distance between luminaire and plant to estimate the YPF, which is converted from radiant flux. Next, the radiant flux value is approached to compare models of LEDs, which are appropriate for the project and specify its profiles. In the end, the work shows a comparison based on values extracted from two scenarios: an experiment of a COB LED operating in rated current conditions, while collecting its flux density by a cosine Receptor in addition with a spectrometer and, the second scenarios consists in the theoretical data found by equations proposed for the design method.

Keywords— Light emitting diodes, Plant growth, Greenhouse design, Cosine Receptor, High Flux COB LED

Resumo— Este artigo se embasa nos conceitos provenientes da interação entre fotossíntese e radiação para propor um método analítico de identificação da densidade de fluxo fotossintéticamente ativo de produção adequado (dependente da espécies de planta tratada) e cálculo do respectivo fluxo fotossintético demandado pela luminária em função da distância entre a mesma e o dossel da planta. Os estudos foram aplicados com *Humulus lúpulos* (Lúpulo), atendida por COB LED de alto fluxo e corrente para operar como fonte radiante para teste e validação de cálculos propostos. O projeto envolve, primeiramente, a densidade de fluxo estipulado e distância entre luminária e planta para estimar o fluxo fotossintético que é convertido em fluxo radiante. Em seguida, o parâmetro de fluxo radiante encontrado é usado para comparar modelos de LEDs adequados de projeto e especificar seu perfil de comportamento radiométrico e elétrico. Ao final, o trabalho mostra uma comparação baseada nos valores extraídos de dois cenários: experimento com dados de densidade de flux de um COB LED operando em condições nominais, e dados provenientes do equacionamento pelo método de projeto proposto.

Palavras-chave— Diodos emissores de luz, Crescimento de plantas, Projeto de estufas, Difusor Cossenoidal, COB LED de Alto Fluxo.

1 Introduction

Currently, the artificial lighting market on horticulture has been growing expressively due to rises on modern light potential of LED in achieving high photosynthetic active radiation rates with feasible costs of production and power consumption. This market reached 690 million dollars in 2016 and 193 millions of it was solely in LED luminaires investments. The Figure 1 shows the growth prognostic until 2020 expressing a continuous increase in this technology for horticulture context.

The radiation is one of the most influent abiotic factors for plants due to its intensity, spectral power distribution and photoperiod) (COSTA, 2006). These aspects have to be considerate crucial on design plan in order to estipulate better luminaire profile for maximum yield and plant growth on greenhouses.

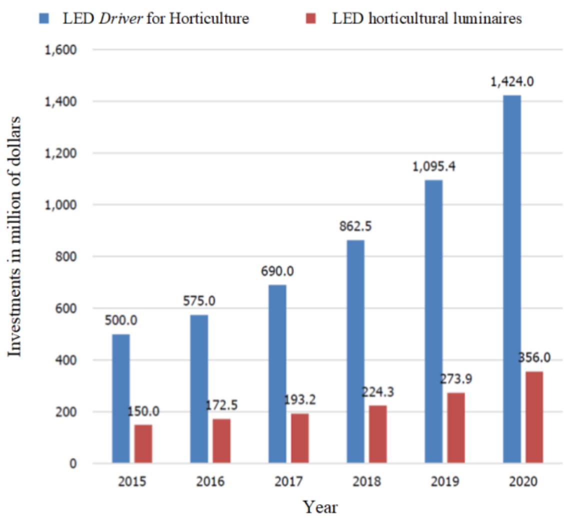

Figure 1. Global Market Growth Trend of LEDs applied on Horticulture subjects (LEDINSIDE, 2017).

This paper approaches a specific species of plant (Hops, Humulus lupulus L.) and luminaire (COB LED) to develop and validate an analytic method proposed to design luminaires for horticulture applications and horticulture environments with no need of radiometric experiments at laboratory. In this context, it is mandatory to considerate power consumption and number of lighting sources optimized to achieve the feasibility without compromising the crop yield. These aspects were evaluated to address the average Photosynthetically Active Radiation (PAR) on latitudes with maximum success on Hop cultivation, around 40-50º (PEARSON, et al., 2016).

The application of this method guarantees two consistent advantages for greenhouse design. First, it provides PAR information that generically professional lighting software designs do not approach (DIALux, 2018) (RELUX, 2018). The second advantage is that there is no need of measuring the YPF (Yield Photon Flux) and YPFD (Yield Photon Flux Density) with complex equipment arrangements as an Integrating Sphere and/or Cosine Receptor, making greenhouses lighting design more feasible for horticulture industry.

This paper is organized as follows: Section II presents a contextualization about radiometric measurement system and a discussion about Photosyntatically Photon Flux Density (PPFD) and YPFD differences and adequacies. Section III reports the mathematical development to propose, in summary, the design equations for the project. Section IV presents details of the experiment: main plant and luminaire features, the experimental arrangement and comparison with analytical results for method validation. Section V summarizes the conclusions of comparison results and design developments for future work propositions to improve luminaire models and experimental routines for validation.

2 Photosynthetic Active Radiation

The lighting issue depends not merely on the radiation source but also the means of spread and radiation receptor. This section approaches quantities of radiometric and Quantum systems to explain the bases of interaction between radiation (natural light and artificial light) and plants. Furthermore, it contextualizes equations applied for systems conversions and radiation quantities estimations .The photometric system will not be contemplated in this work as it refers to human eye perception of radiation and, so that, not properly adequate for *Plantae* radiation parameters (TAIZ & ZEIGER, 2009) (McCREE, 1972).

2.1 Differences in Radiometric and Quantum System

The radiometry is the science dedicated to study the radiative energy transference and it is related to radiometric quantities. These quantities do not relativize the receptor radiation profile to measure radiation. Therefore, its calculus includes the total electromagnetic spectrum of the system.

On the other hand, based on active photons applied in the photosynthesis process, the Quantum system treats the radiation as particles (photons) from its duality (wave/particle). This consideration is more suitable for plant radiation quantities, as photosynthesis is a Quantum process by itself (PINHO, 2008) (McCREE, 1972). This system considers part of the electromagnetic spectrum in which photons are relevant for photosynthetic process. This interval is denominated as PAR, *Photosynthetically Active Radiation*, and it includes 400-700 nm or 360-760 nm of the total electromagnetic spectrum depending on method applied (HOGEWONING, et al., 2012).

2.2 PPF/PPFD and YPF/YPFD Discussion

The PAR system basically describes the portion of electromagnetic spectrum that is useful for photosynthetic process. However, the photons wavelengths in this interval are not equally important for the plant (HOGEWONING, et al., 2012) (McCREE, 1972).

The Photosynthetic Photon Flux (PPF) and PPFD refer to the photons emitted by the radiation source across 400 to 700 nm and equally weighted for photosynthetic matters. Whereas the Yield Photon Flux (YPF) and YPFD is an improved method that considers optimal growth spectrum by the Relative Quantum Efficiency curve (RQE) of average higher plants scanned. Its interval of spectrum comprehends 360-760 nm and weights the photon per nanometer according to its energy and relevance on photosynthetic process. The difference between both methods is clarified and compared with Human Photometric Relative Sensitivity (HPRS) (REA, 2012) in Figure 2.

2.3 Flux, Intensity and Density

Flux (Φ) is the energy transference rate, dQ, per unit time, and it is applied to measure total radiant power emitted by a radiant source (natural or artificial) in a system. It is expressed by J/s or W unit in radiometric system, and in µmol/s, for Quantum system, given by PPF or YPF. The general flux equation is shown in (1):

$$\Phi = dQ/dt \qquad (1)$$

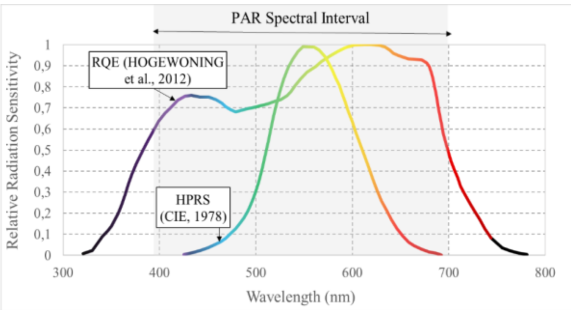

Figure 2. Comparison of Human Photometric Relative Sensitivity with PAR interval and RQE curve.

The Flux Intensity is the radiant power emitted in a certain direction, through a unit solid angle. It is given by W/sr, in radiometric system, and µmol/sr, in Quantum system. Its general equation is presented in (2):

$$I = d\Phi/d\Omega \tag{2}$$

The Flux Density or Irradiance (E) expresses the total radiation incident in a surface (A). In Quantum context, it can be given by PPFD or YPFD depending of the method applied, as mentioned before. Its general equation is shown by equation (3):

$$E = d\Phi/dA \tag{3}$$

As pointed out, all three quantities highlighted in the text have their correspondence in Radiometric and Quantum system, yet sub classified in Photon or Yield quantity according the method applied in the second measurement system. Figure 3 depicts the overall measurements handled in this work and its respective representations in a photic scenario.

3 Luminaire Design for Greenhouse Applications

According Figure 3, there are three parameters necessary for designing a luminaire: the canopy area, the distance between luminaire until the plant canopy (d) and the YPFD for adequate yield and plant growth of the specie treated.

The hops canopy area depends of the tutor structure made during vegetative stage, as it is a climbing plant. For this project, the canopy stipulated for hops is a circumference with 30 cm diameter.

Hops are from temperate zones and do not stand high temperatures in its canopy. The heat generated by luminaires can easily burn leaves in canopy area (PINHO, 2008) (GUPTA, 2017). The LED luminaires presents a lower transference of heat for surrounding areas due to its efficient and directed dissipation through heatsink, higher photic efficiency (photons generated per electric power demanded) and no existence of infrared radiation in its SPD (Spectrum Power Distribution) (HUI, 2017) (PINHO, 2008) (S.SIMPSON, 2003). Thus, LED luminaires can achieve the smaller distance from source to the leaves that varies depending on LED model and plant species applied in the Greenhouse (GUPTA, 2017).

The design of a horticulture luminaire project consists, first, in defining if the artificial light attendance is integral or partial. For this work, it was approached an integral attendance or, in other words, the luminaire has to be responsible to provide all photosynthetic radiation required by the plant daily. Therefore, the subchapter 3.1 describes the method to find adequate levels of YPFD for hops.

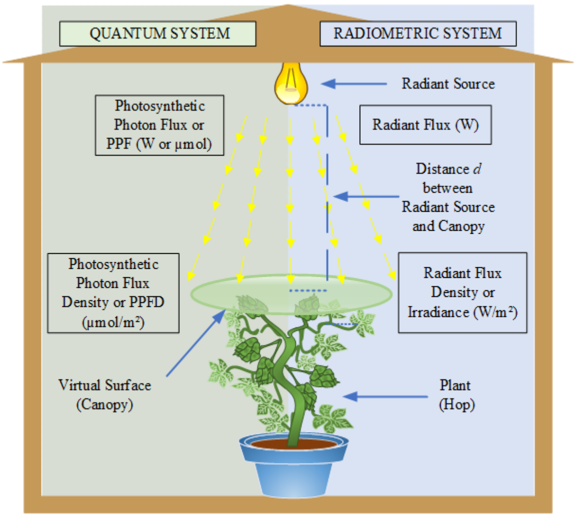

Figure 3. Representation of radiometric and Quantum quantities for a Greenhouse radiation scenario.

3.1 YPFD Determination for Hop Cultivation

The process adopted to find a suitable YPFD for hops was achieved through radiation data collection of latitudes around 40º to 50º north/south where, by evidences of crop amount, the hop plant is more successful in growing (HIERONYMUS, 2012). The Figure 4 shows the chart of PPFD curve variation along the year by four weather conditions, under natural lighting and its respectively average per month and year for PPFD and YPFD at latitude 42º Northen Hemisphere. The YPFD has been obtained by method applied in Costa and Cuello (2013).

The maximum average recorded by Figure 4 was approximately 750 µmol/m² (PPFD) and 674 µmol/m² (YPFD) in June, the month into the summer period, which presents more irradiation levels. Therefore, the luminaire deployment has to achieve a maximum YPFD level of 674 µmol/m² giving a minimum distance to avoid losses of luminaire potential and conciliate with the burnt leaves factor due to overheat atmosphere. Then, other scenarios for the rest of the months can be emulated by luminaire dimming.

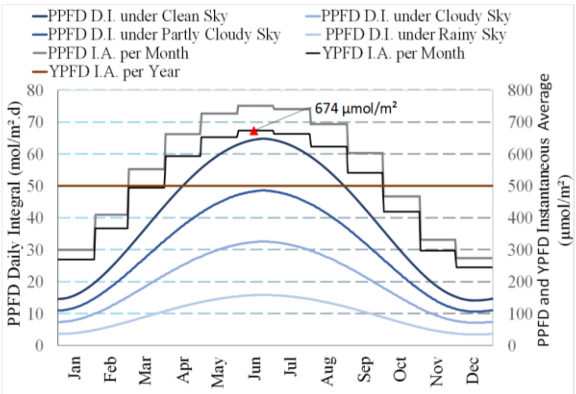

Figure 4. Yearly variation of Daily and Monthly Radiation Integral from the Sun at the Earth's ground level for 42 degrees latitude and different types of weather (ALBRIGHT, et al., 2000).

3.2 Case Analyze and Mathematical Modelling

The second process for the horticulture luminaire design is to determine the irradiated plan, intensity and flux by YPFD previously established. The equation (4) shows the average YPF ($\Phi_{q,YPF}$) in function of average YPFD ($E_{q,YPFD}$), basing on Lambert law (SIMONS & BEAN, 2001), assuming the desired area irradiated (plant canopy) is the same of the radiation incident area by luminaire.

$$\Phi_{q,YPF} = E_{q,YPFD}.\pi.d^2 \quad (4)$$

However, not all incident flux goes through the leaves or, the restricted area of canopy. In addition, there is no information of an average YPF or average radiation flux by datasheet of LED models that equation (4) requires. Hence, the equation (5) bases on Cosine Law to displays the relation between Flux Intensity ($I_{q,max}$) and total YPFD by distance and viewing angle (θ) of the luminaire. This equation is only applicable if the luminaire can be considered as a point source (SIMONS & BEAN, 2001):

$$E_{q,YPFD}(d) = \int_0^{\theta/2} \frac{I_{q,max}}{d^2}.cos\theta.d\theta \quad (5)$$

As most of LED models has cosine or approximately cosine intensity distribution, it can be inferred by equation (2) that the total YPF $\Phi_{q,YPF}(\theta)$ is a sum of intensities $I_q(\theta)$ spread for the whole matter canopy area. It implies the use of zone factor method, which is a derivative ring area that comprehends part of flux incidence and represents a delta part of the solid angle by equation (6). The intensity variation is expressed by equation (7) and equation (8) and it shows the general equation for total YPF estimation in function of the intensity quantity and distribution along the surface. The Figure 5 illustrate the geometric, three-dimensioned interpretation of the calculation method applied:

$$d\Omega = FZ(\theta_m, \theta_n) = 2\pi(cos\theta_m - cos\theta_n) \quad (6)$$

$$I_q(\theta) = I_{q,max}.cos\left(\frac{\theta_m+\theta_n}{2}\right) \quad (7)$$

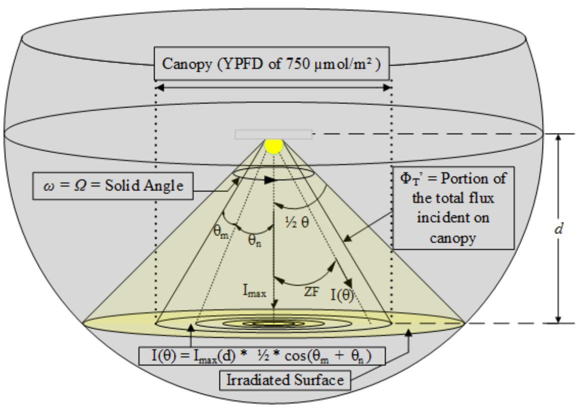

Figure 5. Three dimension geometric interpretation of the photic system composed by point luminaire and canopy of the plant.

$$\Phi_{q,YPF}(\theta) = \sum_0^{\theta/2} FZ.I_q(\theta).\Delta\theta \quad (8)$$

where θ can be related to the canopy radius r and distance d as equation (9) shows:

$$\theta = \tan^{-1}\left(\frac{r}{d}\right) \quad (9)$$

The YPF resulted from equation (4) and (8) is plotted on graph per distance varying from zero to 60 cm, for a constant YPFD of 674 μmol/m², in Figure 6. The YPFD is determined by the method pointed out in section 3.1. In addition, the diameters chosen for theoretical calculus express the variable area in accordance with radiation incident area, chosen diameter of 0.3 m for hop canopy structure (0.071 m²) and approximately ten times the canopy area chosen, for diameter of 1 m (0.078 m²). The dashed blue line indicate the YPF value of 426.1 μmol/s emitted by the luminaire applied in the experiment and presented in the forward section.

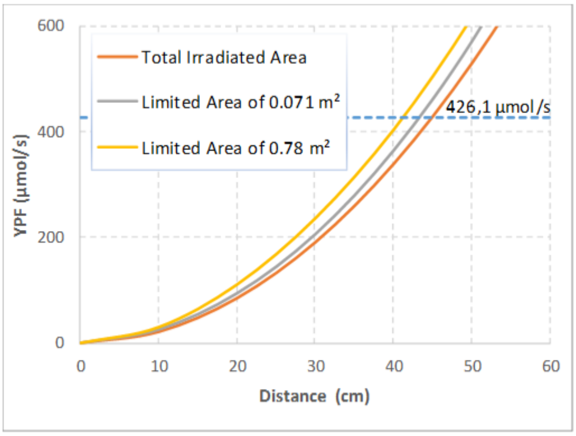

Figure 6. Required YPF per distance to maintain average YPFD of 674 umol/m² on hops canopy.

It can be noticed by Figure 6 the significantly rise of YPF needed in case to increment the distance between luminaire and canopy setting the YPFD as a constant value. Moreover, the increase on canopy area reflects on a slight dislocate the curve to the left. In order words, in order to maintain the YPFD with a considerable increment canopy and constant YPF emitted by a luminaire, it must decrease slightly the distance between luminaire and canopy (by analyze of yellow and grey curve).

4 Experiment Underplot and Method Validation

In order to validate the analytical method proposed in the paper, this chapter reports the experiment deployed with an eligible High-Flux COB LED to supply an adequate level of radiation for a hop adult plant. The chapter consists on detail the luminaire, the experiment arrangement and comparison between empirical and theoretical results found.

4.1 Luminaire and YPF Conversion

The luminaire chosen to perform the experiments was a high-flux COB LED APOLLO 600 by Flip Chip Opto (FLIP-CHIP-OPTO, 2016a). Table 1 shows the main details of the LED by datasheet information.

As can be seen in Table 1 the APOLLO 600 has compact diameter dimension of 60 mm. Thus, the minimum distance, d, to considerate the luminaire as a punctual source is equal or greater than 30 cm, which corresponds to five times the greater dimension of the COB (NFEE, 2009).

Another relevant fact to be considered is that most of LED luminaires are not assigned for horticulture application. Indeed the APOLLO 600 is a cool-white LED applied for general lighting applications as its SPD is more efficient for human eye sensitivity. In cases of higher system efficacy (optimum photosynthesis production per electric power demanded), the Duet Dynamics models are more suitable for horticultural applications as it targets the SPD on higher peaks of RQE curve (FLIP-CHIP-OPTO, 2016b). Nevertheless, as the aim of work focus on validating the theoretical calculus estimation, the APOLLO 600 complies the requirements.

In this context, the APOLLO 600 does not offer adequate information of flux in Quantum system. Therefore, the first stage for theoretical prediction is to convert the radiant flux (available on datasheet) to YPF by equation (10). Then, find a reasonable distance (d) in view of the leaves tolerance temperature and the consideration of punctual radiation source.

$$YPF = 8{,}3612 \int_{360}^{760} \lambda . \phi_{rad,\lambda} . P(\lambda)\, d\lambda \qquad (10)$$

, $P(\lambda)$ is the RQE curve showed in Figure 2.

The YPF of the COB LED found were 426.1 µmol/s based on equation (10) and the rated radiant flux of APOLLO 600 in Table 1. This corresponds to an approximately distance of 41 cm for restricted canopy area of 0.78 m², 43 cm for hop canopy of 0.071 m² and 45 cm for total variable irradiated area (Figure 6). The distance resulted by theoretical method is adequate for the case as the COB is fairly far from the canopy to avoid burned leaves and it is 13 cm further from the minimum distance to considerate it as a punctual radiant source (NFEE, 2009).

Table 1. Rating parameters of COB LED Apollo 600 (FLIP-CHIP-OPTO, 2018).

Parameters	Ratings
Maximum Power Dissipation	608.4 W
DC Forward Maximum Current	12 A
DC Rated Current	6 A
Rated Radiant Flux (Φ_{rad})	107,6 W
Half View Angle ($\theta/2$)	70ºC
Dimensions (diameter)	60 mm

4.2 Photic Experiment

This experiment comprehends the YPFD data acquisition from a surface varying its distance to the COB LED operating in rated current under approximately 25 ºC to avoid temperature flux derating. A Cosine Receptor fixed in virtual canopy level captures the radiation emitted by luminaire and transfer it through an optic fiber to the spectrometer, which process the radiation collected in order to calculate the YPFD in real time, by the software Spectra Suite (OCEAN OPTICS, 2017).The experiment arrangement is given by Figure 7.

The measures has been taken place in a dark room isolated from natural or artificial lighting interferences and varying the Cosine Receptor height each 10 cm from 30 cm to 100 cm away of the luminaire considering total area of the canopy surface. It was taken three measures from each height, creating a virtual radius of the canopy circular plan. The average of measurements from same height was considered the canopy YPFD as the luminaire intensity flux is featured by a radial symmetry.

The results on Figure 8 shows not a satisfactory approximation between both curves (theoretical and experimental). At 694 µmol/m², the theoretical distance calculated was 43 cm (confirming the YPF results in Figure 6), while the experimental tendency line of results for the same YPFD was found in the distance of 58 cm. It means that the measured YPFD

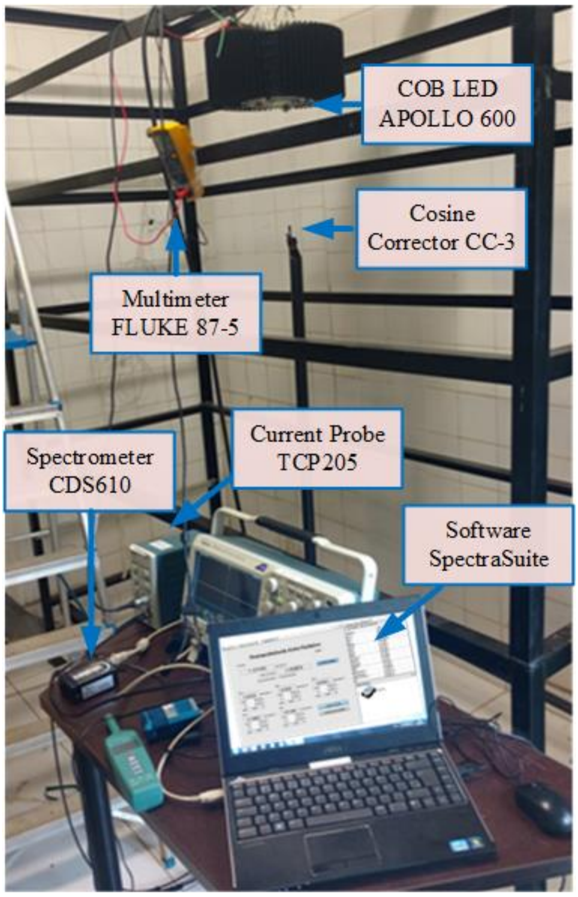

Figure 7. Chart of YPF required per distance to maintain 750 µmol/m² on hops canopy.

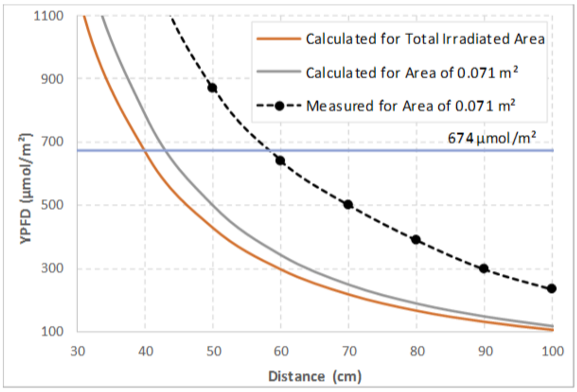

Figure 8. Comparison between calculated (theoretical) and measurements (experimental) curves for canopy irradiated surface.

is higher than YPFD calculated for the same virtual plane. The considerable distance error around 26% can be associated mainly to a reflected wall (white tiles) aside the LED during experiment deployment. This miss procedure can lead to a consistent YPFD increment by adding indirect radiation reflected on the aside tiled wall by means of the measured virtual surface. As the method proposed only considerate direct incident radiation in the calculus, the reflected radiation is not counted in theoretical results.

5 Conclusions

The work presented a brief state of art and an overview of essential concepts in the horticulture lighting context. In addition, it includes a method to design luminaires inserted in greenhouses for horticulture applications. A High Flux LED COB and a Cosine Receptor were applied in a photic experiment as an example for validation of prediction method proposed. The experiment deployment determined the measured YPFD, whereas the luminaire datasheet provided the radiant total flux, which was converted to YPF data for horticulture adequacy.

The errors founded by calculated and experimental data for restrict area of 0.071 m² was 25.8% and for total area was 29.3%. The two calculated methods displays no consistent differences at YPFD interval analyzed. However, both calculated results presented expressive distance errors if compared with the distance found by measurement experiment. As the calculated method proposed only considerate direct incident radiation, a reasonable error factor can be attributed to the consistent portion of indirect radiation reflected by the aside tiled wall of the experiment room (Figure 7). For future work, this case will be evaluated in order to validate the prediction method proposed with inferior errors. The measures will be repeated restrictedly for direct radiation, in addition to adequacy of prediction calculus to approach indirect radiation, also.

Besides the considerable distance of measured and experimental comparison, the method offers an outset on validation the design prediction proposed for restricted area. Therefore, the method offers more feasibility for horticultural application in respect of Integer Sphere and Cosine Receptor are not necessary for the design process and been an alternative tool for PAR calculations to attend the lack of dedicated professional softwares in the market.

Another pertinent consideration is that the prediction method allows to estipulate the amount of luminaires or electric power demanded to attend the specie in focus for a specific area of greenhouse. However, this system is only valid for punctual radiation sources, which restricts the consistence of this application only for COB LEDs in majority of the cases. Thus, the validation with discrete luminaires approaching the punctual model is an aim for future work. In case of errors rises drastically, another design has to be proposed for a more generic calculus method to encompass punctual and discrete compound luminaires applications.

Acknowledgements

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