Research Article

Design and Performance Analysis of a Fuzzy Logic-Based IoT System for Greenhouse Irrigation Control

Agus Ambarwari*[1], Dewi Kania Widyawati[2], Septafiansyah Dwi Putra[3]

[1,3] Internet Engineering Technology, Department of Information Technology, Politeknik Negeri Lampung, Indonesia

[2] Informatics Management, Department of Information Technology, Politeknik Negeri Lampung, Indonesia

* Corresponding Author: ambarwariagus@polinela.ac.id

Abstract: Automatic irrigation has long been used to efficiently irrigate large agricultural areas through drip irrigation systems to minimize water wastage. In greenhouse irrigation, computerized control is essential to improve productivity, as conventional control methods that rely on on-off or proportional control are often inefficient. This research introduces a novel approach to monitor greenhouse environmental conditions and control irrigation duration. The monitoring system architecture consists of sensor nodes and a gateway. The irrigation duration control uses a Fuzzy Logic Controller (FLC) based on the Mamdani method. The FLC is implemented on a NodeMCU ESP8266 board integrated with a DHT22 and soil moisture sensors. Temperature and soil moisture parameters are inputs for the fuzzy logic system in determining the appropriate irrigation duration. The linguistic variables used in the fuzzy membership function include soil moisture (classified as water, wet, and dry), temperature (categorized as cold, normal, and hot), and watering time (classified as zero, short, medium, and long). A rule base consisting of nine fuzzy rules was developed based on these membership functions. Experimental results show that the FLC implemented on the NodeMCU ESP8266 has an average accuracy of 99.41% compared to the MATLAB simulation. This shows the fuzzy logic-based system's high accuracy and effectiveness in controlling the duration of greenhouse irrigation. This developed system offers a promising solution to optimize water usage and improve irrigation management in a greenhouse environment.

Keywords: fuzzy logic; IoT; irrigation control; monitoring; greenhouse.

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1.Introduction

Water is a very important source of life for all living things, including plants. It serves as the primary raw material in the photosynthesis process of plants. Insufficient water supply can negatively impact the survival of numerous living beings. Recent studies indicate that climate change has significantly affected water availability (Carrasquilla-Batista & Chacon-Rodrıguez, 2017). This situation is further worsened by the rapidly growing global population, projected to reach 9.7 billion by 2050 (Cole et al., 2018; Goap et al., 2018; Hemming et al., 2019). This population increase will intensify pressure on the agricultural sector, which is a vital source of food and other raw materials (Gondchawar et al., 2016).

Greenhouse technology has emerged as one of the solutions in sustainable agriculture to meet the increasing demand for food. Greenhouse agriculture aims to increase the quality and quantity of production and minimize production costs (Escamilla-García et al., 2020; Gao et al., 2013; Xing et al., 2017). However, achieving this is highly dependent on accurate monitoring of environmental conditions and efficient use of resources, especially water and energy. Water use efficiency in irrigation is becoming increasingly important given the limitations of this resource (Hemming et al., 2019; Hoque et al., 2023).

Nowadays, monitoring methods and irrigation techniques in greenhouses have developed rapidly with the help of advanced technology, such as Artificial Intelligence (AI) and the Internet of Things (IoT). Modern irrigation systems use sensors to monitor various environmental parameters such as temperature, humidity, light intensity, soil moisture, and soil temperature (Ambarwari et al., 2021; Widyawati et al., 2020). These sensors are connected to a controller that can automatically regulate water flow based on the data received (Pezol et al., 2020). The use of closed-loop-based control systems, which involve feedback from sensors to adjust irrigation in real-time, is more efficient compared to open-loop systems that rely solely on fixed irrigation schedules without considering the actual conditions of the crop (Singh et al., 2022). In addition, the application of IoT technology in irrigation systems enables remote management and monitoring, making it easier for farmers to control irrigation conditions more effectively (Benzaouia et al., 2023).

This research aims to develop intelligent irrigation and environmental condition monitoring in greenhouse farming, utilizing the fuzzy logic method that can control irrigation duration. The proposed system uses a Mamdani-type Fuzzy Logic Controller (FLC) implemented on a NodeMCU ESP8266 board. The system is outfitted with a DHT22 sensor to measure temperature and humidity, along with a soil moisture sensor to monitor the soil's water content. The data from these sensors is used as input for the FLC, which then determines the optimal irrigation duration based on predefined fuzzy rules. Integrating IoT technology into this fuzzy logic-based irrigation system is expected to help farmers make smarter and more efficient irrigation decisions. This system not only optimizes water usage but also increases crop productivity in greenhouses, making agriculture more sustainable and responsive to the challenges of climate change and global population growth.

2. Related Work

Previous research has shown success in applying fuzzy logic and IoT technology to monitor and control irrigation systems. (Benyezza et al., 2021) propose a smart irrigation system utilizing fuzzy control and the IoT to optimize greenhouse irrigation. The system uses a wireless sensor network (WSN) to collect data on soil moisture and temperature (P.D.P.Adi, 2021), which are then processed by an FLC to determine irrigation needs. (Krishnan et al., 2020) proposed a smart irrigation system that uses an FLC to determine the optimal amount of water needed for crops. The system uses GSM to send farmers updates on the status of their fields, including humidity, temperature, and the status of the motor. The FLC takes into account soil moisture, temperature, and humidity to determine when the motor should be turned on or off. (Soheli et al., 2022) propose a smart greenhouse system using the IoT to optimize crop production. The system monitors and controls temperature and humidity using a network of sensors and actuators. Fuzzy logic algorithms process sensor data and trigger adjustments to fans, heaters, and humidifiers based on predefined rules. The study builds upon previous research on greenhouse environment simulators to create a system capable of autonomously maintaining optimal growing conditions.

The study by (Maya Olalla et al., 2023) investigated the effectiveness of an FLC irrigation system for hydroponically grown strawberries in a greenhouse setting. The authors compared the fuzzy logic system to a traditional timed irrigation system. The parameters considered for the FLC system likely included environmental factors and plant growth indicators, but the specific parameters are not detailed in this research. The study was conducted in a greenhouse in Ecuador with a specific variety of strawberries called San Andreas. (Carrasquilla-Batista & Chacon-Rodriguez, 2019) focuses on developing an affordable and efficient standalone FLC for fertigation management in greenhouses. The researchers utilize IoT capabilities to collect real-time data on drainage, electrical conductivity, and pH levels. These parameters serve as input variables for the FLC, which then determines the appropriate fertigation strategy. The system aims to provide agricultural scientists and producers with a tool for data-driven decision-making in greenhouse horticulture, ultimately optimizing resource use and crop production. (Benzaouia et al., 2023) focuses on developing a sustainable precision irrigation system to improve agricultural productivity and reduce water and energy waste. The system combines two irrigation approaches regulated by a feedback FLC and utilizes LoRa protocol for long-range data transmission and monitoring. Data from soil moisture, ambient temperature, solar irradiance, and rainfall sensors are fed into the FLC, which adjusts irrigation times accordingly. The system's effectiveness was tested in real-time field experiments over two different seasons.

These studies show that the use of IoT technology and fuzzy logic in irrigation systems can improve water use efficiency, reduce wastage, and increase agricultural yields. The system designed in this study is expected to provide similar benefits and be widely applied in different types of greenhouse farming.

3. Method

This research was conducted in five primary stages: requirements analysis, system design, implementation, testing, and evaluation. Each stage is explained in detail in the following sub-chapters to provide a clear overview of the process carried out in developing a smart monitoring and irrigation system based on fuzzy logic and IoT.

3.1 Requirements Analysis

The first stage in this research is to identify the needs of the system to be built. Based on the literature study, it is known that many environmental parameters affect plant growth (Ambarwari et al., 2021; Heble et al., 2018), but not all of them can be measured using sensors that are currently available in the marketplace. In this research, only three environmental parameters are monitored at the same time as inputs to control irrigation duration, including soil moisture, temperature, and humidity. In addition, the system should be able to display sensor reading information to a dashboard in real-time, so that farmers can monitor the condition of their greenhouses. Based on the analysis conducted, a list of software and hardware components used is compiled, as shown in Table 1.

Table 1. List of hardware and software requirements

No	Type	Component Name	Description
1	Hardware	Soil moisture sensor	Measuring the soil's water content
2		DHT22 sensor	Measuring air temperature and humidity
3		NodeMCU ESP8266	Sensor data processing
4		Mini solar cell 5V 220mA	Battery charger power source
5		TP4056 module	Battery charger module
6		18650 lithium-ion battery	As a power source for control units and sensors
7		Raspberry pi	Gateway to manage sensor data
8	Software	Mosquitto broker	Message broker for the MQTT communication protocol
9		Node-RED	Visual tools for data processing and system integration
10		InfluxDB	Database management system for handling time series data
11		Grafana	Dashboard for data visualization
12		Arduino IDE	Compiler and uploader for programming the microcontroller

3.2 System Design

The designed system consists of two main components, namely the sensor node and the gateway. The system workflow starts with the reading of data from the soil moisture, temperature, and humidity sensors by the sensor node. Besides functioning as a data collector, the sensor node also performs fuzzy logic processing to determine the duration of irrigation. The sensor reading data and fuzzy processing results are then packaged in one frame of data packets in JSON format to be sent to the gateway via the wireless network at ten-minute intervals. The process of sending data between the sensor node and the gateway is done using the MQTT (Message Queuing Telemetry Transport) protocol, where the sensor node acts as a publisher and the gateway as a subscriber. The data received by the gateway is then extracted and stored in the database for further display to the user. In general, the workflow of the developed system is shown in Figure 1.

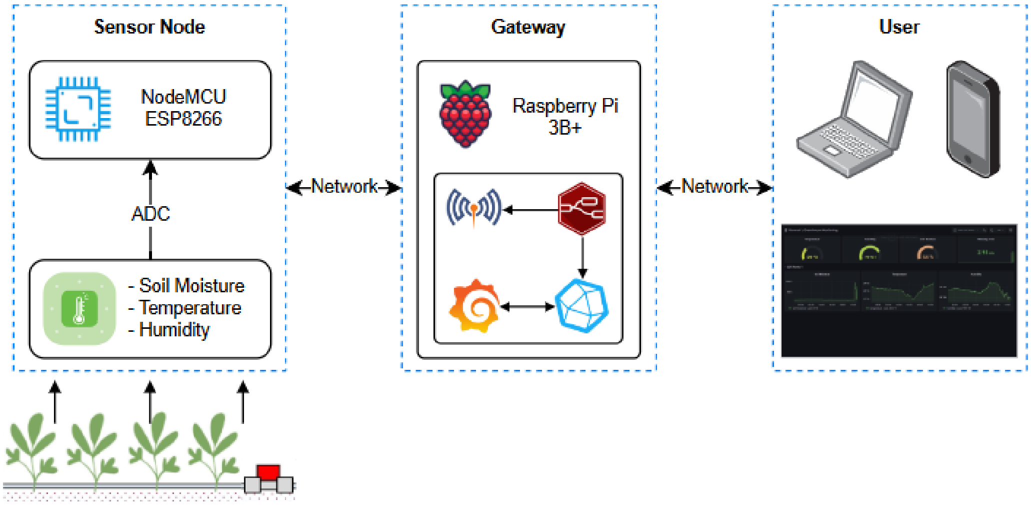


Figure 1. General workflow of the designed system

Moreover, after providing an overview of the components of the Internet of Things or Real-time data use Sensor Node, Gateway, and other components, up to the End User, it is necessary to specifically describe each of these components. The next section will explain in more detail the components of the developed system, including the sensor nodes, the gateway, and the designed FLC system.

3.2.1 Sensor Node

Sensor nodes function as data collectors of environmental conditions and perform fuzzy logic processing to determine the duration of irrigation. The sensor node consists of a NodeMCU ESP8266 board integrated with a DHT22 sensor and soil moisture sensor. The power supply for the sensor node components is sourced from a 2500 mAh Lithium-ion INR 18650 battery, which is installed in the energy control section along with a TP4056 module as a charge controller from two 5V 220mA solar cells. 5V to 3.3V regulator is used to lower the voltage so that components requiring 3.3V voltage, such as the NodeMCU ESP8266, can operate safely. The block diagram of the sensor node hardware is shown in Figure 2.

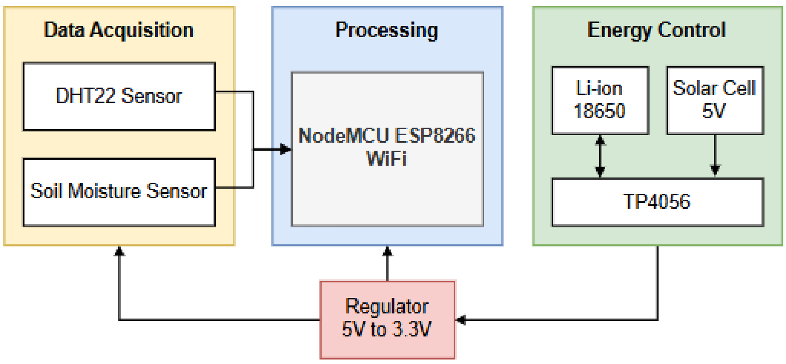


Figure 2. Sensor node hardware block diagram

The workflow in the sensor node starts with program initialization, which sets the variables required for the next process. The device then connects to the access point (WiFi) and establishes a connection with the MQTT broker (gateway). Once connected to both WiFi and the MQTT broker, the sensor node reads data on soil moisture, temperature, and humidity. The temperature and soil moisture data are used as inputs for fuzzy logic processing, which determines the duration of irrigation. This data is subsequently published to the MQTT broker, and the program will pause for 10 minutes before taking the next reading.

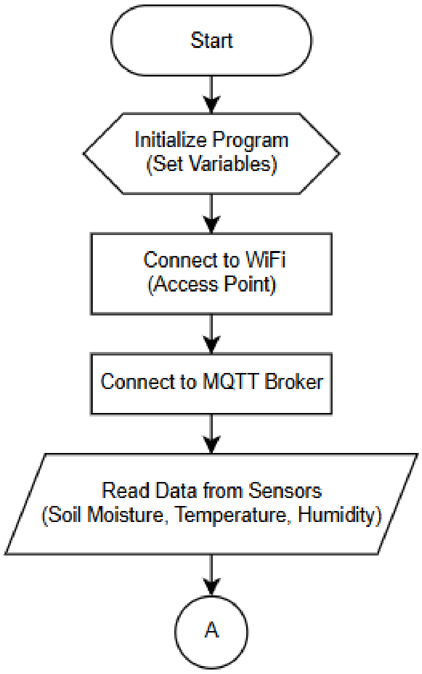


Figure 3. Flowchart depicting the program in the sensor node

3.2.2 Gateway

The gateway serves as middleware for data management and visualization. The gateway is built using a Raspberry Pi 3B+, which has been installed with some essential software to support its functionality. The software includes Mosquitto as the MQTT broker, Node-RED for data processing workflow, InfluxDB v1.8 for storing time-series data, and Grafana for visualizing the data. The workflow inside the gateway system is shown in Figure 4.

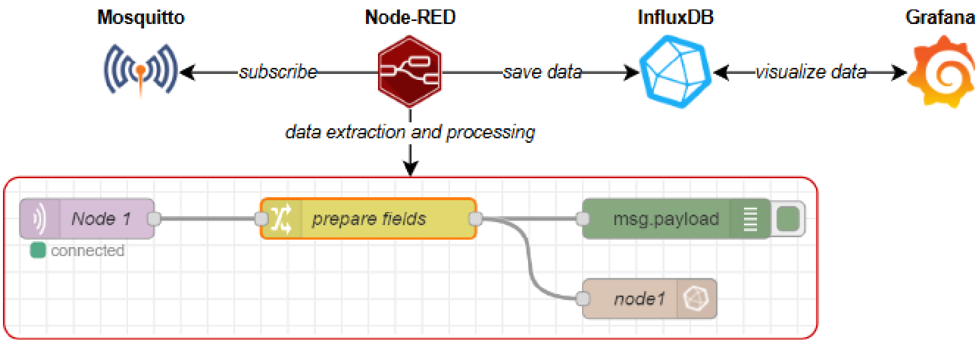


Figure 4. Workflow in the gateway system

3.3 Fuzzy Logic Control System

This intelligent irrigation system uses fuzzy logic to determine irrigation duration based on soil moisture and temperature data. The fuzzy logic process encompasses several key steps: fuzzification, the inference engine and fuzzy rule base, and defuzzification (see Figure 5).

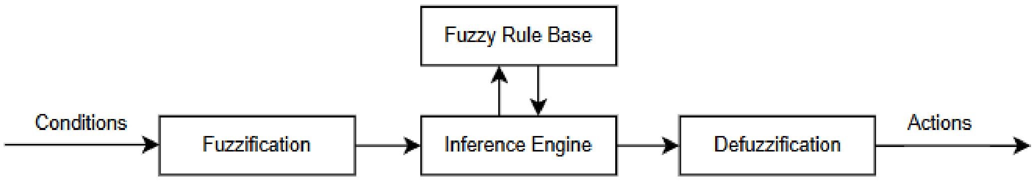


Figure 5. Block diagram of fuzzy logic controller

3.3.1 Fuzzification

Fuzzification is the initial step in the fuzzy logic process, where input values (soil moisture and temperature) are converted into membership degree values in fuzzy sets. In this system, the fuzzy inputs and output used are:

1. Soil Moisture has a membership function (MF) categorized into “water”, “wet”, and “dry”. The values range from 0 to 100, representing the percentage of the soil’s water content.
   - Water – triangular MF with params [0 0 45]
   - Wet-triangular MF with params [25 50 75]
   - Dry-triangular MF with params [55 100 100]
2. The temperature has an MF categorized into “cold”, “normal”, and “hot”. The value ranges from 25 to 45, representing the temperature in the greenhouse area.
   - Cold–triangular MF with params [25 25 35]
   - Normal–triangular MF with params [30 35 40]
   - Hot – triangular MF with params [35 45 45]
3. Watering Time has an MF categorized into “zero”, “short”, “medium”, and “long”. The value ranges from 0 to 300 to denote the duration of irrigation in seconds.
   - Zero–triangular MF with params [0 0 0]
   - Short–triangular MF with params [60 120 180]
   - Medium–triangular MF with params [120 180 240]
   - Long – trapezoidal MF with params [180 240 300 300]

3.3.2 Inference and Fuzzy Rules

In this stage, fuzzy rules are applied to determine the system response based on the membership degree values obtained from the fuzzification stage. These fuzzy rules are determined based on practical experience by trial and error. This system defines nine fuzzy rules, as illustrated in Table 2.

Table 2. Fuzzy rules to determine irrigation duration

Soil Moisture \ Temperature	Cold	Normal	Hot
Water	Zero	Zero	Short
Wet	Zero	Zero	Medium
Dry	Medium	Long	Long

3.3.3 Defuzzification

Defuzzification is the concluding step in the fuzzy logic process, where fuzzy output values are converted into crisp values that can be used by the system to control irrigation duration. The defuzzification method employed in this system is the Center of Area (CoA) (Rajagiri et al., 2019), which calculates the crisp value based on the center of mass of the output membership function (equation 1).

$$CoA = \frac{\int_{x_{min}}^{x_{max}} f(x) \cdot x \, dx}{\int_{x_{min}}^{x_{max}} f(x) \, dx} \quad (1)$$

With CoA as the center of the area, x as the value of the linguistic variable, x_{min}, and x_{max} representing the range of the linguistic variable.

3.4 Implementation

The implementation stage includes assembling the sensor node device and uploading the program code according to the system design. In addition, the installation of supporting software and configuration of the gateway system were also carried out. At this stage, special attention is paid to the program size and programming libraries used to ensure compatibility and efficiency of operation on the available hardware.

3.5 Testing and Evaluation

System testing is conducted to ensure that the system functions by predefined specifications and to evaluate its performance under real operational conditions. These tests include connectivity testing, data storage testing into the database, and performance testing.

4. Result and Discussion

4.1 Sensor Node and Gateway Devices

Based on the system design, all hardware components that make up the sensor node are assembled in a waterproof plastic box. These components consist of a NodeMCU ESP8266 board equipped with a soil moisture sensor to monitor the soil's water content and a DHT22 sensor to measure temperature and humidity. The power source for the system is provided by a 2500 mAh INR 18650 Lithium-ion battery, which is charged using two 5V 220mA solar cells via a TP4056 module for charge control. To ensure components that require 3.3V voltage operate properly, we installed a 5V to 3.3V regulator. The assembled sensor node device is depicted in Figure 6.

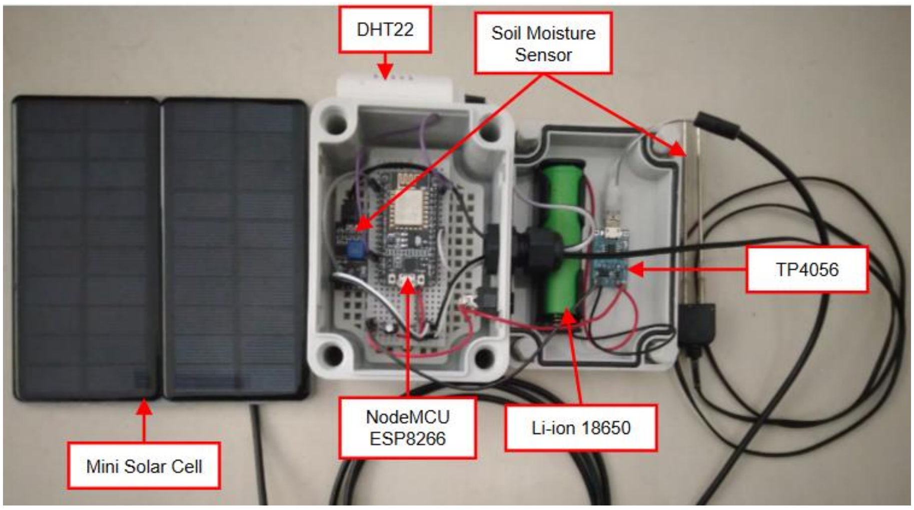


Figure 6. Assembled sensor node device

Furthermore, the integration of the sensor node hardware and software is performed. The sensor node software is programmed in C using the Arduino IDE. It utilizes several programming libraries, including PubSubClient, DHT, ArduinoJson, and Fuzzy. On the Raspberry Pi, serving as the gateway, the installation and configuration of Mosquitto broker, Node-RED, InfluxDB, and Grafana were performed. This gateway device is then connected to the access point via a network cable and installed in the server room. The installation of the gateway device is shown in Figure 7.

Figure 7. Installed and configured gateway device

4.2 Testing and Evaluation

4.2.1 Connectivity Testing

After the sensor node and gateway devices have been assembled and configured, several tests are carried out. The first test is to test the connectivity and data reading from the sensor. The results of this test are displayed through the Arduino IDE serial monitor, as shown in Figure 8. Figure 8 shows that the sensor node is successfully connected to the WiFi network named Warsito. Furthermore, the program's connectivity to the MQTT broker installed in the gateway device was also successful, "Attempting MQTT connection…connected". Sensor data reading is then performed, and fuzzy logic is processed with the results packaged in JSON format to be sent to the gateway. The test of sending data by the sensor node to the gateway was successful based on the "Success sending message" status.

Figure 8. Connectivity testing and sensor data reading

4.2.2 Data Storage Testing

To verify that the data has been received by the gateway, we performed a test of storing the data in the database. We did this by displaying the data in the node1 table in the database, which is a table for storing data from the 1st sensor node device (see Figure 9). Based on Figure 9, it can be seen that all data sent by the sensor node (Figure 8) was successfully received by the gateway and stored in the influxDB database.

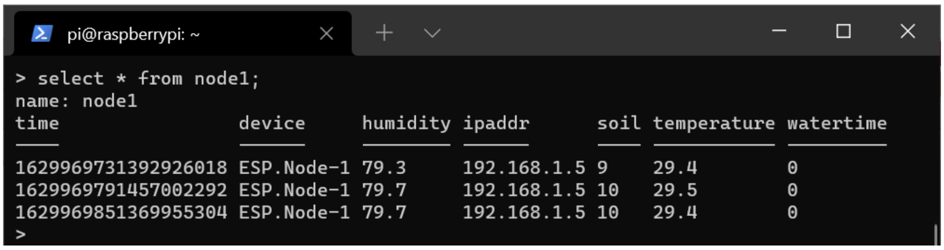
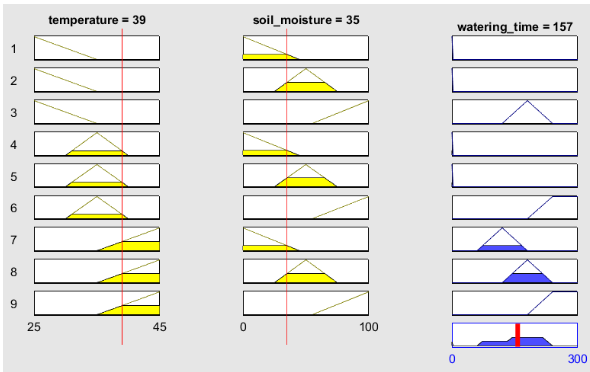


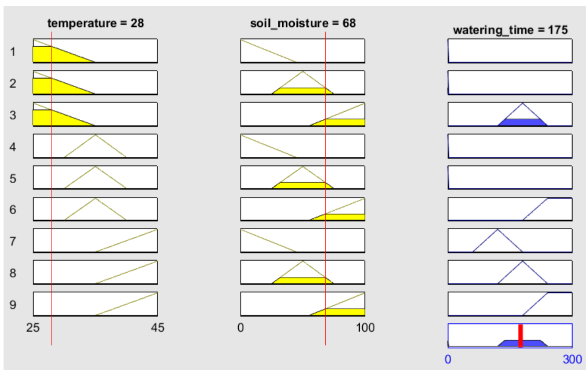
Figure 9. Testing sensor data storage

4.2.3 Performance Evaluation of Fuzzy Logic

The performance evaluation of the fuzzy logic running on the NodeMCU ESP8266 board is done by comparing its output with the results in MATLAB software. We took a sample of 10 data from the database and simulated it in MATLAB software (some examples can be seen in Figure 10). From this data, the difference (Error) and accuracy (100 - Error) were calculated.



(a)



(b)

Figure 10. (a,b) Simulation of the 1st and 5th data samples with MATLAB software

The test results of the fuzzy logic implemented on the NodeMCU ESP8266 board, compared to the simulation on MATLAB software, are presented in Table 3.

Table 3. Fuzzy logic results in MATLAB software and NodeMCU ESP8266 board

No	Soil Moisture	Temperature	Watering Time		Error (%)	Accuracy (%)
			MATLAB	NodeMCU		
1	35	39	157	157	0	100
2	43	29	0	0	0	100
3	53	32	0	0	0	100
4	85	29	180	180	0	100
5	68	28	175	178	1.71	98.29
6	65	35	233	239	2.58	97.42
7	18	32	0	0	0	100
8	8	42	120	119	0.83	99.17
9	78	41	248	247	0.4	99.6
10	96	37	249	248	0.4	99.6
			Average		0.59	99.41

According to Table 3, the difference in watering duration values generated by the fuzzy logic tests on MATLAB software and the NodeMCU ESP8266 is minimal, at 0.59%. This difference is possible because the calculation details in the MATLAB software are higher than in microcontrollers such as the NodeMCU ESP8266. Even so, the overall average accuracy obtained is 99.41%. This indicates that the Mamdani method fuzzy logic applied to the NodeMCU ESP8266 board provides high accuracy, making it a reliable choice for controlling irrigation duration in greenhouses.

4.2.4 Sensor Node Installation in the Greenhouse and Monitoring

After all phases of testing were completed, the sensor nodes v1 were installed inside one of the greenhouses at Lampung State Polytechnic (see Figure 11).

Figure 11. Installation of sensor node v1 in the greenhouse

A customized dashboard has been developed using Grafana to monitor environmental conditions and irrigation duration (see Figure 12). This dashboard displays real-time data collected by sensor nodes, such as soil moisture, temperature, and humidity. This information is displayed in the form of easy-to-read gauges and graphs, allowing users to monitor and analyze greenhouse conditions effectively. In addition, the irrigation duration controlled by fuzzy logic is also displayed on the dashboard, providing a clear picture of the performance of the automatic irrigation system.

Figure 12. Greenhouse monitoring and irrigation system dashboard

5. Conclusion

This research successfully developed and implemented a fuzzy logic and IoT-based intelligent irrigation system for greenhouses. The system consists of sensor nodes using NodeMCU ESP8266, DHT22 sensor, and soil moisture sensor, as well as a Raspberry Pi-based gateway equipped with Mosquitto broker, Node-RED, InfluxDB, and Grafana. The hardware and software implementation process was successful, with program uploads using the Arduino IDE and various programming libraries. Tests showed that the system was able to control irrigation duration accurately and efficiently based on changing environmental conditions. The comparison of fuzzy logic processing between NodeMCU ESP8266 and MATLAB software showed very little difference, with an average error of only 0.59% or system accuracy of 99.41%. In addition, the monitoring dashboard developed with Grafana enables real-time data visualization and historical analysis that helps in greenhouse management. Currently, the system focuses on the design of fuzzy logic in the sensor nodes and the system architecture for monitoring environmental conditions in the greenhouse. However, it needs to be integrated with an actuator to activate the water pump inside the greenhouse. Future research should consider this integration, as well as test the efficiency and reliability of the overall system under various environmental conditions, to improve the effectiveness of automatic irrigation.

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Author contributions: Agus Ambarwari—Conceptualization, Methodology, Implementation, Writing—original draft, Writing—review and editing; Dewi Kania Widyawati—Writing—review and editing, Resources, Supervision, Validation; Septafiansyah Dwi Putra—Writing—review and editing, Resources. All authors have read and agreed to the published version of the manuscript.

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