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Fuzzy Logic-Based Hydroponic Vertical Farming System Using UVC for Pathogen and Pest Control

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Abstract: *Vertical farming using a hydroponics system is a soilless cultivation farming method, in which plants are grown in nutrient-rich water. Industry's most significant problem in recirculating systems is the possibility of the rapid development of microorganisms leading to nutrient-deficient plants. This paper proposes an ultraviolet C (UVC) for water disinfection and yellow sticky traps for this indoor proposed pest control system. The proposed system implements fuzzy logic through an Arduino microcontroller to handle the decision-making and improve monitoring and control of cultivation parameters. The test species used for the experiments is lettuce. Results showed that the proposed system has a higher shoot, root, total biomass, and lower root mass ratio (p<0.05) and had fewer pest infestations than the standard system. This system helps promote chemical-free pathogen and pest control, thereby improving cultivation and plant growth parameters.*

Keywords: Fuzzy logic, Hydroponics, Arduino Mega 2560, UVC, Pathogens

1. INTRODUCTION

In response to rapid global population growth, which increased from 7.0 billion and was projected to reach 9.5 billion within four decades, researchers emphasized the need to double food production to meet rising demands [1,2]. Traditional agriculture, heavily reliant on soil and land availability, faced constraints due to urbanization, climate change, and declining arable land [3,4]. To address these limitations, hydroponic vertical farming emerged as a promising alternative. This method utilized soilless cultivation techniques in stacked or multi-level structures, often integrated within controlled indoor environments [5,6]. These systems enabled the regulation of environmental factors such as light, temperature, humidity, and nutrient levels to enhance plant productivity and resource efficiency [7,8]. Hydroponics allowed crops to grow in water enriched with essential minerals, eliminating the dependency on soil while maintaining or exceeding traditional yield levels [9,10]. However, challenges persisted in vertical hydroponics, particularly the formation of biofilms—aggregates of microorganisms including bacteria and fungi—that thrived in moist environments and threatened plant health [15,16]. These biofilms not only reduced productivity but also introduced risks to human health due to the pathogens they harbored [17]. Prior studies demonstrated that ultraviolet C (UV-C) light, especially within the 200–280 nm wavelength range, had a strong germicidal effect and effectively inhibited microbial growth [18].

Automation also played a crucial role in improving hydroponic systems. Using fuzzy logic-based controllers, researchers successfully monitored and regulated key parameters such as pH, electrical conductivity (EC), temperature, and humidity [13,14]. Automation reduced the labor burden while ensuring consistent and optimal growing conditions. For pest control, integrated solutions like yellow sticky traps and UV-C disinfection offered safer alternatives to chemical pesticides.

This study presented a Fuzzy Logic-Based Hydroponic Vertical Farming System with UVC for Pathogen and Pest Control, designed to address the absence of automated crop damage monitoring in conventional systems. The research aimed to demonstrate improved performance in cultivation management, disinfection efficiency, and pest control compared to standard setups. The prototype, based on an Arduino Mega 2560 platform, was tested using Estrosa lettuce. It featured automated monitoring of environmental conditions and incorporated visual and email notifications. The integration of UVC light targeted microbial pathogens, while yellow sticky traps controlled flying pests.

By leveraging advanced automation and disinfection technologies, this study contributed to the development of more resilient and sustainable agricultural systems. It also supported broader objectives such as reducing pesticide use, increasing food output, and enhancing the efficiency of land and water resources—goals aligned with the initiatives of government agencies like the Department of Agriculture.

2. MATERIALS AND METHODS

2.1 System Overview

The fabricated hydroponic system in this study employed the Nutrient Film Technique (NFT), a widely used method known for its simplicity and high yield, especially suitable for leafy greens like lettuce. Two automated setups were developed for comparison. The first setup was the proposed fuzzy logic-based vertical hydroponic system, which incorporated ultraviolet-C (UVC) light for pathogen and pest control. This system automatically regulated nutrient and pH levels through fuzzy logic, controlled air temperature using exhaust and inlet fans, and used grow lights to simulate sunlight.

UVC treatment was applied to disinfect the water in the reservoir.
The second setup represented a standard outdoor hydroponic system, placed in a greenhouse made of farm nets. While also automated, it only regulated nutrient and pH levels without advanced disinfection or climate control features.

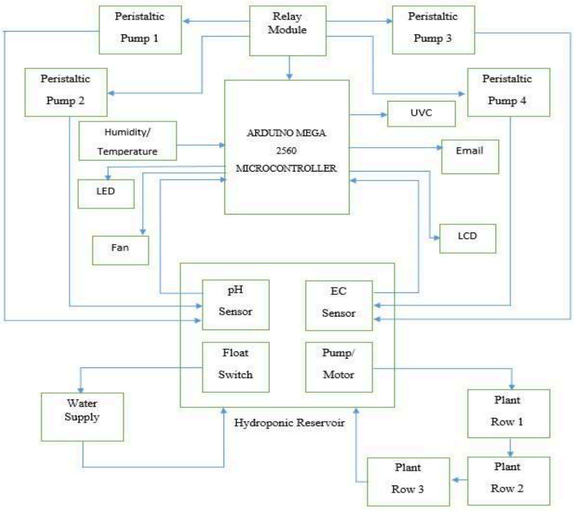

Fig. 1. Block Diagram of the Whole System

Both systems were powered by an Arduino Mega 2560 microcontroller, which served as the central control unit. In the NFT design, nutrient-rich water was pumped from a reservoir through channels where plants were placed in openings supported by growing substrates. The water then recirculated back to the reservoir. Sensors were integrated throughout the system to monitor and automate essential parameters.
Arduino Mega 2560 is the brain of the overall system. All the decision-making processes for the overall operation rely upon this microcontroller. As shown in Fig 1, relay, four peristaltic pumps, pH sensor, EC sensor, humidity/temperature sensor send inputs to the Arduino microcontroller. The Arduino, as the brain of the whole system, processes all inputs.
The four peristaltic pumps dispense with regards to their respective value needed by the plants. The lights connected to the Arduino turn on for 12 hours and turn on again the next day. If the float switch detects the water level is below the recommended, it triggers the pump/motor that made them stop to pump. When the humidity/temperature sensor detects the value is higher than the recommended, the exhaust fan operates. UVC operates within three (3) hours of the day. The LCD displayed all the outputs, which the microcontroller processed and emailed all the outputs.

2.2 System Design

From the reservoir where the sensors and the UVC are located, the water pump will let the water flow to the small pipes and distribute the water in the entire plumbing system. There is a water exit point from each level, where the water streams down to the filter and the UVC box and drains back to the reservoir. It also has a diversion water hose to another small storage to hold the pH sensor and EC sensor where these sensors test each level. The design shown below is the software design of the two setups.

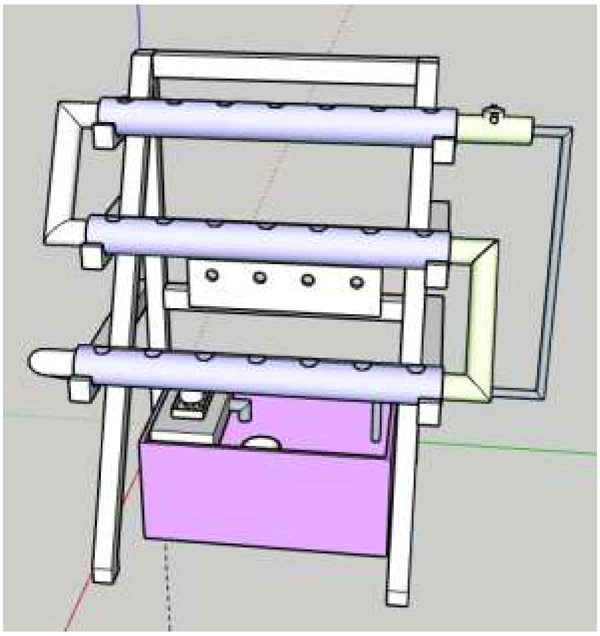

Fig. 2. Hydroponic System for Vertical Farming

Fig. 3(a) and Fig. 3(b) show the flowchart of the system. The operation of the system starts in the morning around 6:00 am. As soon as it starts, the water pump begins to distribute to the system. As the water flows to the system, the EC sensor and PH sensor activate and detect the variable level. At this point, fuzzy logic is being applied to identify the variables used to define the process. If the level of the variable for EC exceeds the recommended value, the peristaltic pump 3 and 4 (solution 3 and 4) is in the OFF state.

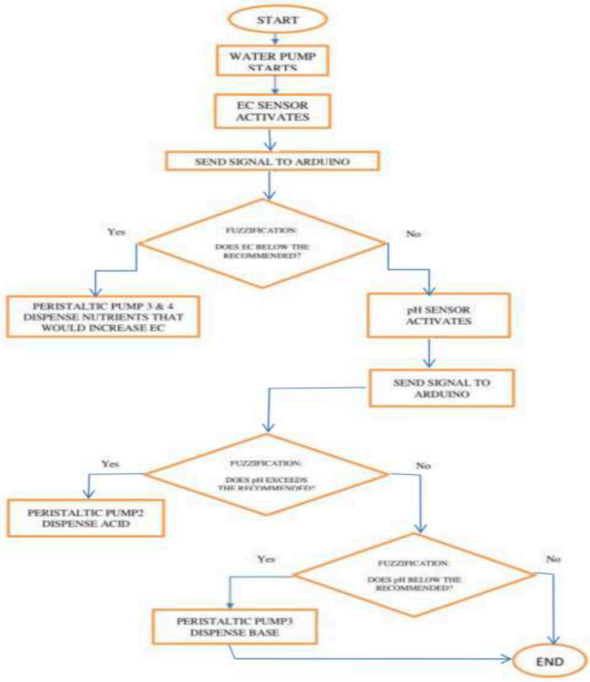

Fig. 3 (a). The whole operation of the system

If the variable level is below the recommended, peristaltic pump: solution 3 and 4 is in ON state and will begin to disperse the nutrient solution and in a few minutes, begin to send a signal to the Arduino. The PH sensor fuzzy logic is also applied in the system. If the variable level below the recommended, peristaltic pump 1 (solution 1) is dispersed to stable the value, and if the variable level exceeds the recommended value, peristaltic 2 (solution 2) dispersed to step down the value. The desired environment is achieved by the system through sensors deployed. The LED as the grow light for the crops, UVC light located at the filter part of the reservoir for disinfecting the water to minimize microorganisms, temperature/humidity sensors, and exhaust fans are being applied to maintain the air temperature and humidity the proposed system.

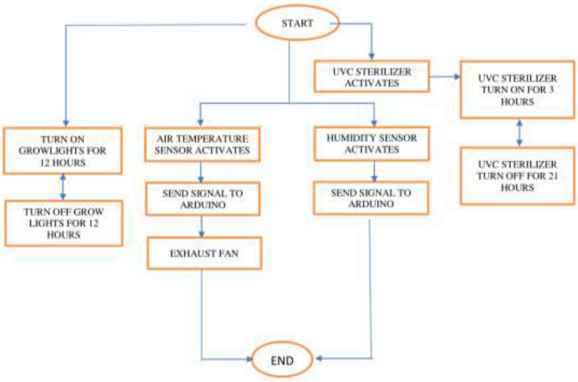

Fig. 3. (b). The whole operation of the system

3.3 Wiring Diagram

The diagram connection is shown in figure 7. To supply power to the Arduino microcontroller, it must be plug into the outlet. For the 20x4 LCD, SDA is connected to pin 21, and SCL is connected to pin 20. EC sensor it is connected to an A13 pin. PH sensor is connected to the A14 pin. The UV sensor is connected to A1. Humidity and Temperature are connected to pin 10. For the closing and opening of the circuits electronically and electromechanically, a relay module is being applied. Pin 1 of the relay for PH low is connected to pin 3 of the Arduino. Pin 2 for PH high is connected to pin 4 of Arduino. Pin 3 for the fan is connected to pin 2 of the microcontroller. For LED, pin 4 of the relay module is connected to pin 6 of Arduino, and for the UVC pin, 5 of the relay module is connected to pin 7 of the Arduino. For EC, pin 8 of the Arduino is connected to the relay pin, and also the float switch sensor is connected to the relay.

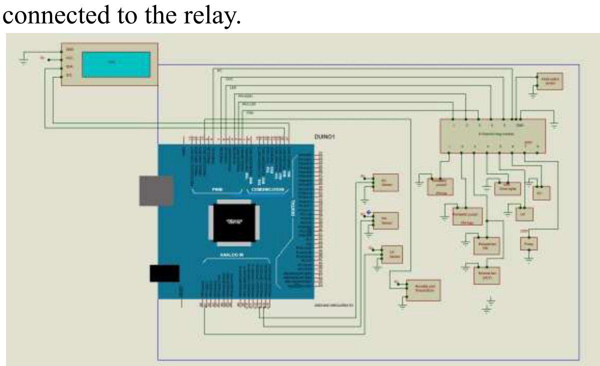

Fig. 4. Diagram of Arduino Connections

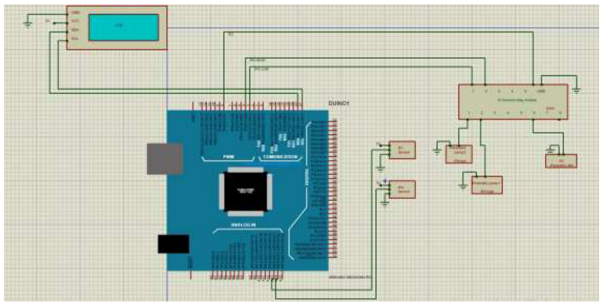

Fig. 5. Diagram for the Arduino Connection (Automated System)

Peristaltic 1 and 2 for high and low is connected to the first and second relay. For the exhaust fan, IN and OUT are connected in parallel to relay 3. The LED for grow lights is connected to relay 4. The UV sensor is connected to relay 5. For EC sensors, both peristaltic 3 and 4 are connected to relay six, and the pump with 220V is connected to relay 7 (220V).

3. RESULTS AND DISCUSSIONS

The constructed actual set up of a hydroponic system, which is shown in Fig. 6 is the first setup, and it has a vertical frame made of an angle bar that holds and supports the PVC pipes that serve as the water channels of the system. In the back middle part of the system, a mini frame is attached to hold on to the four peristaltic pumps that are used for dispensing pH and nutrient solutions. The tank is the water reservoir with an attached UVC box at the upper right side of the tank that holds the UVC inside. A mini hose is connected to the UVC box to divert a small amount of water into a small round container is shown in Figure 7; this container is enough to hold water where the pH and EC sensor is located, it also has an inlet and outlet water channels to keep the water flowing..

Fig. 6. The first set up

Fig. 7. The second set up

The greenhouse tent of the system is made of insulation foam and ½ inch PVC pipes. This setup also has owned control box that keeps the circuitry and other electronic components inside. Fig. 7 is the second setup; its design is the same, just like Fig 6; the only difference is that Fig. 7 has a greenhouse tent made of a farm net

Table 1. Shows the fuzzy logic applied to the proposed hydroponic systems as the controller of the actuators for nutrients needed by the plants.

pH Actuators	
Condition	**Action**
IF pH Higher than the recommended value	THEN, Solution 2 ON
IF pH Lower than the recommended value	THEN, Solution 1 ON
IF pH is at the recommended value	THEN, Solution 1 and 2 OFF

Table 2. Shows the fuzzy logic applied to the proposed hydroponic systems as the

EC Actuators	
Condition	**Action**
IF pH Higher than the recommended value	THEN, Solution 3 and 4 OFF
IF pH Lower than the recommended value	THEN, Solution 3 and 4 ON
IF pH is at the recommended value	THEN, Solution 3 and 4 OFF

The effectiveness of the two hydroponic systems was tested using a plant experiment was carried out using Lettuce (Lactuva Sativa). The plant seedlings were germinated for 15 days. Fifteen (15) lettuce seedlings were transplanted to each hydroponic system for a total of 30 plant seedlings. The foam was used to assist the stability of the plants in the hydroponic system and prevent drowning. The plants were grown and monitored for 15 days in the two systems. Each plant's shoot height and the numbers of leaves were measured every three days (Day 3, 6, 9, 12, and 15) for 15 days in the two systems. After 15 days, the plants were harvested and processed. During the harvest, plants were removed from the holes of the hydroponic system and washed carefully. Plants were cut into the shoot and root biomass and put separately in envelopes. The biomasses were oven-dried at 70°C for 24 hours in the Biochemistry Laboratory Room, Chemistry Department, Caraga State University. After drying, the shoot biomass and root biomass were measured using an analytical balance. The total biomass was calculated from the sum of the shoot and root biomasses. Root mass ratio (RMR) was determined as the
fraction of root mass divided by total biomass.

Before analyses, assumptions of normality and homogeneity of variances were checked. Data were log-transformed if necessary to meet the assumptions. A parametric t-test was used to analyze the differences in the shoot, root, total biomass, and mass root ratio between the proposed and standard systems. Two-way Analysis of Variance (ANOVA) was used to analyze the effects of time (Day 1, 3, 6, 9, 12, 15), system types (proposed vs. standard), and their interaction on the shoot height and the number of leaves. For t-test and ANOVA, mean values and standard error of the mean (SEM) were
calculated. The result of the statistical analysis is considered significant at a probability level (p) of 0.05. Significance levels (p-value) are as follows: $p>0.05$ (ns, not significant), $p<0.05$ (*, significant), $p<0.001$ (**, highly significant) and $p<0.001$ (***, highly significant) [47], [48], [49] means to accept alternative hypothesis (Ha) and reject null hypothesis (Ho). Conversely, non-significant results ($p>0.05$) mean to accept the null hypothesis (Ho) and reject the alternative hypothesis. Data gathering of the parameters and plant growth is performed every three days. Pest data gathering is performed daily. On day 15, the samples collected from the two systems were oven-dried for 24 hours in the laboratory of the Chemistry Department, CSU.

Table 3. The EC, pH, air temperature, and humidity data gathering schedule for both systems

Day	Time	Date
Day 1	5:55 AM	June 15, 2024
Day 3	5:55 AM	June 17, 2024
Day 6	5:55 AM	June 20, 2024
Day 9	5:55 AM	June 23, 2024
Day 12	5:55 AM	June 26, 2024
Day 15	5:55 AM	June 29, 2024

Table 4. The shoot height and number of leaves data gathering schedule for both system

Day	Time	Date
Day 1	1:00 PM	June 15, 2024
Day 3	1:00 PM	June 17, 2024
Day 6	1:00 PM	June 20, 2024
Day 9	1:00 PM	June 23, 2024
Day 12	1:00 PM	June 26, 2024
Day 15	1:00 PM	June 29, 2024

Fig. 8. The (a) transplant of lettuce seedling in day 1 of the proposed system and (b) the final growth of lettuce before harvest in day 15 of the proposed system, (c) transplant of lettuce seedling in day 1 of the standard system and (d) the final growth of lettuce before harvest on day 15 of the standard system.

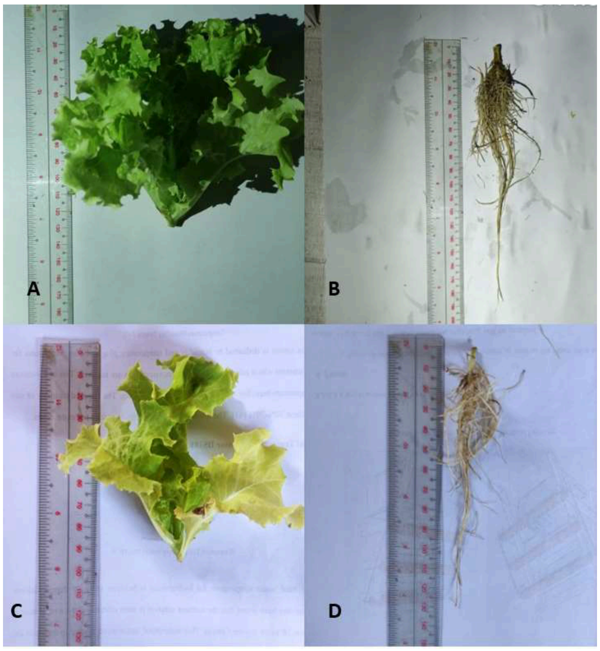

Fig. 9. The shoot and root of lettuce in proposed system (a, b) and standard system (c, d).

Fig. 10. Drying of samples and biomass measurement in Biochemistry Laboratory, CSU

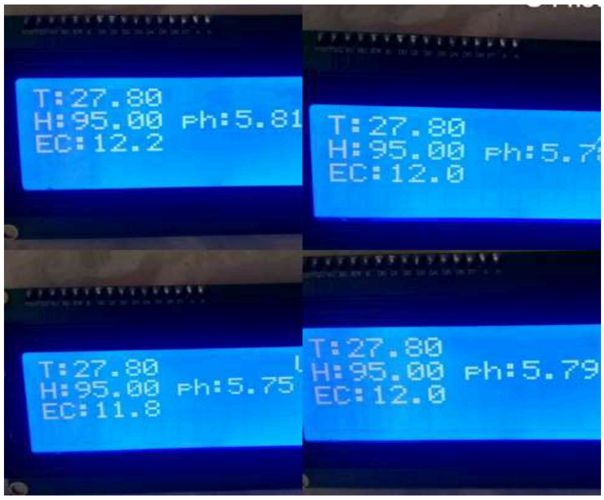

Fig. 11. Parameters monitoring the temperature, humidity, EC and pH in proposed system

Data gathering is performed on Day 1, Day 3, Day 6, Day 9, Day 12, and Day 15. Monitoring of each parameter was taken every 5:55 AM – 5:59 AM every scheduled day of the data gathering.

Table 5 The physico-chemical analysis of water (ph, EC) and air (temperature, humidity). Shown are mean ± standard error of the mean (SEM) and significance value.

Physico-chemical parameters	Proposed	Standard	P value
pH	5.7 ± 0.03	5.9 ± 0.07	p<0.05*
electrical conductivity (dmS/cm)	11.9 ± 0.10	11.8 ± 0.06	P>0.05NS
Air temperature (°C)	27.9 ± 0.22	-	-
Air humidity (%)	93.6 ± 0.95	-	-

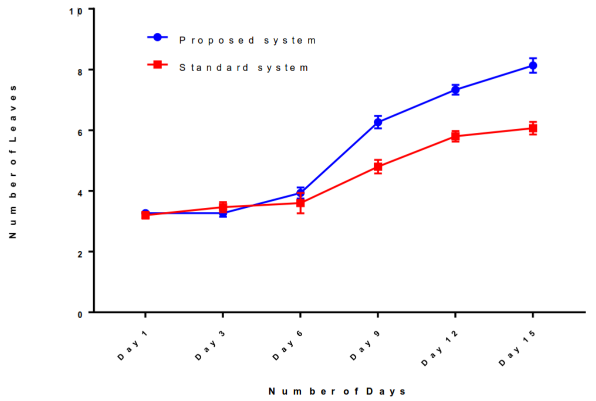

Fig. 12. The differences in the number of leaves of lettuce between proposed and standard grown for 15 days. Shown are mean ± standard error of the mean (SEM) and significance value.

The number of leaves was measured every three days for both the standard and proposed systems. This shows the effects of the time (Day 1, 3, 6, 9, 12, 15) and system types (proposed and standard) on the shoot height and number of leaves of Lettuce (Lactuva Sativa). Data were analyzed using Two-way Analysis of Variance (ANOVA). The number of leaves of the lettuce significantly increases with time ($p<0.001$), and higher in proposed as compared to the standard system ($p<0.001$) (Table 6; Fig. 12). The interaction between the variables in the number of leaves showed that system types have a more significant effect as compared to time (No. of days).

Table 6. Two-way ANOVA results (F-ratios and significance levels) for the effects of time (Days) and system types (proposed vs standard) on the a) shoot height and b) number of leaves of Lettuce.

Source of Variation	% of total variation	P value	P value summary
A. Shoot height			
System Types	72.61	<0.0001	****
Time	5.817	<0.0002	***
Interaction: System x Time	5.418	<0.0001	****
B. Number of Leaves			
System Types	78.04	<0.0001	****
Time	8.473	<0.0001	****
Interaction: System types x Time	8.386	<0.0001	****

The dry mass of the samples was collected from the two hydroponic systems after harvest. The dry mass of a sample was used to calculate its biomass. This procedure was done in the biochemistry instruments room at Caraga State University.

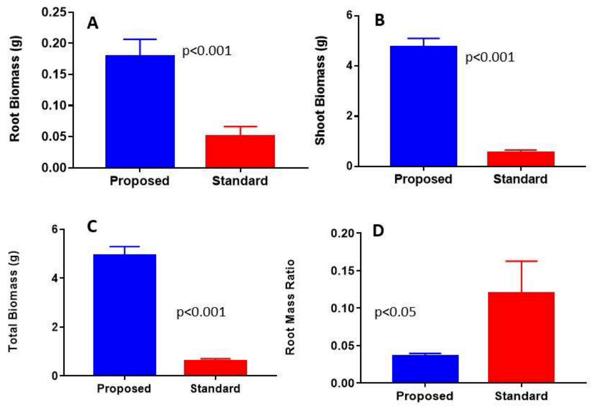

Fig. 13. Comparison of lettuce shoot (a), root (b) total (c) and root mass ratio (d) between proposed and

The biomass of lettuce varied between the proposed and standard systems. The shoot biomass of lettuce showed significantly higher biomass in proposed than standard system ($p<0.001$). Likewise, the root biomass in the proposed system had significantly higher value than the standard system ($p<0.001$). When total biomass is calculated based on root and shoot biomasses, results show a significantly higher total biomass in the proposed than the standard system. This suggests that the proposed system has better cultivation parameters based on the root, shoot, and total biomasses.
Furthermore, the root mass ratio (RMR) showed a significantly higher standard than the proposed system. This means that the lettuce plant allocated more biomass to roots than the shoots. Allocation to roots suggests that the lettuce in the standard system may experience nutrient deficiency [50], microbial and other pathogens presence, or pest infestation, thereby limiting the productivity and growth patterns of the plant.

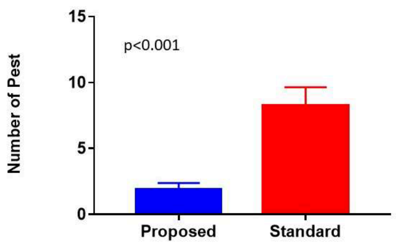

Figure 14. The statistical comparison of the number of pests between proposed and standard systems. Shown are mean ± standard error of the mean (SEM), and significance value.

5. CONCLUSION

The researchers developed two automated hydroponic vertical farming systems to compare their performance: a fuzzy logic-based system (the proposed method) and a standard system. Both systems operated continuously for 15 days to cultivate lettuce (Lactuca sativa). The proposed system featured fuzzy logic-based automated dispensing of pH and nutrient solutions, grow lights as a substitute for daylight, temperature and humidity sensors that activated fans, and UVC treatment to reduce microbial load in the water. The standard system, placed outdoors in a greenhouse, only included basic automation for pH and nutrient solution regulation.

Statistical analyses revealed that the proposed system provided significantly better control of cultivation parameters. Results showed:

1. Highly significant improvements in air and water quality parameters ($p < 0.05$).
2. Significant differences in shoot height and number of leaves between the two systems across multiple time points (Day 1 to Day 15), using two-way ANOVA.
3. Higher total biomass (root and shoot combined) in the proposed system, confirmed by t-test analysis.

Interestingly, the root mass ratio (RMR) was higher in the standard system, indicating more biomass was allocated to roots likely a stress response to nutrient deficiencies, pathogens, or pests. The use of UVC light in the proposed system effectively reduced microbial contamination, supporting findings from related studies on UVC disinfection. Overall, the proposed system demonstrated superior plant growth and health, validating its effectiveness over the standard setup.

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