CHEMICAL ENGINEERING TRANSACTIONS

VOL. 106, 2023

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Peck Loo Kiew, Hon Huin Chin

ISBN 979-12-81206-05-2; **ISSN** 2283-9216

DOI: 10.3303/CET23106090

Efficient and Low-Cost Method of Smart Indoor Vertical Farming for *Lactuca sativa L.* with Machine Learning

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Indoor farming is a good alternative farming technique especially in urban areas which lacks an arable land and space for growing crops. Since indoor farming uses artificial environment, it faces many difficulties such as getting the right amount of water, light, temperature, and humidity that are required by crops. These factors highly affect the proper growth and development of crops, its quality, and the output yield. There are existing indoor vertical farming facilities that can mimic the natural environment but don't address the efficiency and cost of the overall system. In this study, an existing indoor vertical farming was modified by designing a low-cost smart monitoring and control system that uses machine learning technique to autonomously control the actuators such as the cooling fans, water valve, and LED lights based on the following descriptors: temperature, humidity, soil moisture level, and the health status of the *Lactuca sativa L.* or commonly known as lettuce. The modified system achieved a better growth compared to the traditional method. The height, length and width of the lettuce is found to be better by 20 % and the color of the system's output is greener than the usual. The cost incurred is 54 % and 19 % cheaper with regards to the energy consumption and the water consumption.

1. Introduction

Agricultural development is one of the most powerful tools to end extreme poverty, boost shared prosperity, and feed a projected 9.7 billion people by 2050 (World Bank, 2022). One way to partake in this development is through the implementation of modern agriculture such as vertical farming in urban areas which lacks arable land. A study about vertical farming to decrease the land required for growing agricultural products has been proposed by Pimentel and Friedler (2022). It's proposed method relies on the P-graph framework which permits the identification of the n-best alternatives for the system's design. In addition, their previous study is about energy integration for vertical farms to achieve higher efficiency and sustainability (Pimentel et al., 2021). The study resulted into 115 integrated process alternatives with the best structure exhibiting a total cost of 41, 920 EUR/y. Other methods of vertical farming have been reported such as the net-zero energy designs for indoor farming facilities, but it is not cost-effective for US climates (Engler and Krarti, 2022). The paper of Carrasco et al. (2022) reported that vertical farming, combined with intelligent control strategies and monitoring systems, increases productivity, and ensures production sustainability. Indoor urban vertical farming is said to be much more profitable for investors, saving significant resources compared to greenhouse farming (Avgoustaki and Xydis, 2020). The focus of their studies is about the large-scale implementation of vertical farming in non-tropical countries. This study will be focusing on the implementation of indoor vertical farming for small urban residential area specifically here in the Philippines which has one of the most vulnerable agricultural systems in the world (Agritecture, 2021). The study will highlight the artificial environment with the use of machine learning, the implementation of the structure, and its cost. Specifically, the design is an autonomous indoor vertical farming for *Lactuca sativa L.* or loose-leaf type of lettuce. Temperature and humidity, soil moisture, and the health status of the crop were used to train the model. The model was eventually used to autonomously trigger the actuators. Since a specific plant was used in the study, other kind of crops or plants might not be applicable in the system.

Paper Received: 20 April 2023; Revised: 09 July 2023; Accepted: 20 July 2023
Please cite this article as: Garcillanosa M.M., Batino Jr. Z.M., Gabuyo E.A., Mojica T.L., Mundo M.A.D., Impelido D.G., Sison M.P.A.A., 2023, Efficient and Low-Cost Method of Smart Indoor Vertical Farming for Lactuca sativa L. with Machine Learning, Chemical Engineering Transactions, 106, 535-540 DOI:10.3303/CET23106090

2. Materials and methods

2.1 Hardware implementation

The illustrations of the hardware implementation of the system and the actual prototype are shown in Figure 1a and 1b. It consists of the following: indoor vertical rack, smart water system, exhaust and cooling fan, sensors, and the artificial lights. Humidity and temperature sensor, and soil moisture sensor were placed and installed in the rack. The bottom layer was for the tank of the water system and the three remaining layers were allotted for the lettuces' soil bed. The uppermost layer is the Layer 1 and the lowermost is the Layer 4 in this design. The water pipes were located at the left side of the rack while the wirings are at the right side of the rack. The spacing of lettuce was four inches away from each other to avoid competition for light and soil nutrients.

The hardware implementation of the system was composed of the following:

- Indoor vertical rack was built using angle bar or L-bracket, it is a metal in the form of a right angle. It is often used to support beams and other platforms to provide stability. It was considered in the design to provide strength and corrosion resistance. Its strength is good for the load of the indoor vertical rack since it cannot be easily bend or deform. It was also painted to reduce corrosion. Steel rack was chosen instead of aluminum because of its strength, and it is low-cost.
- Smart water system was implemented in a form of subsurface drip irrigation since it is 90 % to 95 % efficient in water management and conservation (Mo et al., 2020) and can be good for small area like indoor farming. It was consisted of two kinds of pipe which were the water pipe and soaker hose. Water pipe is responsible to deliver the required supply of water, while the soaker hose is supposed to send back the excess water from the soaker hose to the tank so to avoid water damming at the right side of each layer.
- Exhaust and cooling fan has been installed in the uppermost layers, Layer 1 and 2. The cooling fan was placed at the left side of each layer 1 and 2, while the exhaust fan was installed at the left side of layer 1 which is three inches away from the top. The purpose of installing a cooling fan and exhaust fan was to control the temperature, humidity, and airflow of the vertical rack. This ensured the reduction of mold, pathogens, and fungi development on the lettuce.
- Humidity and temperature, and soil moisture sensor. The humidity and temperature, and soil moisture sensors were installed after filling layer 1, 2, and 3 of the pre-cultivated soil. DHT22, a basic and low-cost digital temperature and humidity sensor were placed at the top right side of the rack, forty-six inches from the ground of the vertical rack and four inches away from the LED lights since long time exposure to strong light may degrade the sensor's performance. On the other hand, SPM30421S soil moisture sensor module for Arduino was placed in the soil for each lettuce-growing layer (layers 1-3).
- Artificial light**.** A board with a ratio of thirty by thirty red and blue industrial series LEDs strip were built, the size of the board was ten inches wide and thirty-four inches long. LED strip was used since it consumes less power compared to other artificial lighting. The red and blue LED lights with wavelengths 660 nm and 470 nm respectively were used since it increases the phenolic accumulation in the lettuce plant (Yan et al., 2020) and improves photosynthesis. A twelve inches distance was used for the lettuce spacing from the LED lights to let it grow and develop properly and to avoid destruction of the plant since too near artificial light may damage the leaves because of the heat.

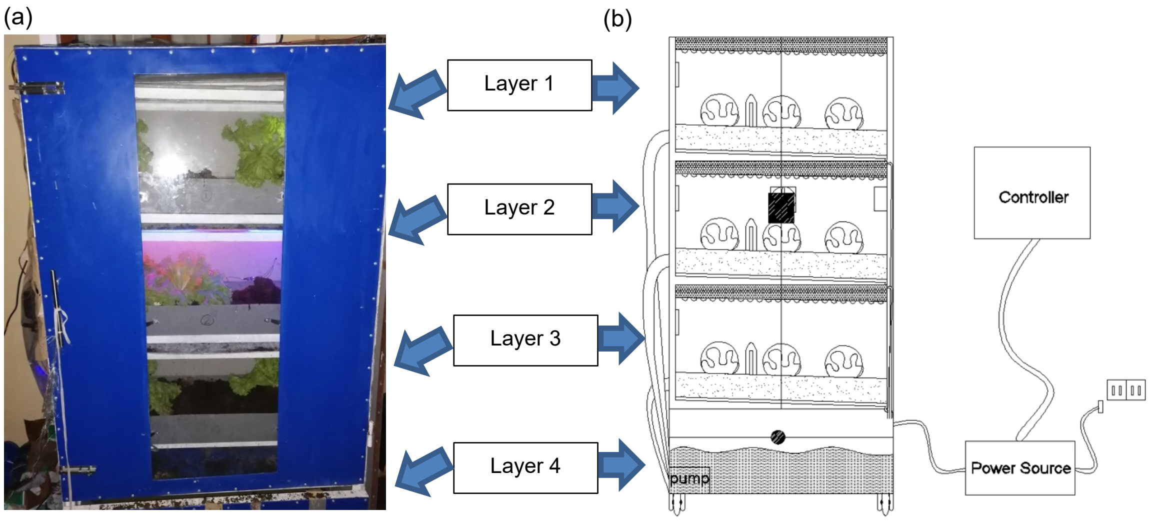

Figure 1: (a) actual implementation (front view), (b) illustration of the hardware implementation of the system

2.2 Data collection

Figure 2a is the process flow for the generation of training datasets that lasted for about three months, while Figure 2b is the type of data that were recorded during the data collection. That is, the group planted and grew healthy lettuce in the indoor vertical farm as seen in Figure 1 above. The sensors deployed in the system gathered the initial data for the temperature, humidity, soil moisture, and health classification of the lettuce planted in an indoor vertical farm using artificial environment. Health classification determines the condition of the lettuce based on its physical characteristics -Raspberry-pi camera was used as the input parameter to this factor. To begin with, the temperature was set to 28 °C (maximum), soil moisture level to 250 (maximum), and LED exposure to 12 hrs. from 6:00 am to 6:00 pm. These initial settings were considered based from the initial result from growing indoor vertical farming of lettuce without machine learning. Comparing it to conventional farming, the height of the lettuce is found to be bigger by 15 % and the color of the system's output is greener than the usual. Exhaust fan remained on during the whole three-month duration to maintain the airflow inside the system. Cooling fan and solenoid valve was turned-on only when the temperature rises the maximum setting, and the soil moisture level is increasing in value. The health classification is the input of the artificial lighting, the LED will be turned-off if based on its classification the lettuce is healthy, otherwise, the LED will be turned-on and will automatically be set to the minimum exposure of 12 h. Manual intervention has been done to adjust some of the parameters if based on the visual checking the lettuce needs more water, light, or generally unhealthy. The capture time of the data was set to every five minutes to obtain enough number of datasets to be trained. The recordings include the following: timestamp, temperature, humidity, soil moistures, cooling fans, and valves. The readings from the sensors and actuators were captured by the Arduino mega and stored in the raspberry-pi microcontroller. The acquired dataset that amounted to about 18,946 for three-month duration was then used to train the model using decision tree algorithm.

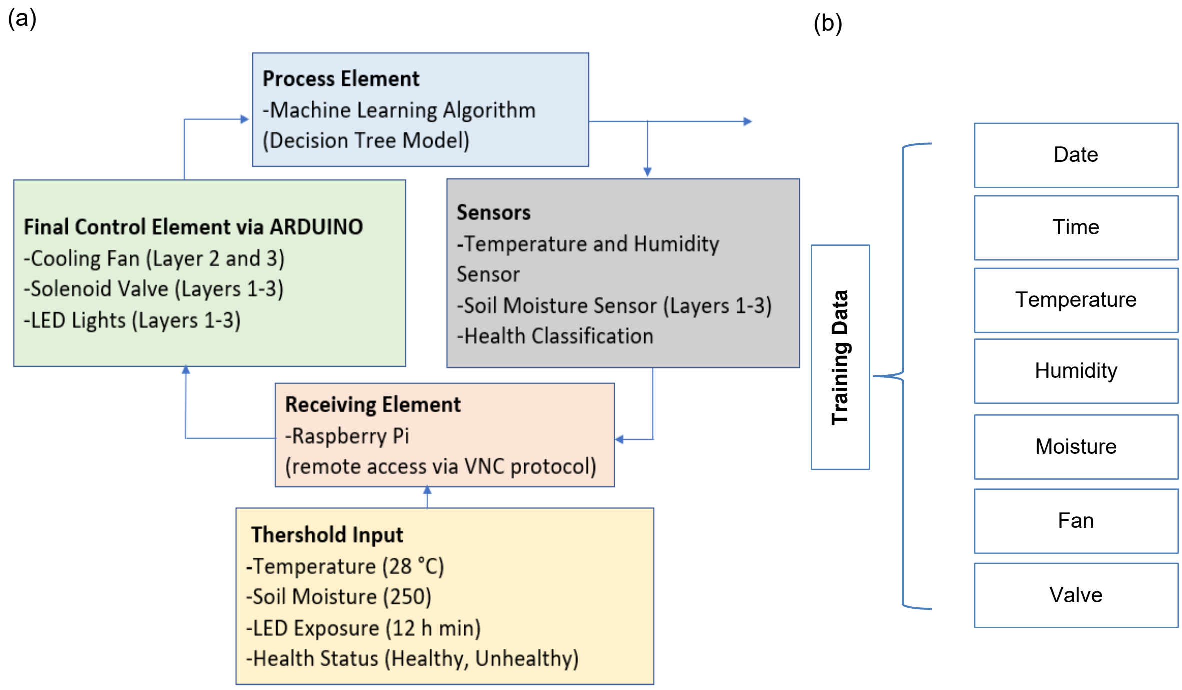

Figure 2: (a) Process flow for the gathering of datasets, (b) type of data that were recorded

2.3 Data training

The acquired datasets of about 18, 946 was used to train the model using decision tree algorithm. The temperature setting was set to a maximum of 28 °C to actuate the cooling fans. The exhaust fan remained "on" since its operation does not depend on the temperature setting. The LED lights on the other hand was set to 12 h and its operation is dependent on the trained datasets for the health classification in which the goal was to check whether the lettuce at a particular layer was healthy or not. The capture time of data and response of actuators remained to every five minutes except for the LED which was set to read every hour. New results was acquired which was equivalent to 8,613 data points. The average results for the data collection and data training are shown in Table 1.

Table 1: Data collection results (18,946 data points) vs. data training results (8,613 data points)

Data Collection Results			Data Training Results		
Temperature (Ave.)	Humidity (Ave)	Soil Moisture (Ave.)	Temperature (Ave.)	Humidity (Ave.)	Soil Moisture (Ave.)
29 °C	88.9 %	Layer 1: 136 Layer 2: 136 Layer 3: 136	29.2 °C	88.9 %	Layer 1: 112 Layer 2: 229 Layer 3: 60

3. Results and discussions

3.1 Validation test

Lettuce was planted and grown for about four times in this study. The first one used the smart autonomous system without machine learning, in this stage the initial settings and parameters for humidity, temperature, and soil moisture were gathered. The second time was when the system was run with the inclusion of health status. All the results from the sensors and actuators were monitored and recorded -this was the data collection part as discussed in Section 2.2. The third time was when the model was trained using the data gathered from the second planting, this part was also discussed in Section 2.3. The last and the fourth time was for the testing and validating of the result using the generated model that was implemented in a fully autonomous system.

The lettuce took about six weeks before harvest during the second planting. During the third and fourth planting, it was reduced to four weeks only upon the recommendation of the licensed Agriculturist. This reduced harvest time was due to the implementation of artificial environment through sensors and actuators operating through the learned model.

It is evident in Figure 3 that the final output of the lettuce has improved in terms of the number of weeks it takes before harvest as seen in the fourth planting during the validation part. It was in this stage where the system is autonomously working using the trained model. Measurements were made in terms of length, width, and height, of the lettuce. The measurement of height as seen in Figure 4a was from the soil top to the tip of lettuce head; the length of leaves was measured from stalk to tip as seen in Figure 4b; and the width of leaves was measured from the widest part of the leaf. Table 2 shows the comparison of the measured parameters. These measured parameters as seen in Table 2 are based on the average results for the length, width, and height of the nine lettuces in the vertical rack.

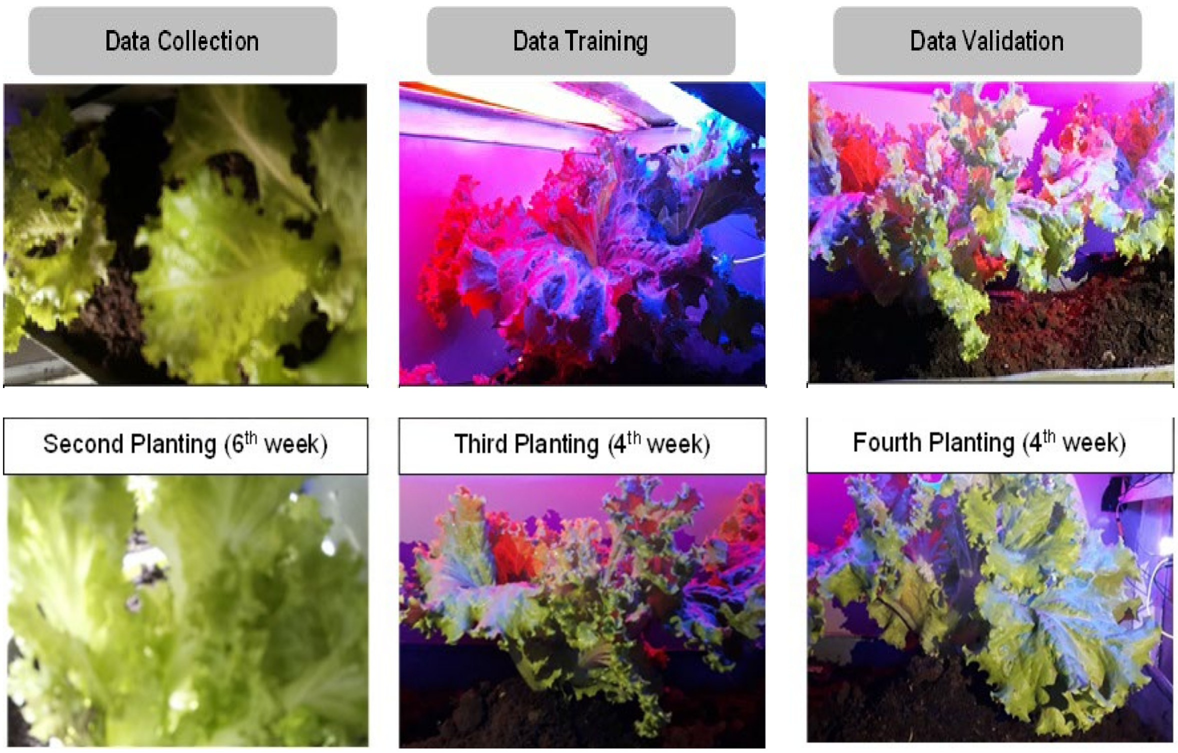

Figure 3: Images of the growth of lettuce during the 6th and 4th week of the second, third and fourth planting

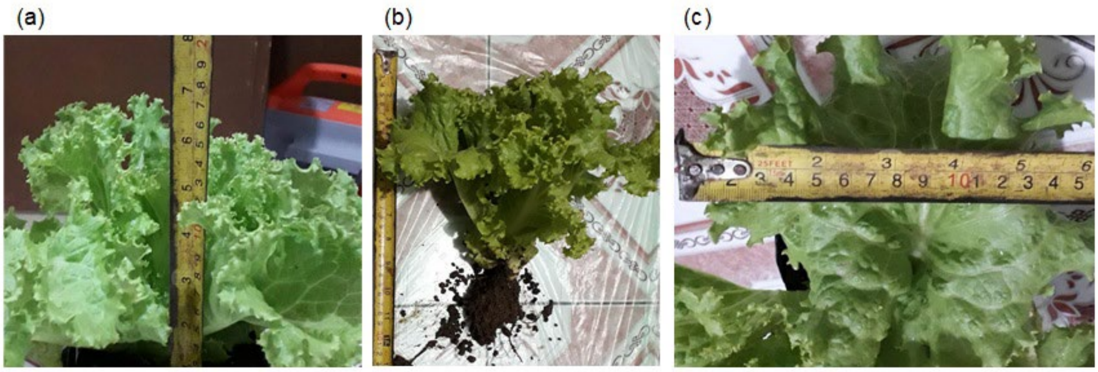

Figure 4: (a) measurement of height, (b) measurement of length, (c) measurement of width

Table 2: Comparison of lettuce's size from the old system vs. the proposed system

	Length (cm)	Width (cm)	Height (cm)
Old System*	20.50	14.50	19.90
Proposed System**	25.70	18.80	25.70

*without machine learning algorithm; **with machine learning algorithm

The sizes of the harvested lettuce were also measured and compared for the old system versus the proposed system. Figure 5a, 5b, and 5c show the comparison for height, length, and width. The yellow line represents the graph of the lettuce growth for the old system while the blue line represents the lettuce growth of the proposed system. It can be seen in Figure 5a that both systems have an increasing trend in terms of height and the only difference is the reduced harvest time for the proposed system, which is only 30 days, while the old system have longer harvest time of 45 days. In terms of length, the proposed system proves to be superior since it has longer leaves in the span of thirty days only. Length measurements of the proposed system increased almost two times versus the old system as shown in Figure 5b. In terms of width, the measurement of the proposed system at the 30th day has an increase of 22 %. Overall, the proposed system got positive results in terms of length and height to about two times better compared to the old system, while the width increased to almost five times. Thus, implementing the new system made a huge impact on the overall size and harvest time of the lettuce.

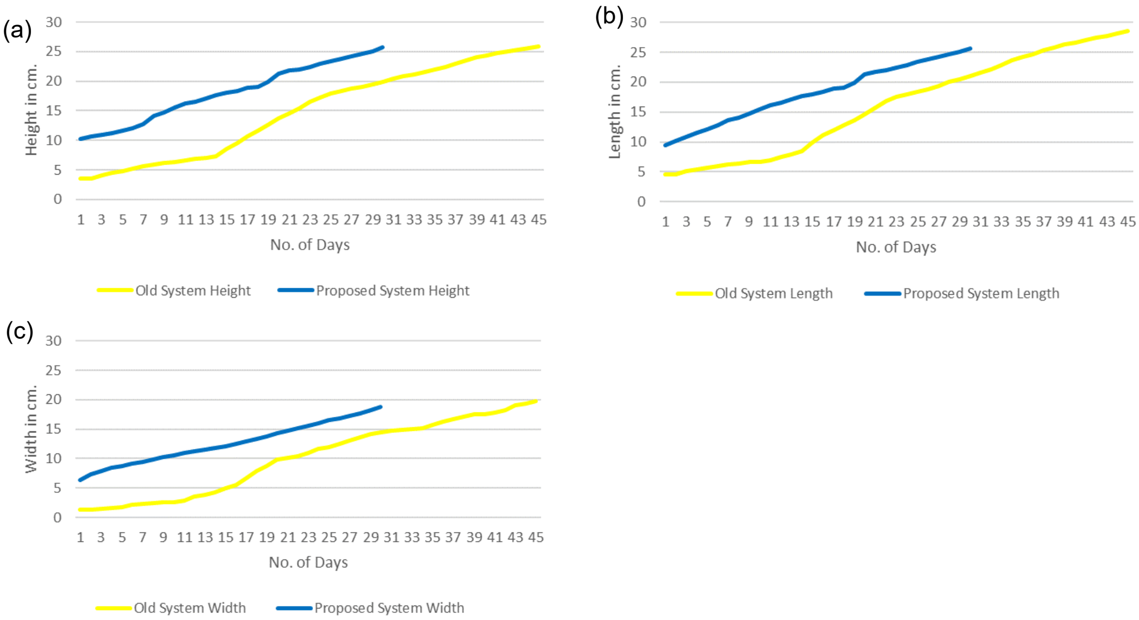

Figure 5: Comparative results of (a) height, (b) length, and (c) width for the old system vs. the proposed system

3.2 Water and energy consumption

The electric rate at the time of the study was 0.15 USD/kWh and the system consumed about 26 kWh only, to which resulted to a total consumption of 3.90 USD for the electric bill. For a month-long water consumption, the system consumed 28.50 L of water which is equivalent to 6.04 USD for a water rate of 2.12 USD per 10 m^3. These values were achieved through the rate given by the Maynilad and Meralco, Philippine's local water service and electric power distribution company respectively. The design is composed of three seed rack only with three lettuce per rack. The design is small but gives a promising result for those who want to have their own indoor vertical farming at a very minimal cost. Comparing it to "The Wall Farm Indoor Vertical Garden" by Click and Grow (Dwell, 2019) which costs about 3,095.95 USD and consumes 57.6 USD kWh/mth of electricity and 35 L of water a month, our proposed design is way much cheaper of about 54 % and 19 % for electricity and water usage.

4. Conclusions

Smart indoor vertical farming for *Lactuca sativa L.* using machine learning has been implemented with promising results. The lettuce length, width and height are better by 20 % and the harvest time was reduced from 45 d to 30 d only. The cost incurred for electricity and water consumption was cheaper compared to the sophisticated vertical indoor farm in the market today. The total cost of the system including the sensors, actuators, cameras, and microcontrollers is only 353.00 USD while the one available in the market today is 3,095.95 USD. The good result proves that the proposed system is possible for Philippine settings where the weather is mostly humid and hot. With these, organic farming of salad greens using indoor vertical method is feasible even in a humid environment with limited sunlight. In addition, this study could be a reference of entrepreneurs here in the Philippines who wish to shift from traditional farming to AI-based vertical farming of *Lactuca sativa L*. Implementing the indoor vertical farming with artificial environment through machine learning made a significant impact on the lettuce size in terms of its length, width and height, its harvest time, and the total cost of the system.

Acknowledgments

This work has been supported by the Electronics Engineering Department of Mapúa Malayan Colleges Laguna, Cabuyao City, Laguna, Philippines 4025.

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