Development and Implementation of an Adaptive LED Lighting System for Controlled Environment Agriculture

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Abstract—**The idea of creating a microclimate condition for plant cultivation which involves controlling critical factors such as light, temperature, water, and nutrient requirement for their satisfactory growth has been the focus of various researches in the recent years. However, the implementation in related studies were either limited to understanding the growth response of plants to different light characteristics or applications that have supervised controls or using complex and expensive sensors which prevent these systems to be deployed on a larger agricultural sector. An improvement of these previous studies is the development and implementation of a lighting system that utilizes solid-state lighting based on the use of light-emitting diodes (LEDs) integrated with an intelligent algorithm to be adaptive to the light requirements of specific plants. In this study, tomato plants were cultivated inside a growth chamber and light characteristics that are delivered to the tomato plants were controlled by the adaptive LED lighting system. Initially, a lighting profile was created which is based on previous studies about the response of tomato plants to different light characteristics. This includes the light quality or spectral distribution of light, light quantity or irradiance levels, and light duration or photoperiod for every growth stage that significantly improve over-all plant development. The lighting profile is the basis of the system in selecting appropriate conditions of light for the plants. This selection was done by a fuzzy logic system as well as the control to the activation and deactivation of the lighting system as needed by the tomato plants. The input ambient light condition to the fuzzy logic system results to the output light characteristics delivered to the plants. The results shows t an adaptive LED lighting system for controlled environment agriculture that delivers necessary light quality, light quantity, and light duration based on the determined lighting profile for tomato plants. Applications of this study are expected to lead to improvements in plant characteristics, energy consumption, and over-all productivity.**

***Keywords*: adaptive LED lighting system; agriculture; controlled environment agriculture; fuzzy logic system; light-emitting diodes; lighting system; tomato plants**

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I. Introduction

The interest in controlled environment agriculture has been brought about by the need for technological innovations. This is to meet the rising food demand of the continuously increasing world population. One of these innovations involve creating an ideal microclimate for the plants by controlling critical factors needed for satisfactory growth such as light, temperature, water, and nutrition [1], [2].

Among the mentioned critical factors, light is the sole provider of energy for plant development and has been the subject of several studies in photosynthesis, photomorphogenesis, and bioenergetics [3]. Light stimulates photosynthesis which is vital to all plants during major parts of their growth cycle as well as to all other life forms on Earth in general [2]. Furthermore, light quality, quantity, and duration are essential characteristics of light that have significant influence to the biological mechanisms of plants [4]. Light quality refers to the spectral distribution of light expressed as wavelengths in nanometers (nm). The quantity is the instantaneous measure of the amount of photosynthetic photon flux on a given surface expressed in micromoles per square meter per second (μmol/m^2/s), and duration or photoperiod is the time that plants are exposed to light. These characteristics of light constitute the lighting profile which varies according to the types of plants and considers their growth stage.

In the field, where natural light from the sun is available, plants receive a wide spectra of light. However, they do not absorb between 400 nm to 700 nm defined as the photosynthetically active radiation (PAR) and photons in different wavelengths within this region have varying efficiencies in stimulating photosynthesis [3], [6]. Also, irregular weather patterns and climate change limit plant productivity as the sufficient amount of light may not be available to plants all the time. These challenges in conventional agriculture open the idea of cultivating plants in controlled environment agriculture facilities such as growth chambers.

In growth chambers, artificial lighting systems traditionally include fluorescent, metal-halide, high-pressure sodium, and incandescent lamps [7]. They are either used to provide supplemental light in addition to natural light or as independent light sources to ensure that necessary light requirements are delivered to the plants. Similar to the natural light, these traditional lighting systems produce unused light spectra which contribute to their inefficient energy consumption and heat generation. One of the recent advancements in lighting technology applied in growth chambers is the solid-state lighting based on the use of light-emitting diodes (LEDs). Among the advantages of LEDs over traditional lighting systems include long operating lifetime and durability, small space utilization, efficient energy consumption, and controllability by having wavelength specificity and linear photon output with electrical input current [8].

The intention to further enhance lighting technologies and maximize the advantages they offer has led to different studies that integrate control algorithms with the lighting systems. A smart illumination system utilizing a pulse modulated chlorophyll fluorescence monitoring system was designed in [9] to study plant growth. The system was used to control commercial LEDs and allow continuous or pulsed radiation of light. In [10], the LED lighting system was experimented with pulse width modulation (PWM) to observe the effects of timing the pulses of radiated light with respect to the development of plants. Two phase control patterns for the two different wavelengths of light with values 0 and 180 degrees were used in the experimentation. A LED plant growth unit with the purpose of plant cultivation even during periods of low natural light was developed in [11]. In this study, the lighting system was supplied with constant direct current and was controlled using a microprocessor connected with environmental sensors. In [12], combined effects of photon flux density, LED wavelength ratios, and intermittent light pulses were considered for improving space lighting system. The light unit was composed of LED modules and a digital controlled generator of power pulses. Pulse timing control of the lighting system and its effect on carnation was presented in [13]. A growth chamber was installed with a PLC system to control the heating, ventilation, fogging, irrigation, fertilizing, and lighting systems. All these previous studies have applied different control algorithms to LED lighting systems which demonstrate the efficacy of LED controllability. However, these implementations were performed either with supervised controls or complex and expensive sensors that may prevent these systems to be deployed on a larger agricultural sector.

In order to address these problems, a LED lighting system integrated with an intelligent algorithm was developed and implemented to further increase the utilization of inherent benefits of LED lighting technology. This type of system was designed to be adaptive to the light requirements of tomato plants inside a growth chamber. Such adaptive system has to be able to reduce complexity and costs compared to other previous implementations while ensuring satisfactory plant growth.

II. ESSENTIAL PARAMETERS OF THE LIGHTING PROFILE

A. Photosynthetically Active Radiation (PAR)

In the development of a lighting profile for specific plants, it is fundamental to establish knowledge on the parameters that constitute these lighting profiles specifically, the light quality, quantity, and duration. Light quality has been mentioned to be the spectral composition of light perceived by plants. However, it has also been emphasized that plants have preferences to specific wavelengths of light which have higher efficiency in stimulating photosynthesis and other biological mechanisms. Measurements of the efficiencies of different wavelengths in the range of 350 nm to 750 nm with respect to producing energy primarily for photosynthesis [6]. This has led to the definition of the photosynthetically active radiation (PAR) which is formed by the range 400 nm to 700 nm and has peaks on the blue (440 nm) and red (620 nm) lights with the blue peak being 70% of that of the red peak. The response of plants to different wavelengths in the PAR region is represented by the quantum yield curve as shown in Fig. 1.

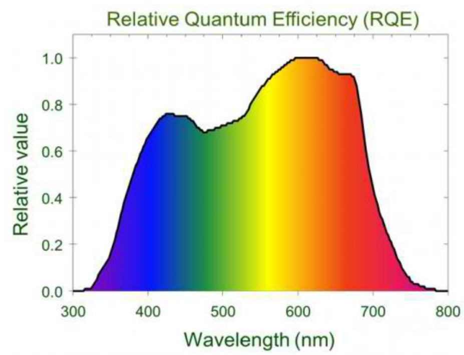

Fig. 1. Relative Quantum Efficiency [14]

However, it must be taken into account that different plants respond differently to the characteristics of light. Thus, findings of previous studies implementing different lighting profiles to tomato plants can serve as bases for further formulation of lighting profiles.

B. Recommended Light Characteristics for Tomato Plants

In order to provide functional guidelines for maintaining desired plant development, [15] divided plant growth into four arbitrary stages as shown in Table I. Recommended conditions of critical parameters to plant growth specifically light quantity and duration were presented in [16] and also summarized in Table I.

TABLE 1
Recommended Light Quantity and Duration for Tomato Plants

Growth Stage	Quantity (μmol/m²/s)	Duration (hours/day)
Propagation	250-450	12-20
Vegetative	450-700	12-20
Flower Development	450-700	12-20
Fruit Development	450-700	12-20

III. Methodology

Initially, a lighting profile for tomato plants was created which would be the basis of the system in determining appropriate light characteristics for every plant growth stage. The system begins with the measurement of ambient light intensity of the sunlight penetrating the growth chamber through the use of a digital light sensor. Then, the fuzzy logic system uses the ambient light measurement as an input and generates recommendations of light characteristics that ensure the constant production of light according to the lighting profile. These recommendations are implemented in the adaptive LED lighting system and outputs light as needed by the plants.

A. Setup in the Growth Chamber

This study utilized tomato plants grown inside a specially-designed chamber with a total area of 7.5 square meters (3 meters by 2.5 meters). It has two identical plant beds with each plant bed having an area of 2.25 square meters (2.5 meters by 0.9 meters). On each plant bed, 4 tomato plants were cultivated for a total of 8 tomato plants inside the growth chamber. The tomato plants were placed equidistant from each other with a separation of 0.625 meters. The adaptive LED lighting system has used LED light bulbs and are installed approximately 1.5 meters above the soil surface. There are 4 light bulbs installed for each plant bed and each light bulb is placed directly above each tomato plant. A dedicated microcontroller, 4-channel relay module, and digital light sensor were installed for each plant bed to implement the intelligent algorithm of the system.

B. Determining the Recommended Period per Cycle

Aside from creating the lighting profile for tomato plants, another essential consideration is the recommended period per cycle of the adaptive LED lighting system. The cycle includes the measurement of the ambient light, the implementation of the fuzzy logic system and controls, and the data collection. Among the light characteristics, the photoperiod and respiration would be affected by the period per cycle. Both photoperiod and respiration must be maintained in recommended conditions based on previous studies as they play important roles in the biological mechanisms of plants. Also, there are other systems in the growth chamber that must be considered in the selection of period per cycle in order not to adversely affect their implementation. One of which is the vision system of another study that needs a period of 30 minutes with no activation of the light bulbs occurring specifically from 12:00pm-12:30pm each day[3].

It was previously reported that tomato plants achieved satisfactory growth with a photoperiod of 12-20 hours and transpiration of 4-12 hours each day. Hence, the adaptive LED lighting system is expected to provide such photoperiod and respiration to the plants. In order to select the period per cycle, an implementation of the system at hypothetical minimum and maximum ambient light conditions were experimented.

In a hypothetical low ambient light condition, the photoperiod, as a result of combination of natural and artificial light is 20 hours and the respiration is 4 hours for one-day cycle. Also in this condition, the adaptive

LED lighting system activated the light bulbs for 16 hours during the whole 24-hour period. While in a hypothetical high ambient light condition, the photoperiod, as a result of combination of natural and artificial light, is 19 hours and 45 minutes and the respiration is 4 hours and 15 minutes for one-day cycle. Also in this condition, the adaptive LED lighting system activated the light bulbs for 14 hours during the whole 24-hour period.

As a result of the experiment, a period of 1 hour and 30 minutes or 1.5 hours per cycle ensures that the recommended light quality and quantity are provided to the tomato plants. This mode is also suitable to be implemented in the growth chamber as it satisfies the needs of other systems such as the vision system of no light bulb activation during the specified period of 12:00pm-12:30pm at any ambient light condition.

C. Calibrating the Digital Light Sensor (BH1750fvi)

The digital light sensor BH1750fvi has 6 modes of measurement categorized as continuous and one-time measurements [17]. In continuous modes, the sensor measures light quantity continuously while in one-time modes, the sensor measures the light quantity once and then it enters the power down mode. By default, the Arduino library from [17] is set at continuous mode but it could be changed according to the intended application through the Arduino Integrated Development Environment (IDE).

In this study, the ambient light condition is assessed periodically through the digital light sensor. Hence, the one-time mode for every cycle is implemented in the system. The available Arduino library returns an integer value which represents the ambient light condition or light quantity measurement in units of lux and the selected mode has the generic range of 0 up to 65,535 lux. However, light quantity is better understood in plant cultivation if it is expressed in terms of photosynthetic photon flux density (PPFD) – $\mu mol/m^2/s$ which means that a calibration method needs to be applied.

Light quantity measurements in lux could be converted to equivalent PPFD - $\mu mol/m^2/s$ through the use of a conversion factor [18]. In order to obtain the PPFD equivalent of the ambient light condition, a conversion factor of 0.0185 was used. As a result of the conversion, the actual light quantity measurement range of the digital light sensor was adjusted to 0 up to approximately 1,212.3975 $\mu mol/m^2/s$. This range is below the light quantity measurement of full sunlight in the field which is approximately 2,000 $\mu mol/m^2/s$ [18] but it must be noted that the ambient light condition inside the growth chamber used in this study would be significantly lower than the full sunlight light quantity measurement. Hence, the digital light sensor (BH1750fvi) would still perform well according to its intended function.

D. Developing the Fuzzy Logic System

In this study, the fuzzy logic system is built using the MATLAB Fuzzy Logic Toolbox. The fuzzy logic system has one input which is the ambient light and one output which is the recommended light characteristics.

Then, membership functions were defined. For the input ambient light, trapezoidal membership function is used with the following parameters for each membership function: [-540 -60 60 540] Low, [60 540 660 1140] Medium, and [660 1140 1260 1740] High. The input values correspond to the ambient light measurements in $\mu mol/m^2/s$. For the output light characteristics, triangular membership function is used with the following parameters for each membership function: [40 45 50] Short, [47.5 52.5 57.5] Mid, and [55 60 65] Long. The output values correspond to the number of minutes of light activation for every 1.5-hour cycle.

A specifc set of rules were followed in the study to ensure that the system works. Particularly, it was set thatif the ambient light is low, then the light characteristics will be corresponding be long. On the other hand, if the ambient light is medium, then the light characteristics is midbut at high ambient light, light characteristics will be considered short.

IV. Results and Discussion

A. Lighting Profile for Tomato Plants

For light quality, the influence of different spectral distributions of light to tomato plant development was observed. It has been known that plants use light primarily as energy source for photosynthesis. The study of McCree in [6] showed that the photosynthetically active radiation (PAR) is in the range of 400 nm to 700 nm and has peaks on the blue (440 nm) and red (620 nm) lights with the blue peak being 70% of that of the red peak. The blue light emission has an effect of peak chlorophyll absorption and acceleration of vegetative growth with photosynthesis [5]. The red light emission has an effect of large energy absorption for photosynthesis and acceleration of vegetative, flowering, and fruiting growths [5]. An implementation with 5:1 red to blue light quality ratio achieved a consistent high fruit production [19]. Increase in fresh weight, dry weight, stem diameter, and health index of tomato plants were also observed with the red and blue light applications [20]. Hence, a lighting system that has emissions of light quality within the PAR region is necessary and specifically gives tomato plants a high red to blue light quality ratio. In this regard, light bulbs with spectral distribution of 620 nm red and 440 nm blue light emissions are used in the lighting system. The light bulbs have a high 86:20 red to blue light ratio (actual LED count). One light bulb is dedicated for each tomato plant

Fig. 2. Emission of light in plants

being cultivated in the growth chamber. An image of the light bulb during light emission is shown in Fig. 2.

For light quantity, the influence of irradiance levels or light intensity levels for tomato plant development was observed. A lower light intensity level was found to producedsmaller leaves with higher length-to-width ratio, elongation of internodes, reduced concentration of chlorophyll, and less dry weight while a higher light intensity level compared to the necessary would lead to stimulation of auxiliary branch growth, proliferation of growing points, photodestruction of chlorophyll, and stress symptoms such as increased anthocyanin production [3].. It emphasized that for a satisfactory plant development, light quantity must be maintained within the recommended levels.

During the propagation stage necessary irradiance level is 250-450 μmol/m^2/s and during the vegetative, flowering, and fruiting stages necessary irradiance levels are similar and equal to 450-700 μmol/m^2/s. The tomato plants being cultivated inside the growth chamber are in their vegetative to fruiting stages due to the setting that propagation stage is accomplished outside the chamber. This allows the utilization of a lighting system with constant light quantity emissions within the recommended levels.

The light quantity being produced by the light bulbs used in the system was measured using the digital light sensor. The result shows that the light emission of the light bulb is approximately 530 μmol/m^2/s. PPFD measurements show that the irradiance level of the light bulb is within the recommended light quantity for tomato plants during the vegetative, flowering, and fruiting stages.

In order to ensure satisfactory plant development, the adaptive lighting system must deliver light to plants within the recommended light durations. In this study, a minimum photoperiod is set at 19 hours and 45 minutes per day and the maximum photoperiod is set at 20 hours per day considering the combination of natural and artificial light. For the adaptive LED lighting system alone, the maximum time for the activation of the lights bulbs is 16 hours and the minimum time is 14 hours. This ensures that plants are given time for respiration or periods without light exposure for other biological mechanisms. The maximum respiration period is 4 hours and 15 minutes and the minimum respiration period is 4 hours.

Table II summarizes the lighting profile for tomato plants that is being used in the adaptive lighting system. The lighting profile is set to ensure that light characteristics delivered by the adaptive LED lighting system to the tomato plants are based on the recommended conditions for satisfactory plant development.

TABLE 2

Lighting Profile for Tomato Plants

Vegetative Growth Stage	
Light Quality	620 nm (Red) and 440 nm (Blue) 86:20 Red to Blue Light Ratio
Light Quantity	~ 500 to 600 mol/m^2/s
Light Duration	16 Hours during Low Light Conditions 14 Hours during High Light Conditions
Flowering Growth Stage	
Light Quality	620 nm (Red) and 440 nm (Blue) 86:20 Red to Blue Light Ratio
Light Quantity	~ 500 to 600 mol/m^2/s
Light Duration	16 Hours during Low Light Conditions 14 Hours during High Light Conditions
Fruiting Growth Stage	
Light Quality	620 nm (Red) and 440 nm (Blue) 86:20 Red to Blue Light Ratio
Light Quantity	~ 500 to 600 mol/m^2/s
Light Duration	16 Hours during Low Light Conditions 14 Hours during High Light Conditions

B. Generation of Recommended Light Characteristics

In this study, the adaptive LED lighting system is set to generate recommendations of light characteristics based on the prevailing parameters significant in making these selections. Recommended light quality and quantity were set on fixed values due to the fact that the light bulbs used in the system have constant light emissions of 86:20 red to blue light quality ratio and approximately 500 to 600 μmol/m^2/s light quantity. For the determination of recommended light duration as well as for providing controls to the lighting system, a fuzzy logic system was used. The fuzzy logic system has 1 input, ambient light, and 1 output. The recommendations was in accordance with the lighting profile for tomato plants that are using adaptive LED lighting system.

Using the fuzzy logic toolbox in MATLAB, the output of the system was tested with different possible input values. The input ambient light has 3 membership functions: low that peaks on the range 0 to 60, medium that peaks on the range 540 to 660, and high that peaks on 1140 to 1260. The input values correspond to the ambient light measurements in μmol/m²/s. The output light characteristics has 3 membership functions: short that peaks on 45, mid that peaks on 52.5, and long that peaks on 60. The output values are equivalent to the number of minutes of light activation during the 1.5-hour cycle.

A summary of the tests conducted presenting a possible value for the input ambient light and the corresponding output photoperiod or light duration is shown in Table III. The test results indicate the adjustments to the photoperiod being assessed by the fuzzy logic system with respect to the prevailing amount of ambient light.

TABLE 3
SUMMARY OF TEST RESULTS

Ambient Light	Photoperiod
44.4 μmol/m²/s	60 minutes
278 μmol/m²/s	56.5 minutes
600 μmol/m²/s	52.5 minutes
933.7 μmol/m²/s	48.4 minutes
1144 μmol/m²/s	45 minutes

C. Implementation of Recommended Light Characteristics

A microcontroller and a 4-channel relay were used on each plant bed to control the 4 light bulbs installed for each tomato plant. Since the light quality and light quantity have fixed values, the control of the light duration is done on the system. The adaptive lighting system is set to run all the time with periods of light activation and deactivation. Each day has 16, 1.5-hour cycle.

The initial outputs of the system for plant bed 1 and plant bed 2 are presented in Fig. 3 and 4. During the implementation, the ambient light or irradiance level measurements on plant bed 1 and plant bed 2 are 0.15 μmol/m²/s and 0.14 μmol/m²/s, respectively which are both considered by the system as low ambient light conditions. Hence, the long light duration or 60-minute ON and 30-minute OFF during the 1.5-hour cycle is implemented by the system on both plant beds. This also provides a total of 20 hours photoperiod to all tomato plants for a whole-day cycle with 16 hours LED light bulb activation. The light quality was maintained at 86:20 red to blue light quality

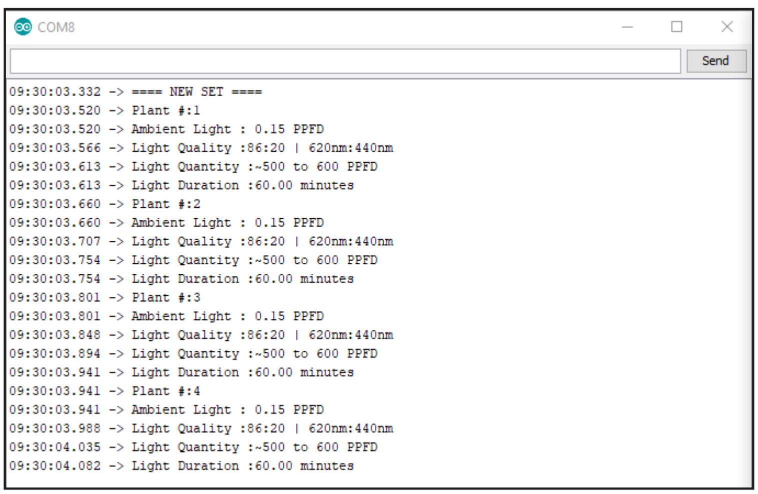

Fig. 3. Output of the Adaptive LED Lighting System on Plant Bed 1

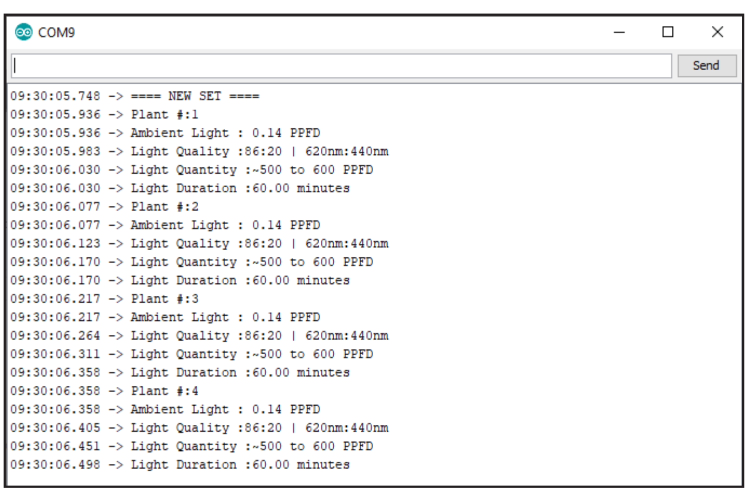

Fig. 4. Output of the Adaptive LED Lighting System on Plant Bed 2

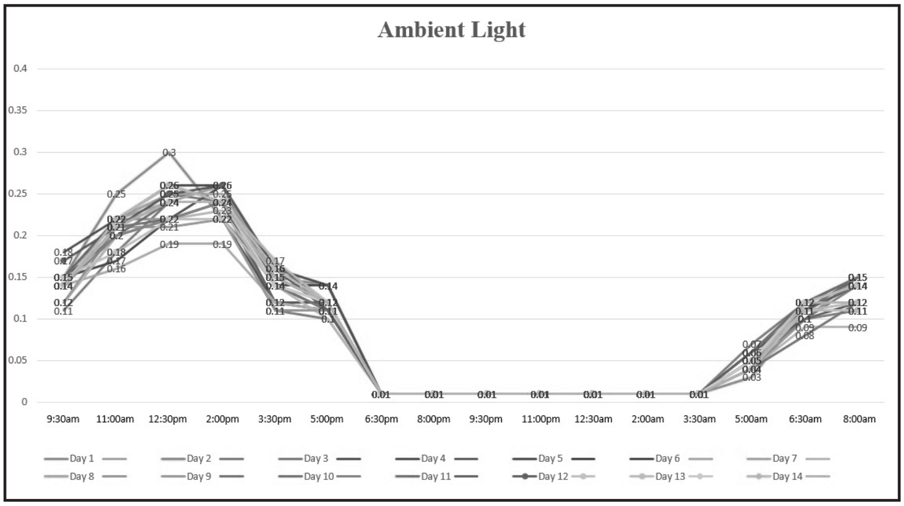

Fig. 5. Graph of Ambient Light on Plant Beds 1 and 2 for 14 Days

ratio (actual LED count) and light quantity was maintained at approximately 500 to 600 μmol/m^2/s.

In Fig. 5, a graphical representation of the ambient light conditions for 14 days observation on plant beds 1 and 2 was shown. The cycle of measurements is set to 11.5hrs. During daytime, ambient light ranged from 0.10-0.30 μmol/m^2/s and 0.08-0.25 μmol/m^2/s on plant beds 1 and 2, respectively. During nighttime, ambient light ranged from 0.01-0.07 μmol/m^2/s and 0.01-0.06 μmol/m^2/s on plant beds 1 and 2, respectively.

The measured ambient light conditions inside the growth chamber were observed to be constantly below the recommended irradiance levels for tomato plants. Hence, the supplementary light from the adaptive LED lighting system satisfied the energy needs of the tomato plants by providing light characteristics in appropriate spectral distribution, intensity, and duration.

V. CONCLUSIONS

The objective of this study is to develop and implement an adaptive LED lighting system for controlled environment agriculture that delivers necessary characteristics of light based on the determined lighting profiles for tomato plants.

In creating a lighting profile for tomato plants which includes recommended light quality, quantity, and duration for every plant growth stage, previous studies about the influence of different light characteristics to tomato plants are considered. The solid-state lighting based on the use of light-emitting diodes (LEDs) is capable of producing wavelength specific light such as the red and blue light qualities. Utilizing the wavelength specificity of LEDs, light spectra that do not significantly impact plant development may be disregarded and consequently minimizing heat generation of the lighting system. It must also be taken into account that LEDs have the potential to reduce over-all costs associated with lighting systems for controlled environment agriculture mainly due to their power efficiency and long operating lifetime. Hence, LED light bulbs with high red to blue light quality ratio can be used in the adaptive LED lighting system.

For light quantity, a specific range of irradiance level must be maintained to ensure continuous development of the tomato plants with enough energy for photosynthesis and other biological mechanisms. The tomato plants are observed to have similar requirements for irradiance levels during their vegetative, flowering, and fruiting growth stages. Hence, LED light bulbs that produce irradiance levels that are constantly within the recommended light quantity for tomato plants are used in the adaptive LED lighting system. These are set to supplement the light quantity received by the plants from sunlight.

For light duration, a recommended photoperiod or exposure to light is maintained while ensuring that respiration or period of no light is also provided to the tomato plants. A minimum photoperiod was set at 19 hours and 45 minutes per day and the maximum photoperiod is set at 20 hours per day considering the combination of natural and artificial light. For the adaptive LED lighting system alone, the maximum time for the activation of the lights bulbs is 16 hours and the minimum time is 14 hours. This ensures that plants were given time for respiration or periods without light exposure for other biological mechanisms. The maximum respiration period is 4 hours and 15 minutes and the minimum respiration period is 4 hours.

In generating recommendations of light characteristics, only ambient light conditions are considered. In general, the plant growth stage is a relevant parameter due to the fact that a specific growth stage requires specific light characteristics to support the biological mechanisms of the plant. However, tomato plants have similar requirements of light quality, quantity, and duration across all their growth stages inside the chamber. Hence, the system maintained these parameters at recommended values for satisfactory plant growth. A fuzzy logic system was used to generate the recommended light characteristics, specifically the light durations, while considering the ambient light conditions. It was selected due to its excellent intuitive approach and ability to be formed based on the knowledge of experts and prior studies. Also, its characteristic of being based on natural language makes it simple to understand and be applied particularly to the agricultural sector.

In developing an intelligent algorithm that implements the recommended light characteristics to the lighting system of a growth chamber, the fuzzy logic system is used. The generated recommendations from the previous specific objective is, then, implemented on the adaptive LED lighting system for light activation and deactivation. The adaptive lighting system was set to ensure that the tomato plants receive a minimum of 12 hours photoperiod and maximum of 16 hours photoperiod depending on the ambient light conditions while providing the recommended light quality and light quantity across all growth stages. The mentioned settings are in accordance with the lighting profile for satisfactory tomato plant development.

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