TEKNIKA: JURNAL SAINS DAN TEKNOLOGI

Homepage journal: http://jurnal.untirta.ac.id/index.php/ju-tek/

Original research article

Automation system in Oyster mushroom cultivation using Mamdani fuzzy logic

Andrian Zola, Lindawati [*], Sholihin

Department of Electrical Engineering, Sriwijaya State Polytechnic, Jl Srijaya Negara Bukit BesarPalembang 30139, Indonesia

A R T I C L E I N F O

Article history
Submitted 2 July 2025
Received in revised form 19 July 2025
Accepted 21 July 2025
Available online 30 July 2025

Keywords
Arduino microcontroller
Capacitive soil moisture
Oyster mushroom cultivation
Mamdani fuzzy logic
MQTT algorithm

Editor:
Agusutrisno

Publisher's note:
The publisher remains neutral regarding jurisdictional claims in published maps and institutional affiliations, while the author(s) bear sole responsibility for the accuracy of content and any legal implications.

A B S T R A C T

Oyster mushrooms often struggle to grow optimally due to unpredictable environmental factors like temperature, air humidity, and growing medium moisture. To address this, an IoT-based automation system with Mamdani fuzzy logic and MQTT communication was developed to carefully regulate these conditions. This study created such a system to optimize the growing environment. It uses a DHT22 sensor to monitor temperature and humidity, a capacitive soil moisture sensor connected to an ESP32 microcontroller, and a Mitsubishi FX3U-14MR PLC for management. Mamdani fuzzy logic and the MQTT protocol process and share data in real-time. Tests show the system is highly accurate, with an error rate below 5% compared to manual calculations, while also reducing crop failure risks, speeding up harvests by up to one day compared to traditional methods, and enhancing yield quality and efficiency. This approach offers a practical, scalable solution for modern oyster mushroom farming, minimizing human effort and ensuring environmental stability.

1. Introduction

Oyster mushrooms are one of the most widely cultivated types of fungi, prized for their high nutritional value and year-round cultivation potential [1]. This has led to increasing popularity in small, medium, and large-scale oyster mushroom cultivation among farmers and the general public. However, current environmental monitoring in mushroom cultivation houses often relies on rudimentary tools like hygrometers, or even subjective estimations by farmers [2]. Optimal oyster mushroom growth critically depends on maintaining specific environmental conditions [3]. Specifically, ideal ranges for temperature, air humidity, and soil moisture are 22° C to 28° C, 80% to 90%, and 50% to 65%, respectively [4]–[6].

Managing these environmental parameters is crucial, yet traditional oyster mushroom cultivation remains heavily reliant on manual processes. Farmers typically spray water twice daily—in the morning and evening—

* Corresponding author
Email address: lindawati@polsri.ac.id

DOI: http://dx.doi.org/10.62870/tjst.v21i1.34489

to regulate temperature, humidity, and soil moisture [6], [7]. This manual approach demands constant operator involvement, which diminishes efficiency and frequently leads to suboptimal growing conditions [8]. Growing oyster mushrooms is no small feat—temperature, humidity, and moisture levels can make or break their growth. Even slight fluctuations in these conditions can mess with the mushrooms' metabolic processes and stunt their development [8], [9]. That's why there's a pressing need for a system that can automatically keep tabs on and fine-tune the microclimate inside mushroom cultivation houses. Automation could be a game-changer, boosting the precision and efficiency of environmental control and, ultimately, leading to better mushroom yields [10].

Thankfully, recent strides in microcontroller and Internet of Things (IoT) technologies are opening up exciting possibilities. Research shows that automated systems consistently outperform manual methods when it comes to managing temperature, humidity, and soil moisture in farming [11]–[13]. Among these, fuzzy logic-based control systems stand out, offering better effectiveness and efficiency than traditional fixed-threshold approaches [13]–[15].

Several studies have already explored environmental monitoring and control systems for oyster mushroom cultivation. For example, one study [16] built a system using an Outseal Programmable Logic Controller (PLC) and the Node-RED platform, relying on RS485 communication in a master-slave setup. It was highly accurate but stuck to fixed setpoints, missing the adaptability of fuzzy logic. Another study [17] used an ESP32 microcontroller with DHT22 sensors, integrated with the Blynk app for real-time monitoring and manual control via virtual buttons. While functional, it lacked smart decision-making and robust communication protocols like MQTT. On the other hand, a different approach [18] used Mamdani fuzzy logic in an IoT-based system with an ESP32 and DHT22 sensors to control a fan and mist maker. It delivered solid accuracy but was only tested in small-scale setups and didn't incorporate industrial-grade components like PLCs or scalable communication protocols, limiting its potential for larger operations.

These studies highlight some recurring issues: limited control stability, lack of intelligent decision-making, and incomplete environmental monitoring—especially when it comes to soil or growing medium moisture, which is critical for mushrooms. To tackle these gaps, this study proposes a new system that combines Mamdani fuzzy logic with a Mitsubishi FX3U-14MR PLC and an ESP32 microcontroller. Sensor data is processed as fuzzy inputs to precisely control actuators, ensuring ideal growing conditions. The system uses the MQTT protocol for reliable, scalable data communication. Most importantly, it doesn't just monitor temperature and air humidity—it also keeps track of and regulates soil moisture, a key factor often ignored in mushroom cultivation.

The goal is to create a smart, reliable environmental control system for oyster mushroom farming, blending Mamdani fuzzy logic with industrial-grade hardware and IoT communication protocols. This setup aims to deliver better accuracy, stability, and scalability, offering practical benefits for small- to medium-scale mushroom farms. By providing a more precise and integrated solution, this system could significantly boost yields and streamline operations.

2. Material and method

This section details the materials used and the methodologies applied to design and implement the intelligent environmental control system for oyster mushroom cultivation. The system integrates industrial-grade hardware with fuzzy logic and Internet of Things (IoT)-based communication protocols.

2.1. Material

The system's design encompasses both hardware and software components. Hardware selection was meticulously carried out to ensure robustness and prevent damage during long-term operation, while software development focused on efficient system management and precise data processing. The overall system's architecture and component interactions are depicted in Fig. 1.

2.1.1. Hardware component

Arduino ESP32 is a system-on-chip (SoC) microcontroller that serves as a successor to the ESP8266. This module integrates various peripherals, including Bluetooth and Wi-Fi. The benefits of the ESP32 include its low cost, ease of programming, many I/O pins, and a built-in Wi-Fi adapter that enables internet connectivity [19], [20].

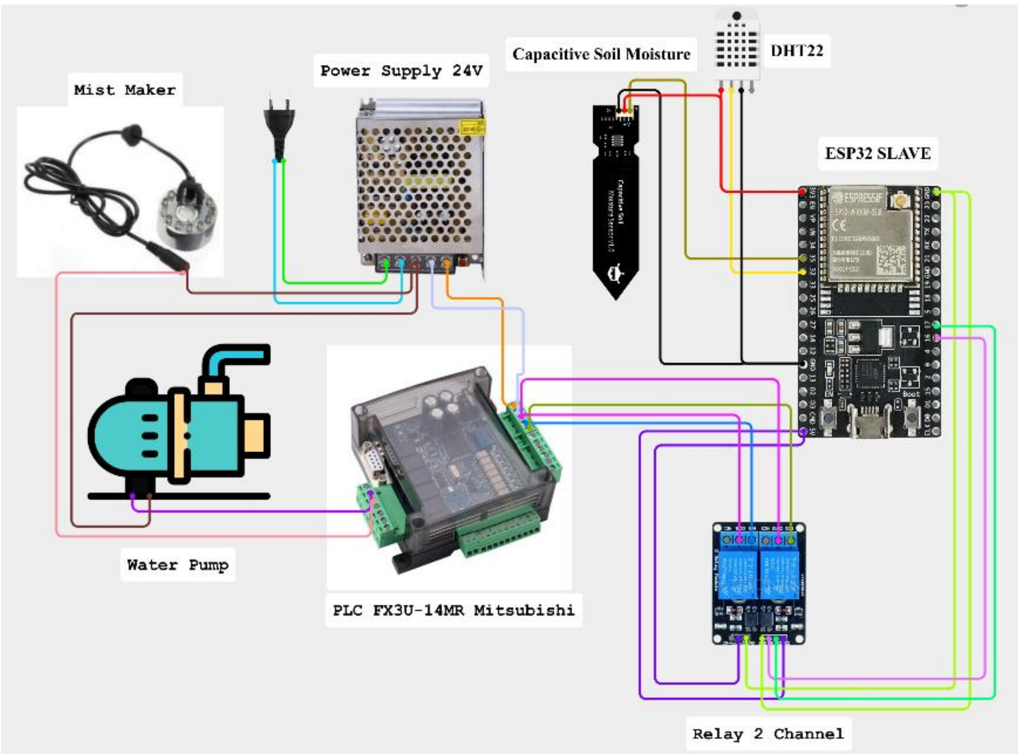

Fig. 1. Oyster mushroom automatic system design.

The DHT22 sensor is well known for its precision in measuring temperature and air humidity. Compared to DHT11, the DHT22 offers a significantly wider temperature range, higher temperature accuracy, and improved humidity range and accuracy [21]. Capacitive soil moisture sensors measure the moisture level by detecting resistance between two current-conducting probes [22]. Maintaining appropriate relative humidity and soil moisture levels—both measurable by capacitive sensors—is essential for increasing oyster mushroom yields [23].

Programmable Logic Controllers (PLCs) are designed to perform specific tasks such as logic control, sequencing, timing, counting, and arithmetic operations. PLCs use digital or analog I/O modules to store instructions in programmable memory [24]. They do not burden ESP32 and are more suitable for long-term use in automated systems. When the ESP32 is subjected to heavier loads under direct control, it tends to have a shorter operational lifespan. In this system, the PLC is used to control the water pump and mist maker via a 2-channel relay. A 24V power supply is used to power all components. The 2-channel relay acts as a bridge between the ESP32 and the PLC. While the ESP32 directs the relay, the PLC executes the system outputs.

As shown in Fig. 1, the ESP32 microcontroller is used to read input from both sensors, and the collected data is processed by the Mamdani fuzzy logic system to generate control decisions. The processed data is transmitted to both the MQTT communication system and the PLC, which is connected to the microcontroller. The water pump and mist maker are then regulated by the PLC based on the received data. The ESP32-based fuzzy logic control system is designed to operate locally, without full reliance on network connectivity. Although the MQTT connection facilitates real-time data monitoring, decision-making processes continue uninterrupted even if the Wi-Fi connection is lost. This ensures the autonomous and continuous operation of the system in regulating temperature, air humidity, and soil moisture.

2.1.2. Software components

The software design focuses on developing the necessary programs for comprehensive system management and intelligent data processing. This includes the implementation of Mamdani fuzzy logic algorithms and protocols for data communication.

2.2. Method

This section details the methodologies applied in the development of the automated oyster mushroom cultivation system, including the system's architectural approach, the comprehensive design of the Mamdani fuzzy logic controller, and the implementation of the Message Queuing Telemetry Transport (MQTT) communication protocol.

2.2.1. *Mamdani fuzzy logic design*

One component of intelligent control systems based on artificial intelligence and classical control is a fuzzy logic controller [25]. Like the human brain, it helps any system to be executed into logical processes that could enhance new technologies on accordance with system requirements. Therefore, it is an appropriate method for creating an automated environmental control system [26]. Specifically, fuzzy logic yields exact answers to data that is confusing, imprecise, or ambiguous. When it comes to modeling system that have input or output uncertainty, fuzzy logic has shown itself to be a useful tool [27]. Processing complicated, fluctuating data and establishing subtle control over the growing environment require the use of this AI technology [28], [29]. Gathering information for every input variable and constructing a membership function for every fuzzy set based on the smallest data value and the lowest data value for every fuzzy variable are the steps involved in the fuzzification process. After that, a rule is set up for every input variable [30].

Table 1
Temperature membership set level.

No	Temperature (° C)	Status
1	0-24	Cold
2	22-28	Ideal
3	29-32	Heat

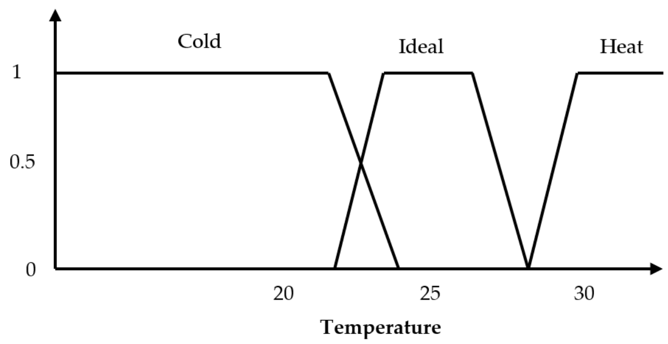

Fig. 2. Temperature membership chart.

Table 2
Air humidity membership set level.

No	Air humidity (%)	Status
1	0-75	Low
2	70-90	Ideal
3	85-100	Humid

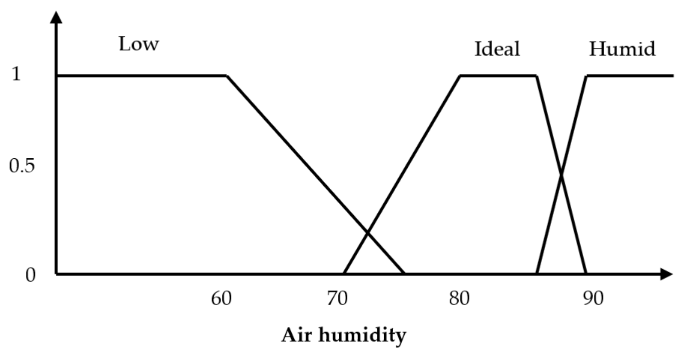

Fig. 3. Air humidity membership chart.

Table 3
Soil moisture membership set level.

No	Soil moisture (%)	Status
1	0-55	Dry
2	50-65	Ideal
3	60-80	Wet

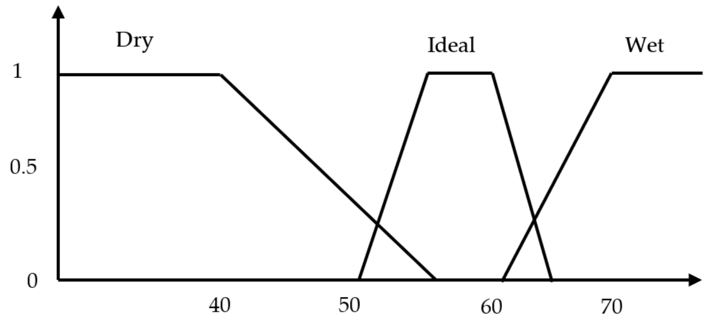

Fig. 4. Soil moisture membership chart.

Table 4
Water pump and mist maker membership set level.

No	Water pump and mist maker(s)	Status
1	0	OFF
2	1-15	ON

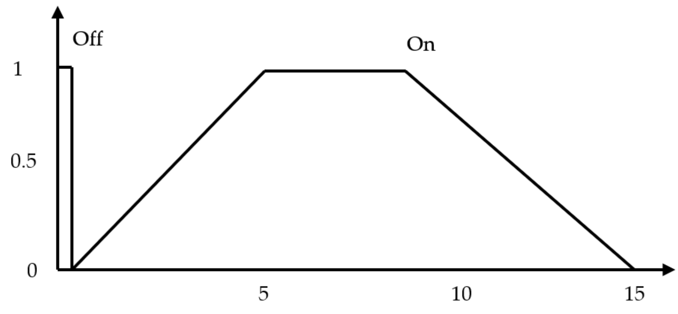

Fig. 5. Water pump and mist maker membership chart.

The Mamdani fuzzy logic method is utilized to design the intelligent control structure of the oyster mushroom cultivation automation system, ensuring that the hardware components operate with precision and efficiency. The design of the Mamdani fuzzy inference system consists of three core stages: fuzzification, rule evaluation (inference engine), and defuzzification.

In the fuzzification stage, crisp numerical inputs from the sensors are translated into fuzzy linguistic terms. This transformation is accomplished by defining membership functions for each fuzzy set, based on the operational range of each variable. For instance, the temperature input variable (°C) is divided into three fuzzy sets: Cold, Ideal, and Heat, with membership functions defined in Table 1 and visualized in Fig. 2 using Eqs. (1)–(3). Similarly, air humidity (%) is categorized into Low, Ideal, and Humid, with membership definitions shown in Table 2, Fig. 3, and Equations (4)–(6). The soil moisture (%) input follows the same pattern, using the fuzzy sets Dry, Ideal, and Wet, as detailed in Table 3, Fig. 4, and Equations (7)–(9). Finally, the output variable, which controls the activation duration (in seconds) of the water pump and mist maker, is defined by two fuzzy sets: OFF and ON, with details in Table 4, Fig. 5, and Equations (10)–(11).

The inference engine applies fuzzy rules constructed from expert knowledge and desired control conditions for optimal mushroom growth. Based on three fuzzy sets each for temperature, air humidity, and soil moisture, and two output conditions (ON and OFF), a total of twelve IF-THEN rules are developed. These rules form the basis of the decision-making process and are systematically outlined in Table 5.

Table 5
Mamdani fuzzy logic rules.

No.	Input			Output	
	Temperature	Air humidity	Soil moisture	Water pump	Mist maker
1.	Cold	Low	Dry	ON	OFF
2.	Cold	Ideal	Ideal	OFF	OFF
3.	Cold	Humid	Wet	OFF	OFF
4.	Ideal	Low	Dry	ON	OFF
5.	Ideal	Ideal	Ideal	OFF	OFF
6.	Ideal	Humid	Wet	OFF	OFF
7.	Heat	Low	Dry	ON	ON
8.	Heat	Ideal	Ideal	OFF	ON
9.	Heat	Humid	Wet	OFF	OFF
10.	Heat	Low	Wet	OFF	ON
11.	Heat	Ideal	Dry	ON	ON
12	Heat	Low	Ideal	OFF	ON

$$\mu_{cold}(x) = \left\{ \begin{array}{ll} 1, & x \leq 22 \\ \int \frac{24-x}{2}, & 22 < x \leq 24 \\ 0, & x > 24 \end{array} \right\} \quad (1)$$

$$\mu_{ideal}(x) = \left\{ \begin{array}{ll} 0, x \leq 22 \; or \; x \geq 28 & \\ \int \frac{x-23}{1}, & 22 < x \leq 23 \\ 1, & 23 < x \leq 25 \\ \int \frac{28-x}{3}, & 25 < x < 28 \end{array} \right\} \quad (2)$$

$$\mu_{heat}(x) = \left\{ \begin{array}{ll} 0, & x \leq 28 \\ \int \frac{x-30}{4}, & 28 < x \leq 30 \\ \int \frac{32-x}{2}, & 30 < x < 32 \\ 1, & x \geq 32 \end{array} \right\} \quad (3)$$

$$\mu_{low}(x) = \left\{ \begin{array}{ll} 1, & x \leq 60 \\ \int \frac{75-x}{15}, & 60 < x \leq 75 \\ 0, & x > 75 \end{array} \right\} \quad (4)$$

$$\mu_{ideal}(x) = \left\{ \begin{array}{ll} 0, x \leq 70 \; or \; x \geq 90 & \\ \int \frac{x-80}{10}, & 70 < x \leq 80 \\ 1, & 80 < x < 85 \\ \int \frac{90-x}{5}, & 85 < x < 90 \end{array} \right\} \quad (5)$$

$$\mu_{humid}(x) = \left\{ \begin{array}{ll} 0, & x \leq 85 \\ \int \frac{x-85}{10}, & 85 < x \leq 95 \\ 1, & x > 95 \end{array} \right\} \quad (6)$$

$$\mu_{dry}(x) = \left\{ \begin{array}{ll} 1, & x \leq 40 \\ \int \frac{55-x}{15}, & 40 < x \leq 55 \\ 0, & x > 55 \end{array} \right\} \quad (7)$$

$$\mu_{ideal}(x) = \left\{ \begin{array}{ll} 0, x \leq 50 \; or \; x \geq 65 & \\ \int \frac{x-50}{5}, & 50 \leq x \leq 55 \\ 1, & 55 < x \leq 60 \\ \int \frac{65-x}{5}, & 60 < x \leq 65 \end{array} \right\} \quad (8)$$

$$\mu_{wet}(x) = \left\{ \begin{array}{c} 0, \quad x \leq 60 \\ \int \frac{x-60}{10}, 60 < x \leq 70 \\ 1, \quad x > 70 \end{array} \right\} \tag{9}$$

$$\mu_{OFF}(x) = \left\{ \begin{array}{c} \int 1, \quad x = 0 \\ \int 0, \quad x > 0 \end{array} \right\} \tag{10}$$

$$\mu_{ON}(x) = \left\{ \begin{array}{c} 0, \quad x \leq 0 \\ \int \frac{x-0}{5}, 0 < x \leq 5 \\ 1,5 < x > 8 \\ \int \frac{15-x}{8}, 8 < x < 15 \\ 0, \quad x > 15 \end{array} \right\} \tag{11}$$

The final step, defuzzification, converts the fuzzy outputs from the inference process into a single crisp numerical value suitable for controlling the actuators. This study employs the Centroid (Center of Gravity) method, which determines the output by calculating the center of the area under the aggregated membership function. The result is a weighted average that effectively guides the water pump and mist maker to respond accurately to environmental changes.

2.3. Structural approach

The Mamdani fuzzy logic method is employed to design the structure of the oyster mushroom cultivation automation system, ensuring that the hardware system function correctly. This system comprises the following elements:

(1) Node MCU ESP32: Microcontroller that processes input command from the DHT22 sensor and the Capacitive soil moisture sensor. These commands are subsequently processed using fuzzy logic.
(2) Sensor DHT22: The DHT22 sensor is a digital temperature and air humidity that is capable of detecting the temperature and humidity in oyster mushroom cultivation chambers. It can be accessed using a microcontroller.
(3) Sensor Capacitive soil moisture: The Capacitive soil moisture sensor is designed to detect moisture in oyster mushroom baglog.
(4) Mamdani fuzzy logic: The Mamdani fuzzy logic operates by receiving data from the microcontroller, processing it using fuzzification rules, and subsequently controlling the output in the form of a mist maker dan water pump through the PLC.
(5) MQTT algorithm: A communication on the ESP32 that facilitates the efficient and real-time transmission of data between devices is the MQTT algorithm.
(6) PLC (Programmable Logic Control): The mist maker and water pump are controlled by the PLC, which acquires data from Mamdani fuzzy logic.
(7) Water pump: Water pump are employed to automatically irrigate oyster mushroom beds by employing water sprinkler as a media.
(8) Mist maker: The mist maker is responsible for maintaining the temperature and air humidity in the oyster mushroom, which is managed by a PLC.

3. Results and discussion

This automation system for oyster mushroom cultivation is designed to evaluate Mamdani fuzzy logic by comparing the system calculation result to those of manual calculations, as well as to evaluate the MQTT algorithm by examining the consistency of the original data and the data displayed by the algorithm.

3.1. Mamdani fuzzy logic testing

The Mamdani fuzzy logic will be tested by comparing the result of systematic calculation with manual calculations. The purpose of this test is to evaluate the suitability of fuzzy logic result. Five samples with different input values were used in this test. The following are the result of the Mamdani fuzzy logic test.

Table 6
Result of Mamdani fuzzy logic testing.

No	Sensor DHT22		Sensor capacitive soil moisture	Output		Status output	
	Temperature	Air humidity	Soil moisture (%)	System	Manual	Water pump	Mist maker
1	30° C	72.7%	40%	0.33	0.33	ON	ON
2	30.3° C	71.0%	40%	0.28	0.28	ON	ON
3	30.2° C	71.6%	89%	0.23	0.23	OFF	ON
4	28.3° C	50.6%	39%	0.15	0.15	ON	ON
5	28.1° C	49.7%	57%	0.05	0.05	OFF	ON

Table 7
Testing the Mamdani fuzzy logic systems.

No	Date/Time		DHT22 sensor		Capacitive soil moisture	Actuator		Data result
			Temperature	Humidity	Soil moisture	Water pump	Mist maker	
1.	16/06/2025	M	30.6° C	68.5%	39%	On	On	
		A	31.7° C	65.8%	41%	On	On	
		E	30.3° C	71.9%	71%	Off	On	
2.	17/06/2025	M	32.5° C	65.5%	40%	On	On	
		A	33.4° C	62%	43%	On	On	
		E	32° C	67.9%	84%	Off	On	
3.	18/06/2025	M	32.7° C	65.8%	45%	On	On	
		A	33.5° C	63.3%	49%	On	On	
		E	30.6° C	73%	60%	Off	On	
4.	19/06/2025	M	29.4° C	65%	50%	On	On	
		A	29.7° C	59.7%	53%	On	On	
		E	29.3° C	75%	60%	Off	On	
5.	20/06/2025	M	30.3° C	68%	55%	On	On	
		A	31.5° C	63.6%	61%	Off	On	
		E	30° C	78%	67%	Off	On	

Note: M = morning (08.00 AM), A = afternoon (12.00 PM), E = evening (17.00 PM)

By providing the output state of the water pump and mist maker, the acquired data was modified to Table 5, to determine the fuzzy logic rules. Once the fuzzy rule for the water pump or mist maker has been decided, Table 4 will be activated for fifteen seconds. Table 6, llustrates that the Mamdani fuzzy logic employed in the automation system to monitor temperature, air humidity, and soil moisture is consistent with the fuzzification formula. Additionally, manual testing was implemented in accordance with the fuzzification formula. Temperature, air humidity, and soil moisture are all considered when conducting manual testing. Fig. 1, displays the temperature fuzzification formula, Fig. 2, display the air humidity fuzzification formula, Fig. 3, display the soil moisture fuzzification formula.

3.2. Overall system data testing using Mamdani fuzzy logic

At this point, a fuzzy logic approach was used to test the entire system. DHT22 and capacitive soil moisture sensors operated as intended due to this method. The system was tested to ensure complete data capture. The information collected included manual comparisons of oyster mushroom growth and photos taken over a five-day period. Table 7 displays the test data collected three different times over five consecutive days using the Mamdani fuzzy logic system. White buds appeared on the surface of the baglog medium on the first day, marking the beginning of oyster mushroom growth.

On the second day, oyster mushrooms began to grow and spread over a portion of the baglog medium. On the third day, oyster mushrooms grew rapidly, covering the baglog medium with an increasing number of mushrooms. On the fourth day, one baglog was ready for harvest after demonstrating optimal oyster mushroom growth. On the fifth day, yellow patches began to emerge around the oyster mushrooms, indicating potential damage if not harvested immediately. Meanwhile, the oyster mushrooms on the other baglogs showed signs of full development and were nearly ready for harvest. From the first to the fifth day, the sensor data demonstrated effective outcomes, with each sensor data point approaching or exceeding the optimal level. According to the data collected, the water pump consistently shut off in the afternoon when the soil moisture reached the optimal level. Since the mist maker's goal is to reduce the temperature by 1–3° C and increase air humidity, it remained in operation from day one to day five. After data collection using the Mamdani fuzzy logic method, oyster mushroom growth data was manually gathered over five days. Photos of growth were taken daily for a maximum of five days to collect data.

According to Fig. 6, which shows data collection results, the oyster mushroom baglog displayed tiny white shoots on the first day, corresponding to the data collected using the Mamdani fuzzy logic method. This was done to precisely identify oyster mushroom growth. On the second day, the shoots began to expand, though they remained white on the oyster mushroom baglog, with less growth compared to the data from the Mamdani fuzzy logic method. On the third day, oyster mushrooms began to develop and spread to a portion of the baglog, but their growth remained modest. On the fourth day, the mushrooms were slightly larger than on the third day, suggesting they would continue to grow over the next few days. By the fifth day, the oyster mushrooms had expanded significantly and were ready for harvesting before they could deteriorate or turn yellow.

According to the two sets of data collected, oyster mushroom growth using the Mamdani fuzzy logic method differs from the manual approach. The difference is noticeable on the fourth and fifth days: oyster mushrooms cultivated with Mamdani fuzzy logic can be harvested on the fourth day, whereas those cultivated manually can be harvested on the fifth day. The data collected on oyster mushroom growth indicates that using an automation system with Mamdani fuzzy logic is highly effective for farmers, enabling faster oyster mushroom development compared to manual methods.

3.3. MQTT algorithm testing

The MQTT protocol is employed as a monitoring platform at this junction, displaying data on temperature, air humidity, and soil moisture. Testing the MQTT platfrom by examming the similarities in the data result that were obtained. In Fig. 7, graphs are employes to illustrate all data concerning temperature, air humidity, and soil moisture. A red line indicates temperature data, a blue line indicates air humidity data, and a green line indicates soil moisture data. This demonstrates that the MQTT algorithm platform is functioning properly and can be modified whenever data is updated.

(a) (b) (c) (d) (e)

Fig. 6. Manual data collection in oyster mushroom growth from: (a) the first day, (b) the second day, (c) the third day, (d) the fourth day, and (e) the last (fifth) day.

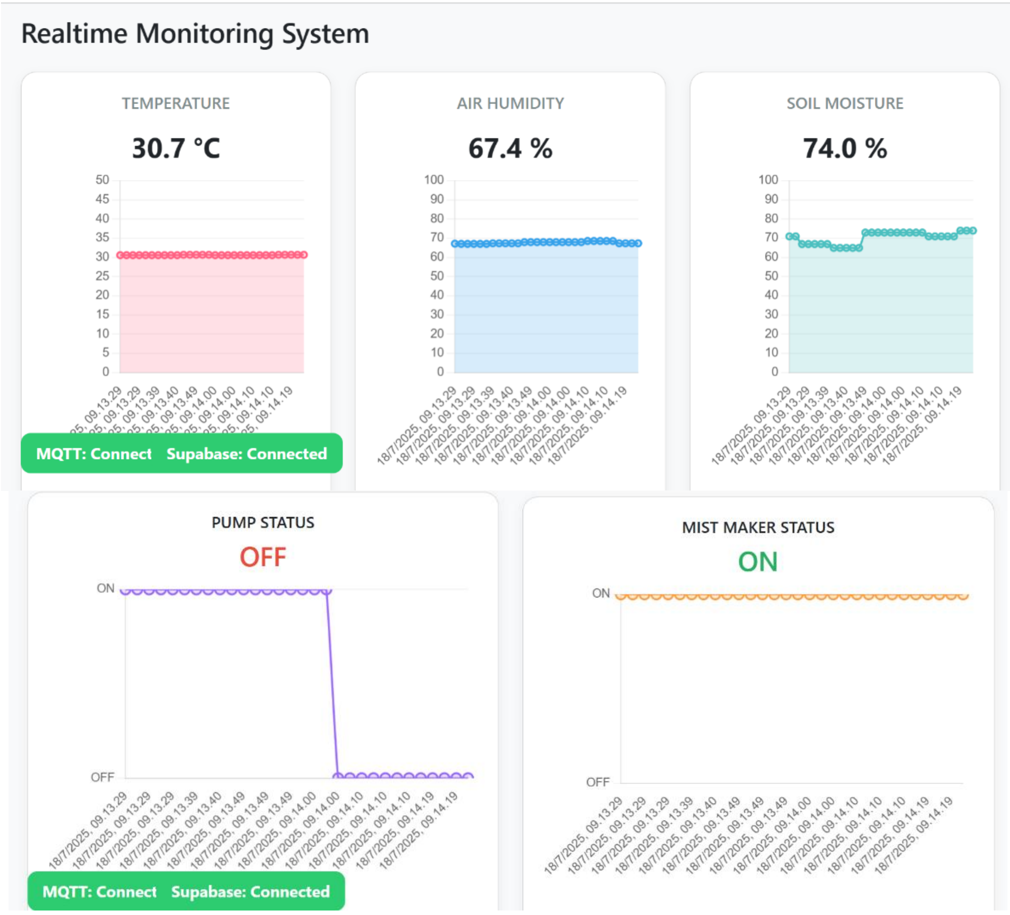

Fig. 7. Platform MQTT algorithm.

3.4. Comparison with others relevant research

To better contextualize the contribution of our proposed automation system—built on Mamdani fuzzy logic—for oyster mushroom cultivation, this section compares it with previous studies on environmental control systems in agriculture, particularly those focusing on mushroom farming. The comparison looks at system architecture, control algorithms, scalability, and practical performance, shedding light on both the strengths and limitations of our approach.

A study by [16] developed an environmental control system for oyster mushroom cultivation using an Outseal Programmable Logic Controller (PLC) and the Node-RED platform with RS485 communication. While the system offered accurate monitoring of temperature and humidity, it relied on fixed setpoints for control. This made it less responsive to dynamic environmental changes, which are essential for optimal mushroom growth. In contrast, our system leverages Mamdani fuzzy logic to enable adaptive decision-making based on real-time sensor data for temperature, air humidity, and soil moisture. As a result, it provides more precise environmental regulation, as demonstrated by an error rate of less than 5% when compared with manual calculations (see Table 6).

In another relevant study, [17] introduced an IoT-based system using an ESP32 microcontroller and DHT22 sensors, integrated with the Blynk app for remote monitoring and manual control via virtual buttons. Although this system enabled remote access, it lacked intelligent automation and still required human intervention, limiting its autonomy. Furthermore, the absence of a robust communication protocol such as MQTT hindered its scalability for larger applications. Our system addresses these issues by employing MQTT for reliable, real-time data transmission and incorporating Mamdani fuzzy logic for autonomous operation. This ensures the system can continue functioning even without a stable network connection—an essential feature for remote or low-infrastructure farming environments.

Similarly, [18] proposed an IoT-based control system using Mamdani fuzzy logic with ESP32 and DHT22 sensors to manage a fan and mist maker. Although the system achieved good accuracy in small-scale settings, it did not utilize industrial-grade hardware such as PLCs and failed to include soil moisture monitoring—a critical parameter for oyster mushroom cultivation. Our system fills these gaps by integrating a Mitsubishi FX3U-14MR

PLC for reliable industrial control and a capacitive soil moisture sensor for more comprehensive environmental monitoring. The ability to control soil moisture directly affects mushroom quality, which is evident in our results showing faster harvesting (one day earlier than manual methods) and more consistent yields (see Section 3).

A more recent study by [31] explored the use of fuzzy logic in greenhouse vegetable farming, utilizing temperature and humidity sensors with a Raspberry Pi controller. Although it delivered high precision, the system was computationally intensive and required a constant internet connection—making it less suitable for small to medium-scale farms with limited infrastructure. In contrast, our system is built on the lightweight ESP32 platform and can operate autonomously without full reliance on internet connectivity. This makes it a more practical option for small-scale oyster mushroom farmers. Additionally, the use of MQTT enables seamless scalability across multiple devices, as supported by [32].

When compared to [33], which applied deep learning for environmental control in mushroom farming, our approach proves to be more cost-effective and computationally efficient. Deep learning systems often require significant resources and large datasets for training, which may not be feasible for smallholder farmers. Our fuzzy logic-based system, however, delivers similar accuracy (with error rates below 5%) and faster harvesting results with far lower computational demands—making it more accessible for widespread use.

That said, our system is not without limitations. It currently relies on a single ESP32 and PLC unit, which may present challenges for very large-scale operations that require distributed control. Future work could explore distributed control architectures to improve scalability, as recommended by [34]. Additionally, while MQTT provides reliable communication, its performance in areas with poor network stability could be further improved through the integration of edge computing, as discussed in [35].

In summary, our proposed system advances existing solutions by combining Mamdani fuzzy logic, industrial-grade hardware, and MQTT-based IoT communication into a robust, autonomous, and scalable system for oyster mushroom cultivation. It improves upon fixed-setpoint systems [16], manually controlled IoT setups [17], and small-scale fuzzy logic models [18] through adaptive control, soil moisture monitoring, and more robust communication. Compared to computationally heavy approaches [31, 33], it offers a practical, affordable alternative for small to medium-scale farmers—delivering tangible benefits in harvest efficiency and yield consistency.

4. Conclusions

The primary objective of this study was to design and implement an IoT-based automation system utilizing Mamdani fuzzy logic and MQTT communication to optimize environmental conditions for oyster mushroom cultivation. The system integrated a Mitsubishi FX3U-14MR PLC, an ESP32 microcontroller, DHT22 sensors for temperature and humidity, and capacitive soil moisture sensors to precisely regulate critical parameters—temperature (22°C–28°C), air humidity (80%–90%), and soil moisture (50%–65%). The findings demonstrate that the system achieved high accuracy, with an error rate below 5% compared to manual calculations, reduced crop failure risks, and accelerated harvest times by up to one day compared to traditional methods. These results highlight the system's ability to enhance yield quality and operational efficiency by maintaining stable environmental conditions with minimal human intervention.

Despite its successes, the system has limitations, notably its reliance on a single ESP32 and PLC unit, which may constrain scalability for large-scale operations. The MQTT protocol, while reliable, could face challenges in areas with unstable network connectivity. The implications of this study suggest that the proposed system offers a practical, scalable solution for small- to medium-scale oyster mushroom farmers, improving productivity and reducing labor. For future research, exploring distributed control architectures and integrating edge computing could enhance scalability and performance in low-connectivity environments. Additionally, incorporating advanced machine learning techniques could further refine environmental control precision, building on the foundation established by this fuzzy logic-based approach.

Declaration statement

Andrian Zola is a final-year undergraduate student, was accountable for the final review, supervision, literature review, sample preparation, data collection, initial draft writing, methodology, and overall research design of the manuscript**. Lindawati and Sholihin** were involved in the writing process, specifically in the areas of review and editing, literature review, validation, anf manuscript writing**.**

Acknowledgement

The author is profoundly grateful to all individuals who have assisted in the investigation process. Furthermore, we would like to extend our gratitude to the lecturers and acquaintances who have provided assistance during the data collection phase of this research.

Disclosure statement

The authors declare no conflicts of interest.

Funding statement

The study was conducted independently without external financial support.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article or its supplementary materials.

AI Usage Statement

This manuscript utilizes generative AI and AI-assisted tools to improve readability and language. All AI-generated content has been reviewed and edited by the authors to ensure accuracy and scientific integrity. The authors take full responsibility for the content and conclusions of this work and disclose the use of AI to maintain transparency and comply with publisher guidelines.

References

[1] R. Nur et al., "Pengatur suhu, kelembaban, dan intensitas cahaya pada kumbung jamur tiram menggunakan IoT," *J. Acad. Multidiscip. Res.*, vol. 1, no. 1, pp. 15–23, 2021.

[2] B. C. Wibowo, I. A. Rozaq, and T. P. Pratama, "Implementation of monitoring and control temperature and humidity based on IoT in the oyster mushroom cultivation room," *PROtek: J. Ilm. Tek. Elektro*, vol. 10, no. 2, pp. 85–90, 2023, doi: 10.33387/protk.v10i2.4863.

[3] N. A. Purwitasari, A. Umayah, R. Pratama, and A. Safitri, "Utilization of MEA medium for isolation and characterization of white oyster mushroom (*Pleurotus ostreatus*) and growth assessment on baglog," *J. Sci. Appl.*, vol. 9, no. 1, pp. 1–8, Jun. 2025, doi: 10.25081/jsa.2025.v9.9597.

[4] F. Irwanto et al., "IoT and fuzzy logic integration for improved substrate environment management in mushroom cultivation," *Smart Agric. Technol.*, vol. 7, pp. 100427, Feb. 2024, doi: 10.1016/j.atech.2024.100427.

[5] H. Rahman et al., "IoT enabled mushroom farm automation with machine learning to classify toxic mushrooms in Bangladesh," *J. Agric. Food Res.*, vol. 7, p. 100267, Mar. 2022, doi: 10.1016/j.jafr.2021.100267.

[6] S. P. Budiarto, "Intelligent system design for oyster mushroom cultivation using Mamdani fuzzy inference with Internet of Things (IoT)," *J. Inf. Syst. Eng. Bus. Intell.*, vol. 10, no. 1, pp. 86–104, 2024, doi: 10.47709/jisebi.v10i1.3178.

[7] R. J. Setiawan, A. Tarnadi, and I. Surfani, "Design and manufacture an automatic mushroom sprinkler based Internet of Things to increase oyster mushroom productivity," *JMPM (Jurnal Mater. dan Proses Manufaktur)*, vol. 5, no. 1, pp. 1–9, Jun. 2021, doi: 10.18196/jmpm.v5i1.12043.

[8] K. R. S. Suda, I. W. A. Suteja, M. A. S. Antara, I. G. E. W. Putra, and I. B. P. Wija, "Automatic temperature and humidity regulation system design for oyster mushroom growth," *Tepian*, vol. 6, no. 2, pp. 127–132, Jun. 2025, doi: 10.51967/tepian.v6i2.3251.

[9] A. N. Adzraa, "Program budidaya jamur tiram dalam meningkatkan minat berwirausaha warga belajar di Pusat Kegiatan Belajar Masyarakat (PKBM) Abdi Pertiwi Kota Serang," *J. Pengabdi. Kpd. Masy.*, vol. 2, no. 1, pp. 1–10, 2023.

[10] S. Arsella, M. Fadhli, and L. Lindawati, "Optimasi pertumbuhan jamur tiram melalui monitoring suhu dan kelembaban menggunakan teknologi IoT," *J. Resist. (Rekayasa Sist. Komputer)*, vol. 6, no. 1, pp. 34–42, Apr. 2023, doi: 10.31598/jurnalresistor.v6i1.1405.

[11] H. S. Dayananda, P. Thaneswer, H. S. Jiten, S. Naseeb, and P. Anubhab, "Design and implementation of an IoT-based microclimate control system for oyster mushroom cultivation," *Int. J. Agric. Technol.*, vol. 20, no. 4, pp. 1431–1450, Aug. 2024.

[12] D. A. Setiawati, S. G. Utomo, Murad, and G. M. D. Putra, "Design of temperature and humidity control system on oyster mushroom plant house based on Internet of Things (IoT)," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 712, no. 1, p. 012002, Mar. 2021, doi: 10.1088/1755-1315/712/1/012002.

[13] Y. Hendrawan, D. K. Anta, A. M. Ahmad, and S. M. Sutan, "Development of fuzzy control systems in portable cultivation chambers to improve the quality of oyster mushrooms," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 546, no. 3, p. 032013, Jun. 2019, doi: 10.1088/1757-899X/546/3/032013.

[14] W. R. Mendes, F. M. U. Araújo, R. Dutta, and D. M. Heeren, "Fuzzy control system for variable rate irrigation using remote sensing," *Expert Syst. Appl.*, vol. 124, pp. 13–24, Jun. 2019, doi: 10.1016/j.eswa.2019.01.043.

[15] R. Ben Ali, S. Bouadila, and A. Mami, "Development of a fuzzy logic controller applied to an agricultural greenhouse experimentally validated," *Appl. Therm. Eng.*, vol. 141, pp. 798–810, Aug. 2018, doi: 10.1016/j.applthermaleng.2018.06.014.

[16] F. O. Dayera and M. B. Palungan, "Smart farming: Sistem monitoring dan pengendalian lingkungan berbasis IoT untuk budidaya jamur tiram," *G-Tech: J. Teknol. Terap.*, vol. 8, no. 1, pp. 186–195, Jan. 2024.

[17] J. Tiram and M. Esp, "Sistem monitoring suhu dan kelembaban pada budidaya," *J. FORTEI Reg. VII*, vol. 4, no. 1, pp. 20–26, 2023.

[18] A. W. Dani, D. Y. Siahaan, Y. Yuliza, F. Sirait, and F. Supegina, "Rancang bangun smart garden untuk budidaya jamur tiram dengan metode sistem fuzzy Mamdani berbasis Internet of Things (IoT)," *J. Teknol. Elektro*, vol. 13, no. 2, pp. 108–115, Jul. 2022, doi: 10.22441/jte.2022.v13i2.008.

[19] K. Agustianto, R. Wardana, P. Destarianto, E. Mulyadi, and I. G. Wiryawan, "Development of automatic temperature and humidity control system in kumbung (oyster mushroom) using fuzzy logic controller," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 672, no. 1, p. 012090, Apr. 2021, doi: 10.1088/1755-1315/672/1/012090.

[20] D. Kusumayani and C. Suhery, "Simulasi Internet of Things (IoT) pada budi daya jamur tiram," *J. Inform. dan Rekayasa Elektron.*, vol. 6, no. 2, pp. 170–180, Nov. 2023, doi: 10.36595/jire.v6i2.966.

[21] K. P. Lestari, L. Lindawati, and S. Sholihin, "Implementasi NodeMCU ESP8266 pada alat pelacak kendaraan menggunakan global positioning system dan MiFi berbasis IoT," *J. Teknol. Sist. Inf. dan Apl.*, vol. 6, no. 2, pp. 229–236, Apr. 2023, doi: 10.32493/jtsi.v6i2.32558.

[22] A. Jaafar et al., "Grey Oyster Mushroom Automated System (GrOyMAS)," *APS Proc.*, vol. 7, pp. 45–57, Aug. 2023, doi: 10.5281/zenodo.8191838.

[23] A. Hardiwiguna and A. R. Nugraha, "Penentuan kelembaban tanah menggunakan metode fuzzy logic dengan capacitive soil moisture sensor dan Arduino Uno R3," *J. Teknol. Elektro*, vol. 12, no. 3, pp. 139–146, Sep. 2024.

[24] V. Popovych, M. Les, T. Shuplat, P. Bosak, M. Fitak, and N. Popovych, "The effects of temperature and moisture stress content on the extensive cultivation of the oyster mushroom," *Bull. Iraq Nat. Hist. Mus.*, vol. 15, no. 4, pp. 473–489, Dec. 2019, doi: 10.26842/binhm.7.2019.15.4.0473.

[25] T. W. O. Putri and M. I. Mowaviq, "Prototype of automatic conveyor system using programmable logic controller for educational purpose," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1173, no. 1, p. 012037, Jul. 2021, doi: 10.1088/1757-899X/1173/1/012037.

[26] R. Urbieta Parrazales, M. T. Zagaceta Álvarez, K. A. Aguilar Cruz, R. Palma Orozco, and J. L. Fernández Muñoz, "Implementation of a fuzzy logic controller for the irrigation of rose cultivation in Mexico," *Agriculture*, vol. 11, no. 7, p. 576, Jul. 2021, doi: 10.3390/agriculture11070576.

[27] D. Dipali, T. Subramanian, and G. S. Kumaran, "A smart oyster mushroom cultivation using automatic fuzzy logic controller," *J. Discret. Math. Sci. Cryptogr.*, vol. 26, no. 3, pp. 601–615, May 2023, doi: 10.47974/JDMSC-1731.

[28] S. R. Yahya et al., *Metode Fuzzy Logic*. Jakarta, Indonesia: Penerbit Universitas Indonesia, Jan. 2023.

[29] S. A. Ardy, "Enhancing mushroom yield productivity and cultivation efficiency with fuzzy logic and Internet of Things," *J. Appl. Eng. Technol. Sci.*, vol. 2, no. 2, pp. 83–94, Jun. 2024.

[30] A. Prasetyo, Y. Litanianda, F. Fadelan, A. R. Yusuf, and S. Sugianti, "Irrigation control using fuzzy logic on the Internet of Things agriculture system," *CESS (J. Comput. Eng. Syst. Sci.)*, vol. 7, no. 2, pp. 572–579, Jul. 2022, doi: 10.24114/cess.v7i2.37195.

[31] A. Prasetyo, M. B. Setyawan, Y. Litanianda, S. Sugianti, and F. Masykur, "Fuzzy method design for IoT-based mushroom greenhouse controlling," *INTENSIF: J. Ilm. Penelit. dan Penerapan Teknol. Sist. Inf.*, vol. 6, no. 1, pp. 81–91, Feb. 2022, doi: 10.29407/intensif.v6i1.16786.

[32] M. A. Spohn, “On MQTT Scalability in the Internet of Things: Issues, Solutions, and Future Directions,” *Journal of Electronics and Electrical Engineering*, vol. 1, no. 4, p. 4, Oct. 2022, doi: 10.37256/jeee.1120221687.
[33] C.-P. Lu, J.-J. Liaw, T.-C. Wu, and T.-F. Hung, “Development of a Mushroom Growth Measurement System Applying Deep Learning for Image Recognition,” *Agronomy*, vol. 9, no. 1, p. 32, Jan. 2019, doi: 10.3390/agronomy9010032.
[34] K. P. Schneider *et al.*, “A Distributed Power System Control Architecture for Improved Distribution System Resiliency,” *IEEE Access*, vol. 7, pp. 9957–9970, Jan. 2019, doi: 10.1109/access.2019.2891368.
[35] Tayyaba Anees, Q. Habib, A. S. Al-Shamayleh, W. Khalil, M. A. Obaidat, and Adnan Akhunzada, “The Integration of WoT and Edge Computing: Issues and Challenges,” *Sustainability*, vol. 15, no. 7, pp. 5983–5983, Mar. 2023, doi: 10.3390/su15075983.

Authors information

Andrian Zola is an undergraduate student in the Department of Electrical Engineering at Sriwijaya State Polytechnic, Indonesia. He is a final year student whose academic interest are in the Internet of Things (IoT), sensor-based applications, and microcontroller-based technology development for practical and low-cost engineering solutions.

Lindawati is an Associate Professor in the Department of Electrical Engineering at Sriwijaya State Polytechnic, Indonesia. She received her master’s degree from University of Indonesia. Her research interest include Data Modelling.

Sholihin is an Associate Professor in the Department of Electrical Engineering at Sriwijaya State Polytechnic, Indonesia. He received his master’s degree from Bandung Institute of Technology. His research interest include telecommunication, robotik, and antenna.