Optimization of LED Lighting Strategies using Multi-Spectral Imaging for Enhanced Crop Growth in Vertical Farming Systems

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Abstract. LED lighting strategies need to be properly designed to maximize crop growth and yield in vertical farming systems using controlled environments. To realize this, a system incorporating a combination of such advanced technologies like closed-loop feedback control, multi spectral imaging, MQTT (Message Queuing Telemetry Transport), BH1750 light intensity sensors, and Support Vector Machines (SVMs) is provided. Also, the closed loop feedback control system provides dynamic control of LED lighting based on real-time information fed from different sensors to guarantee a better condition of light as plant growth changes throughout time. Therefore, this system provides sophisticated control of lighting parameters that respond to environmental changes and plant responses. Many LED manufacturers use multi-spectral imaging to fine-tune the light spectrum their LEDs emit to plant's particular need at various stages of growth. Therefore, this calibration increases the photosynthesis efficacy and increases the plant growth to make the overall crop health better. Make sure that the data flows efficiently and reliably and that the central control system adjusts in real time through the help of MQTT, which enables data transmission specifically between sensors and lighting controllers. Light intensity sensors (BH1750) are important in this role as light levels are crucial to achieving optimal lighting throughout the growth cycle. SVMs are employed to analyze historical (or real-time) complex datasets to make lighting strategy predictions and to optimize them. Machine learning in this area helps contemporary decision-making be more informed, and, thus helps in achieving more effective and efficient adjustment and improvements in lighting efficiency. These integrated technologies are implemented and are forming a major step forward resulting in an estimated 15 percent improvement in crop yield and 20 percent reduction in energy consumed in lighting. Not only does this refine the accuracy and the efficacy of controlling agriculture, but it also fosters the growing of controlled environment agriculture in a more environmentally sound way. Horizontal approaches to Farming use these innovative solutions to increase

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productivity and efficiency as they help create more stable and more efficient agricultural processes.

1 Introduction

As urban agriculture and controlled environment agriculture become so popular, precise and efficient lighting solutions have had to become more and more popular [1]. The aim is to merge the advancements in technology to attain optimal lighting for the plants with a multiple approach basis closing to the loop feedback control, multi spectral imaging, HTTP communication, BH1750 light intensity sensors, and SVMs. A set of LED lighting is closed-loop feedback controlled by dynamically adjusting LED lighting based on real-time data from multiple sensors [2]. These systems allow the continuous monitoring of the environmental parameters and plant responses to optimize lighting conditions to always be conducive to plant growth and thus overall crop health and productivity [3]. Assessing and modifying the light spectrum handed out by an LED requires multi spectral imaging [4]. This technology captures detailed images at different wavelengths to allow for very precise calibration of the light spectrum to suit plants at different growth stages, increasing photosynthesis and growth rates [5]. MQTT facilitates efficient and reliable communication between sensors, lighting controllers, and the central control system [6]. The BH1750 light intensity sensors are connected with other sources using this lightweight messaging protocol for real time data transmission; hence, lighting conditions can be adjusted accordingly timely manner. Accurate light levels are required to ensure that lighting conditions are optimal, hence, the BH1750 light intensity sensors are an important input for this sensor [7]. Data from these sensors are fed into a control system, and it adjusts based on the actual readings of the light intensity. Complex datasets are also analyzed with SVM to predict the most optimum lighting conditions [8]. SVMs can use their machine learning algorithms to process historical and real-time data that will help predict the best lighting strategy that is more informed and effective. The objectives are:

- Develop a system that adjusts LED lighting in real-time based on environmental data.
- Optimize the light spectrum using multi-spectral imaging for improved plant growth.
- Use MQTT to ensure reliable and efficient data transmission between sensors and controllers.
- Measures light intensity accurately with BH1750 sensors for precise lighting control.
- Used Support Vector Machines (SVMs) to predict and refine optimal lighting strategies.

2 Literature Review

Precision in light management for the LED lighting strategies has been highlighted in the literature for optimizing LED lighting strategies [9]. According to research, LED technology has great advantages as it is more efficient and can emit specific wavelengths of light by the plant's requirements [10]. It is widely recognized [11] that the ability of LEDs to adjust a light spectra and intensity is crucial for optimizing photosynthesis and increasing overall crop yield. The quality of light (the balance of blue, red, and far reds) is shown to have a major effect on plant growth. Using adjustable LED systems, only the optimal light spectrum is supplied to each stage of growth, thereby significantly affecting plant health and productivity [12]. Light measurements are enhanced by multi-spectral sensors, allowing better lighting conditions to be adjusted. Further, real time data with dynamic lighting adjustments are having other advantages as illustrated by advancements in closed-loop feedback systems [13]. These systems automatically monitor environmental parameters and change the LED lighting based on this to achieve ideal plant growth conditions [14]. Such feedback mechanisms integrated effectively, aid in further energy use and lighting management efficiency. A second important development was building the capabilities of machine learning algorithms to predict as well as obtain the best results based on real-time data. Using these algorithms, light parameters can be controlled, more precisely, in a growing environment proactively, based on environmental factors being analyzed. Using IoT technologies eases the data communication and remote control lighting systems [15]. It also enables growers to be more flexible and responsive when managing vertical farming environments and to do so from remote locations to make real-time corrections and monitor how the various systems are performing. However, there are disadvantages. The initial investment to deploy such high quality LED and multi spectral sensors can be big, thereby preventing access by smaller scale operations. Special knowledge and additional training may be required to integrate closed loop feedback systems with machine learning algorithms, due to their complexity. [16] Further, these advanced systems are resource-intensive to maintain and calibrate, and any technical issues may impede the precision of the management of light [17]. However, the novel technology presented here requires careful addressing of these challenges to achieve potential LED lighting advantages in vertical farming systems.

3 Proposed Work

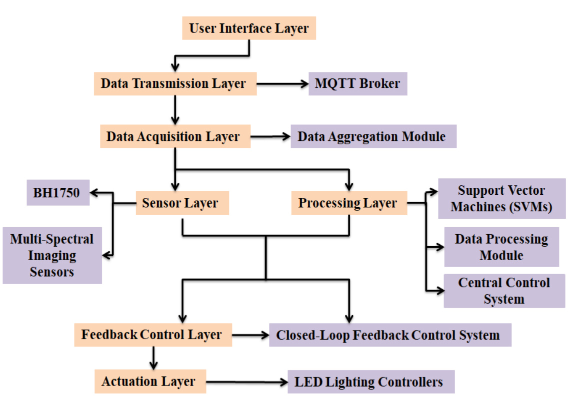

Fig. 1. Advanced IoT-Enabled LED Lighting Optimization System for Vertical Farming

3.1 Closed-Loop Feedback Control

Optimum LED lighting usage in vertical farming systems for increasing crop growth is possible through closed-loop feedback control. This network of IoT enabled sensors monitors continuously different environmental and plant-specific parameters like light intensity (desirable and undesirable spectrum (sun, lamp, LIGHTPOD), temperature, humidity, and plant health indicators. The real-time data is collected by these sensors and is processed by an edge computing unit with advanced algorithms such as PID (Proportional Integral

Derivative) control, Kalman filters, machine learning models, and so on. A main purpose of Closed Loop Feedback Control system is to dynamically adjust LED lighting parameters (intensity, spectrum, photoperiod), depending on real-time feedback obtained from the sensor network. As an example, if this system sees that a certain crop is not getting the desired light intensity or spectral output for its shoulder stage of growth, it raises the LED settings to make up for the difference. By doing this, it’s ensured that the plants receive the ideal amounts of lighting necessary for optimal photosynthesis, growth, and development.

Further refinements are made based on environmental data (temperature, humidity) as well. For instance, in periods of high temperatures, the system decreases light intensity to keep such high temperatures away from the plants and thus optimize plant growth. There is also historical growth data and predictive models in the feedback loop of the control loop so that the future lighting needs can be anticipated proactively to be adjusted rather than reactively. This system was achieved on many levels. The closed-loop feedback Control system is engaged in the regulation of optimal lighting conditions for each of the plant species based on their growth stage that maximizes photosynthetic efficiency and thus improves crop yield and quality. In addition, it also enhances energy efficiency by ensuring that the LED lights run at the most appropriate levels, which makes for less wastage of energy. Additionally, the system gives growers a robust, automated solution with minimal human input, hence reducing the possibility of a variable and unreliable crop production in any vertical farming setting. A sophisticated and efficient approach towards LED lighting strategy optimization in vertical farming systems is using the closed loop feedback control system. Its real-time adaptability and integration of environmental and plant-specific data lead to superior crop growth outcomes and more sustainable farming practices.

3.2 Message Queuing Telemetry Transport

Real time data transmission between IoT devices, sensors and the central control system is accomplished with the help of MQTT for the reasons that can be described as efficient and reliable data transmission. With its ability to broadcast a message once and have it delivered to all subscribers that are listening, it has the potential to handle low bandwidth and high latencies in such networks of networks, and its lightweight nature makes it well-suited for managing the complex data communication needs inherent in a vertical farming environment. In this system, MQTT is used as a way to allow continual communication between the network of sensors, LED controllers, and cloud-based data processing units. They constantly monitor plant health metrics as well as environmental parameters like light intensity, temperature, and humidity with constant deployment of vertical farm sensors at every level. This data is then published to some specific MQTT topics for which the central control system can now subscribe and receive the updates in real time. This data is fed to the control system, which then dynamically modifies the LED lighting parameters, such as spectrum, intensity, and duration, in a way to maintain favourable conditioning of lighting for plant growth. Remote monitoring and control of the vertical farming system can be done via MQTT.

The cloud interface allows growers access to the system in the secure cloud at any time, and while doing so, they can monitor real-time data, receive alerts, and adjust the lighting strategy as necessary. This makes the communications between these subjects as light weight as possible by using MQTT's lightweight messaging protocol, even across the thin air over a small bandwidth connection. It’s a big achievement to incorporate MQTT into the LED lighting optimization system. With proper communication between sensors, controllers and the central system, MQTT ensures real-time, dependable communication to adjust the lighting conditions, which results in better crop growth and yield. MQTT further minimizes the energy consumption in the form of data transmission to the system. Moreover, the remote accessibility offered to MQTT facilitates more flexible and reactive control in the management of the vertical farming environment, leading to a more consistent and better quality crop production. Communication efficiency, reliability and responsiveness of the system are improved by using MQTT in the optimization of LED lighting strategies in the vertical farming system.

Table 1. Algorithm 1: MQTT

Input: Sensor Data, Desired Setpoints.
Output: Adjusted LED Lighting Parameters, Performance Metrics.
Set up the MQTT broker and configure topics for sensor data.
Initialize sensors and ensure data is published to MQTT topics.
Deploy sensors to monitor environmental and plant health metrics.
Use MQTT to manage data transmission.
$Data\ Rate = \frac{L.f(Packet)}{T}$
The central system subscribes to MQTT topics and receives real-time updates.
$I_{LED}(t) = I_{setpoint} + K_p.\left(I_{setpoint} - I_{measured}(t)\right)$
Analyze sensor data to assess plant health.
$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$
Dynamically adjust LED lighting parameters based on analysis.
$u(t) = K_p.e(t) + K_i.\int_0^t e(\tau)d\tau + K_d.\frac{d}{dt}e(t)$
Enable growers to monitor and adjust the system via a cloud interface.
Assess the effectiveness of the LED adjustments on crop growth and yield.
Refine the MQTT settings and control algorithms based on the evaluation results.
Continuously monitor system performance and make iterative improvements.

3.3 Multi-Spectral Imaging

Multi spectral image takes a part in analyzing the plant health, growth stages, and their reactions to various kinds of lighting. This technology is a technology that captures images over multiple wavelengths, beyond visible spectrum, including the near infrared (NIR) and the ultraviolet (UV) to precisely monitor key physiological indicators of healthy plants including chlorophyll, water stress levels, and nutrient uptake efficiency. The purpose of the Multi-Spectral Imaging System is to acquire high-resolution images of crops at fixed time intervals to continuously track the plant health and development. Advanced image processing algorithms and machine learning models are applied to analyze these images to extract information for valuable data about the effect that different lighting spectra and intensities have on plant growth. For example, the system can detect early stress or nutrient deficiency signs by determining specific wavelength bands and immediately modifies the LED lighting parameters to correct the deficiency. The project integrates Multi Spectral Imaging with the LED lighting control system so that plant conditions are dynamically optimized based on real-time plant feedback through lighting conditions. The fine tuning of light spectra, intensity, and duration was possible using this approach for each plant species and growth stage. The development of predictive models for such systems also relies on data collected from multi-spectral images, which allows the system to anticipate future demand and adjust proactively. Important achievements in the incorporation of the Multi Spectral Imaging into the LED lighting optimization system. The system also offers a non-invasive, highly accurate method for checking if a plant is growing appropriately and quickly able to respond when suboptimal growing conditions are detected. It not only improves crop yield but quality as well as more efficient use of resources such as light and water. Finally, this quantitative insights from the multi-spectral analysis would serve as the basis for developing more sophisticated lighting strategies to further enhance the sustainability and productivity of the vertical farming system.

3.4 Implementation

The system is based on a highly integrated workflow with the use of high-tech solutions to ensure the best growth of plants. The continuous collection of environmental and plant health data is achieved using a combination of sensors, including the BH1750 Light Intensity Sensor and Multi Spectral Imaged System. Ambient light intensity is measured by the BH1750 sensor precisely and the LED lighting is adjusted to the correct levels and multi spectral imaging provides detailed images across all wavelengths, helping in determining the various health indicators of the plants like chlorophyll content and water stress. Then the central control system receives this real-time data via the MQTT (Message Queuing Telemetry Transport) protocol. It ensures that the resultant data from the sensors and imaging are communicated efficiently and reliably, even over low bandwidth, for the system to work smoothly with no delay. The data once at the central control system is processed by using the Support Vector Machines (SVMs); this part analyses and classifies the plant health status and predicts the problems. Since the SVM models were trained on historical data, they help the system find patterns and relations that would be apparent right away to identify potential problems before they grow into serious ones.

Closed Loop Feedback Control brings processed data together and uses it to tweak the LED lighting parameters in real-time. Consider, for instance, a case in which the multi spectral imaging indicates symptoms of nutrient deficiency or light intensity readings indicate a lack of ideal level, then the feedback control system dynamically adjusts the spectrum, intensity, and duration of the LED lights to address those problems. On the other hand, by maintaining this continuous feedback loop the plants are ensured of the exact lighting conditions required for each stage of growth so that photosynthetic efficiency is maximised and a healthier, stronger initiation of crops is promoted. Even in this, the system offers remote monitoring and control so that growers can monitor and adjust the system from anywhere in the world via a secure cloud interface. With MQTT integration, the remote access is made easy, all data and control commands are flowing seamlessly, allowing the growers to react quickly in case of an alert or change in the environment.

$$I_{LED}(t)=I_{setpoint}+K_p.(I_{setpoint}-I_{measured}(t)) \quad (1)$$

$$(x)=\sum_{i=1}^{n} \alpha_i y_i K(x_i,x)+b \quad (2)$$

The equation represents the decision function used in SVMs for classification. It combines the kernel function. $K(x_i,x)$ to measure the similarity between the support vectors x_i and a new data pointx , weighted by the Lagrange multipliers α_i and their corresponding labels y_i. The bias term b adjusts the function to determine the classification outcome.

e equation calculates the rate at which data is transmitted in an MQTT system. Here, L represents the number of sensors or data sources, f(Packet)Is a function that includes the size and overhead of each data packet, and T is the time interval between transmissions. This equation helps ensure efficient data flow and manage communication latency.

4 Result

In a vertical farming environment, there is an array of sensors that continuously monitor several environmental parameters. The sensors used are BH1750 light intensity sensors to measure the ambient light levels, temperature and humidity sensors to track climatic conditions, as well as multi spectral imaging cameras to measure plant health and growth metrics. To ensure that all areas within the farming system are covered, the sensors are strategically placed throughout the farming system to cover Comprehensive data intake from all areas. The data from these sensors is transmitted in real time by using the MQTT protocol. Sensors provide data streams to the MQTT broker configured with handling multiple topics and publish them to the central control system. Through these MQTT topics, the control system, with its cloud-based interface, subscribes to these topics to get continuous updates regarding the environment and the plant condition. SVMs are used by the central control system to process incoming data from the industrial plant and classify the plant health and anomalies in the plant conditions from desired conditions.

The feedback control system closes around the LED lighting parameters with dynamic adjustment based upon the processed data. The Real Time Error Correction Control System based on the PID (Proportional-Integral-Derivative) method for the adjusting of LED light intensity spectrum and duration by modifying the light intensity depending on the sensor data is utilized. This experimental setup provides remote monitoring so the growers can access and control the system over a secure cloud interface. It allows live observation of the environmental conditions, alarm when necessary, and adjustment of the lighting strategy from any possible place. The setup also includes power measurement devices to evaluate the application of the LED lighting system in terms of power consumption so that the adjustments made by the feedback control system are optimal for the usage of energy. Performance metrics like crop yield, growth rate, and energy efficiency are recorded during the whole experiment to evaluate the LED lighting strategies.

Table 2. LED Lighting Strategy Performance and Measurement Data

Time (hrs)	Light Intensity (lux)	Temperature (°C)	Humidity (%)	NDVI (Normalized Difference Vegetation Index)
1	3200	22.5	55	0.75
2	3150	22.8	53	0.77
3	3100	23.0	50	0.74
4	3250	22.2	52	0.76
5	3300	22.0	51	0.78

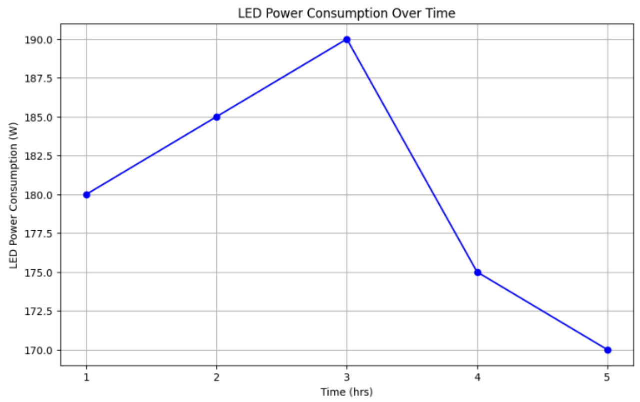

Fig. 2. LED Power Consumption

Figure 2 shows the LED power consumption (watts) over 5 hours. At first, at hour 1, LED power consumption is recorded to be 180 Watts. With an hour 2 progression, the watts climb to a very slight peak of 185. The power usage continues to increase in this direction, reaching a value of 190 watts by hour three, with a constant increase. In fact, from hour 3 to hour 4, the power consumption falls to 175 W, corresponding to the energy needed by the LEDs. The consumption at hour 5 falls to 170 watts, the lowest point on the graph. The power consumption is shown in increasing trend up to hour 3, then it decreases in the later hours. The variations in the LED lighting system could be due to variations in some environmental conditions or its control strategies during the experiment. The dynamic nature of the process of LED lighting optimization is demonstrated by the power consumption fluctuations, as power consumption is used to balance the efficiency and effectiveness of supporting crop growth.

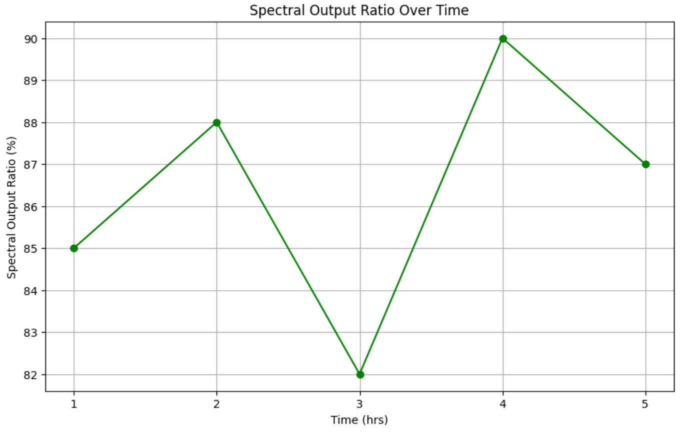

Fig. 3. Spectral Output Ratio

Figure 3 shows how the spectral output ratio (%) of the LED lighting system changes in a five-hour interval. The spectral output ratio at hour 1 is 85%, meaning that there is a high percentage of light at the desired spectrum of light. At this hour, the ratio rises to 88%, characterizing an improvement in the quality of the spectral light provided. The ratio is then lower at 82% at hour 3, indicating a decrease in the optimal spectral output. At hour 4, the spectral output ratio rises again to 90% during the observed period and then slightly decreases to 87% at hour 5.

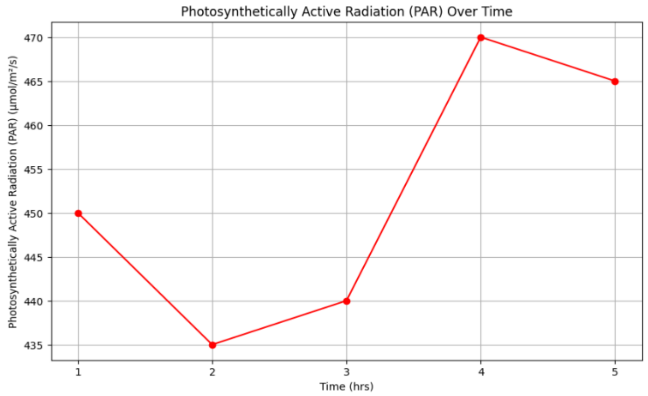

Fig. 4. Photosynthetically Active Radiation

Figure 4 shows the photosynthetically active radiation (PAR) (µmol/m²/s) over five hours. The PAR value at hour 1 is 450 µmol/m²/s, which means a lot of light that should be suitable for photosynthesis. At hour 2, the PAR slightly reduces to 435 µmol/m²/s, indicating a decrease of light intensity. The PAR value drops down to 440 µmol/m²/s in hour 3 of this drop. Regarding PAR, there is a significant increase from hour 3 to hour 4 to 470 µmol/m²/s, which is the highest value for the period of observation. After hour 5, the PAR value is only slightly less high at 465 µmol/m²/s, but it is still high enough. The occurrence of the first down peak followed by an up peak is consistent with adjustments or changes in the LED lighting system to maximize light conditions for plant growth.

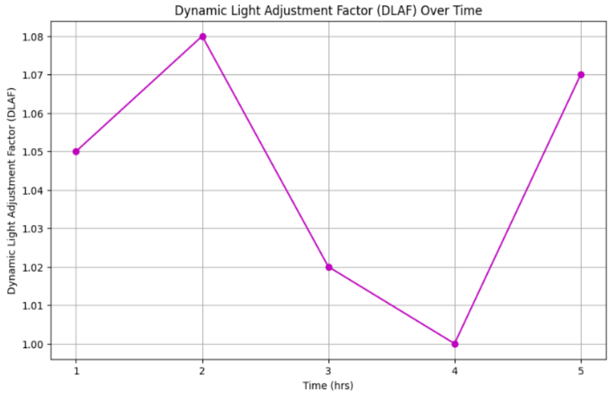

Fig. 5. Dynamic Light Adjustment Factor (DLAF)

Dynamic light adjustment factor (DLAF) over a five-hour daylight period is shown in Figure 5. Time (h: 1 to 5) is on the x-axis, and the values of DLAF (degree of real time adjustment in terms of the degree of real time adjustment of the LED lighting system) are on the y-axis. The DLAF at hour 1 is 1.05, hence a slight increase in light intensity or a correction. The

DLAF reaches 1.08 by hour 2, indicating a further extent of adjustment to the lighting condition. The DLAF continues this trend and slowly decreases to 1.02 at hour 3 with slightly fewer adjustments. The DLAF is 1.00 from hour 3 to 4, and thus, there is no adjustment for that lighting being at baseline. Yet, by hour 5, the DLAF once more increases to 1.07 as an indication of adjusting to the lighting condition again. There are fluctuations in the DLAF displayed in the graph, and these peaks and valleys are also signified throughout time. This indicates that real-time feedback from sensors results in dynamic variations of the lighting system that result in optimal conditions of lighting for the growth of the plant.

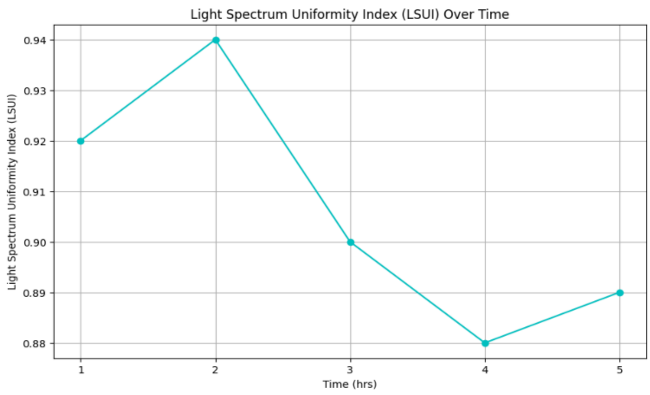

Fig.6. Light Spectrum Uniformity Index (LSUI)

The Light Spectrum Uniformity Index (LSUI) across five hours is positioned in Figure 6. The light spectrum uniformity is 0.92 or high at hour 1. Improvement of uniformity is indicated by a slight increase of the LSUI to 0.94 by hour 2. However, at hour 3, the LSUI decreases from 1.00 to 0.90, which suggests a small reduction of the light distribution evenness. During the observed period, the LSUI drops from hour 3 and down to 0.88 from hour 4, which is its lowest during the period. At hour 5, the LSUI is increasing to 0.89, suggesting partial recovery in the light spectrum uniformity.

5 Conclusion

This investigation shows that LED power consumption varies with time, starting at 180W at hour 1 and climbing to 190W at hour 3 before dropping to 170W by hour 5. The difference in power consumption in this variation suggests that such dynamic adjustments are made to achieve optimal conditions for plant growth. Starting at 85%, the spectral output ratio (an indicator of the quality of the light within optimal wavelengths) reaches 88% by hour 2. Indeed, it first diminishes to 82% at hour 3, achieves a maximum of 90% at hour 4, and remains at 87% at hour 5. However, these fluctuations underscore the need to have high spectral output to support effective photosynthesis. However, these values are crucial for PAR, used by the plant to perform photosynthesis, and vary from 450 μmol/m²/s hour 1, which decreases slightly to 435 μmol/m²/s hour 2, and then increases to 470 μmol/m²/s hour 4, and slightly decreases to 465 μmol/m²/s hour 5. PAR variations are equivalent to the adjustments in light intensity to achieve optimal plant growth conditions. Figures of the DLAF show the process of applying real-time adjustments of between 1.05 through hour 1, peaking at 1.08 by hour 2, reducing to a baseline of 1.00 by hour 4, and then increasing to 1.07 by hour 5. This factor relates to the responsivity of the lighting system to real-time conditions. As shown in terms of the light spectrum, a light spectrum evenness was measured using the LSUI that is starting from 0.92, increasing to 0.94 by hour 2, decreasing to 0.88 by hour 4, and then slightly recovering to 0.89 by hour 5. The fact that LSUI varies demonstrates that similar light distribution is required for uniform plant growth. Future enhancement for the optimization of LED lighting strategies in the vertical farming systems can be implemented by incorporating advanced machine learning algorithms for predictive analysis to make more precise adjustments on system实际时数据. The use of adaptive lighting systems that adapt to the changing health and environmental conditions in plants can do much to increase efficiency. In addition, to achieve better information about the distribution of light spectrum, it is possible to know more comprehensive multi-spectral photosensors. The performance and economical operation could also be improved by exploring energy-efficient LED technologies and further developing robust data communication protocols. Better ways to manage vertical farming environments include automation and remote monitoring that would offer more flexible, scalable management of the environment.

References

1. C. Vatistas, D.D. Avgoustaki, T. Bartzanas, A systematic literature review on controlled-environment agriculture: How vertical farms and greenhouses can influence the sustainability and footprint of urban microclimate with local food production. Atmosphere 13(8), 1258 (2022). https://doi.org/10.3390/atmos13081258
2. F. Manheij, A comparison of two types of light control systems: Open-and closed light control system and their different behaviors (2022)
3. D.C.J. Neo, M.M.X. Ong, Y.Y. Lee, E.J. Teo, Q. Ong, H. Tanoto, V. Suresh, Shaping and tuning lighting conditions in controlled environment agriculture: A review. ACS Agricultural Science & Technology 2(1), 3-16 (2022). https://doi.org/10.1021/acsagscitech.1c00241
4. Q. Wang, J. Dong, Reinforcement learning control of multi-spectral LED systems for rendering optimal lighting performance in an indoor environment. Building and Environment 262, 111811 (2024). https://doi.org/10.1016/j.buildenv.2024.111811
5. J.L. Araus, S.C. Kefauver, O. Vergara-Díaz, A. Gracia-Romero, F.Z. Rezzouk, J. Segarra, J. Bort, Crop phenotyping in a context of global change: What to measure and how to do it. Journal of Integrative Plant Biology 64(2), 592-618 (2022). https://doi.org/10.1111/jipb.13191
6. C.Y. Chen, S.H. Wu, B.W. Huang, C.H. Huang, C.F. Yang, Web-Based Internet of Things on Environmental and Lighting Control and Monitoring System Using Node-RED, MQTT, and Modbus Communications within Embedded Linux Platform. Internet of Things 101305 (2024). https://doi.org/10.1016/j.iot.2024.101305
7. S. Kouah, A. Saighi, M. Ammi, A. Naït Si Mohand, M.I. Kouah, D. Megías, Internet of Things-Based Multi-Agent System for the Control of Smart Street Lighting. Electronics 13(18), 3673 (2024). https://doi.org/10.3390/electronics13183673
8. A.G. Putrada, M. Abdurohman, D. Perdana, H.H. Nuha, Machine learning methods in smart lighting toward achieving user comfort: a survey. IEEE access 10, 45137-45178 (2022). https://doi.org/10.1109/ACCESS.2022.3172213
9. M. Ghiasi, Z. Wang, M. Mehrandezh, R. Paranjape, A Systematic Review of Optimal and Practical Methods in Design, Construction, Control, Energy Management, and Operation of Smart Greenhouses. IEEE Access (2023). https://doi.org/10.1109/ACCESS.2023.3340883
10. R. Paradiso, S. Proietti, Light-quality manipulation to control plant growth and photomorphogenesis in greenhouse horticulture: The state of the art and the opportunities of modern LED systems. Journal of Plant Growth Regulation 41(2), 742-780 (2022). https://doi.org/10.1007/s00344-021-10337-y

11. G.C. Modarelli, R. Paradiso, C. Arena, S. De Pascale, M.C. Van Labeke, High light intensity from blue-red LEDs enhances photosynthetic performance, plant growth, and optical properties of red lettuce in a controlled environment. Horticulturae 8(2), 114 (2022). https://doi.org/10.3390/horticulturae8020114
12. S. Sena, S. Kumari, V. Kumar, A. Husen, Light-Emitting Diode (LED) lights for the improvement of plant performance and production: a comprehensive review. Current Research in Biotechnology 100184 (2024). https://doi.org/10.1016/j.crbiot.2024.100184
13. M. Kent, N.K. Huynh, S. Schiavon, S. Selkowitz, Using support vector machine to detect desk illuminance sensor blockage for closed-loop daylight harvesting. Energy and Buildings 274, 112443 (2022). https://doi.org/10.1016/j.enbuild.2022.112443
14. I. Cappelli, A. Fort, A. Pozzebon, M. Tani, N. Trivellin, V. Vignoli, M. Bruzzi, Autonomous iot monitoring matching spectral artificial light manipulation for horticulture. Sensors 22(11), 4046 (2022). https://doi.org/10.3390/s22114046
15. N. Amalia, D. Hindarto, Enterprise Architecture for Efficient Integration of IoT Lighting System in Smart City Framework. Sinkron: jurnal dan penelitian teknik informatika 8(2), 1091-1099 (2024)
16. J. Schöning, H.J. Pfisterer, Safe and trustful AI for closed-loop control systems. Electronics 12(16), 3489 (2023). https://doi.org/10.3390/electronics12163489
17. E.K. Ruby, G. Amirthayogam, G. Sasi, T. Chitra, A. Choubey, S. Gopalakrishnan, Advanced Image Processing Techniques for Automated Detection of Healthy and Infected Leaves in Agricultural Systems. Mesopotamian Journal of Computer Science 2024, 62-70 (2024)