JTEP Jurnal Keteknikan Pertanian,
Vol. 13 No. 2, p 340-361, 2025
P-ISSN 2407-0475 E-ISSN 2338-8439

Available online:
http://journal.ipb.ac.id/index.php/jtep
DOI: 10.19028/jtep.013.2.340-361

Performance Comparison of Microclimate Control ANFIS vs Fuzzy Logic in Plant Factory

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Article Info

Submitted: 15 September 2024
Revised: 27 May 2025
Accepted: 14 July 2025
Available online: 22 July 2025
Published: June 2025

Keywords:
Plant Factory, ANFIS Controller, Fuzzy Logic Controller, Microclimate.

How to cite:
Hanifah, A. A., Ardiansyah.,Sumarni, E. & Pusvyta, Y. (2025). Performance Comparison of Microclimate Control ANFIS vs. Fuzzy Logic in Plant Factory. Jurnal Keteknikan Pertanian, 13(2): 340-361. https://doi.org/10.19028/jtep.013.2.340-361.

Abstract

Population growth and the reduction of agricultural land necessitate the application of technology to enhance agricultural productivity. A plant factory is an advanced agricultural technology that enables indoor plant production by precisely regulating the microclimate for optimal growth. While fuzzy logic algorithms have been applied for microclimate control, the use of an adaptive neuro-fuzzy inference system (ANFIS) has not been explored. This research aims to develop a microclimate monitoring and control system based on ANFIS and fuzzy logic in a plant factory and compare their performance. The study involves five stages: designing control system schemes, developing hardware and software, testing, analyzing data, and comparing system performance. Microclimate data from both systems were analyzed using the Mean Absolute Error (MAE) metric and visualized through performance graphs. The results indicate that the plant factory with ANFIS control achieved MAE temperature values of 1.18°C and 1.48°C and MAE humidity values of 14.68% and 12.48%, while the fuzzy logic control system yielded MAE temperature values of 1.68°C and 1.60°C and MAE humidity values of 13.02% and 12.31%. Based on the MAE values, the ANFIS control system demonstrated better temperature regulation than fuzzy logic; however, neither system provided optimal microclimate control. These findings highlight the potential of ANFIS for improving temperature regulation in plant factories, suggesting the need for further refinement and optimization of control strategies to enhance overall system performance.

Doi: https://doi.org/10.19028/jtep.013.2.340-361

1. Introduction

Agricultural productivity faces challenges such as unsuitable growing environments and inefficiency at the scale of agricultural production. The decline in productivity in Indonesia's agricultural sector is due to the decreasing number of farmers and uneven development across various sectors (Maulana et al., 2015). The quality of human resources in land management and agricultural farming models remains limited (conventional) and difficult to change, as these practices have become

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deeply ingrained over the years (Bafdal & Ardiansah, 2022). Based on these issues, it is time for urban agriculture to be intensively developed to support food availability. One urban agricultural technology that is currently being intensified is plant factories. A plant factory is a plant cultivation method carried out in a controlled indoor environment (Kozai, 2012). This system has the advantage of increasing crop yields because it is isolated from the external environment and requires less land, thereby addressing the problem of shrinking agricultural land (Maya et al., 2019). Plant factories need to be further developed so that plant growth conditions can be monitored in real time anywhere (Ardiansyah et al., 2022).

Plant factories use advanced technology that facilitates the control of microclimates (light, air temperature, air humidity, CO2, and nutrients), and cultivation becomes predictable through facilities and growth monitoring, as well as enabling year-round cultivation with planned production (Kwon et al., 2014). The microclimate is extremely important because it directly affects plants, influences pests and diseases, irrigation and watering, productivity, and crop quality, as well as planting planning and farm management. Plant factories are key to achieving the maximum yield and efficiency in agricultural management. Monitoring and managing the microclimate can help farmers overcome challenges related to unpredictable weather fluctuations.

An adaptive neuro-fuzzy inference system (ANFIS) is an adaptive network based on fuzzy inference systems. ANFIS is a combination of fuzzy logic and artificial neural networks (ANN) (Wijaya et al., 2022). ANFIS can be implemented using various methods, one of which is to create a model using the TensorFlow library. Fuzzy logic excels in modeling the qualitative aspects of human knowledge and decision making by applying rule-based systems. ANN are advantageous in pattern recognition, learning, and training to solve problems without using mathematical models (Lenhard & Maringer, 2022). ANN can also operate based on input historical data (training data) and can predict future conditions based on these data.

The fuzzy system implements a nonlinear system using linguistic variables directly. Unlike Boolean logic, which assumes that every fact is completely true or false, fuzzy logic extends Boolean logic to address vague and imprecise expressions. Fuzzification, inference systems, and defuzzification are the main components of fuzzy logic. Both these control systems have many inputs and produce only a single output. Each has its own advantages and disadvantages when applied to microclimate control systems in agriculture (Fajriani et al., 2018). Agricultural cultivation through plant factories has also been conducted using fuzzy logic approaches in various countries (Umam et al., 2023). Research on the use of fuzzy logic in plant factories was previously conducted by Haryani (2019), resulting in an average error of 2.51°C for air temperature and 3.95% for air humidity.

Understanding when and how to use fuzzy logic or ANFIS is important, as it can help in effective system modeling, especially in real-world situations with uncertain data. Performance comparisons will improve the accuracy of microclimate regulation in plant factories. This comparison also provides

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insights for choosing between a more static approach, such as fuzzy logic, or a more adaptive approach, such as ANFIS, according to the specific needs and characteristics of the system being modeled. Based on this, the aim of this study is to develop an ANFIS-based and fuzzy logic-based microclimate monitoring control system for plant factories, and to compare the performance of the ANFIS control system and fuzzy logic algorithm.

2. Material and Methods

2.1 Material and Tools

The tools and materials used in this study were plant factories measuring 85 × 70 × 200 cm, as shown in Figure 1. The control system used a Raspberry Pi 4 Model B (Quad-core Cortex-A72, 4GB RAM, Raspberry Pi Foundation, UK) and an Arduino Mega 2560 R3 (ATmega2560, Clock Speed 16 MHz). Data storage utilized a SanDisk Ultra 32GB SD Card. The sensors used included a DHT22 (temperature range -40°C to 80°C, humidity 0–100%, Aosong Electronics, China) for temperature and humidity, as well as a GL5528 LDR sensor module (resistance 500 Ω - 200KΩ, wavelength 540 nm) for light intensity. The climate control system consisted of a 24V Ultrasonic humidifier (Mist Output ≥ 350 ml/h), 220 V 100 W PTC Heater, and 220V AC 50 W fan.

The electrical components included DuPont jumper wires, a 5V 10A relay module (Songle SRD-05VDC-SL-C, China), and a USB FTDI TTL-232R-5V cable. The software used was Visual Studio Code, Raspbian OS, Python 3.11.2, Fritzing, Arduino IDE, Google Firebase, Kodular, and Microsoft Excel 2019. The lamps used were LED Grow Lights (red 660 nm, blue 450 nm, Bridgelux, USA), and a DS3231 RTC Module was used for time recording.

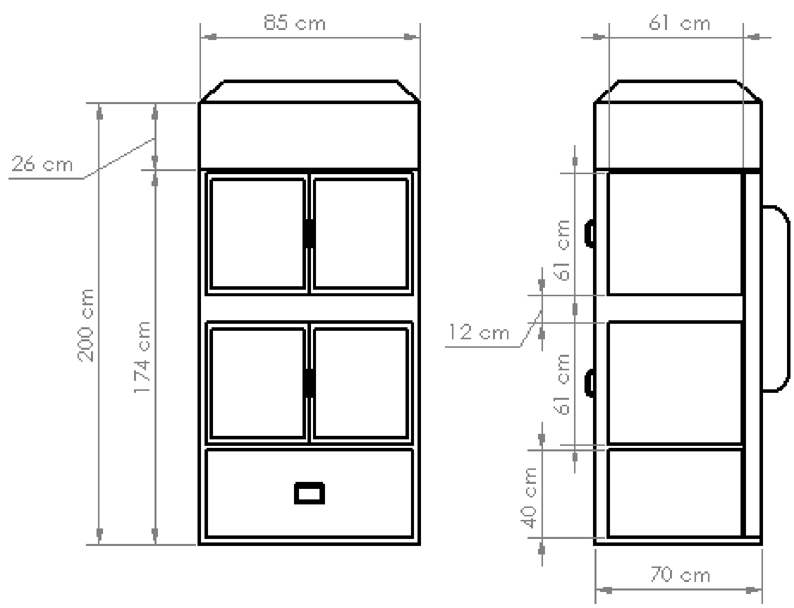

Figure 1. Plant factory dimensions.

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2.2 Research Procedure

The research design was divided into four stages as follows:

1. Control system planning stage

The system control planning stage includes the design of the input, process, output, and real-time databases. The input used data from the DHT22 sensor to obtain the temperature and humidity levels. The input data are then processed on a Raspberry Pi and Arduino Mega 2560, which subsequently send the information to actuators such as a heater, humidifier, and fan. FireBase was used as the database.

2. Software planning stage

The software design stage includes planning the ANFIS and fuzzy logic, user interface design, and Android application design. ANFIS development was carried out in Python using TensorFlow. The user interface was created using the PyQt5 library, whereas the Android application uses kodular.io.

3. Hardware planning stage

In the hardware design stage, the components within the system are integrated so that they function as intended. The components consist of control units, such as the Arduino Mega 2560 and Raspberry Pi, sensors, such as the DHT22 and LDR, and actuators, including a fan, humidifier, and heater. A diagram of the hardware system developed in this study is shown in Figure 2.

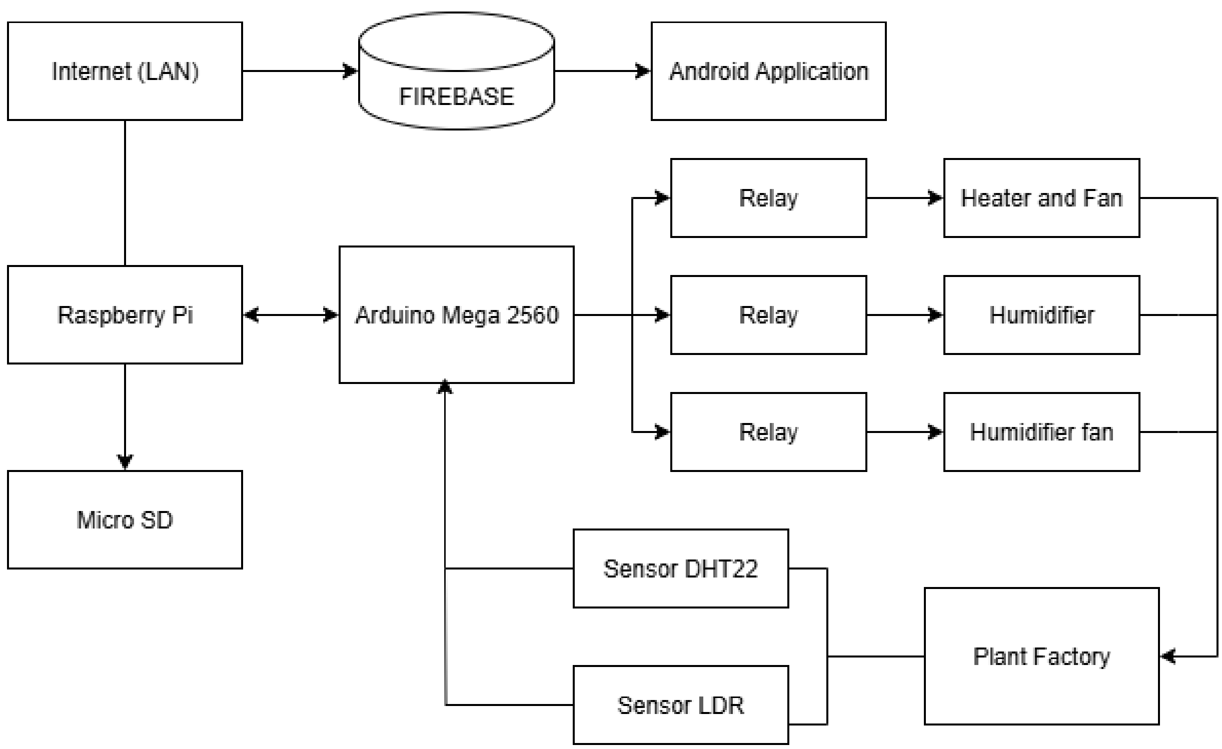

Figure 2. Hardware system diagram.

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The plant factory used in this study had two planting racks, each equipped with a sensor and actuator components. The placement of sensors and actuators in the plant factory is shown in Figure 3.

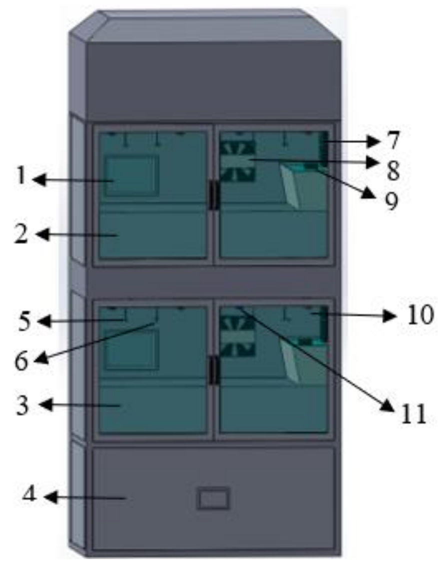

Figure 3. Plant factory components.

Figure 3 Consists of 1(AC vent), 2 (upper nutrient tank), 3 (lower nutrient tank), 4 (main nutrient tank), 5 (LDR sensor), 6 (DHT22 sensor), 7 (fan), 8 (fan and heater), 9 (humidifier), 10 (red LED), and 11 (blue LED).

4. Sensor calibration stage

The calibration was performed by comparing the measurement results of the sensor being tested with a reference sensor with a higher level of precision. In this study, calibration was conducted using a thermo-hygrometer to measure temperature and humidity, as well as a luxmeter to measure the light intensity. The data obtained from the reference sensor were used as a benchmark to adjust and correct the measurement results of the calibrated sensor.

The calibration process involves recording the readings from both the reference sensor and calibrated sensor, which are then displayed in graphical form. The y-axis of the graph shows the values measured by the reference sensor, whereas the x-axis shows the values measured by the calibrated sensor. From this graph, the relationship between the two values can be analyzed, and calculations can be performed to determine the correction factor or calibration equation required.

5. System testing phase

System testing is carried out by ensuring that all software and hardware operate correctly by observing and checking data acquisition in the control system, including both air temperature and humidity data, as well as light intensity.

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The variables measured in this study were the light intensity, temperature, and humidity. Light intensity was monitored without any control process, whereas temperature and humidity were both monitored and controlled.

Data analysis was performed by analyzing the data obtained from the Raspberry Pi in the CSV format. The data were then acquired and plotted as graphs. The acquired data included temperature, humidity, and light intensity. Each of these datasets is then visualized in an xy graph, with the x-axis showing time (t) and the y-axis showing temperature (°C), humidity (%), and light intensity (lux), respectively.

The ANFIS and fuzzy logic control systems were tested alternately on the same plant factory, each for 10 days, with the data acquisition frequency set every 5 min. An analysis was conducted to determine the success of the developed control system program by calculating the error and delta error for each control system. The error was determined by subtracting the set-point value from the actual value of each parameter. The delta error is obtained by subtracting the current error from the previous error. After obtaining the results, the data were compared to assess the performance of both the control systems. Optimal results are achieved when each parameter, both temperature and air humidity, is more stable and closer to the set point, or has a smaller error value.

3. Results and Discussion

3.1 Hardware Design

The hardware design for the microclimate control system in the plant factory includes design using software for circuit simulation and direct design. The software used for circuit design is Fritzing version 0.9.5 for Windows 64-bit. A circuit simulation using this software is shown in Figure 4.

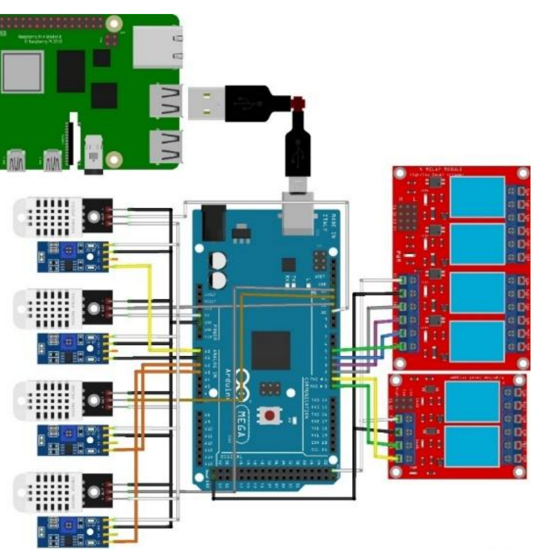

Figure 4. Hardware circuit design.

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Figure 4 consists of 1) a 2-channel relay (heater), 2) a 4-channel relay (humidifier and fan), 3) Arduino Mega 2560, 4) LDR sensor module, 5) DHT22 sensor, and 6) Raspberry Pi 4 Model B.

The system consists of two main circuits: a relay circuit and a sensor circuit.

1. Relay circuit

A relay circuit was used to transmit the output values to the control system actuators. The plant factory control system uses 2-channel and 4-channel relay modules. Each relay module has VCC, GND, and In pins in quantities based on the relay type. The VCC and GND pins of both relay modules were connected in parallel and linked to the 5V and GND pins on the Arduino.

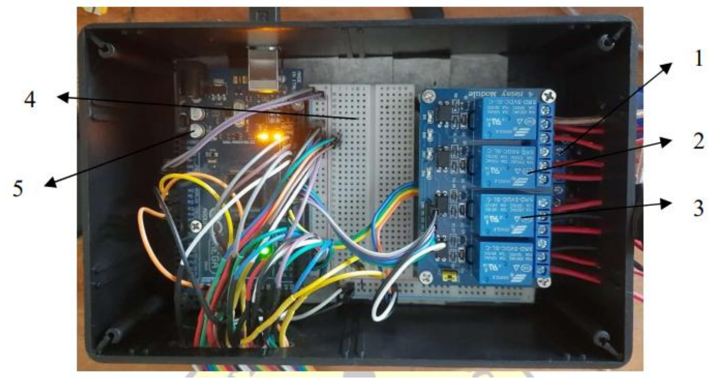

Figure 5. Hardware series of sensors and relays.

Figure 5 shows 1) heater relay, 2) fan relay, 3) humidifier relay, 4) breadboard, and 5) Arduino Mega 2560.

2. Sensor circuit

A series of sensors are used to send input signals from the digital sensor of the DHT22 and the analog signal from the LDR sensor module. The plant factory used four sensors in the control system, with two DHT22 sensors and two LDR sensor modules installed on each plant rack. These eight sensors were then connected to an Arduino Mega according to their respective pins.

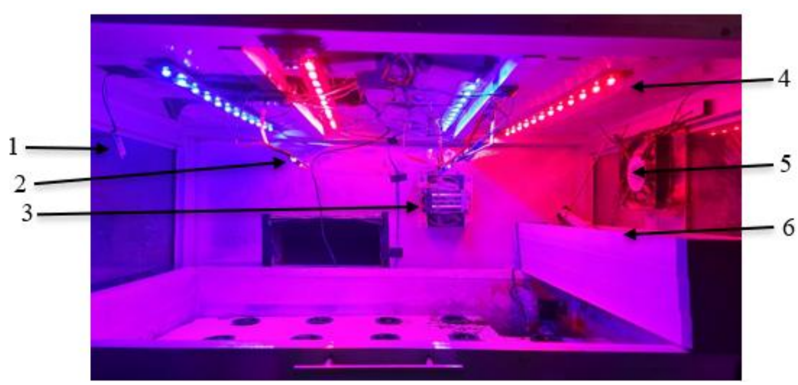

Figure 6. Sensor and actuator circuits.

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Figure 6 consists of 1) a DHT22 sensor, 2) an LDR sensor module, 3) a heater, 4) a red-blue LED lamp, 5) a fan, and 6) a humidifier.

3.2 Software Design

The software design in this study includes the design of the ANFIS program code, fuzzy logic design, and the design of the monitoring and control system. The program was developed on a laptop device and runs through a Raspberry Pi.

1. ANFIS Design

TensorFlow library was used to build the ANFIS model. The design of ANFIS begins by collecting the dataset. The dataset included error values and delta errors for temperature and air humidity along with the fuzzy output. Before being used for training, the dataset was cleaned through several stages, namely handling missing data with linear interpolation or deletion if there was too much missing data, outlier detection using z-score (threshold ±3 standard deviations), which were then corrected or removed, data normalization to the [0,1] range using Min-Max Scaling, and removal of redundant data to avoid bias during training. The ANFIS architecture was created by setting the model's name, number of inputs, number of membership functions, batch size, type of membership function, loss function, and number of iterations. The data were then trained and used for model evaluation and validation. An appropriate model was downloaded and loaded into the main program.

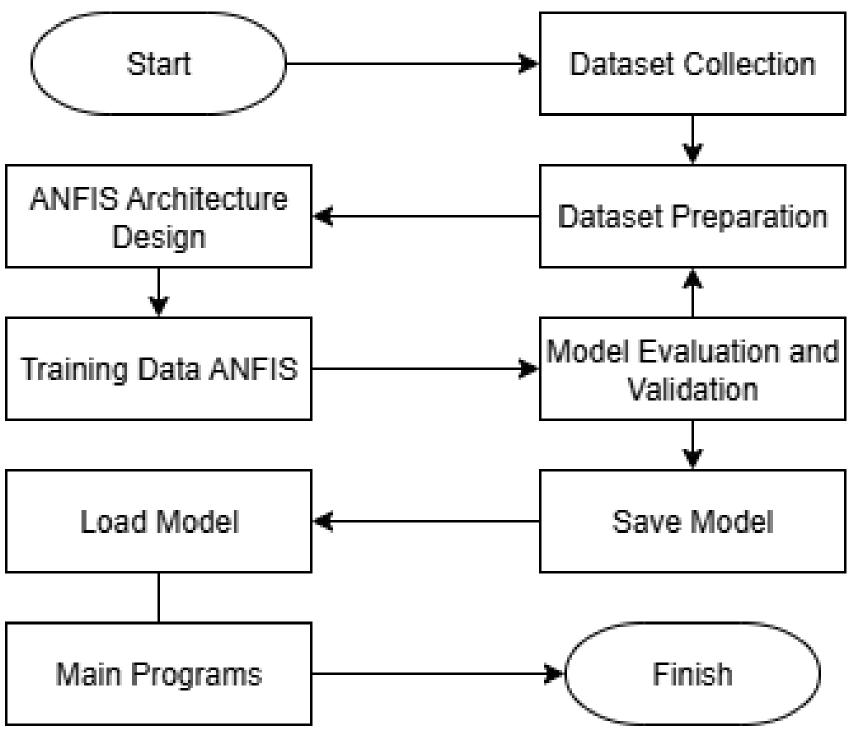

Figure 7. Stages of ANFIS model development.

jTEP Jurnal Keteknikan Pertanian,
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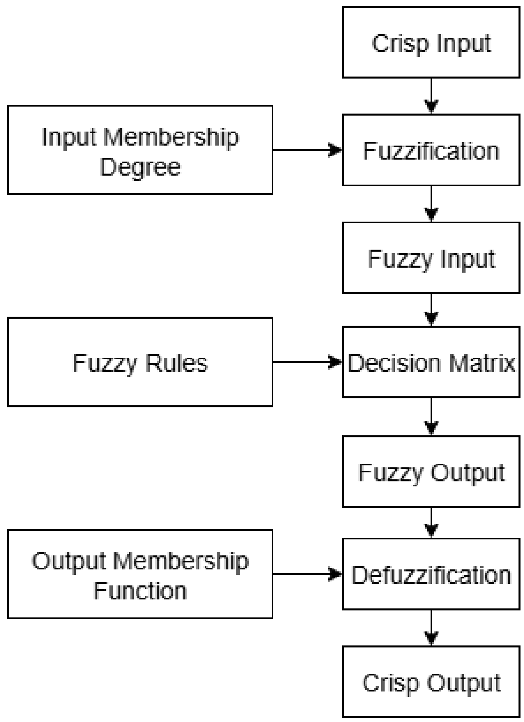
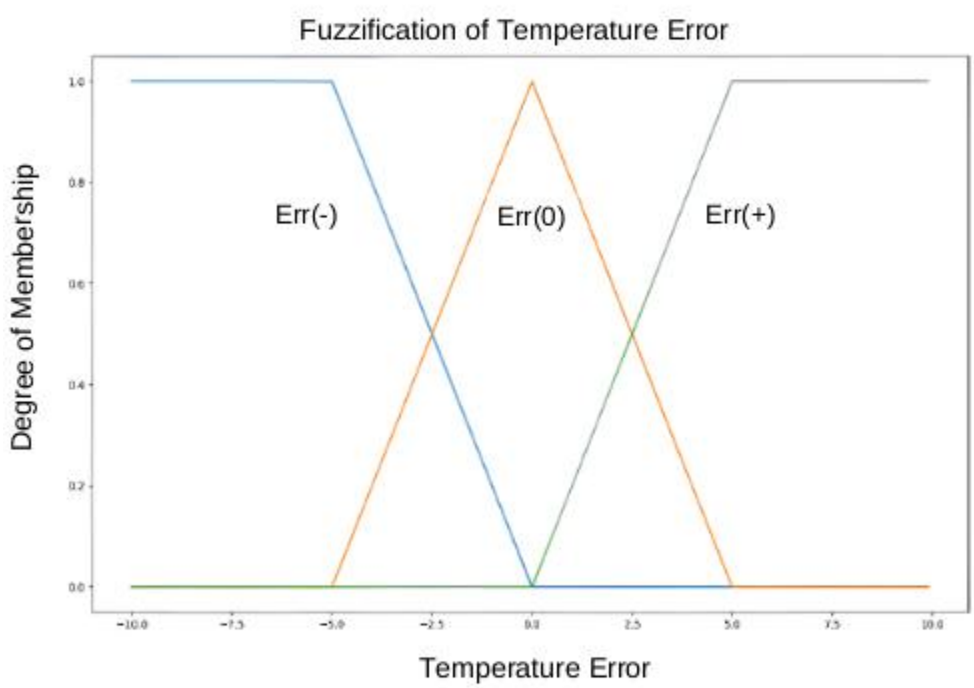
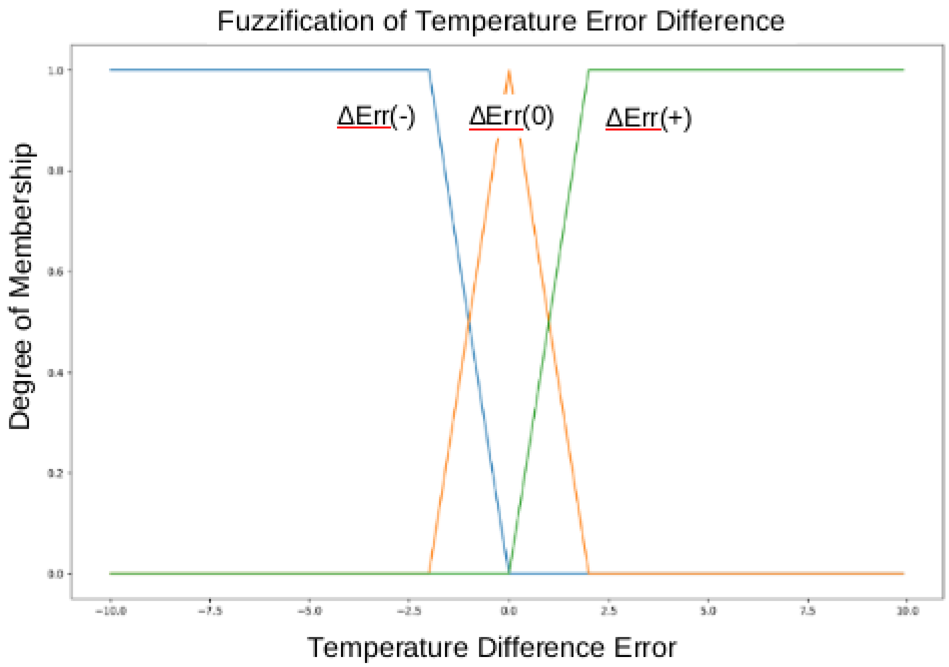
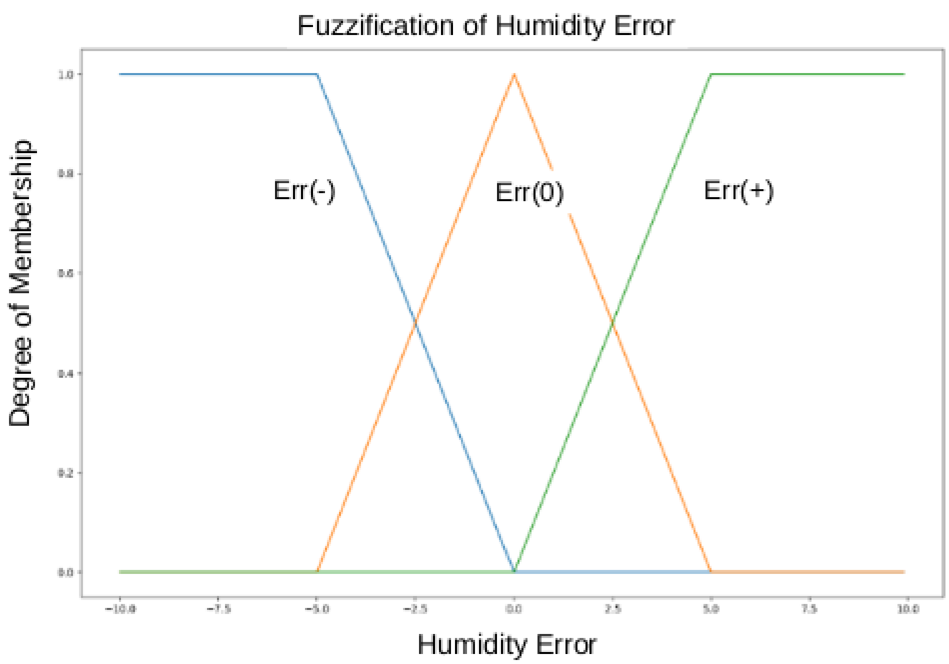
2. Fuzzy logic design

The fuzzy logic creation stage involves determining the fuzzy set values for each input. Each fuzzy output is generated from two inputs: namely error and delta error.






Fuzzification of Temperature Error Difference
ΔErr(-)
ΔErr(0)
ΔErr(+)
Degree of Membership
Temperature Difference Error


Fuzzification of Humidity Error
Err(-)
Err(0)
Err(+)
Degree of Membership
Humidity Error

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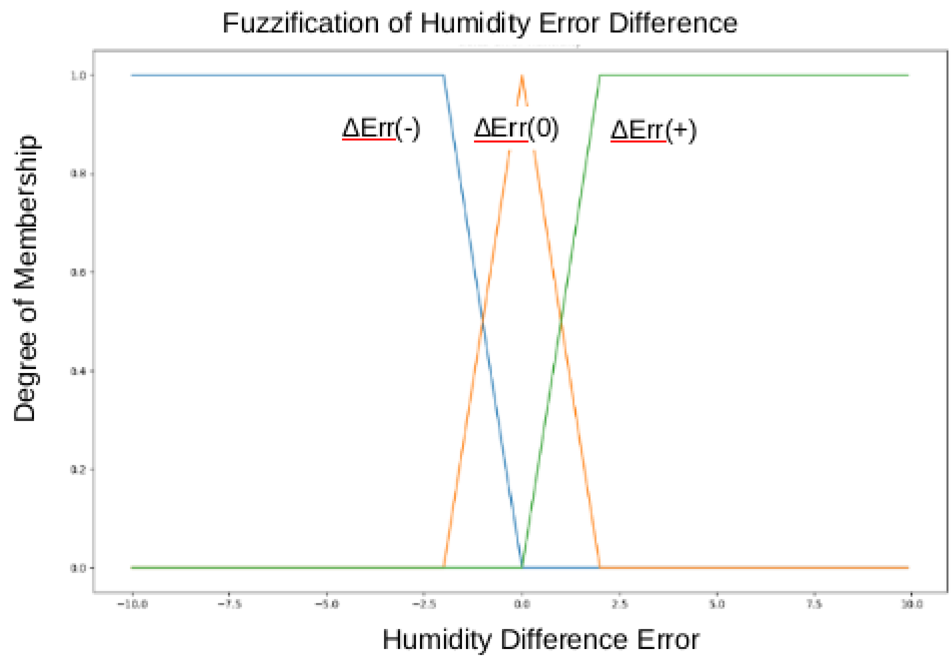

Err / ΔErr	Err (-)	Err (0)	Err (+)
ΔErr (-)	0	0	0,3
ΔErr (0)	0	0	0,6
ΔErr (+)	0	0,3	1

Figure 8. Fuzzification of Error and Error Difference of Temperature and Humidity and Decision Matrix.

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3. Monitoring and control system design

The design of the monitoring and control system is shown in Figure 9.

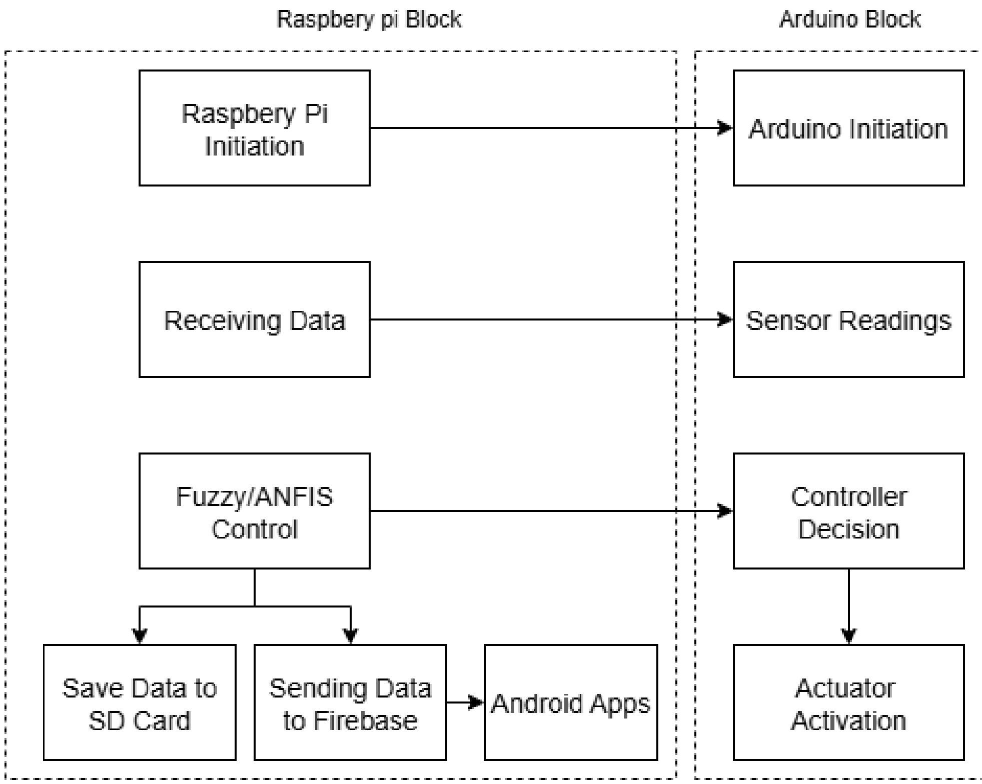

Figure 9. Mechanism of the monitoring and control system.

3.3 Design of Realtime Database, Android Application, and User Interface

1. Realtime Database

Creating a real-time database using Firebase, which is a Google platform. Firebase has many features and can connect control systems to websites and mobile applications.

2. Android application

The Android application was designed using a web-based Android app provider, kodular.io. This Android application will display plant factory microclimate data based on data from the Firebase real-time database, making it useful for microclimate monitoring. The interface is designed to be as simple as possible to make it easy for users to access available information. The displayed data included setpoint values for temperature and humidity, as well as the real-time conditions of temperature and humidity inside the plant factory. Sensor or actuator malfunctions can be detected if there are abnormal values or if the actual temperature and humidity readings are significantly different from the setpoints.

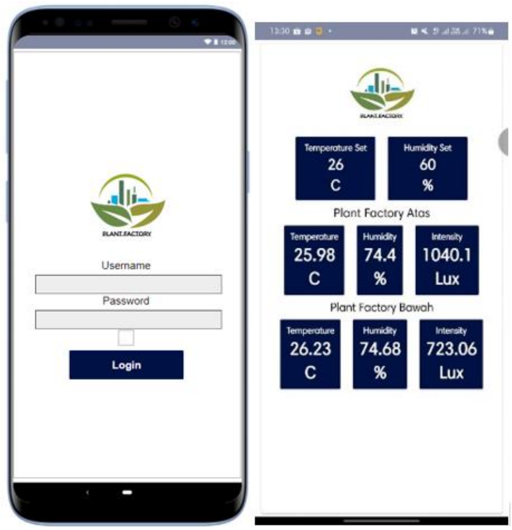

Figure 10. Android application display.

3. User interface

The user interface was created in Visual Studio Code using the PyQt5 library. The sections displayed in the user interface include air temperature setting, air humidity setting, upper rack air temperature, upper rack air humidity, upper rack light intensity, lower rack air temperature, lower rack air humidity, lower rack light intensity, and data updates. The values shown on the user interface are the average readings from the sensors. The user interface also displays graphs of the last ten readings of air temperature and humidity on both the upper and lower racks.

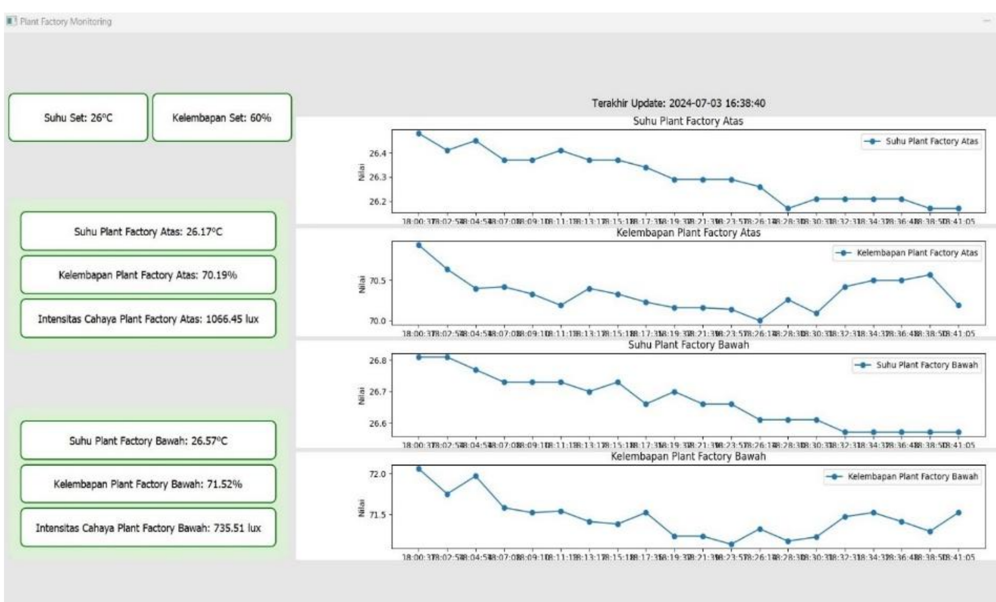

Figure 11. User interface display.

jTEP Jurnal Keteknikan Pertanian,
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3.4 Calibration Result of DHT22 and LDR Sensors

1. DHT22 Sensor Calibration

A DHT22 sensor was used to measure air temperature and humidity. The calibration process was carried out by comparing the data produced by the sensor with a standard measuring instrument, namely, a digital thermo-hygrometer.

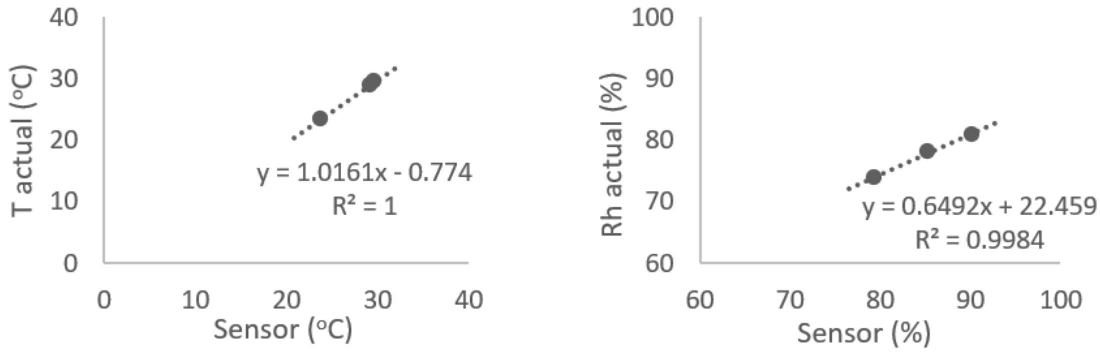

Figure 12. DHT sensor calibration (1).

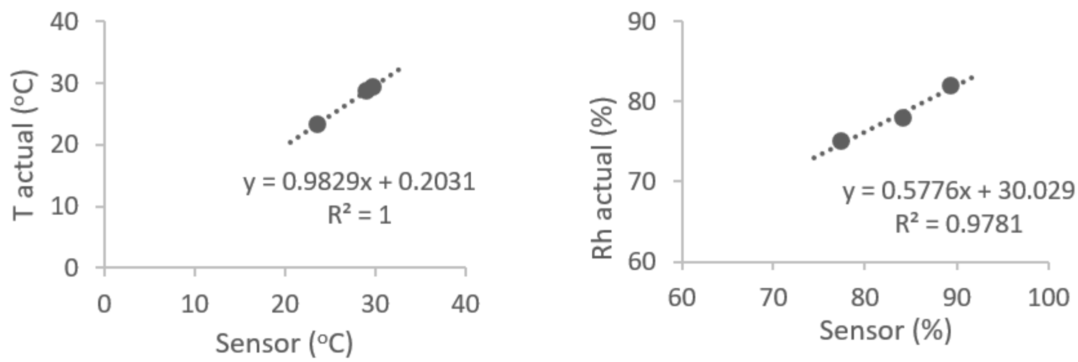

Figure 13. DHT sensor calibration(2).

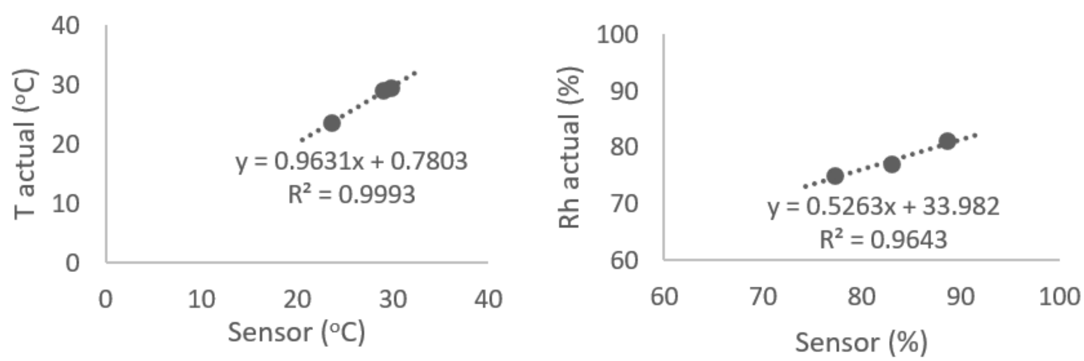

Figure 14. DHT sensor calibration (3).

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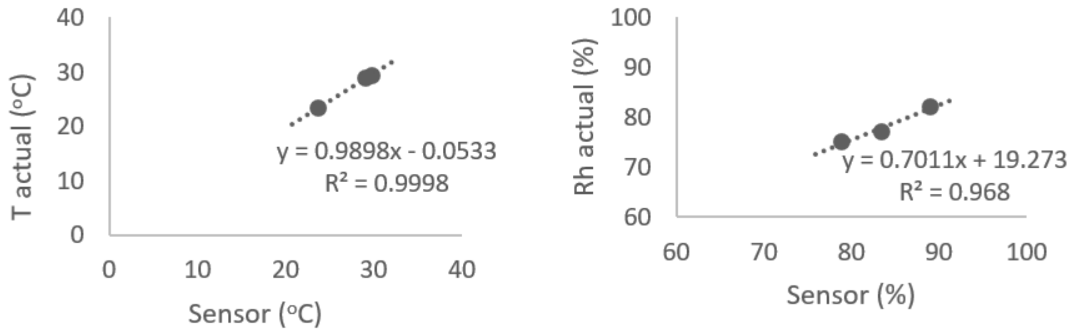

Figure 15. DHT sensor calibration (4).

2. LDR Sensor Calibration

A light-dependent resistor (LDR) sensor is used to detect light intensity based on changes in resistance. Calibration was performed by comparing the LDR output voltage data with light intensity values measured using a lux meter.

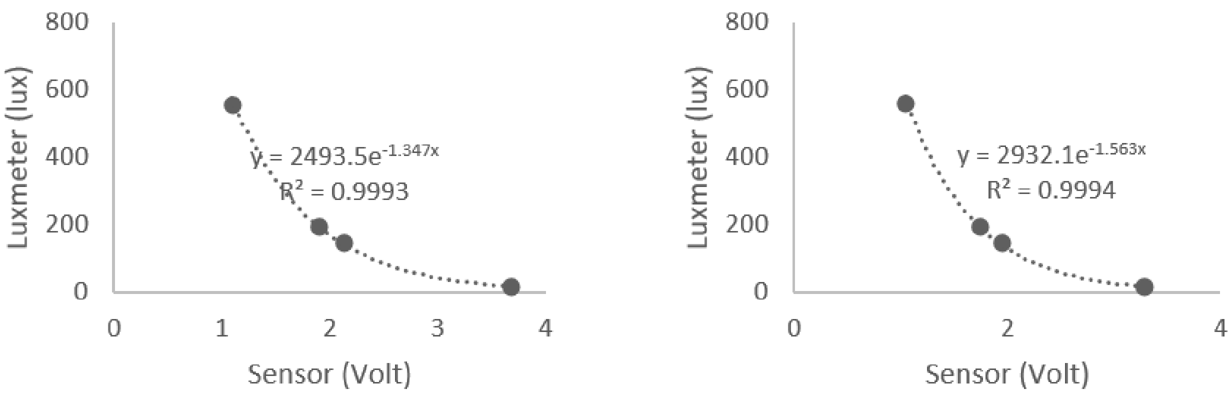

Figure 16. Calibration of the LDR sensor (1) and LDR (2).

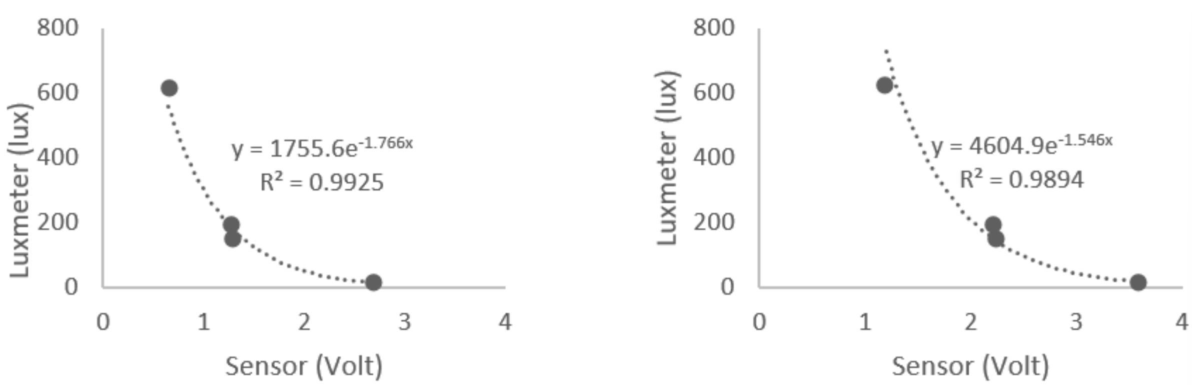

Figure 17. Calibration of LDR sensors (3) and (4).

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3.5 Analysis of Data Acquisition System

This study uses fuzzy logic and ANFIS to compare their performances in controlling microclimates. Both methods were run separately, and control data were collected and analyzed to evaluate the performance of each system. Each system was designed to control the temperature and air humidity in the plant factory within a temperature range of 26 °C and a humidity of 60 %. Data were collected over a period of 10 days for each system.

1. ANFIS data acquisition
    a. Temperature

Table 1. Air temperature data of the ANFIS control system.

	Upper Rack Temperature (°C)	Lower Rack Temperature (°C)
Max	28.70	29.85
Min	25.32	25.60
Average	27.10	27.48

    b. Humidity

Table 2. Air humidity data of the ANFIS control system.

	Top Shelf Humidity (%)	Lower Rack Humidity (%)
Max	83.09	82.34
Min	56.35	52.75
Average	74.68	72.47

2. Fuzzy logic data acquisition
    a. Temperature

Table 3. Air temperature data of the fuzzy-logic control system.

	Upper Rack Temperature (°C)	Lower Rack Temperature (°C)
Max	30.52	29.28
Min	22.42	22.03
Average	27.26	27.17

    b. Humidity

Table 4. Air humidity data of the fuzzy logic control system.

	Top Shelf Humidity (%)	Lower Shelf Humidity (%)
Max	82.06	83.14
Min	65.42	64.89
Average	73.02	72.31

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3.6 Performance Comparison of ANFIS and Fuzzy Logic

The ANFIS and fuzzy-logic control systems were successfully implemented. Both control systems were operated in the plant factory at different times, but with the same setpoint values. The temperature setpoint for the plant factory was 26°C, and the air humidity setpoint was 60%. The cooling unit was set to the same temperature as that of the setpoint. The selection of temperature and humidity setpoints was based on the optimal temperature and humidity for spinach plant growth.

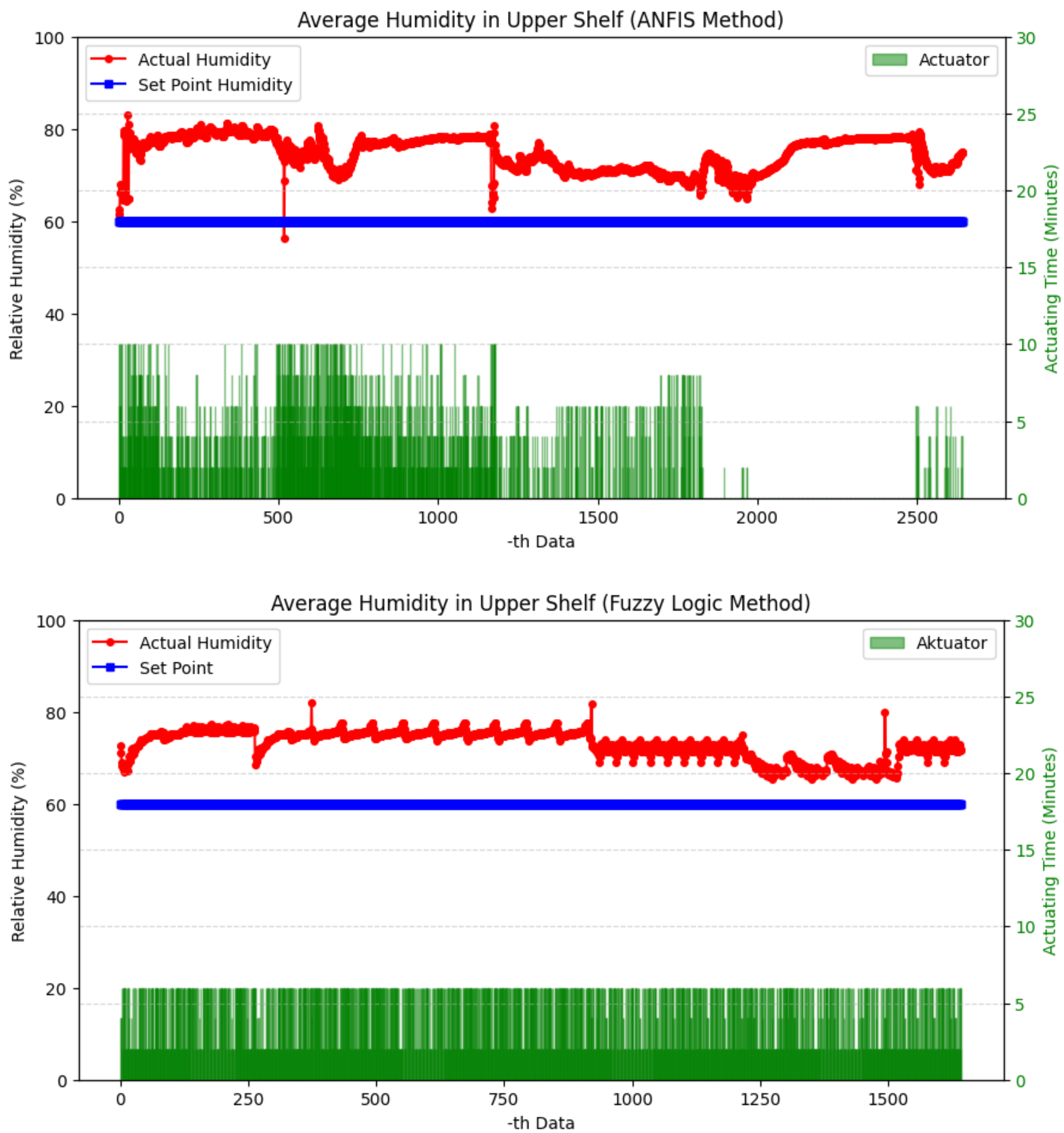
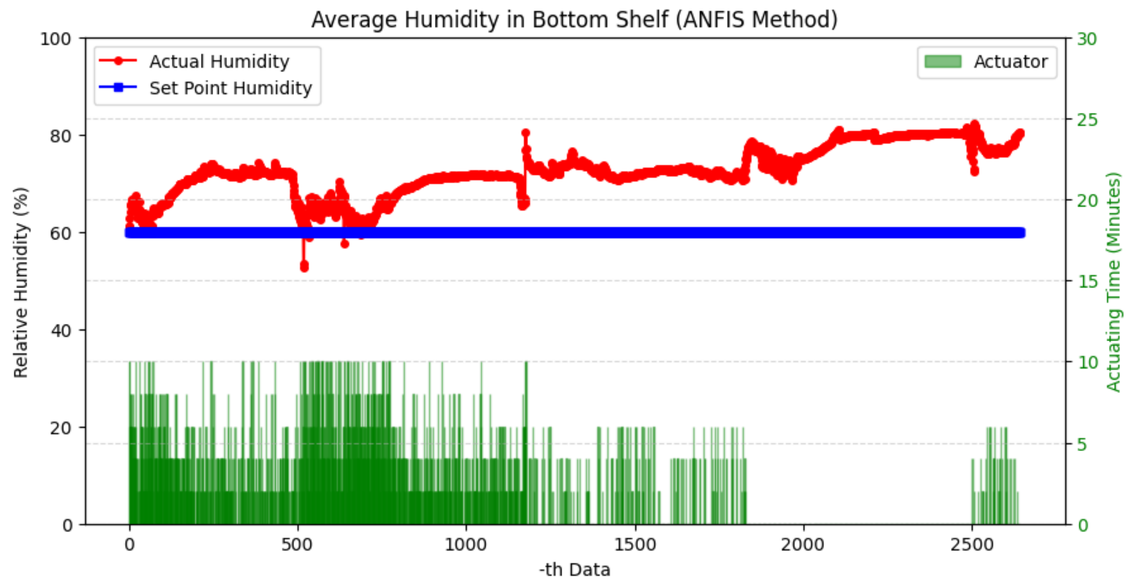


Figure 18. Upper-shelf humidity graph.



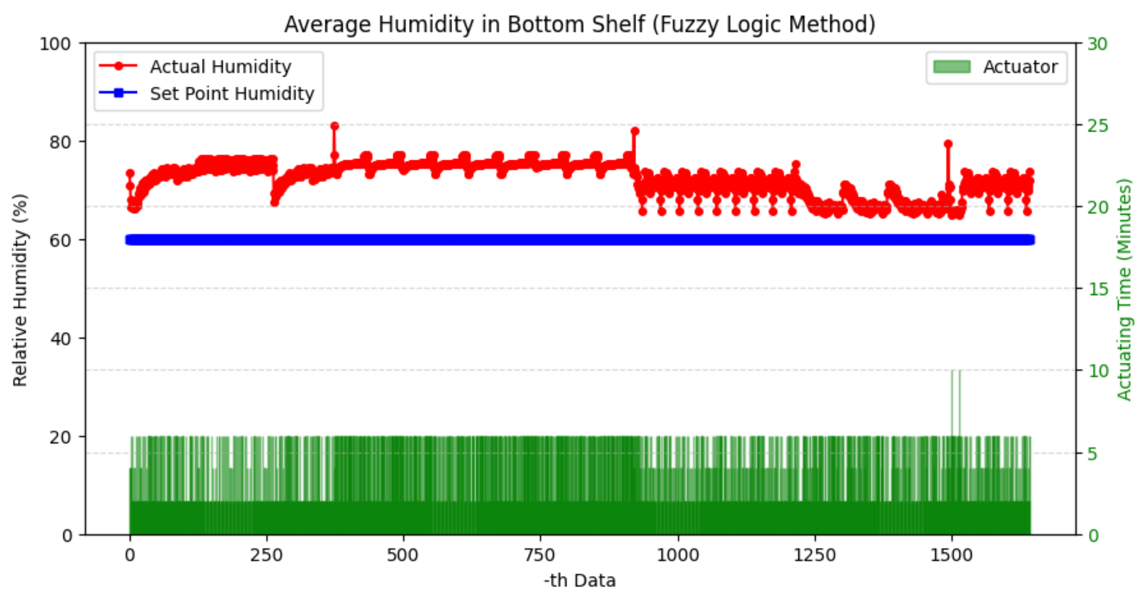
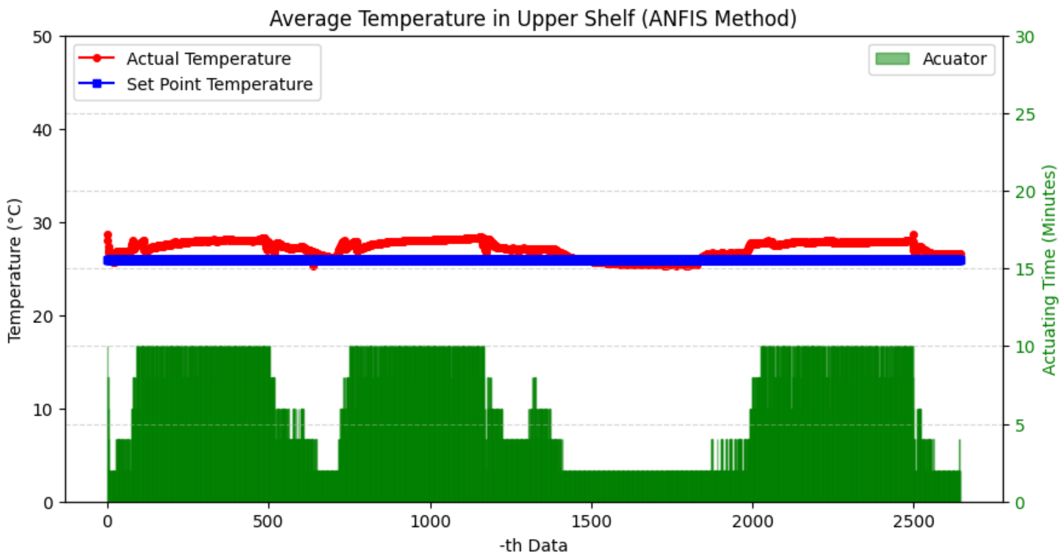


Figure 19. Lower rack humidity graph.

On the upper rack, the ANFIS control system yielded a Mean Absolute Error (MAE) for a humidity of 14.68%, whereas the fuzzy logic control system yielded a humidity MAE of 13.02%. On the lower rack, the ANFIS control system yielded a humidity MAE of 12.48%, whereas the fuzzy-logic control system yielded a humidity MAE of 12.31%. Based on the results of running the ANFIS and fuzzy logic control systems, both produced relatively high MAE values for humidity and did not exhibit oscillations in the running graph of the control system. This is because no actuator was installed in the plant factory to reduce the humidity.



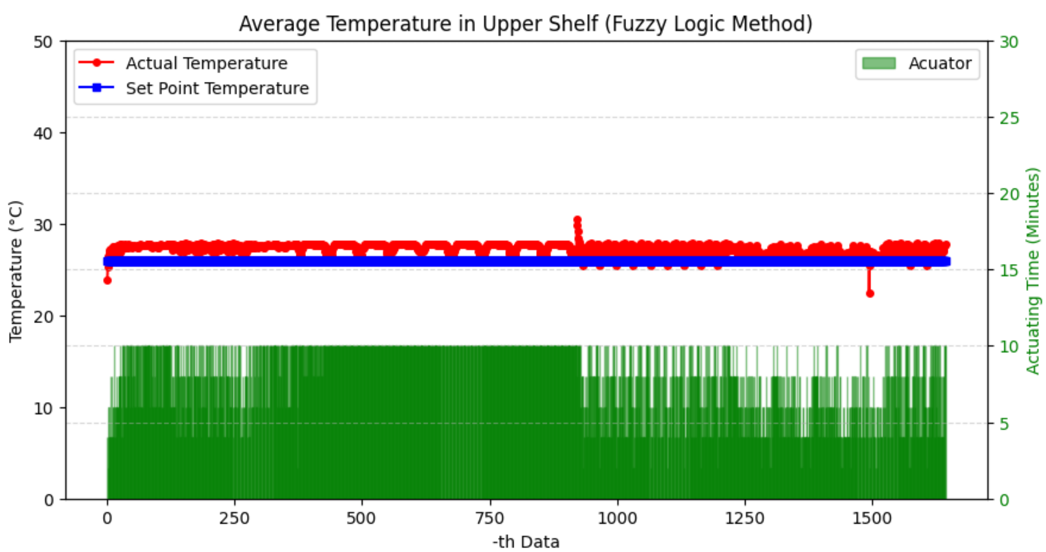


Figure 20. Top shelf temperature graph.

The results of running the ANFIS and fuzzy logic control systems showed that both provided fairly good MAE values for temperature. On the upper shelf, the ANFIS control system yielded an MAE value of 1.18°C, while the fuzzy logic control system yielded an MAE value of 1.68°C. On the lower shelf, the ANFIS control system produced an MAE value of 1.48°C, while the fuzzy logic control system produced an MAE value of 1.60°C. Based on the graph, both systems still reached temperatures slightly above the setpoint and only experienced oscillations a few times. Based on the MAE values, the ANFIS control system delivered a better MAE value than the fuzzy logic control system, but not by a significant margin.

Based on the graph, neither control system was able to achieve temperature stability at the setpoint. The ANFIS control system only occasionally experiences undershoot and more frequently experiences overshoot, whereas the fuzzy-logic control system is more prone to fluctuations during operation.

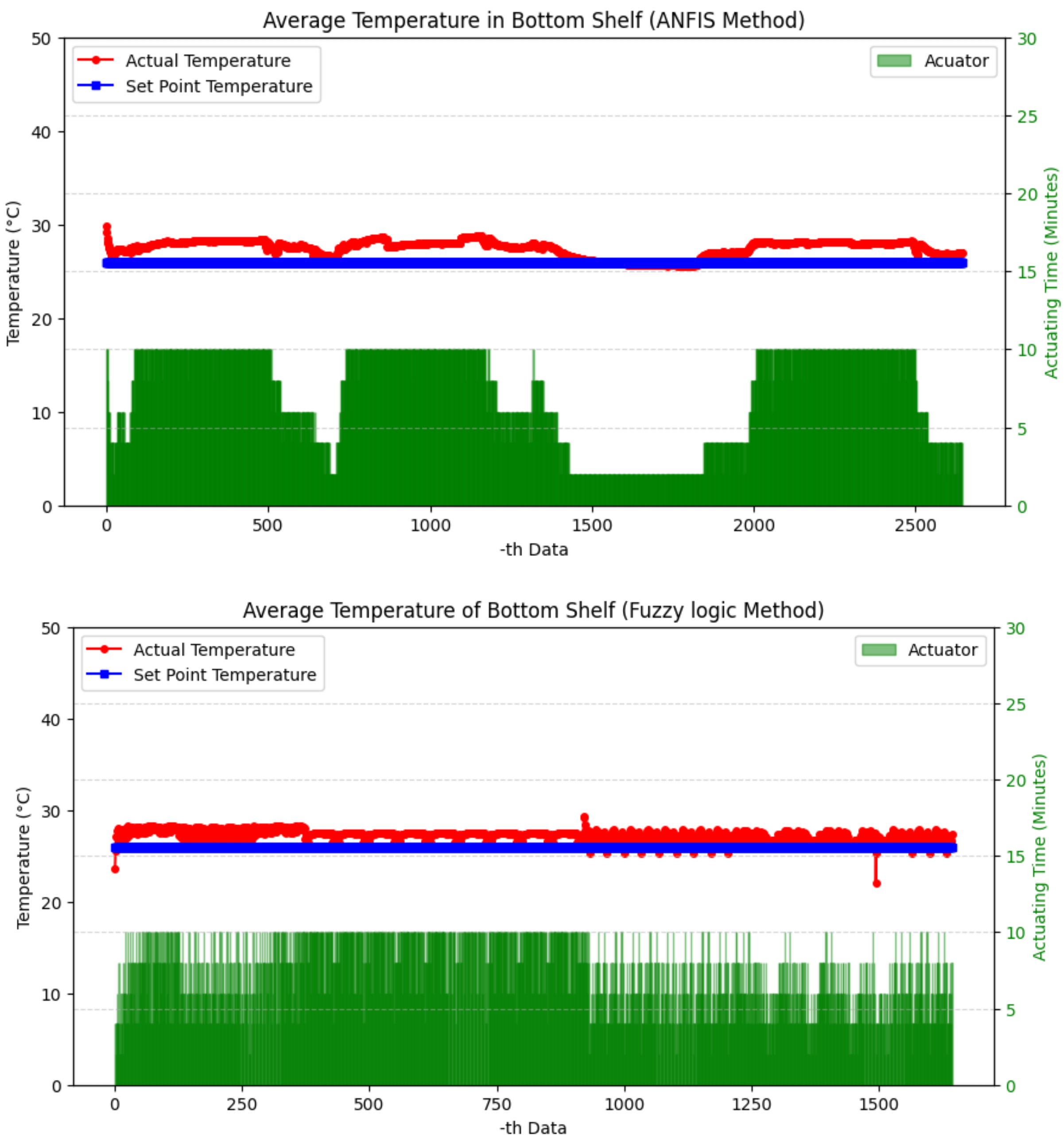


Figure 21. Bottom rack temperature graph.

Available online:
http://journal.ipb.ac.id/index.php/jtep
DOI: 10.19028/jtep.013.2.340-361

4. Conclusion

The development of a microclimate control and monitoring system for air temperature and humidity in a plant factory using ANFIS and fuzzy logic, as well as the creation of an Android application for remote monitoring, have been successfully completed. The research results show that air temperature control using both systems yields good results, with a Mean Absolute Error (MAE) range of 1–2 °C, whereas humidity control did not produce satisfactory results, with MAE values of 12–15%. This is because of errors in the use of actuators to control humidity. In terms of performance, the ANFIS control system outperforms fuzzy logic in temperature regulation, with MAE values for ANFIS of 1.18°C and 1.48°C, compared to 1.68 °C and 1.60°C for fuzzy logic.

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