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Comparison Effectiveness of Fuzzy Mamdani and Sugeno for Automatic Irrigation of Brazilian Spinach Crops

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ABSTRAK

Penelitian ini membahas perbandingan algoritma Fuzzy Mamdani dan Fuzzy Sugeno dalam sistem penyiraman otomatis tanaman bayam Brazil. Sistem ini dirancang menggunakan Arduino Uno dengan sensor kelembapan tanah dan suhu DS18B20 sebagai input fuzzy, serta sensor kelembapan udara untuk monitoring lingkungan. Modul RTC DS3231 digunakan untuk penyiraman terjadwal. Logika fuzzy menentukan durasi penyiraman berdasarkan kondisi lingkungan. Kedua metode diuji pada kondisi identik untuk menilai respons sistem, efisiensi air, dan akurasi kendali. Hasil menunjukkan bahwa Sugeno unggul dalam kecepatan eksekusi, namun Mamdani lebih fleksibel dalam pengaturan aturan dan memberikan kendali yang lebih presisi. Berdasarkan evaluasi, metode Fuzzy Mamdani dipilih untuk implementasi akhir karena lebih sesuai dengan kebutuhan sistem irigasi berbasis mikrokontroler. Penelitian ini mendukung pengembangan sistem irigasi hemat air dan adaptif terhadap kondisi lingkungan tanaman.

Keywords:

Fuzzy Mamdani
Fuzzy Sugeno
Automatic irrigation
Arduino Uno

ABSTRACT

This research discusses the comparison of Fuzzy Mamdani and Fuzzy Sugeno algorithms in an automatic watering system for Brazilian spinach plants. The system is designed using Arduino Uno with DS18B20 soil moisture and temperature sensors as fuzzy inputs, and an air humidity sensor for environmental monitoring. RTC module DS3231 is used for scheduled watering. Fuzzy logic determines the duration of watering based on environmental conditions. Both methods were tested under identical conditions to assess system response, water efficiency, and control accuracy. Results show that Sugeno excels in execution speed, but Mamdani is more flexible in rule setting and provides more precise control. Based on the evaluation, the Fuzzy Mamdani method was chosen for the final implementation as it better suits the needs of microcontroller-based irrigation systems. This research supports the development of a water-efficient irrigation system that is adaptive to crop environmental conditions.

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1. INTRODUCTION

Optimal water availability and adaptive irrigation systems are important aspects in supporting plant growth, especially in modern agriculture. Brazilian spinach (Alternanthera sissoo) is one type of plant that requires a maintained soil moisture level to maintain optimal crop quality and quantity. One of the main challenges in agriculture is inefficient watering, either due to excess or lack of water, which can have an impact on plant health.[1][2] An automatic watering system supported by intelligent control technology is a solution to overcome this problem. By combining microcontroller technology and fuzzy logic, irrigation systems can be made more responsive to environmental conditions.

A number of studies have explored the use of fuzzy logic for automatic irrigation systems. For example, Furqan et al [3] applied the Fuzzy Sugeno method to an eggplant watering system with soil moisture and air temperature parameters. The results show that a watering duration of 21 seconds is able to maintain soil moisture in the optimal range of 40-60%.

Chakchouk & Ben Regaya [4] compared the performance of Mamdani and Sugeno in an automatic flower irrigation system. They found that although the difference in output between the two methods was not significant, the Sugeno method gave a simpler integer value as output, while Mamdani produced a more detailed value (real number).

This research proposes a comparative implementation of Mamdani and Sugeno fuzzy methods on an automatic watering system for Brazilian spinach plants based on Arduino Uno. The system is equipped with an RTC DS3231 module for scheduled watering and an ESP8266 module for IoT-based monitoring through the Blynk platform. The system is designed to improve watering accuracy by regulating watering duration based on soil moisture and air temperature conditions. The main objective of this research is to evaluate the performance of the two fuzzy methods in terms of responsiveness, water use efficiency, and decision accuracy, in order to determine the most appropriate method for final implementation in a microcontroller-based watering system.

2. RESEARCH METHODS

This research uses an experimental approach by comparing two fuzzy logic methods, namely Fuzzy Mamdani and Fuzzy Sugeno, in an automatic watering system for Brazilian spinach plants based on the Internet of Things (IoT). The purpose of this research is to evaluate the effectiveness of both methods in regulating the duration of watering based on environmental parameters in the form of soil moisture. Research Methods can be seen in Figure 1.

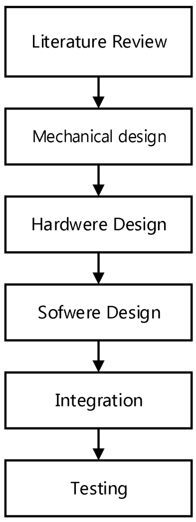

Figure 1. Flowchart in this Research

The flowchart in Figure 1 illustrates the sequence of major steps in the system design and development process. The stages start from; (i) Literature Study, which collects theories and information as the basis for system

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development. (ii) Mechanical Design, including the preparation of the physical structure and framework of the system. (iii) Hardware Design, which is the process of determining and designing the physical components needed. (iv) Software Design, includes making logic and programming to organize system work. (v) System Integration, where all hardware and software components are combined so that the system works in an integrated manner. (vi) Testing, carried out to ensure the system runs according to the functions and objectives that have been designed.

2.1 Mechanical Design

Mechanical design is carried out using TinkerCAD software to form 3D visualization. the main structure in the form of an angle iron frame functions as a support for the plant pot later. The main material used is angle iron with a thickness of 1.1 cm which forms the main frame and table dimensions of 41x47 cm. The top is equipped with a plant pot with dimensions of 41x15.5x10 cm to accommodate soil and Brazilian spinach plants. The back of the top is equipped with a hose for watering. The mechanical design is shown in Figure 2.

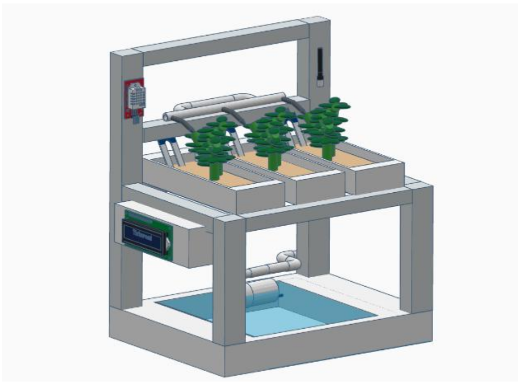

Figure 2. Mechanical Design

2.2 Hardware Design

The hardware design includes the process of arranging and manufacturing the system by considering the selection of components appropriately to minimize the risk of damage during the testing phase. The designed hardware circuit is shown in Figure 3.

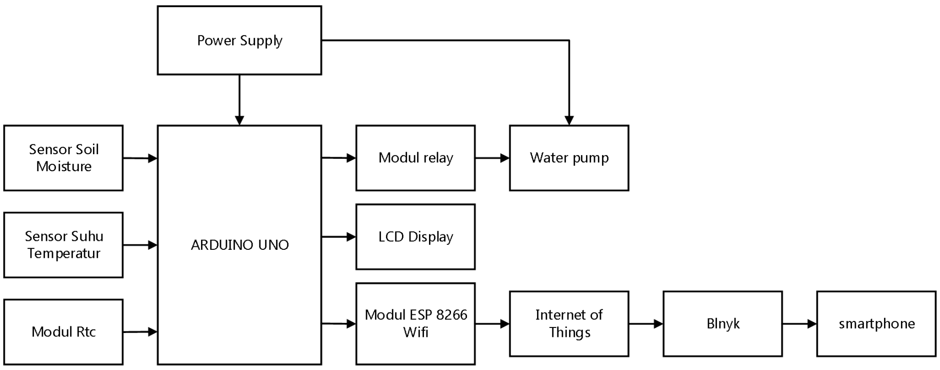

Figure 3. Hardware Design

The explanation of figure 2; (i) The Arduino Uno is an ATmega328P-based microcontroller that serves as the main processing unit for reading data from sensors and controlling actuators such as relays and pumps. It has digital and analog input/output interfaces and supports serial, I2C, and SPI communication, which makes it suitable for sensor-based automatic control systems.[5]; (ii) The ESP8266 module is a WiFi module used to connect the system to the internet network. This module enables wireless communication between the automatic watering system and the Blynk app via the TCP/IP protocol, so that data can be monitored in real-time via a smartphone.[6]; (iii) The Soil Moisture Sensor is used to measure soil moisture content. Its working principle is based on electrical resistance;

wetter soil conducts electricity better, resulting in a lower ADC value. This sensor is essential for determining when plants need to be watered.[7]; (iv) DS18B20 temperature sensor is a digital temperature sensor with 1-Wire protocol. It is capable of measuring temperatures in the range of -55°C to 125°C with an accuracy of ±0.5°C. Each sensor has a unique ID, so multiple sensors can be connected in one data line.[8]; (v) The DS3231 RTC (Real-Time Clock) module is used to store and set the time and schedule for automatic watering. The module continues to function even if the system is turned off, as it is powered by a backup battery. The RTC communicates via an I2C interface with the Arduino.[9]; (vi) LCD is an electronic device used to display information in the form of characters, numbers, or graphics. This technology works by utilizing a layer of liquid crystals located between two transparent glass coated electrodes. When an electric voltage is applied, the orientation of the liquid crystal molecules changes to follow the electric field, thereby regulating the reflected or transmitted light to form a visual display. LCDs do not produce their own light, but instead rely on external lighting or backlighting to display information clearly.[10]; (vii) Relay is an electromechanical switch that works using electromagnetic principles. This component consists of a coil and switch contacts that move when current flows. With a small current, relays are able to control higher voltage currents. In automated systems, relays are used to control actuators such as pumps. Relays are widely used for automatic control, protection, and regulation of electric current.[11]; (viii) A pump is a device that functions to move water from one place to another by increasing pressure. The mechanism of action involves the conversion of mechanical energy into hydraulic energy, allowing water to flow at the desired pressure.[12]; (ix) Power supply is an electronic component that functions to provide the voltage and current required for the entire system, including Arduino, relays, pumps, and sensors. In this research, an efficient and stable 5V-12V DC switching power supply is used.[13]; (x) IoT refers to the ability of systems to communicate and exchange data over the internet. In this system, IoT is realized by connecting Arduino and ESP8266 to the Blynk platform for remote supervision and control.[14]; (xi) Blynk is a cloud-based IoT platform that allows users to monitor sensor data, set watering times, and control automatic watering systems through an interface on a smartphone. Blynk supports a variety of visual widgets to facilitate system operation[15]; (xii)Smartphones are smartphones that have more sophisticated computing capabilities than ordinary cell phones. Smartphones are used as a medium for application-based control and monitoring. Through the Blynk app, users can view real-time data, receive notifications, and manage manual and automatic watering remotely.[16]

2.3 Software design

Software design includes systematic management of the control system and data processing of the entire operated program.

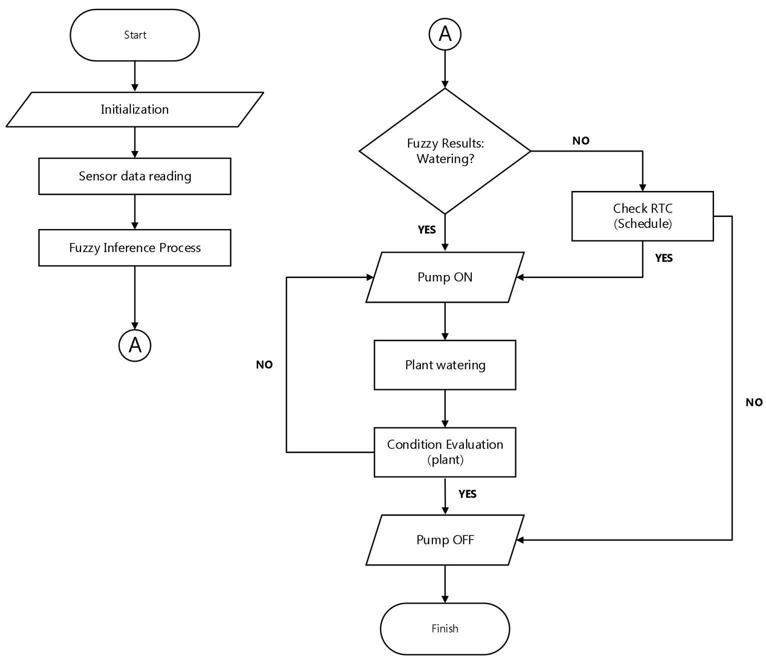

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Figure 4. Software Design

1. The process begins when the system is turned on and all devices receive power supply.
2. The Arduino Uno initializes all sensors, including the soil moisture sensor, DS18B20 temperature sensor, and air humidity sensor (for monitoring).
3. The Arduino then reads the sensor data to obtain the humidity and ambient temperature values as a basis for decision-making.
4. The read sensor values are processed using Mamdani fuzzy logic, with inputs of soil moisture and temperature, to determine whether the plants need watering.
5. If the fuzzy result indicates that watering is not required, the system will check the time using the RTC DS3231 module to check if it is currently a routine watering schedule.
6. If the fuzzy result or RTC schedule states that watering is needed, the system will activate the pump through a relay to start the plant watering process.
7. As long as the pump is active, the plant watering process takes place according to the duration determined by the system.
8. After watering, the Arduino will re-evaluate the condition of the plants by re-reading the soil and temperature sensor data.
9. If the humidity and temperature conditions are in accordance with the setpoint, the system will turn off the pump and the watering process is declared complete.
10. If the conditions are not yet suitable, the pump will remain active and the system returns to the watering process until the conditions are met.

2.4 Fuzzy Logic

Fuzzy logic is a data processing method developed by Lotfi Zadeh in 1965 to handle uncertain or vague information. Unlike binary logic which only recognizes two definite states, fuzzy logic allows truth values to be between 0 and 1. It uses linguistic terms such as high, medium, or low to describe a state. The process in fuzzy logic includes the stages of fuzzification, IF-THEN rule processing, and conversion of the results through defuzzification into usable numbers. The advantages of this method lie in its ability to mimic the way humans think and its simplicity in application. Therefore, fuzzy logic is widely utilized in control systems and applications that require flexibility in handling uncertain data.[17] The following is an explanation of fuzzy logic mamdani and fuzzy logic sugeno:

2.4.1 Fuzzy Logic Mamdani

Fuzzy Mamdani is a fuzzy logic method that uses linguistic rules to mimic the way humans think in decision-making. The process includes fuzzification, application of IF-THEN rules, aggregation of rule results, and defuzzification. Both inputs and outputs in this system are expressed in terms of linguistic terms. One of its advantages is its ability to handle uncertainty and produce more flexible decisions. This method is often used in control and decision support systems.[18] Defuzzification is usually done using the centroid method to get the final value. The formula used in the Centroid method defuzzification process is:

$$Z^* = \frac{\sum_{i=1}^{n} zi \; x \; \mu(zi)}{\sum_{i=1}^{n} \mu(zi)} \quad (1)$$

where zi is the output value of each active fuzzy rule, and $\mu(zi)$ is its membership degree. This formula allows the system to produce output values that represent the fuzzy membership distribution as a whole. The Mamdani fuzzy method consists of four main stages: fuzzification, rule base, inference, and defuzzification. The initial stage converts numerical inputs into linguistic form using triangular or trapezoidal membership functions. IF-THEN rules are formed to represent expert logic. Inference evaluates all active rules using the logical operators MIN and MAX. The results are still in fuzzy form, and then converted to strict values through defuzzification, usually with the centroid method. This formula allows the system to produce outputs that represent the fuzzy membership distribution thoroughly and produce flexible decisions like human logic.[19]

2.4.2 Fuzzy Logic Sugeno

Sugeno Fuzzy Logic is one of the fuzzy inference methods introduced by Takagi and Sugeno in 1985. This method is designed to provide faster and more efficient solutions than the Mamdani method, especially in numerical data-based decision-making systems. The uniqueness of the Sugeno method lies in the output or consequent part of the rule which no longer uses a fuzzy set, but a mathematical function, either linear or constant. This allows the system to directly produce output in the form of numerical values without going through the defuzzification process. The defuzzification process in the Sugeno method is carried out using the weighted average (WA) method, where the final result is calculated using the following formula:

$$Z = \frac{\sum_{i=1}^{n} \alpha i \; x \; zi}{\sum_{i=1}^{n} \; \alpha i} \tag{2}$$

Sugeno's method is suitable for real-time systems and limited devices such as microcontrollers because it is computationally lightweight. The process includes five stages: fuzzy rule formation, fuzzification, fuzzy logic operations, inference, and defuzzification. IF-THEN rules have consequents that are linear or constant functions. The input values are converted to linguistic form, then the degree of truth is calculated and the weights are determined. The final result is calculated by the weighted average method, making this method efficient, fast, and suitable for data-driven decision-making systems.[20]

3 RESULT AND ANALYSIS

This section describes the results and analysis of the hardware and software implementation of the automatic watering system using the most effective Mamdani and Sugeno fuzzy logic methods. The system is tested directly on Brazilian spinach plants to evaluate the performance of monitoring and controlling watering automatically.

3.1 System Design Results

In the process of designing this automatic watering system, both hardware and software components have been successfully implemented and tested. The system is designed to monitor soil moisture conditions and ambient temperature, then process the data using fuzzy methods to determine when the water pump needs to be activated automatically.

3.2 Mamdani Fuzzy Implementation

The Mamdani fuzzy method is implemented to determine the watering duration based on two main inputs, namely soil moisture and air temperature. The inputs from these sensors are then processed through a Mamdani fuzzy system that consists of three core components: fuzzification, Inference, and defuzzification. The first stage converts the numerical values of the inputs into linguistic representations using membership functions. Next, the system matches the input with a set of IF-THEN rules to produce a decision in fuzzy form. The result of this inference process is still a fuzzy linguistic value which is then converted back into a numerical value through the defuzzification stage. The final output value is the duration of watering in seconds, which is then used to activate the water pump automatically.

3.2.1 Fuzzification Result

Fuzzification is the initial stage in the Mamdani fuzzy inference system which functions to convert numerical data from sensors into linguistic values based on membership degrees. The system uses two main inputs, namely soil moisture and air temperature. Humidity is classified into three categories: dry (0-40%), medium (35-70%), and wet (65-100%), while temperature is divided into cold (0-18°C), normal (18-30°C), and hot (≥30°C). Each category is formed using triangular and trapezoidal membership functions. For example, if 37% humidity is detected, the value can have a membership of 0.75 for "dry" and 0.25 for "medium". These values will be used in the inference stage to determine the watering duration. The visualization of the membership function is shown in Figure 5 and Figure 6.

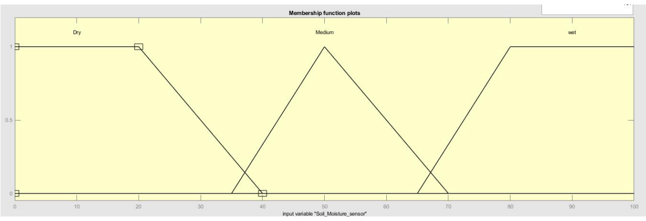

Figure 5. soil moisture sensor membership

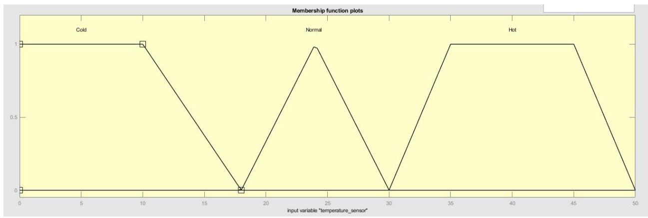

Figure 6. temperature sensor membership

3.2.2 inference Result

The inference stage in the Fuzzy Mamdani method functions as decision making based on the fuzzified membership degree values of the soil moisture and air temperature inputs. Both inputs are classified into three linguistic categories: "dry", "medium", and "wet" for humidity, and "cold", 'normal', and "hot" for temperature. The combination of all categories resulted in nine IF-THEN-based fuzzy rules that were used to determine the watering duration. For example, rule R3: IF soil moisture is dry AND air temperature is hot THEN watering = many. The activation of each rule is determined by the AND (minimum) logical operator, which takes the smallest membership value of the two inputs. The complete list of rules can be seen in Table 1.

TABEL 1: Rules base mamdani

Rules	Soil Moisture	temperature	water pump
R1	Dry	cold	Many
R2	Dry	normal	Many
R3	Dry	hot	Many
R4	Medium	cold	Medium
R5	Medium	normal	Medium
R6	Medium	hot	Many
R7	Wet	cold	Few
R8	Wet	normal	Few
R9	Wet	hot	Medium

The fuzzy outputs of all active rules are then combined (aggregated) using the MAX (union) operator before entering the defuzzification stage. This stage allows the system to respond to changes in environmental conditions proportionally and not rigidly, because the inference result does not depend only on one rule, but on all active rules simultaneously. Figure 7 shows a visualization of the combination of Mamdani fuzzy rules used in this system.


Figure 7. Rules Fuzzy

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3.2.3 Defuzzification Result

The defuzzification stage is the final process of the Mamdani fuzzy inference system which aims to convert fuzzy outputs into firm (crisp) values that can be controlled directly by the actuator, namely the water pump. In this study, the defuzzification method used is the centroid or center of gravity (COG) method. This method works by calculating the center point of the combined area of fuzzy inference results, and is known to produce outputs that are proportional and stable to changes in input. For discrete cases such as in this system, integration can be replaced with numerical calculations using the weights of each active fuzzy rule. For example, based on the inference results from the inputs of soil moisture of 50% and air temperature of 25°C, three fuzzy rules are active with membership degrees respectively: 0.3 for little output (z = 2.5 seconds), 0.6 for medium output (z = 5 seconds), and 0.2 for a lot output (z = 8 seconds). Then the defuzzification result can be calculated as:

$$Z^* = \frac{\sum_{i=1}^{n} zi \; x \; \mu(zi)}{\sum_{i=1}^{n} \; \mu(zi)} \tag{3}$$

$$Z^* = \frac{(0.3x2.5)+(0.6x5)+(0.2x8)+(0.2x8)}{0.3+06+0.2} = \frac{0.75+3.0+1.6}{1.1} = 4.86 \; Second \tag{4}$$

The crisp value is then used to determine the length of time the pump runs in seconds. With this method, the automatic watering system is able to provide watering duration in accordance with environmental conditions based on fuzzy logic. Figure 8 displays the results of the defuzzification graph generated from the combination of active fuzzy rules.

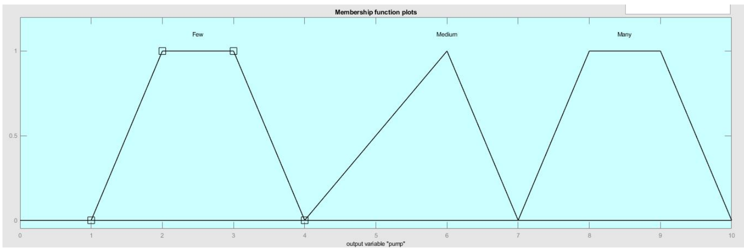

Figure 8. Defuzzification Fuzzy

3.3 Sugeno Fuzzy Implementation

The Sugeno fuzzy method in this system uses two main inputs, namely soil moisture and air temperature, and one output in the form of watering duration. Unlike Mamdani which produces a fuzzy output, Sugeno uses a constant value as a consequent, so it does not require a defuzzification process. Inputs are converted into linguistic values through fuzzification, then processed with IF-THEN rules and calculated using the weighted average method. The result is an exact number as the duration the pump is on. This method excels in execution speed, but the results tend to be rigid and less flexible than Mamdan

3.3.1 Fuzzification Result

The fuzzification stage in the Sugeno method serves to convert numerical data from sensors into linguistic values based on membership degrees. Just like in the Mamdani method, this system uses two main inputs, namely soil moisture and air temperature. Humidity is divided into three categories: dry (0-40%), medium (35-70%), and wet (65-100%), while temperature is classified into cold (0-18°C), normal (18-30°C), and hot (≥30°C). The membership functions used are triangular and trapezoidal. Sensor input values that fall between two categories will have double membership degrees, which are then used as weights in the weighted average calculation at the inference stage. This process makes the Sugeno method more computationally efficient and suitable for microcontroller-based systems.

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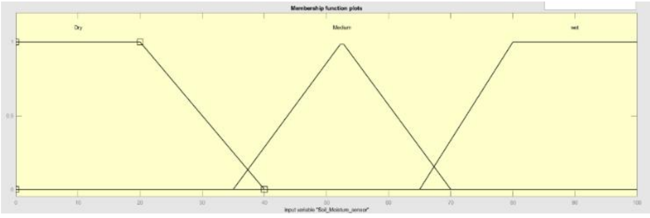

Figure 9. soil moisture sensor membership

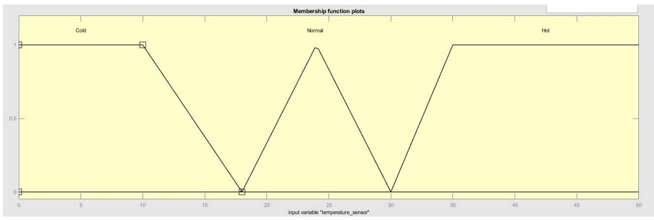

Figure 10. temperature sensor membership

3.3.2 inference Result

The inference stage in the Fuzzy Sugeno method is the process of evaluating IF-THEN rules based on the results of input fuzzification from soil moisture and air temperature sensors. Each fuzzy rule has a consequent in the form of a constant value as output, which is the duration of watering in seconds. In this system, there are a total of nine rules covering all combinations of three humidity categories (dry, medium, wet) and three temperature categories (cold, normal, hot). For example, rule R3 reads: IF soil moisture is dry AND air temperature is hot THEN watering duration = 9 seconds. After the fuzzification process, each input has a degree of membership to a particular linguistic category, and the corresponding rules are activated. The rule base table can be seen in Table 2 below.

TABEL 2: Rules base sugeno

Rules	Soil Moisture	temperature	water pump
R1	Dry	cold	On (6 seconds)
R2	Dry	normal	On (8 seconds)
R3	Dry	hot	On (9 seconds)
R4	Medium	cold	On (3 seconds)
R5	Medium	normal	On (3 seconds)
R6	Medium	hot	On (5 seconds)
R7	Wet	cold	Off
R8	Wet	normal	Off
R9	Wet	hot	On (3 seconds)

The activation degree of each rule is calculated using the AND (minimum) logical operator, which is by taking the smallest value of the membership of the two inputs involved. The results of the active rules are then used as weights in the calculation of the output value using the weighted average method, where the final output is calculated by averaging the consequent values of the active rules based on their weights. This process does not produce a fuzzy output, but directly a crisp number that represents the duration of watering. This makes the Sugeno method computationally lighter and suitable for implementation in microcontroller-based devices such as Arduino. A visualization of the Sugeno rule is shown in Figure 11.

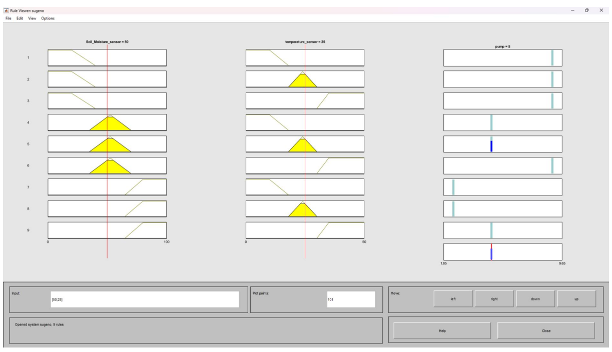

Figure 11. Rules Fuzzy

3.3.3 Defuzzification Result

The defuzzification process in Sugeno's Fuzzy method is done by calculating the weighted average of each active fuzzy rule output, based on its membership degree. This method is known as the weighted average method, where the consequent of each rule is a constant value (singleton). This process produces the final output value directly in the form of a crisp number, without requiring the defuzzification stage as in the Mamdani method. if three rules are active with output values of 2.5 seconds (α=0.3), 5 seconds (α=0.6), and 8 seconds (α=0.2) respectively, then the defuzzification result is calculated as follows:

$$Z = \frac{\sum_{i=1}^{n} \alpha i \ x \ zi}{\sum_{i=1}^{n} \ \alpha i} \quad (5)$$

$$Z = \frac{(0.3x2.5)+(0.6x5)+(0.2x8)+(0.2x8)}{0.3+06+0.2} = \frac{0.75+3.0+1.6}{1.1} = 4.86 \ Second \quad (6)$$

This final value of 4.86 seconds will be sent to the water pump as a command to determine the length of watering based on the current environmental conditions. This method proves to be effective for implementation in microcontroller-based automatic watering systems because it is computationally lighter and able to respond to real-time conditions.

3.4 System Testing Result

Tests were conducted to evaluate the performance of the Mamdani and Sugeno fuzzy methods on an automatic watering system for Brazilian spinach plants. Tests were conducted with 12 random combinations of soil moisture and air temperature values. Each data is processed through the stages of fuzzification, fuzzy rule evaluation, and defuzzification (for Mamdani) or weighted average calculation (for Sugeno) to produce watering duration (seconds). The output is a firm value that determines the length of time the pump is on. The test results are presented in sections 3.4.1 and 3.4.2 as a basis for analyzing the performance of the two fuzzy methods.

3.4.1 System Testing Result mamdani

This test is conducted to assess the system's response to input variations from the soil moisture sensor and air temperature sensor. Each incoming data is processed through the stages of fuzzification, fuzzy rule evaluation (rule base), and defuzzification to produce an output value in the form of watering duration (in seconds) that regulates the duration of the water pump. The complete results of the system testing are shown in Table 3.

TABEL 3: System Testing Result mamdani

Soil Moisture (%)	Temperature (°C)	Fuzzy Input	Rule Base Output	Defuzzification Result
34	15	Dry - Cold	Long	8.48
51	22	Medium - Normal	Medium	4.78
33	32	Dry - Hot	Long	7.17
74	16	Wet - Cold	Short	2.04
47	22	Medium - Normal	Medium	5.51
23	32	Dry - Hot	Long	7.4
89	28	Wet - Normal	Short	2.33
55	15	Medium - Cold	Medium	6.02
40	28	Dry - Normal	Long	7.68
39	21	Dry - Normal	Long	8.91
63	18	Medium - Cold	Medium	4.69
32	26	Dry - Normal	Long	8.69

Based on the test results in Table 3, it can be seen that the system is able to produce a stable and consistent watering duration against given variations in soil moisture and air temperature values. Any change in the input value

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of the sensor produces a proportional difference in output, reflecting the sensitivity of the system to changes in environmental conditions. The resulting watering duration values do not show extreme spikes or drops, thus proving that the applied fuzzy logic design works well in controlling the working time of the water pump automatically and efficiently. This shows that the watering system can run adaptively according to real conditions in the field.

3.4.2 System Testing Result Sugeno

This test was conducted to assess the performance of the Sugeno fuzzy logic-based automatic watering system in responding to input variations from soil moisture and air temperature sensors. Each input combination is processed through the stages of fuzzification, application of fuzzy rules (rule base), and calculation of output values using the weighted average method. The resulting output is a crisp value in the form of watering duration (seconds) to set the active time of the water pump.

TABEL 4: System Testing Result sugeno

Soil Moisture (%)	Temperature (°C)	Fuzzy Input	Rule Fired	Output Value(sec)	weighted average
71	27	Wet - Normal	R8	0	0
42	22	Medium - Normal	R5	3	2.85
31	23	Dry - Normal	R2	8	8.14
87	32	Wet - Hot	R9	3	2.75
82	21	Wet - Normal	R8	0	0
47	26	Medium - Normal	R5	3	3.19
47	19	Medium - Normal	R5	3	2.98
42	33	Medium - Hot	R6	5	4.9
87	17	Wet - Cold	R7	0	0.02
71	16	Wet - Cold	R7	0	0
20	28	Dry - Normal	R2	8	7.82
88	17	Wet - Cold	R7	0	0

From the system test results presented in Table 4, it can be seen that each combination of humidity and air temperature values is classified into linguistic categories such as Dry, Medium, Wet for humidity, and Cold, Normal, Hot for temperature. The combination of these categories then triggers a specific fuzzy rule (for example: R2 for Dry-Normal) that has a fixed consequent value, such as 8 seconds. The final calculation is performed based on the membership degree of each active rule and its associated output value, so as to obtain the final value of watering duration directly and efficiently.

3.5 Comparison of Mamdani and Sugeno Methods

Both Mamdani and Sugeno fuzzy methods are capable of producing automatic watering systems that are adaptive to changes in soil moisture and air temperature. However, they have fundamental differences in output characteristics and system performance.

Mamdani uses fuzzy outputs that are then described through a defuzzification process (centroid method), resulting in watering decisions that are more flexible and resemble human logic. Test results show that Mamdani watering duration is more proportional and realistic.

In contrast, Sugeno uses a constant value output and calculates the final result with a weighted average. This process is faster and computationally lightweight, but tends to result in more rigid watering decisions.

From the 12 test scenarios, both methods gave fairly close results. However, Mamdani excels in control flexibility and ability to handle input uncertainty, so it is more recommended for sensor-based automatic watering systems such as in this study.

4 CONCLUSION

This research successfully implements and compares the Mamdani and Sugeno fuzzy logic methods on an automatic watering system for Brazilian spinach plants based on microcontrollers and IoT. The system uses inputs from soil moisture and air temperature sensors to determine the duration of watering automatically. Both methods are able to respond adaptively to environmental conditions, but have different characteristics.

The Mamdani method provides more flexible and precise results because it considers the membership distribution thoroughly, while Sugeno is superior in execution speed with constant-valued consequences. Although both results are relatively close, Mamdani offers more accurate control for dynamic agricultural conditions.

Thus, the Mamdani method is more suitable to be implemented in an automatic watering system because it is able to provide more adaptive and accurate results. This research is expected to be a reference in the development of an efficient and environmentally friendly smart irrigation system.

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