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IMPLEMENTATION OF IoT AND MAMDANI FUZZY LOGIC IN A GREENHOUSE DECISION SUPPORT SYSTEM

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Abstrak

Management of lettuce (Lactuca sativa L.) greenhouses at BUMDes Kasengan Village, Sumenep, has so far been manual, without standard instruments, so temperature, soil moisture, and light monitoring rely on worker estimates, risking delayed care responses. This study builds an IoT-based Decision Support System (DSS) combining an ESP32 microcontroller with DS18B20 (temperature), capacitive soil moisture, and LDR (light) sensors to monitor conditions in real time, automate watering via Mamdani Fuzzy Logic, and generate care recommendations via Simple Additive Weighting (SAW) shown on a website. The system used the Waterfall model: requirement identification, system design, hardware assembly, software implementation, and testing. Sensor data is processed by the ESP32 and sent via Wi-Fi to Blynk Cloud and a MySQL database for real-time access on the web dashboard. Testing showed the DS18B20 sensor had an average deviation of ±0.4°C, the soil moisture sensor below 5%, the relay responded within 1 second, and the 5V line stayed stable at 4.92 to 5.08V with the pump active. A three-day field test across 18 observation points showed SAW produced accurate watering decisions and recommendations for every observation, a 100% success rate exceeding the 85% target hypothesis. The system helps BUMDes Kasengan managers monitor conditions remotely, automate watering, and reduce reliance on manual supervision

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INTRODUCTION

A greenhouse is an agricultural building structure specifically designed to create a controlled growing environment for plants through the use of transparent materials such as UV plastic or glass, so that fluctuations in external weather can be suppressed while microenvironmental factors such as temperature, humidity, and light intensity can

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be kept within an optimal range (Gitakarma & Tjahyanti, 2024). As the concept has developed, it has evolved into the smart greenhouse, which combines sensors with an automatic Internet of Things (IoT)-based control system so that all environmental parameters can be monitored precisely and continuously (Rahman et al., 2024), improving operational efficiency without relying entirely on subjective manual supervision (Riskiawan et al., 2024).

BUMDes Kasengan Village grows lettuce (Lactuca sativa L.) because of its fast harvest cycle and high economic value (Rahman et al., 2024). However, its management is still manual and lacks standard measurement instruments; monitoring of temperature, soil moisture, and light intensity relies solely on workers' estimates, which risks delaying care responses when extreme environmental changes occur (Hutahaean et al., 2023). IoT technology offers a solution through the DS18B20 sensor for temperature, a soil moisture sensor for soil moisture, and an LDR for light intensity, capable of collecting data in real time over the internet (Purwiyanti et al., 2024), and has proven reliable for internet integration (Tundo et al., 2024). The sensor data is then processed using a Decision Support System (DSS) to generate structured action recommendations for managers (Hutahaean et al., 2023), combined with the Mamdani Fuzzy Logic method to improve accuracy in handling ambiguity in sensor values (Akhlak et al., 2024). This method processes environmental variables into IF-THEN logic rules to drive an automatic watering system adaptively (Pamungkas et al., 2025), and previous research has shown that IoT-based fuzzy approaches are effective in automating plant watering accurately (Nur et al., 2025) and can optimize water resource use compared with manual methods (Setiawan & Witanti, 2025).

Based on these issues, this study designs and implements an IoT-based DSS that displays DS18B20, soil moisture, and LDR sensor data in real time on a website interface (Liu et al., 2025), automates watering precisely using the Mamdani Fuzzy Logic method (Muttaqi et al., 2024), and generates care recommendations through the Simple Additive Weighting (SAW) method so that BUMDes Kasengan managers can maintain stable greenhouse microclimate conditions automatically (Ramadhani et al., 2025), allowing work efficiency and lettuce harvest quality to improve sustainably (Setiawan & Witanti, 2025).

The research problems addressed in this study are: (1) how an ESP32-based IoT system with DS18B20, soil moisture, and LDR sensors can monitor greenhouse environmental conditions in real time; (2) how applying a DSS on a website interface can automate watering and provide fast, accurate care recommendations; and (3) how the Mamdani Fuzzy Logic method can help the system translate sensor data into appropriate care recommendations. In line with these problems, this study aims to build an IoT-based monitoring system using an ESP32 and the three sensors above, apply a DSS to automate watering and provide care recommendations, and implement the Mamdani Fuzzy Logic method so that managers can make watering decisions quickly and efficiently. The system is limited to the lettuce greenhouse at BUMDes Kasengan Village with three input parameters (temperature, soil moisture, light intensity), using an ESP32 microcontroller, and produces two output forms: automatic watering duration and textual care recommendations on a web dashboard.

More broadly, digitalizing agricultural practices through IoT and DSS contributes to transforming village agriculture from experience-based management toward data-based management. For BUMDes with limited human resources for

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intensive round-the-clock supervision, an automatic system that can independently monitor and make care decisions provides added value in the form of labor efficiency, consistent care quality, and documentation of plant condition history that can serve as a basis for evaluating and planning the next planting cycle. This study is expected to serve as a reference for the application of appropriate technology for other village-owned enterprises with similar agricultural business characteristics.

LITERATURE REVIEW

Several prior studies serve as references in developing this system. Marpaung et al. designed a plant water requirement determination system using conceptual Fuzzy Sugeno without hardware implementation (Marpaung et al., 2026), whereas this study implements Fuzzy Mamdani directly on an ESP32 connected to physical sensors in real time. Imran et al. developed ESP32- and Fuzzy Logic-based greenhouse temperature monitoring with a DHT22 sensor and fan control (Imran et al., 2024), while this study monitors three parameters simultaneously and focuses on automatic watering. Rahman et al. developed a threshold-based smart greenhouse monitoring prototype for lettuce with an Android application (Rahman et al., 2024), whereas this study adds a Fuzzy Mamdani intelligence layer and uses a website interface. Nur et al. designed IoT- and Fuzzy Mamdani-based plant monitoring for durian seedlings with pH and rain sensors (Nur et al., 2025), differing in object and sensors from this study. Setiawan et al. developed an automatic grape watering DSS using ESP8266, Fuzzy Mamdani, and the Blynk application with an error of 0.01167 (Setiawan et al., 2024), whereas this study uses an ESP32 and an independent website interface with an added LDR sensor. Liu et al. developed a web-based DSS with Fuzzy TOPSIS for ranking superior production plant types (Liu et al., 2025), whereas this study integrates the website directly with field IoT sensor data through the SAW method.

A Decision Support System (DSS) is a computer-based system designed to support decision-makers in processing data, information, and decision models to produce careful and accurate recommendations, without fully replacing the role of the human decision-maker (Rahman et al., 2024). The main components of a DSS include Data Management, Model Management, and the Communication Subsystem (Rahman et al., 2024). In the context of agriculture, a DSS plays an important role because crop cultivation involves many dynamic environmental variables, so integrating a DSS with IoT and Fuzzy Logic enables real-time processing of sensor data and produces measurable action recommendations (Kurniasari et al., 2025).

The Internet of Things (IoT) connects physical devices such as sensors, actuators, and microcontrollers to the internet so they can communicate with one another and be controlled remotely and automatically; in modern agriculture this concept is known as Smart Farming (Mahkota & Kusriyanto, 2025). Implementing IoT in a greenhouse enables real-time monitoring of environmental conditions, which has been shown to increase productivity and resource-use efficiency, particularly for water and energy (Purwiyanti et al., 2024).

The ESP32 is a 32-bit dual-core Xtensa LX6 microcontroller equipped with an integrated 2.4 GHz Wi-Fi and Bluetooth module, making it well suited as the main device of an IoT system without additional communication modules, with a clock speed of up to 240 MHz and many GPIO pins to support simultaneous sensor and actuator connections (Purwiyanti et al., 2024). Compared with the ESP8266 or Arduino Uno, the

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ESP32 offers higher processing capability and a 12-bit ADC useful for reading analog sensors precisely (Hutahaean et al., 2023). Combining the ESP32 with fuzzy logic has been shown to produce a watering system with an automation success rate of over 93% (Marpaung et al., 2026).

This system uses three main sensors. The DS18B20 is a waterproof digital temperature sensor with an accuracy of ±0.5°C over a range of -55 to 125°C that uses the One-Wire protocol, requiring only a single data line (Pamungkas et al., 2025). The capacitive soil moisture sensor measures soil water content based on changes in the dielectric constant of the capacitive probe, is more corrosion-resistant than resistive sensors, and its output is converted by the ESP32's ADC into a moisture percentage (Setyawan et al., 2024). The LDR (Light Dependent Resistor) is a passive resistive component whose resistance is inversely proportional to light intensity, configured as a voltage divider so that changes in light produce an analog voltage that is categorized into fuzzy linguistic sets (Naufal et al., 2023).

Fuzzy logic was introduced by Lotfi A. Zadeh in 1965 as an extension of conventional binary logic, allowing a value to have a degree of membership on a continuous range from 0 to 1, effectively handling the uncertainty of linguistic variables such as "high temperature" or "very dry soil" that have no sharp boundaries (Mahkota & Kusriyanto, 2025). The Mamdani method, pioneered by Ebrahim Mamdani, was chosen because it produces intuitive and easily interpretable output, and consists of four main stages: (1) fuzzification, converting crisp input values from sensors into membership degrees in fuzzy sets using triangular, trapezoidal, or bell-shaped membership functions; (2) rule evaluation, evaluating each IF-THEN rule based on the input's membership degree; (3) aggregation, combining all rule-evaluation results into a single output fuzzy set; and (4) defuzzification, converting the output fuzzy set into a crisp value using methods such as centroid or mean of maximum (Akhlak et al., 2024).

Simple Additive Weighting (SAW) is a DSS method that assigns weight values to each criterion, then performs a ranking process that selects the best alternative based on the weighted sum of performance ratings for each alternative across all attributes. In this study, SAW is used to normalize three environmental criteria (temperature, soil moisture, and light intensity) into a priority score that determines care recommendations and pump actuation decisions (Liu et al., 2025).

The use of a greenhouse has been shown to significantly increase productivity and harvest quality compared with open-field cultivation, since plants can grow year-round undisturbed by rainy seasons, drought, or pests (Gitakarma & Tjahyanti, 2024). Lettuce (Lactuca sativa L.) has a harvest cycle of 30-45 days, grows optimally at a temperature of 15-25°C, soil moisture of 60-80% of field capacity, and light intensity of 10,000-20,000 lux, so understanding these physiological requirements forms the basis for defining the fuzzy membership functions in the system (Nur et al., 2025).

RESEARCH METHODS

This study falls under software engineering and hardware engineering (embedded systems) research, of the research and development type, intended to engineer, build, and test an IoT- and fuzzy logic-based DSS for lettuce care recommendations in the BUMDes Kasengan Village greenhouse. The approach used is quantitative, since the data collected are numerical sensor measurement results analyzed

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through descriptive statistics, complemented by a qualitative approach during the requirements analysis stage through interviews with the greenhouse manager.

The research object is the IoT- and fuzzy logic-based DSS implemented in the lettuce greenhouse owned by BUMDes Kasengan Village, Sumenep. The input variables include growing-medium temperature (°C) from the DS18B20, soil moisture (%) from the capacitive soil moisture sensor, and light intensity (ADC/lux) from the LDR. The process variables include Mamdani Fuzzy Logic to determine automatic watering duration and the SAW-based DSS to determine care recommendations. The output variables consist of automatic watering duration (seconds) controlled through the water pump and textual care recommendations displayed on the DSS website.

System development uses the Waterfall model, chosen because the project's characteristics require clear requirement specifications from the outset, close interdependence between hardware and software, and well-defined stages. The research stages include problem identification and requirements analysis, system design, hardware assembly, software implementation, and system testing, as shown in Figure 1.

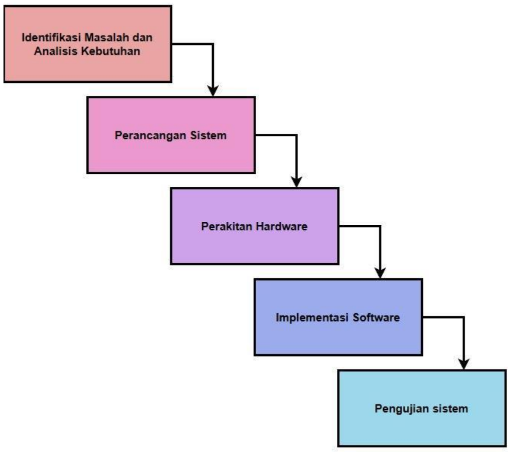

Figure 1. Research Flow Diagram (Waterfall Model)

Sumber: Researcher Documentation (2026)

The problem identification stage was carried out through observation and interviews at the BUMDes Kasengan greenhouse to determine the parameters to be monitored and the requirements for the DSS website system. The system design stage produced hardware and software block diagrams, the system workflow, and the Fuzzy Logic membership functions and rule base. The hardware assembly stage included component selection, circuit design, and sensor installation in the greenhouse. The software implementation stage covered programming the ESP32 using the Arduino IDE for sensor reading, the fuzzy process (fuzzification, inference, defuzzification), and sending data to the DSS website via Wi-Fi. The system testing stage ensured sensor reading accuracy, recommendation accuracy, data accuracy on the website, and real-time system stability. Details of the hardware components are presented in Table I.

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Table I. System Hardware Instruments

No.	Component	Main Function
1	ESP32 DevKit V1	Main processing unit, runs Fuzzy Logic and Wi-Fi communication
2	DS18B20	Growing-medium temperature sensor, accuracy ±0.5°C, One-Wire protocol
3	Capacitive Soil Moisture	Soil moisture sensor, 0-3.3V analog voltage output
4	LDR	Light intensity sensor as a voltage divider
No.	**Component**	**Main Function**
5	1-Channel Relay Module	Galvanically isolated electronic switch for the pump
6	Mini DC Water Pump	Watering actuator, 3-5V, flow rate 1-3 L/min
7	5V DC Adapter	Power supply for the ESP32, sensors, and relay module

Source: Data processed by the researchers (2026)

The software instruments include the Arduino IDE for programming the ESP32, XAMPP (Apache, MySQL, PHP) as the local server stack, Visual Studio Code for building the website interface, the PHP programming language for running the SAW logic, MySQL for storing sensor time-series data, and a web browser as the visualization medium for users, as summarized in Table II.

Table II. System Software Instruments

No.	Software	Main Function
1	Arduino IDE	ESP32 programming, Wi-Fi configuration, and sensor sampling
2	XAMPP (Apache, MySQL, PHP)	Local server stack for the web and database
3	Visual Studio Code	Website interface development editor
4	PHP	SAW calculation logic and database queries
5	MySQL	Storage of sensor time-series data and history
6	Web Browser	Dashboard visualization medium for users

Source: Data processed by the researchers (2026)

In addition to sensors, the system is also equipped with actuators and supporting components. The 1-channel relay module functions as an electronic switch that provides galvanic isolation between the low-voltage ESP32 control circuit and the water pump circuit, which requires greater power, thereby protecting the microcontroller from back-current surges while improving the system's overall operational safety. The mini DC water pump physically distributes water to the lettuce growing medium and operates automatically based on the Fuzzy Logic decision processed by the ESP32, so that watering only occurs when the plants genuinely need water. The 5V DC adapter serves as the power source that converts AC voltage from the electrical grid into a stable DC voltage suited to the needs of all electronic components in the system, where output voltage stability is a critical aspect since voltage fluctuations can cause sensor reading errors or permanent damage to the microcontroller (Sadali et al., 2024).

The system design is divided into three main components: input, process, and output, as shown in Figure 9. The input component consists of the Soil Moisture and LDR sensors and the air temperature/humidity sensor, which periodically read the greenhouse's physical conditions. The process component includes data reading by the ESP32, sending data to Blynk Cloud via Ngrok tunneling, SAW calculations to normalize criteria and weight water-need priorities, determining care recommendations,

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and storing results in the database. The output component displays sensor data in real time, care recommendations, and recommendation history on the website dashboard.

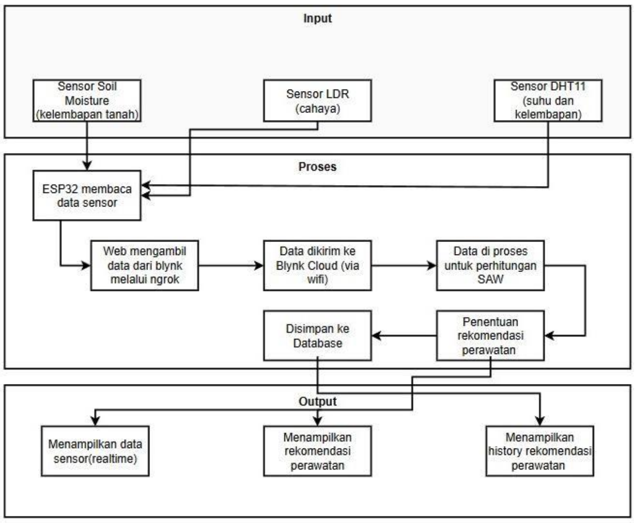

Figure 2. System Design (Input, Process, Output)

Sumber: Researcher Documentation (2026)

The system database is an important foundation in the IoT ecosystem for storing and managing data collected from various sensors; in the context of a smart greenhouse, the database serves not merely as storage but also as a source of information for review and decision-making (Aryawan & Supriyanto, 2025). The system database consists of two main, interrelated tables based on the system workflow, as summarized in Table III.

Table III. System Database Table Structure

Table	Main Fields	Function
sensor_data	temperature, humidity, light, soil1-3, pump_status, created_at	Real-time buffer of sensor reading results
history_tanam	jam, t1-t3, kondisi_akhir, rekomendasi	Periodic log of SAW analysis results and recommendations

Source: Data processed by the researchers (2026)

The sensor_data table serves as a dynamic, continuously updated input data buffer, while the history_tanam table serves as a log table that records data periodically based on the results of SAW method processing. Each time the SAW method runs, the calculation results and sensor values at that moment are copied into the history_tanam table so that the system's decision history is well documented, making it easier for users to track past irrigation performance through the history feature on the monitoring dashboard.

The system hardware design connects the Soil Moisture sensors at three plant points to the ADC pin, the temperature and humidity sensor to the DHTPIN pin, and the LDR sensor to the LDR_PIN pin. The ESP32 Development Board runs the SAW algorithm to determine watering priority and sends data via Wi-Fi to Blynk Cloud and the local MySQL server. The main output is a relay module that operates on active-low logic to control the water pump, supported by separate power supplies of 5V DC for the logic components and 12V DC for the pump.

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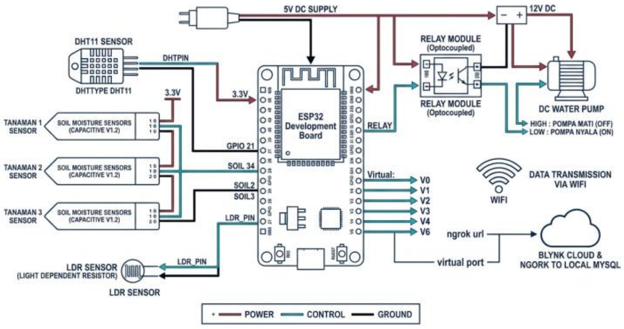

Figure 3. System Hardware Design Schematic

Sumber: Researcher Documentation (2026)

Data collection in this study used four techniques: field observation, interviews, literature review, and experimentation. Field observation was carried out through direct observation at the BUMDes Kasengan Village greenhouse to understand the actual conditions, manual monitoring process, and problems faced by the manager. Interviews were conducted with the greenhouse manager to gather information on environmental parameters that are often problematic, lettuce care habits, and expectations for the system to be developed. The literature review was conducted through the study of journals, books, proceedings, and theses relevant to the topics of IoT, greenhouses, Mamdani Fuzzy Logic, SAW-based DSS, and the DS18B20, soil moisture, LDR, and ESP32 sensors. Experiments, or direct measurements, were conducted to collect primary data in the form of temperature, soil moisture, and light intensity values, the watering duration produced by the system, and the care recommendations displayed during field testing.

Data analysis was conducted descriptively and quantitatively through several techniques. Sensor accuracy analysis compared the readings of the DS18B20, soil moisture, and LDR sensors against a reference measuring instrument. Mamdani Fuzzy Logic validation analysis measured the time from sensor reading to pump actuation using the ESP32's millis function so the system responds within ≤ 10 seconds. Finally, system stability analysis measured the percentage of time environmental conditions remained within the optimal range for lettuce growth.

RESULTS AND DISCUSSION

The hardware implementation focuses on integrating the ESP32 Development Board as the central computing unit that manages all sensor inputs and actuator outputs. All sensors have been connected with organized wiring, and separating the power supply lines between the logic components (5V) and the water pump actuator (12V) proved effective in preventing voltage drop when the pump is activated. The layout of the IoT components in the planting container is shown in Figure 4, where the ESP32 module is connected to the humidity sensor, light sensor, and ambient temperature sensor, with the rule that the humidity sensor must be placed level with the base of the planting container for ideal water management. The physical form of the assembled system is shown in Figure 5, while the placement of the humidity sensor in the planting container is shown in Figure 6.

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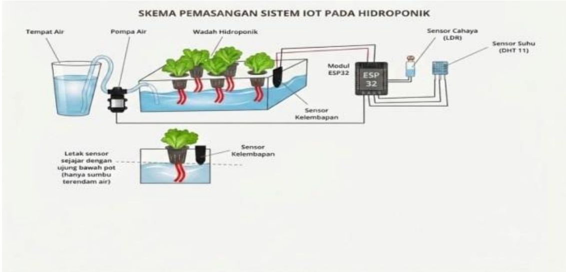

Figure 4. Layout of the IoT System in the Planting Container

Sumber: Researcher Documentation (2026)

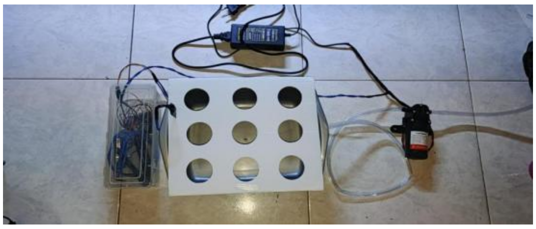

Figure 5. System Hardware Implementation

Sumber: Researcher Documentation (2026)

Figure 6. Placement of the Soil Moisture Sensor in the Planting Container

Sumber: Researcher Documentation (2026)

Functionality testing covered Wi-Fi connectivity, sensor reading, SAW logic, and relay actuation. All tests were declared successful, as presented in Table IV.

Table IV. System Functionality Testing Results

No.	Feature	Result	Notes
1	Wi-Fi Connection	Successful	Stable
2	Sensor Reading	Successful	Matches calibration
3	SAW Logic	Successful	Matches criteria
4	Relay Actuation	Successful	Real-time

Source: Data processed by the researchers (2026)

This implementation proves that integrating IoT devices with the SAW method can make plant care more efficient. The system shows good responsiveness, where changes in soil moisture conditions detected by the sensor are immediately processed by the ESP32 to automatically trigger the pump relay. In addition, storing data in the MySQL database enables long-term performance analysis, which ultimately provides more measurable care recommendations compared with conventional manual methods.

Sensor accuracy testing was carried out by comparing the readings against a calibrated reference measuring instrument, as presented in Table V. The DS18B20 sensor showed an average deviation of ±0.4°C, still within the manufacturer's

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specification tolerance (Setyawan et al., 2024); the capacitive soil moisture sensor produced an average deviation of less than 5% and proved stable, unaffected by electrode corrosion (Setyawan et al., 2024); while the LDR sensor was able to respond to changes in light intensity consistently, making it reliable for categorizing lighting conditions into fuzzy linguistic sets (Naufal et al., 2023).

Table V. Sensor Accuracy Testing Results

No.	Sensor	Test Parameter	Test Result	Notes
1	DS18B20	Temperature accuracy	Deviation ±0.4°C	Within specification
2	Soil Moisture	Moisture accuracy	Deviation < 5%	Stable, corrosion-resistant
3	LDR	Light response	Responsive & consistent	Distinguishes dark/dim/bright

Source: Data processed by the researchers (2026)

Actuator testing focused on the 1-channel relay module and the mini water pump, which function as the automatic watering system, to ensure that commands from the ESP32 can be executed accurately and without significant delay. The relay module responded to ESP32 control signals in under 1 second, so watering could be carried out in real time according to the fuzzy logic results, and the mini water pump proved to turn on with a stable flow rate when the relay was active. Using a relay provides galvanic isolation between the low-voltage ESP32 control circuit and the water pump circuit, which requires greater power, thereby protecting the microcontroller from back-EMF surges that could damage components.

Power stability testing was carried out by measuring the voltage on the 5V and 12V lines while the system was operating at full load, including when the water pump was ON, as presented in Table VI.

Table VI. Power Supply Stability Testing Results

Line	Component	Load Condition	Measured Voltage
5V DC	ESP32 & sensors	Pump OFF	5.05 V
5V DC	ESP32 & sensors	Pump ON	4.92-5.08 V
12V DC	Mini water pump	Pump ON	11.8-12.1 V

Source: Data processed by the researchers (2026)

Based on Table VI, separating the power supply lines proved effective in maintaining voltage stability. When the water pump was activated, no significant voltage drop occurred on the 5V line supplying the ESP32 and sensors; the voltage remained within the 4.92V-5.08V range, still within the ESP32's operational tolerance, so sensor readings and computation were not disrupted by power fluctuations caused by the actuator (Sadali et al., 2024). As a result, the system was able to operate continuously and stably for 24 hours without power supply disruption.

Connectivity testing was carried out to ensure the ESP32 could connect to the Wi-Fi network and send data to Blynk Cloud and the local database server via Ngrok tunneling consistently, since the entire monitoring and decision-making process depends on the availability of real-time data, as summarized in Table VII.

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Table VII. Wi-Fi Connectivity and Data Communication Testing Results

No.	Test Scenario	Result	Notes
1	Wi-Fi connection to router	Successful	Stable, sufficiently strong signal
2	Data transmission to Blynk Cloud	Successful	Data sent in real time
3	Communication via Ngrok to local server	Successful	Dynamic session, needs periodic renewal
4	Brief connection loss	Successful	Automatic reconnection without data loss

Source: Data processed by the researchers (2026)

The results in Table VII show the ESP32 successfully connected to the Wi-Fi network and transmitted data at each predetermined interval. When a brief connection loss occurred, the ESP32 was able to reconnect automatically without significant data loss. For data communication via Ngrok, the system successfully transmitted data from the ESP32 to the local server, although the tunneling session is dynamic and requires renewal if the connection is interrupted for a long time. Overall, the system's connectivity was found to be reliable for supporting remote monitoring operations.

Plant condition testing was carried out over three days with a total of 18 observation points at predetermined time intervals, covering readings of temperature (DS18B20), light intensity (LDR), and soil moisture (capacitive soil moisture) processed in real time to produce environmental condition status along with care recommendations and pump actuation decisions. A portion of the observation results from the first day is presented in Table VII. The system proved to respond adaptively to every condition change; for example, the irrigation pump activated automatically when the temperature reached 31°C with dry soil conditions, and stopped immediately once soil moisture was restored.

Table VIII. Example Plant Condition Observation Results, Day 1

Time	Temperature	Light	Soil	DSS Status	Pump
08:00	24.5°C (Ideal)	Bright	Wet	Low Score	OFF
11:30	29.2°C (Hot)	Bright	Moist	Medium Score	OFF
13:00	31.0°C (Hot)	Bright	Dry	High Score	ON
13:05	29.8°C (Hot)	Bright	Wet	Medium Score	OFF
16:00	26.0°C (Ideal)	Dim	Moist	Low Score	OFF
19:30	22.1°C (Ideal)	Dim	Wet	Low Score	OFF

Source: Data processed by the researchers (2026)

The same pattern repeated consistently on the second and third days of testing: the pump was only active when the SAW score was in the high category due to the combination of high temperature and dry soil, while under other conditions the system provided non-actuation recommendations, such as advising to open the ventilation when the temperature was high but the soil was still moist, or a warning of suboptimal light intensity in the afternoon and evening.

Testing of the SAW method was carried out over three days with a total of 18 observation points to measure the system's success in generating automatic watering decisions based on the normalization of three environmental criteria. The system successfully detected three critical conditions and responded by activating the pump appropriately, while keeping the pump off in the other 15 non-critical conditions, as presented in Table IX.

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Table IX. Simple Additive Weighting (SAW) Calculation Results

Day	Total Observations	Critical Conditions	Correct Decisions	Success Rate
1	6	1	6	100%
2	6	1	6	100%
3	6	1	6	100%
Total	18	3	18	100%

Source: Data processed by the researchers (2026)

$$Success\ Rate\ (\%) = \frac{Number\ of\ Correct\ Decisions}{Total\ Observations} \times 100\%$$

Based on Table IX and equation, out of a total of 18 observations, all of the system's decisions were found to be correct, achieving a 100% success rate. This result exceeds the study's initial hypothesis, which targeted a care recommendation accuracy of ≥85%, supported by the system's ability to normalize multiple criteria proportionally against the combined weights of temperature, soil moisture, and light intensity simultaneously. The irrigation pump consistently activated automatically when the soil was detected as dry at high temperature (above 31°C) and stopped immediately once soil moisture was restored, while textual recommendations such as "open the ventilation" or "light intensity suboptimal" were displayed dynamically on the dashboard according to the greenhouse's actual conditions.

The results obtained were then combined with a discussion containing an in-depth interpretation of these findings. The discussion not only explains what was found, but also relates it to theory, concepts, and relevant prior research, thereby contributing more broadly to reinforcing or even challenging previous findings. The relationship between the research results and a broader context includes an analysis of the factors influencing the outcomes, the practical implications that may arise, and the potential for further research development, all supported by logical, structured argumentation grounded in credible data and scientific references. Overall, the findings confirm that the automatic watering decisions and care recommendations produced by the system are consistent with the actual environmental conditions of the greenhouse, reinforcing the practical value of combining IoT sensing with Mamdani Fuzzy Logic and SAW-based decision support for small-scale precision agriculture.

CONCLUSION

This study has successfully developed an Internet of Things (IoT)- and fuzzy logic-based greenhouse Decision Support System (DSS) designed to support lettuce plant care at BUMDes Kasengan Village. The system uses an ESP32 integrated with a DS18B20 sensor, a capacitive soil moisture sensor, and an LDR (Light Dependent Resistor) sensor to monitor environmental conditions in real time. Through the implementation of fuzzy logic, the system can control watering duration automatically and adaptively. The system's main advantages lie in its ability to automate more proportional decisions, isolated power stability, data transparency through MySQL, and flexible remote monitoring.

Although it achieved 100% success at 18 observation points, the system still has several limitations, such as dependence on an internet connection, the dynamic nature of Ngrok tunneling, and limited scalability for wider coverage areas. In addition, the limited observations have not yet covered variations in extreme weather conditions over

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a full planting cycle, so long-term testing is still needed to validate the consistency of its performance. The functional testing results show good operational stability, with the DS18B20 sensor having an average deviation of ±0.4°C and the soil moisture sensor below 5%, along with a fast relay module response and a stable 5V line voltage. Overall, this system has great potential for optimizing plant care, reducing the risk of harvest failure, and improving water-use efficiency. Future work should extend field testing across a full planting cycle and a wider range of weather conditions, and explore local data processing to reduce dependence on external tunneling services.

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