Optimal LED Lighting Design for Indoor Farm to Realize Economical Crop Production

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Abstract: This paper presents an optimization method to realize economical crop production in indoor farms through LED lighting design. The method considers crop's light recipe, biomass output, and energy usage. It consists of an optimizer supported by a lighting simulation engine and a biomass machine-learning engine. The lighting simulation engine evaluates the lighting environment for the candidate lighting designs recommended by the optimizer. The biomass machine-learning engine predicts the biomass for the lighting recipes generated by the candidate lighting designs. The optimization procedure evolves by evaluating the candidate lighting designs until an optimal LED lighting design with least energy usage and maximum crop biomass production is achieved.

Index terms: Crop production, LED lighting, energy, optimization, machine learning.

I. INTRODUCTION

Urban farming is demanding in rapidly developing cities for food security and sustainability. Growing crops in controlled environment agriculture (CEA) is positioned to offer a solution for this problem. However, profitability poses a big challenge for farmers due to high cost of electricity from LED lighting. Lighting design is therefore one of the commonly discussed and considered as the most expensive component in CEA [1]. Albright used control decisions to manage greenhouse light to a consistent daily integral [2]. Ferentinos and Albright developed a genetic algorithm technique for the optimal design of a lighting system for crop production [3]. Olvera-Gonzalez et al. developed a smart illumination system (ILSys) to study the growth process of green plants [4]. In [5], a multiple objective optimization of genetic algorithm for controlled environment agriculture (CEA) facilities was developed to produce a design layout of LED lamps that meets a required amount of DLI, uniformly distributes light over the plant growing area, and minimizes the investment and operating costs associated with the lighting system. Durmus recently proposed an integrative horticultural lighting system that allows real-time sensing and control and uses artificial intelligence to optimize and adjust the output [6].

Plants need a variety of wavelength and intensity of light for growth and development, i.e., light recipe, which is depending on the type of plant and the growth phase. Studies have also shown that light intensity and light quality can affect plant growth. Having a right lighting environment for plants to grow thus making it easier to increase yield and quality and reduce cost and energy usage poses one challenge to growers. Optimizing LED lighting in CEA to realize economical crop production is thus critical in farm design. This research addresses this problem and proposes an optimization method to solve it.

II. MATERIAL AND METHODOLOGY

2.1 Lighting Design

The LED lighting design here is to design a LED panel suitable in an indoor vertical farm to provide light to an individual leafy green based on the crop's light recipe, and the panel thus has an area of 20 cm x 20 cm that approximately represents the canopy of the crop. The panel is designed by allocating LED beads with different spectrum and intensity on it. The designed panel can be easily used to make a LED fixture that provides light for an area where multiple plants grow.

2.2 Optimization

The framework of the optimization to develop an optimal LED lighting for crops in an indoor vertical farm is shown in Figure 1.

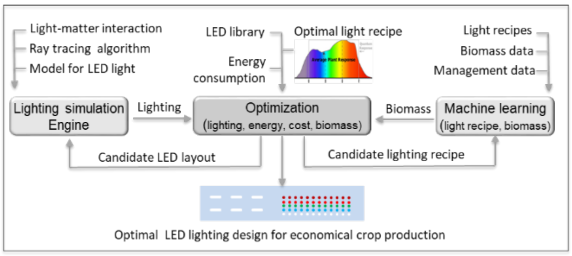


Figure 1: Framework of the optimization methodology

The lighting simulation engine is the tool developed to simulate lighting environment in a farm. It consists of two modules, natural lighting module and LED lighting module. The LED lighting module is used here to simulate the lighting environment for the candidate LED layouts and provides the results of lighting distribution to the optimizer in this optimization. Each LED bead has the information of the photometric data, the spectral power distribution, the electricity usage, etc. An LED library is built to store these information, and users can add needed LED lights to the library by following the data format.

The machine-learning engine is developed to predict optimal light recipe and biomass for crops based on experiment data. The experiments are conducted to investigate how different light recipes affect the crops' biomass, and thus to obtain the optimal light recipe with the maximum crop biomass. The crops her refer to leafy greens. The biomass, here the digital biomass, is calculated as the product of height and 3D leaf area assuming that the plant has a regular body of which the volume can be computed by taking into account height and length. A crop library is built that contains the experiment data with biomass under various light recipes. The library provides the database to the machine-learning engine for the training and prediction. The optimal light recipe of a crop and the biomass under it, both of which are generated by the machine learner, serve as the target inputs to the optimizer. During the optimization process, the machine-learning engine simulates biomasses for the candidate lighting recipes. These simulated biomasses are the intermediary results in the optimization.

Both of the lighting simulation engine and the machine-learning engine support the optimizer. The lighting simulation engine evaluates the lighting condition for a candidate lighting layout recommended by the optimizer. The machine-learning engine predicts the biomass for the lighting recipe produced by the candidate lighting layout. The optimization procedure evolves by evaluating candidate lighting layouts until an optimal LED lighting panel with least energy usage, and maximum crop biomass production is realized.

III. IMPLEMENTATION OF THE OPTIMIZATION ALGORITHMS

The procedure to realize the optimization described in Section II is shown in Figure 2. The implementation starts with the inputs, followed by the diagnosis and the location optimization, and ends with the outputs.

1) INPUTS: the target light recipe is one of the inputs and represented by spectral distribution of Photosynthesis Photo Flux Density (PPFD). The data of available LED beads in the library is another input, which have the information of the type of the LED beads, the photometric data and spectral power distribution for each type. Other data needed include the planting bed and the plane where LED beads to be placed. Both are specified in length (L) or width (W) dimensions. The distance between LED beads and the reference points to evaluate the lighting environment also have to be given.

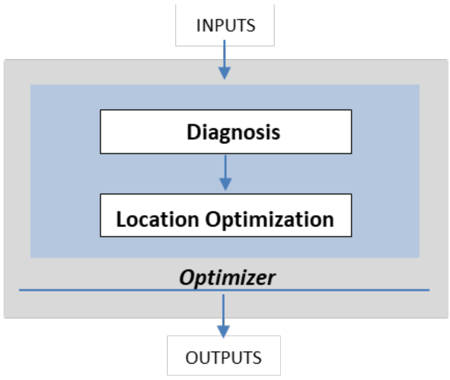


Figure 2: Procedure of the optimization methodology

2) Diagnosis: it is to select the type of LED beads and to determine the number of each selected LED beads. The selection is based on the target light recipe with the consideration of energy usage and the layout restrict on the location plane. A set of LED beads with the type and the number are obtained after the diagnosis process by searching LED beads from the library. The chosen LED beads are the ones having the best match to the pattern of spectral power distribution of the target light recipe with least energy usage. The pattern match ensures that the maximum biomass can be produced. The number of the LED beads for each selected type is determined by both the intensity required by the target light recipe and the maximum number of LED beads that can be placed on the location plane.

3) Location optimization: the selected LED beads from diagnosis are further placed on the location plane through a random search algorithm. The optimization is carried out for each selected type of the LED beads. The objective is to optimize the locations of those LED beads to produce lighting that meets the desired intensity specified in the target light recipe, and to ensure the lighting distribution on the planting area is as uniform as possible. Candidates locations are generated on the LED panel for the location optimization, by considering the dimension of the

layout area of the panel, and the photometric and geometrical data of the selected LED beads.

4) Outputs: the output of the optimization process is the optimal locations of the selected LED beads, the achieved lighting recipe, i.e., the PPFD distribution of the designed LED panel, and the predicted biomass under the achieved lighting environment.

The optimization is carried out based on the assumptions that the LED beads with various types are located randomly at a plane (the LED panel) over and centered to an interested planting area. The objective is to obtain the optimal locations to generate the desired spectral intensity specified by the target light recipe. Both the planting area and the LED panel are discretized. The LED panel is discretized with an interval determined by the dimension of the layout area of the panel, and the number and the geometrical data of the selected LED bead. The discretized points on the planting surface are used as light receivers. The distance between the planting surface and the LED panel is assumed constant.

IV. RESULTS AND DISCUSSIONS

An optimal light recipe for Choy Sum generated by the machine-learning engine trained by the experiment data is shown in Figure 3. The total PPFD of the light recipe is around 366 μmol.m^{-2}.s^{-1} with the ratio of blue to red light around one to one. The predicted digital biomass at this light recipe is around 10033 cm^{3}.

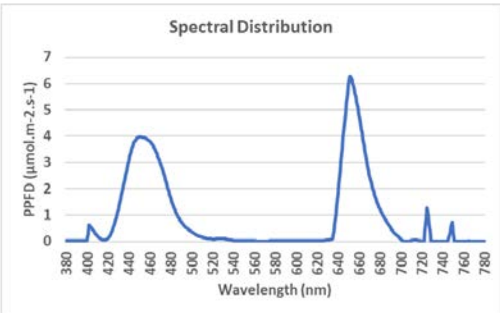
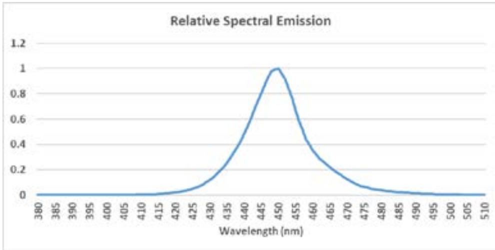
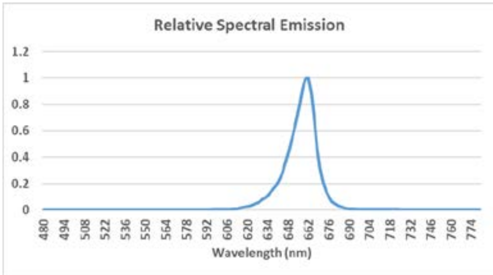


Figure 3: Target light recipe

Through the diagnosis of the optimal light recipe, two types of blue and red LED beads which have the best match of the spectral distribution are identified. Their relative spectral emissions are shown in Figures 4a-b. The number for each type is 29 for the red beads and 56 for the blue beads, which are determined by the intensity of the optimal light recipe. With one watt input for each LED bead, the total input electricity usage is around 85 watt.



a) Blue LED bead



b) Red LED bead

Figure 4: Relative spectral distributions of the selected LED beads

The result of the locations of the LED beads on the LED panel of 20 cm x 20 cm through optimization is shown in Figure 5. The LED panel is assumed located over and centered to the plant canopy surface with the distance of 25 cm.

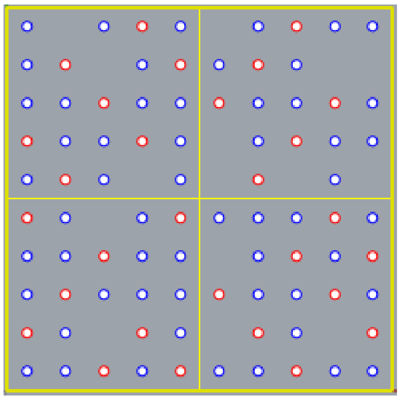


Figure 5: Result of the layout of LED beads: blue color for blue LED beads, red color for red LED beads

The PPFD distribution on the plant canopy of 20 cm x 20 cm is shown in Figures 6-8 for the red LED beads, blue LED beads, and total LED beads, respectively. The averaged total PPFD for the planting area is around 364 μmol.m^{-2}.s$^{-1,}$ with 178 μmol.m^{-2}.s^{-1} contributed from the 29 red LED beads and 186 μmol.m^{-2}.s^{-1} from the 56 blue LED beads. The digital biomass under the designed lighting conditions is around 9965 cm^{3}.

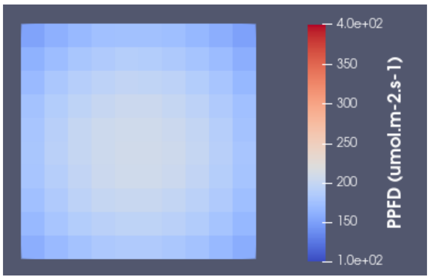


Figure 6: PPFD distribution for red LED beads

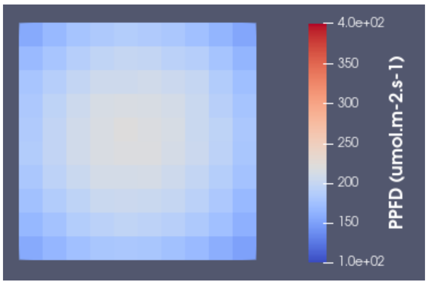


Figure 7: PPFD distribution for blue LED beads

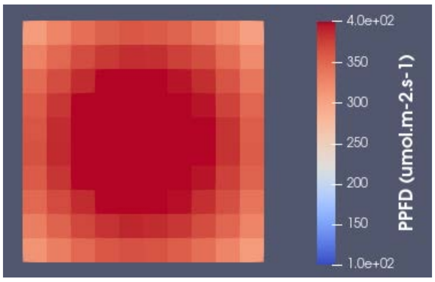


Figure 8: Total PPFD distribution

The above results demonstrate the developed technologies can realize economical LED lighting design based on the available LED lighting resources. By varying the types, positions and the spectrum of the LED beads, this method can deliver optimized lighting condition to plants in a specified area. The optimal lighting has the optimal spectrum, intensity, and uniform distribution. The specified area could be as large as the entire indoor space, or could be as small as a single light fixture. With the optimized lighting condition, farmers can maximize their crop production with least energy usage.

CONCLUSION

A method to realize economical crop production by optimizing LED lighting design in indoor farms is presented. The optimization considers crop's light recipe, biomass output, and energy usage. It consists of an optimizer, a lighting simulation engine and a biomass machine-learning engine. The lighting simulation engine evaluates the lighting environment for the candidate lighting layouts recommended by the optimizer. The biomass machine-learning engine predicts the biomass for the lighting recipes generated by the candidate lighting layouts. To realize an optimal layout (positions) of LED lights, the spectral intensity of different types of LED lights is optimized using a random search algorithm in a discrete plane, accelerated by leveraging on the rectangular shape of a typical farm (or area of interest within the farm). Depending on the specific need(s), operating constraint(s) etc. of the farm, this method allows for the spectrum, the intensity, the number, or the position of the LED lights to be varied, or all. This work leverages different algorithms to account for all the factors affecting lighting conditions in indoor farms, instead of the subset accounted by prior art, with each of the different algorithms customized for the farm application. Farmers can use the developed technologies to optimize LED lighting designs to maximize crop biomass production and reduce energy usage.

ACKNOWLEDGEMENT

This research is supported by A*STAR C221018003 and A19D9a0096.

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