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Design Implementation of AI-assisted Variable Lighting System for the Optimal Growth of Lactuca sativa 'Olmetie' in a Hydroponic Vertical Indoor Farm

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This study introduces an AI-driven approach to sustainable agriculture by integrating real-time image analysis with adaptive lighting in hydroponic vertical indoor farming (VIF) systems. Focusing on *Lactuca sativa* 'Olmetie', YOLOv11 and EfficientNetV2S models monitored leaf coloration to assess plant health and adjust light intensity accordingly. Trials compared AI-assisted variable lighting with a conventional 16-hour constant setup, measuring shoot length, leaf width, leaf height, fresh weight, dry weight, root length, and leaf count. Under cooler conditions, the AI-assisted system improved growth uniformity and resource efficiency, achieving a fresh weight of 119.62 g, root length of 18.313 cm, and an average of 22 leaves. Findings highlight the potential of AI-integrated lighting to boost productivity and advance sustainable urban farming.

1. Introduction

With rising global food demand and limited arable land, indoor and vertical farming offer year-round cultivation in controlled environments, optimising space and resources, especially when paired with smart technologies like automated lighting and embedded sensors (Dhanaraju et al., 2022). Light strongly influences plant growth, with red and blue LED wavelengths shown to boost chlorophyll, biomass, and antioxidants in lettuce (Amoozgar et al., 2017; Lupo et al., 2022; Pardo G., 2014). Optimal growth is linked to a 16-hour photoperiod and DLI of ~14.4 mol m^{-2} d^{-1} (Pennisi et al., 2020), while excessive exposure can cause oxidative stress (Zha et al., 2019). Alternative regimes such as fluctuating or cyclic lighting have yielded mixed results (Shao et al., 2020), though Warner et al. (2023) found a single 16/8 light-dark cycle maximised yield. Machine learning and automated red-blue lighting have shown promise in vertical hydroponics (Garcillanosa et al., 2023; Dhuri et al., 2023), though often without validated growth data. This study designs a hydroponic VIF with AI-assisted variable lighting that adjusts exposure based on plant health, comparing growth parameters statistically to improve resource efficiency and support autonomous urban food production.

2. Materials and Methods

This study used a quantitative experimental design to explore how an AI-assisted variable lighting system affects the growth of *Lactuca sativa* 'Olmetie' lettuce in a hydroponic VIF system. The research, conducted in Cabuyao, Laguna, Philippines, (14.2491° N, 121.1324° E) had two phases: setting up the system and then deploying the experiment to test the plants' responses to light intensity and how the system performed in different conditions.

2.1 System Overview

The VIF with AI-assisted variable lighting system integrated both hardware and software components to autonomously monitor and adjust lighting conditions. Figure 1 shows the hardware comprises a multi-layered rack (91.44 cm x 68.58 cm x 162.56 cm) with three functional layers and a reservoir layer, insulated with polyethylene foam to minimize external influences. It utilizes a Nutrient Film Technique (NFT) for consistent water and nutrient delivery, circulated by a 60 W submersible pump from a 30L reservoir. LED lighting is crucial,

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with two panels per functional layer, each containing 16 LEDs (12 red, 4 blue) in a 3R:1B ratio, positioned 17 cm above the channels. Six 12 V fans ensure continuous air exchange. A sensor network includes DHT11 humidity and temperature sensors in each layer and three 1080p webcams for crop monitoring.

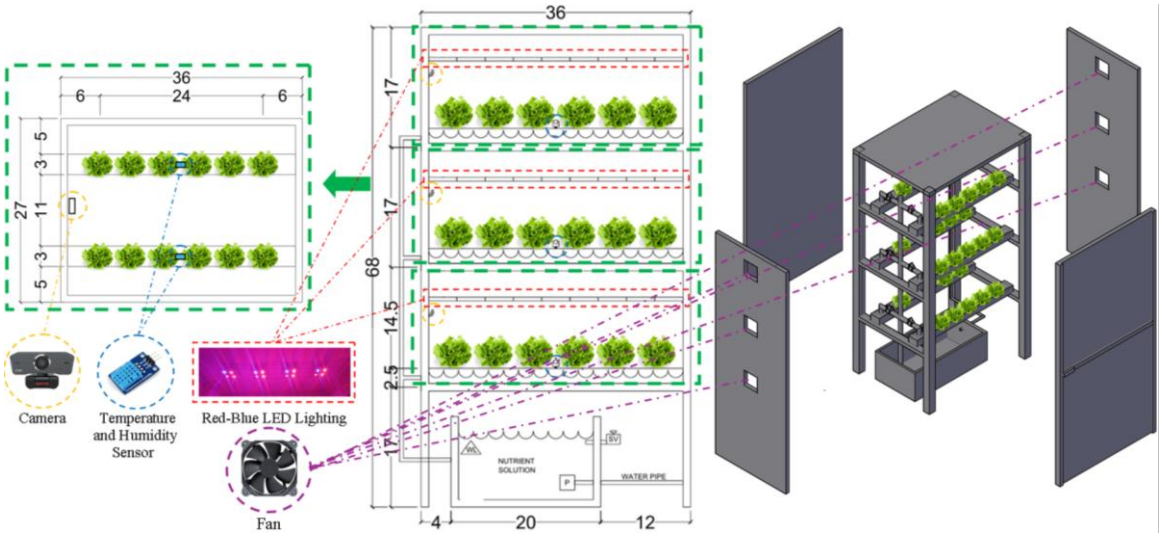

Figure 1: Top, front, and exploded view of the system

On the software side, the system uses an AI-assisted variable lighting logic that dynamically modifies light levels based on crop health and environmental factors. Data is collected at specific times (6:00 AM, 11:20 AM, 4:40 PM, 10:00 PM Manila time). The image processing pipeline involves YOLOv11 for detecting lettuce instances and EfficientNetV2S for classifying their health as healthy, unhealthy, or null. Confidence Weighted Majority Voting (CWMV) was used to determine the overall health status of crops within a layer. Temperature and humidity data from DHT11 sensors are categorized (e.g., humidity: Low, Optimal, High; temperature: Low, Optimal, High). These categorized inputs then feed into a dictionary-based LED output map to determine the appropriate light intensity (see Figure 2 and Table 1 and 2).

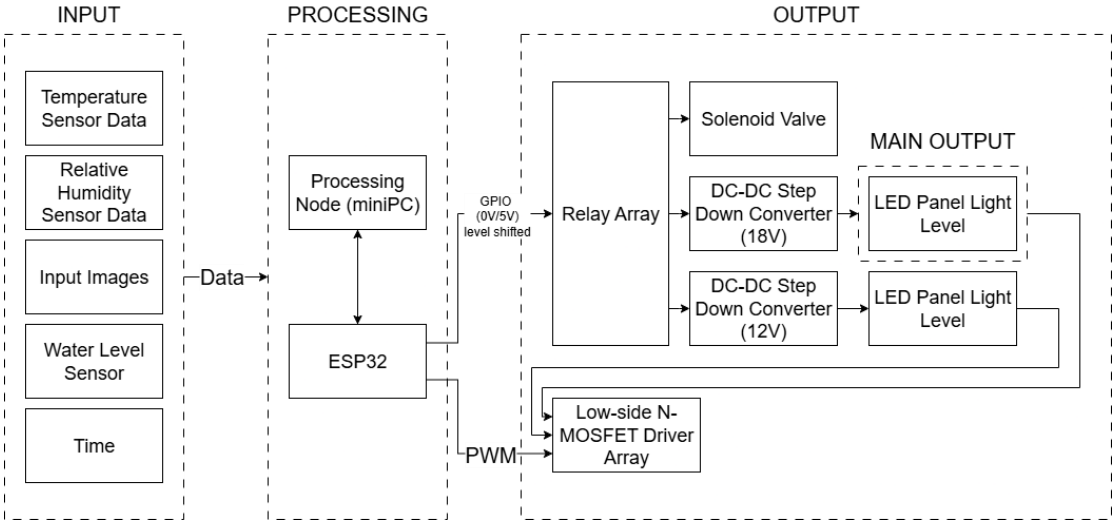

Figure 2: IPO framework of the system

Table 1: Humidity and Temperature Thresholds

Humidity		Temperature	
Low	< 60 % RH	Low	< 20 °C
Optimal	60 % – 85 % RH	Optimal	20 °C – 26 °C
High	> 85 % RH	High	> 26 °C

Table 2: LED Output Map (Dictionary)

Humidity	Temperature	Image	LED Status
Low	Cold	Healthy	Medium
Low	Cold	Unhealthy	High
Low	Normal	Healthy	Medium
Low	Normal	Unhealthy	High
Low	Hot	Healthy	Low
Low	Hot	Unhealthy	Medium
Medium	Cold	Healthy	Low
Medium	Cold	Unhealthy	Medium
Medium	Normal	Healthy	Low
Medium	Normal	Unhealthy	Medium
Medium	Hot	Healthy	Low
Medium	Hot	Unhealthy	Medium
High	Cold	Healthy	Low
High	Cold	Unhealthy	Medium
High	Normal	Healthy	Low
High	Normal	Unhealthy	Medium
High	Hot	Healthy	Low
High	Hot	Unhealthy	Medium

2.2 Preliminary Setup and Data Gathering

Lactuca sativa 'Olmetie' seedlings were germinated in cocopeat for 7–14 days under a 16-hour white LED cycle, transferred to styrofoam cups on Day 8, and transplanted on Day 14 into a vertical hydroponic system disinfected with 3 % hydrogen peroxide. The initial experiment grew 36 crops (six per channel) using a SNAP solution (25 mL SNAP A + 25 mL SNAP B per 10 L water) with pH ~6.2 and EC 1900 µS/cm, containing Ca, N, K, P, S, Mg, Fe, Mn, B, Zn, Cu, Cl, and Mo. DHT11 sensors continuously monitored temperature and humidity to ensure identical conditions for control and AI-assisted groups. The first deployment had two AI-assisted lighting layers and one constant-light control layer (16-hr constant lighting). A second deployment of 18 crops (three per channel) followed the same protocol to reduce leaf occlusion and improve image classification. Weekly measurements were taken, and dry weight was determined post-harvest by oven-drying (La Germania kitchen oven) at 65 °C for 4 hours periodically checking whether it was crispy or crumbly and was returned if it retained moisture.

2.3 Overview of AI Model

To optimize the growth of *Lactuca sativa* 'Olmetie', the AI-assisted lighting system uses two convolutional neural networks. YOLOv11 handles object detection, chosen for its faster inference time of 13.5 ms compared to YOLOv8's 23 ms. EfficientNetV2S is used for health classification, as it's faster and more resource-efficient than other models. The YOLOv11 model was trained on 841 images containing 1,920 lettuce instances. The images were resized to 720x720 px and augmented. The dataset was split into 70% for training, 20% for validation, and 10% for testing. The training was done on a Google Colab NVIDIA Tesla T4 GPU for 100 epochs, which took 1.325 hours. The batch size was 16, and the learning rate was 0.002.

YOLOv11 achieved strong results: 0.927 precision, 0.864 recall, 0.947 mAP50, 0.786 mAP50-95, and an F1 score of 0.894. However, the model mislabelled 100 % of backgrounds as lettuce, prompting the addition of a 'null' class in the classification stage to eliminate false positives (Meyen et al., 2021). Table 3 presents the lettuce detection performance of the YOLOv11 model.

Table 3: Confusion Matrix of YOLOv11 Model for Lettuce Detection

		Predicted	
		Lettuce	Background
True	Lettuce	0.91	0.09
	Background	1.00	0.00

2.4 Statistical Treatment

The study used a T-Test to determine if significant differences existed between the growth parameters of the AI-assisted and control groups. To account for multiple comparisons, a Bonferroni correction adjusted the

significance threshold from 0.05 to 0.00714 (0.05 ÷ 7 parameters). Statistical analysis was done in Microsoft Excel using =T.TEST(Array1, Array2,2,3), where Array1 contained AI-assisted data and Array2 contained control data. A two-tailed distribution ('2') and Welch's T-Test ('3') were applied due to unequal sample sizes.

3. Results and Discussion

3.1 First Deployment

The first deployment (April 19–May 24, 2025) implemented AI-assisted lighting, adjusting intensity every 5 hours 20 minutes based on leaf colour feedback, with expanded LED coverage for better light distribution. As shown in Table 4, the model achieved moderate accuracy, correctly classifying 7 healthy and 5 unhealthy samples but misclassifying 6 healthy as unhealthy, 3 unhealthy as healthy, and missing 3 healthy samples. These errors were likely due to internal reflections and limited plant spacing. Overall, performance metrics showed precision at 0.577, recall at 0.511, F1-score at 0.530, accuracy at 50 %, and specificity at 0.633, indicating only average detection capability.

Table 4: Confusion Matrix for First Deployment

		Predicted		
		Healthy	Unhealthy	Null
True	Healthy	7	6	2
	Unhealthy	3	5	1
	Null	0	0	0

Table 5 compares post-harvest averages between control samples (16-hour constant lighting) and AI-assisted variable lighting, showing generally better performance under AI-assisted conditions. However, weekly growth patterns suggest that high ambient temperatures (avg. 32.44 °C) caused physiological stress and inhibited growth. Despite effective light optimisation, the absence of full climate control (e.g., HVAC) limited mitigation of heat-related stress. Studies by Roeber et al. (2022) and Zha et al. (2019) similarly note that high temperatures and excess light can induce oxidative stress, reduce photosynthesis and temporarily stunt growth.

Table 5: Average Growth Parameter Values of AI-Assisted vs. Control for First Deployment

Parameter	AI-Assisted	Control
Shoot Length	9.51569 cm	8.6346 cm
Leaf Width	3.5680 cm	3.3117 cm
Leaf Height	7.6993 cm	7.2858 cm
Fresh Weight	95.83875 g	84.072 g
Dry Weight	6.747 g	6.050 g
Root Length	15.2216 cm	13.113 cm
Leaf Count	13	11.42

3.2 Second Deployment

In the second deployment (May 31 to July 5, 2025), the same AI-assisted system was used under cooler conditions (~29.58 °C), which led to more consistent and uniform plant growth. The confusion matrix in Table 6 indicates moderate model performance, with 4 healthy and 3 unhealthy samples correctly identified. Although misclassifications persisted, their absolute numbers were lower compared to earlier tests, and only one unhealthy sample went undetected. The model achieved a precision of 0.65 and recall of 0.625, leading to an F1-score of 0.6076, which reflects relatively balanced detection. The overall accuracy of 58.33 % suggests fair classification ability, while the specificity of 0.75 indicates a reasonable capacity to correctly identify negative cases.

Table 6: Confusion Matrix for Second Deployment

		Predicted		
		Healthy	Unhealthy	Null
True	Healthy	4	3	1
	Unhealthy	1	3	0
	Null	0	0	0

Table 7 shows that AI-assisted variable lighting produced improved and more uniform growth than the first deployment, aided by cooler ambient temperatures that created favourable conditions. Post-harvest parameters were slightly higher and more consistent across layers, with steady weekly growth linked to optimal light exposure and cooler conditions. The red-blue LED spectra with scheduled variation enhanced productivity and chlorophyll levels (Nájera et al., 2022), while the consistent 16-hour photoperiod and moderate Daily Light Integral (DLI) matched Warner et al. (2023), who found these settings maximised yield without causing photooxidative stress.

Table 7: Average Growth Parameter Values of AI-Assisted vs. Control for Second Deployment

Parameter	AI-Assisted	Control
Shoot Length	8.0103 cm	7.5342 cm
Leaf Width	6.4177 cm	5.9444 cm
Leaf Height	4.8214 cm	4.5178 cm
Fresh Weight	119.62 g	110.5 g
Dry Weight	8.3125 g	7.8783 g
Root Length	18.313 cm	15.63 cm
Leaf Count	22	19

The AI model's dynamic light adjustments allowed for fine-tuned energy distribution during plant development, supporting stable biomass accumulation. The acquisition of dry weight was adopted from the paper of Zha et al. (2019), which used *Lactuca sativa* L. 'Yidali' for their study. Studies by Kong and Nemali (2023) and Nur Syafini et al. (2022) further validate that variable lighting, especially with increased blue light in later growth stages, enhances vegetative growth, phytochemical density, antioxidant levels, and total chlorophyll content.

3.3 T-test Result

T-Test analysis together with the Bonferroni Threshold in Tables 8 and 9 were conducted to determine the statistical significance of AI-assisted lighting on growth parameters. In Deployment 1, root length and fresh weight showed significant differences; while in Deployment 2, only root length was statistically significant.

Table 8: T-Test Results for Deployment 1

Parameter	p-Value	Bonferroni Threshold	Verdict
Shoot Length	0.0316		Not Significant
Leaf Width	0.0171		Not Significant
Leaf Height	0.1919		Not Significant
Fresh Weight	0.0005	0.00714	Significant
Dry Weight	0.0006		Significant
Root Length	0.0393		Not Significant
Leaf Count	0.0174		Not Significant

Table 9: T-Test Results for Deployment 2

Parameter	p-Value	Bonferroni Threshold	Verdict
Shoot Length	0.0316		Not Significant
Leaf Width	0.0171		Not Significant
Leaf Height	0.1919		Not Significant
Fresh Weight	0.0005	0.00714	Significant
Dry Weight	0.0006		Significant
Root Length	0.0393		Not Significant
Leaf Count	0.0174		Not Significant

3.4 Resource Efficiency

The system consumed 92.4 kWh of electricity and 0.0875 m^3 of distilled water per deployment. Potential savings could be achieved by using treated tap water. The VIF's vertical design also allowed for efficient use of space, suitable for residential or small-scale urban farming. Additionally, the system's design allows for future expansion with three more layers and increased planting channels, maximizing cultivation capacity.

4. Conclusion

This study demonstrates the potential of AI-assisted variable lighting in improving the growth of *Lactuca sativa* 'Olmetie' in hydroponic vertical indoor farming systems. While the system showed significant improvements in root length and fresh weight over constant lighting, the lettuce classification accuracy was limited by environmental factors like internal reflections and tight plant spacing. Environmental conditions, particularly high temperatures, also affected plant performance, highlighting the need for better climate control. Despite these challenges, the system proved water and space-efficient, and viable for small-scale or urban indoor farming.
To enhance its effectiveness, future research should incorporate total climate control systems and improve energy efficiency to reduce costs. Adding more channels, using safer electrical connections, and testing other leafy greens are also recommended to broaden its application and improve scalability.

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