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Development of IoT-based Drip Irrigation System for Tobacco Crops Using Fuzzy Logic: A Case Study in Indonesian Agriculture

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***Abstract*—Tobacco is one of the leading agricultural commodities in Indonesia, making a significant contribution to the local economy, particularly in tobacco-producing regions. However, tobacco cultivation, which generally takes place during the dry season, faces challenges such as limited water availability and the high labor intensity required for irrigation. The research aims to develop an Internet of Things (IoT)-based drip irrigation system to enhance water-use efficiency and simplify the irrigation process for tobacco farmers. The system integrates a DHT11 temperature sensor, a soil moisture sensor, and a soil pH sensor. An Arduino Uno and an ESP8266 microcontroller are used to process sensor data and transmit it in real-time to Firebase. Moreover, Mamdani fuzzy logic method is applied to determine irrigation duration based on temperature and soil moisture readings. Experimental results indicate that the system can reduce water usage by up to 36.67% compared to conventional manual watering methods, with an average water consumption of 297.32 mL per automated irrigation cycle. Moreover, the system demonstrates high accuracy, with an average deviation of only 0.33 between fuzzy logic results generated by the Arduino Uno and MATLAB simulations. The novelty of the research lies in the integration of an IoT-based drip irrigation system utilizing Mamdani fuzzy logic, specifically designed for tobacco cultivation, which enables real-time monitoring by farmers. This system is expected to offer an innovative solution to support precision agriculture and promote efficient water resource management.**

***Index Terms*—Internet of Things (IoT), Drip Irrigation System, Tobacco, Fuzzy Logic**

I. Introduction

THE agricultural sector plays a significant role in the development of the overall economy of many countries. The global rapid increase in population makes food and crop production important [1]. Tobacco (*Nicotiana tabacum L.*) is a commercially cultivated plant whose leaves are primarily used for cigarette manufacturing and chewing. It is the most widely grown non-food crop worldwide, with its leaves representing the most economically significant part of the plant. Consequently, tobacco is regarded as a valuable cash crop [2, 3]. In the agricultural sector, tobacco is widely cultivated in Indonesia as a key commodity that supports the economic development of local communities, particularly in regions where tobacco is produced. The country's tropical climate provides favorable conditions for tobacco cultivation. According to data from the Directorate General of Plantations, tobacco accounted for approximately 0.30% of the agricultural sector and 0.03% of the national GDP, with an average annual production of 198,296 tons during the period from 2010 to 2017 [4].

Although tobacco requires relatively little water and can grow during the dry season, farmers must still pay close attention to its water requirements. Adequate water supply is essential to maintain the appropriate temperature and humidity for optimal plant growth [5]. Hence, water scarcity is a major factor contributing to reduced yields and crop failures. It is a challenge exacerbated by climate change in many regions worldwide, thereby necessitating improved food production efficiency [6, 7]. Drought is one of the most limiting factors in crop production, as moisture plays a crucial role in plant growth by maintaining turgor pressure in cells [8]. To address water shortages during the dry season, drip irrigation technology is required to conserve water and enable the automated watering of tobacco plants. At present, various smart technologies

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are developed in the agricultural sector. Smart agriculture refers to the integration of advanced technologies, such as robotics, Artificial Intelligence (AI), and the Internet of Things (IoT), into farming practices [9]. Automated drip irrigation systems represent an innovative approach to irrigation management, enabling continuous real-time monitoring of soil moisture, maintaining specified soil water levels to prevent plant stress, and optimizing harvests in terms of both quality and quantity [10].

Internet of Things (IoT) is a concept that aims to expand the benefits of continuous Internet connectivity, allowing people to connect machines and equipment, manage their performance, and enable machines to collaborate and even act on newly acquired information independently [11]. In recent years, advances in low-cost sensor technology and IoT-based solutions have allowed the implementation of new multi-pollutant monitoring systems. They have helped overcome shortcomings of traditional monitoring methods, such as cost, interference with local activities (due to noise), and the need for specialized human resources [12–14].

Previous research has demonstrated that an IoT-based drip irrigation system, equipped with an ESP32 microcontroller, solenoid valves, and various sensors (including soil moisture, temperature, air humidity, and water flow), can significantly save water usage significantly. It is controlled through the Blynk IoT application [15]. Meanwhile, another research has used six soil moisture sensors, a DHT11 sensor, a BH1750 light intensity sensor, and a relay, with an Arduino Uno microcontroller and ESP8266. Data are sent to the ThingSpeak server in real-time to support the irrigation system during the germination process, resulting in optimal seedling growth at a specific moisture threshold [16].

In previous research, numerous drip irrigation systems have been developed and implemented for various crops, including tomatoes and shallots, utilizing IoT technology. However, studies on the implementation of IoT and fuzzy logic methods for tobacco plants remain quite limited. For this reason, the researchers aim to develop an IoT-based drip irrigation system specifically for tobacco plants. In the research, unlike previous research that has applied automatic irrigation systems to horticultural crops such as tomatoes, the irrigation parameters are further adjusted based on the specific watering needs of tobacco plants, which are sensitive to soil moisture and air temperature. These implemented parameters are then processed using Mamdani fuzzy logic to produce a more optimal watering duration output. The Mamdani fuzzy system, in particular, relies on a set of human-defined fuzzy rules to make decisions, providing a more intuitive approach to control [17, 18].

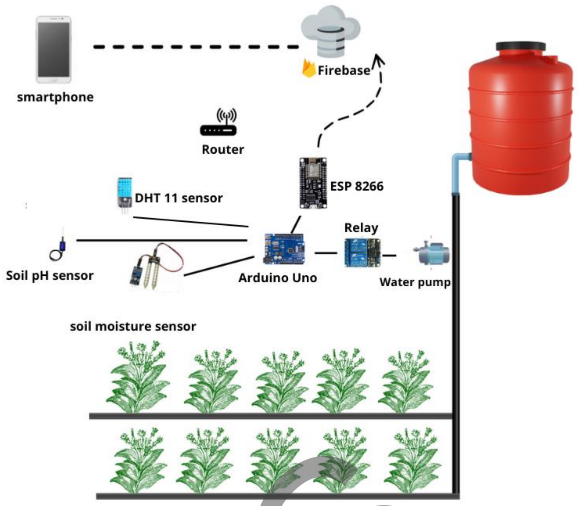

Fig. 1. Design of a drip irrigation system for tobacco plants.

II. Research Method

The research is conducted on approximately 100 m^2 of tobacco farmland in Bojonegoro Regency, East Java. The tobacco variety used in the research is Javanese tobacco, which is widely cultivated in the Bojonegoro region. This variety is selected for its distinct characteristics, thin leaves, bright coloration, and relatively low nicotine content, which make it a preferred raw material for producing light clove cigarettes. Hence, this variety is recognized for its distinctive quality and flavor in the production of cigarettes. Moreover, the soil in the experimental area is alluvial, typically found in riverine regions and formed from river silt deposits. The soil used in the Internet of Things (IoT)-based drip irrigation trials is fertile, with the capacity to retain nutrients and moisture over extended periods. The experiment was conducted over one month, in September 2024.

A. System Design

The system design implemented in the IoT-based tobacco plant drip irrigation system is illustrated in Fig. 1. Several components are integrated into the system design. These components include the Arduino Uno, which serves as a widely recognized microcontroller. It is often regarded as a cornerstone of various electronic applications due to its powerful and versatile capabilities. It enables the connection of different sensors, actuators, and other electronic components via its digital and analog input/output ports, based on the ATmega328P microcontroller [19]. Arduino boards can be used to measure various parameters, such as light, temperature, pressure, sound, and digital signals, for which corresponding electronic sensors exist [20]. In this system, the Arduino Uno microcontroller controls multiple sensors and pump relays within the IoT-based tobacco plant drip irrigation setup.

In addition to the Arduino microcontroller, the system also employs a relatively low-cost chip, the ESP8266 System-on-Chip (SoC), which forms the basis for the development of open-source software and hardware known as Node Microcontroller Unit (NodeMCU). The ESP8266 firmware is open source and developed using the Software Development Kit (SDK) provided by the chip manufacturer. It utilizes the Lua programming language, which is known for being quick and easy to use, supported by a large developer community [21]. With the built-in wireless module, the ESP8266 in this system functions to receive data from all sensors connected to the Arduino Uno, which is then transmitted to Firebase Realtime. The use of ESP8266 is considered an appropriate choice for this IoT-based irrigation system due to its advanced wireless communication capabilities, which simplify the creation of IoT projects.

This system also incorporates a soil moisture sensor, widely used in monitoring soil moisture content and providing data for decision-making in precision agriculture [22]. Soil moisture sensors are commonly applied in agricultural and environmental contexts to measure the water content of soil [23]. Various types of soil moisture sensors are available on the market. The sensor used in this system can determine whether the soil condition for the tobacco plant is dry, normal, or wet.

Furthermore, a DHT11 sensor is employed to measure temperature and humidity. They are two key parameters for assessing environmental conditions [24]. The DHT11 reads ambient temperature and humidity around the tobacco plant to ensure watering is only triggered under specific conditions (e.g., when the temperature is low). Hence, it can optimize irrigation for tobacco cultivation.

Additionally, one of the important factors supporting agricultural success is soil quality, which determines the plant's growth medium and influences productivity [25]. The system includes a pH sensor, which measures the acidity or alkalinity of a solution by evaluating the hydrogen ion concentration. Soil pH influences chemical reactions, enzyme activities, and overall ecosystem health [26]. In this system, the pH sensor plays a crucial role in monitoring soil acidity or alkalinity, which in turn affects nutrient availability, plant growth, and microbial activity. A pH calibration with two points or more must be possible with the pH measurement system. The Calibration section provides a comprehensive overview of the accuracy of the pH measurement system. The pH measurement system should have a resolution of at least 0.01 pH. Calibration is performed using standard buffer solutions with pH values of 4.0 and 7.0 prior to data collection in the field. To minimize potential sensor reading drift caused by temperature fluctuations or electrode degradation, recalibration is conducted weekly [27].

To enable real-time data monitoring, this system uses Firebase. Firebase serves as a cloud-hosted real-time database, where data is stored in JavaScript Object Notation (JSON) format, facilitating real-time synchronization with each connected client. Firebase receives data from the ESP8266, which previously establishes serial communication with the Arduino Uno. In addition to monitoring sensor data, Firebase is also used to monitor the relay system. A relay is an electronic component that functions as an electric switch, operated by electrical power. It consists of two main parts: an electromagnet and switch contacts. The relay module, operable at 5V and accommodating a current of 10A, is equipped with a 2-channel relay interface board [28].

B. System Block Diagram

In the design of this IoT-based tobacco plant drip irrigation system, several sensors are integrated to assist farmers in monitoring key parameters, namely temperature, soil moisture, and soil pH. The sensor data obtained are then processed by an Arduino Uno microcontroller, and a fuzzy algorithm is implemented. In addition to using the Arduino Uno, the system is connected via serial communication to the ESP8266, allowing data transmission to Firebase. The overall system design is illustrated in Fig. 2.

Figure 2 presents a block diagram of the tobacco drip irrigation system, which consists of three main components: input, fuzzy logic control, and output. The inputs include soil pH, soil moisture, and ambient temperature sensors. Then, the Arduino Uno functions as a fuzzy logic controller, in which the Mamdani fuzzy algorithm is embedded to process sensor data and determine the appropriate watering duration. The outputs are a relay to control the water pump and a NodeMCU ESP8266 module to transmit sensor data and pump status to Firebase in real time. However, the research is currently conducted using a small-scale prototype (one set of sensors and one pump). For large-scale farms, the system can be expanded with multiple sensor nodes and microcontrollers in either a distributed or centralized configuration.

C. System Flowchart

The algorithm used in the research is the Mamdani fuzzy method, which controls the drip irrigation system

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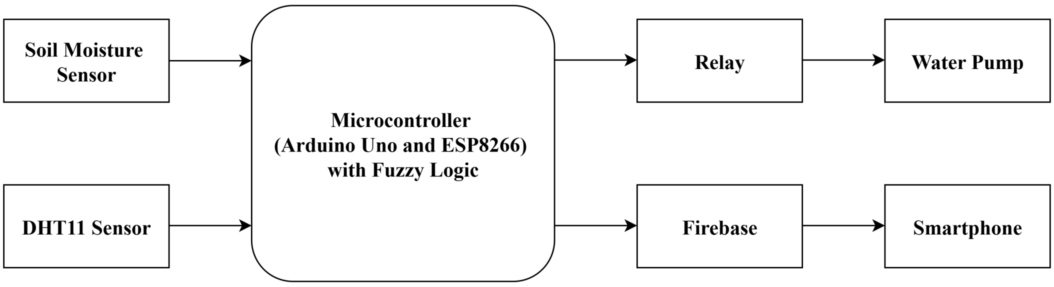

Fig. 2. Block diagram of the tobacco drip irrigation system.

based on soil moisture conditions and ambient temperature. The pump operates according to the rules defined by the Mamdani fuzzy system. This method is chosen because it is capable of handling uncertain, vague, and linguistic data, such as soil moisture levels and temperature conditions. The Mamdani fuzzy approach enables more flexible decision-making compared to deterministic methods. One of the applications of fuzzy logic is in controlling variables, parameters, or processes [29]. A fuzzy set is characterized by a membership function that assigns a degree of membership to each element of the universal set [30]. Fuzzy logic is particularly useful when the available sources of information are qualitative, inexact, or uncertain.

In addition, the Fuzzy Inference System (FIS), developed based on fuzzy logic, serves as a powerful tool to assist decision-makers in solving real-world problems through approximate reasoning and linguistic terminology. It uses fuzzy “if–then” rules to model the qualitative aspects of human knowledge without requiring precise quantitative analysis [31]. The drip irrigation system for tobacco plants, which require special watering conditions, employs this fuzzy method. Fuzzy control systems generally consist of four main components: fuzzification, rule base, fuzzy reasoning, and defuzzification [32].

The initial stage of the tobacco plant drip irrigation system using the fuzzy method, as illustrated in Fig 3, begins by reading data values from the temperature and soil moisture sensors. These values are used to determine whether to activate the irrigation system. The sensor data is then fuzzified. Numerical values are converted into linguistic categories, such as hot, normal, or cold for temperature data, and dry, medium, or wet for soil moisture data. Fuzzification is the process of converting precise numerical input into fuzzy membership functions [33].

Next, fuzzy rules are applied to evaluate the sensor conditions. The evaluation results are then processed through the defuzzification stage, which produces

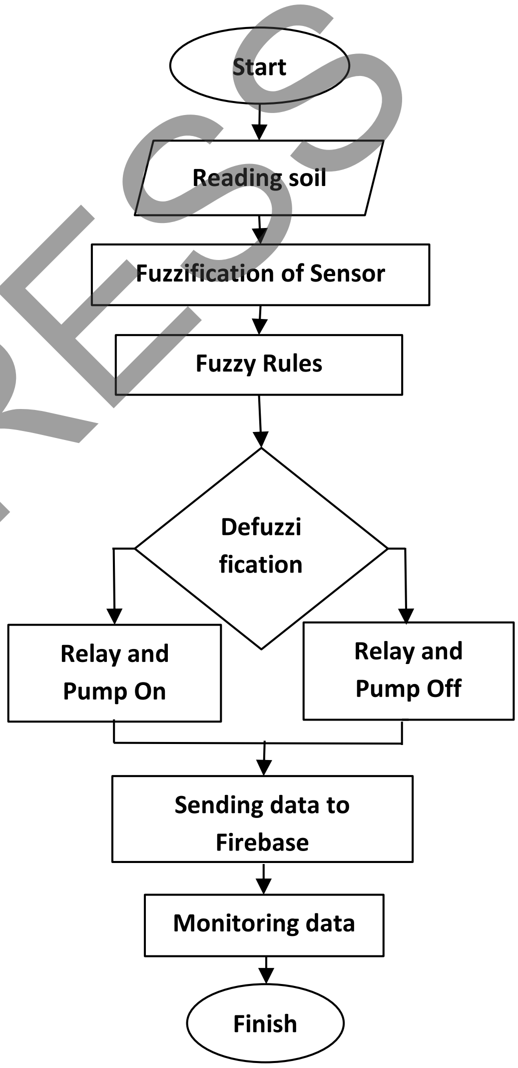

Fig. 3. Flowchart of IoT-based drip irrigation system for tobacco crops.

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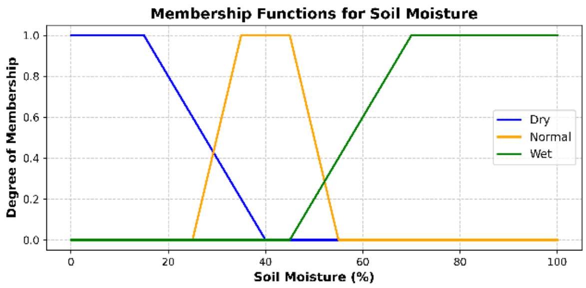

Fig. 4. Soil moisture membership function.

a clear decision regarding irrigation. This decision, whether or not to water the plants, is then sent to Firebase, allowing farmers to remotely monitor their tobacco crops. In the Mamdani system, each output is derived from the output fuzzy membership function using an implication method. The final result is obtained through the defuzzification process [34].

D. Fuzzy Logic Design

The research utilizes the Mamdani fuzzy method due to its superiority in handling various complex and non-linear characteristics in control systems, particularly in managing input variables that are linguistic and uncertain, such as temperature and humidity. The development of membership functions in the research considers three primary approaches: expert knowledge, literature review, and empirical adjustments. In the expert knowledge approach, the range of membership functions is determined through interviews and consultations with local tobacco farmers and agricultural practitioners who have a deep understanding of the watering needs of tobacco plants. A literature review of previous studies is also conducted to ensure that the range of membership function values has a sound scientific basis. For instance, previous research has suggested that soil moisture depletion for tobacco plants should be approximately between 50% and 55% to initiate irrigation [35]. Additionally, empirical tuning is performed through field tests to align the output of the Mamdani fuzzy system with actual field conditions.

Several membership functions are utilized in the research. For the soil moisture sensor, the categories considered are dry, normal, and wet. The membership functions for soil moisture are presented in Fig 4. These functions are defined using trapezoidal shapes to represent the gradual transitions between different soil conditions in tobacco cultivation. The dry category corresponds to low soil moisture, the normal category represents sufficient water content for optimal plant growth, and the wet category indicates excessive soil moisture. This classification enables the fuzzy logic system to interpret sensor data more effectively and make appropriate decisions regarding the irrigation of tobacco plants.

Equation (1) represents the membership function for dry soil conditions. A membership value of 1 is assigned when the soil moisture is between 15% and 40%. The x denotes the soil moisture level measured by the sensor, expressed as a percentage (%). Values of x below 15% indicate very dry conditions, gradually increasing toward full membership, while values above 40% decrease in membership until reaching zero at 60%. This formulation enables the fuzzy logic system to model the gradual transition between non-dry and dry soil states. By incorporating these boundaries, the system can more accurately represent real-world soil conditions and provide a reliable basis for irrigation decision-making in tobacco cultivation.

$$\mu\text{Dry}(x) = \begin{cases} 0 & \\ \frac{x-0}{15} & x < 0 \text{ or } x > 60 \\ 1 & 0 \leq x \leq 15 \\ \frac{40-x}{35} & 15 \leq x \leq 40. \end{cases} \tag{1}$$

Equation (2) defines the membership function for soil in tobacco plants under normal conditions, with a membership value of 1 when soil moisture ranges between 40% and 60%. For values of x between 25% and 40%, the membership value gradually increases, indicating the transition from dry to normal conditions. Conversely, when the soil moisture of tobacco plants ranges from 60% to 80%, the membership value decreases, representing the shift from normal to wet conditions.

$$\mu\text{Normal}(x) = \begin{cases} 0 & x < 25 \text{ or } x > 80 \\ \frac{x-25}{15} & 25 \leq x \leq 40 \\ 1 & 40 \leq x \leq 60 \\ \frac{80-x}{20} & 60 \leq x \leq 80. \end{cases} \tag{2}$$

Equation (3) represents the membership function for wet soil conditions, with full membership values ranging from 90% to 100%. When x ranges from 70% to 90%, the membership value gradually increases, reflecting the transition from normal to wet soil conditions. Beyond 90%, the soil is classified as completely wet, corresponding to excessive water content in the soil. This representation enables the fuzzy logic system to effectively capture conditions of over-irrigation and adjust the control of the irrigation system to prevent waterlogging in tobacco cultivation.

$$\mu\text{Wet}(x) = \begin{cases} 0 & \\ \frac{x-70}{20} & x < 70 \text{ or } x > 100 \\ 1 & 70 \leq x \leq 90 \\ \frac{100-x}{10} & 90 \leq x \leq 100. \end{cases} \tag{3}$$

For the temperature sensor, the membership func-

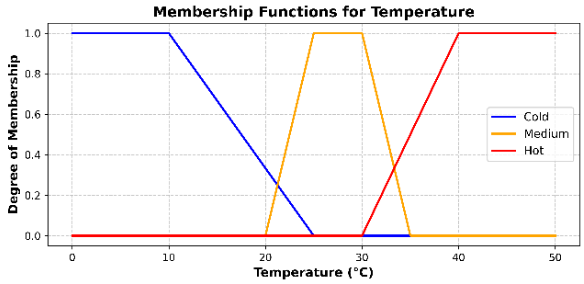

Fig. 5. Temperature membership function.

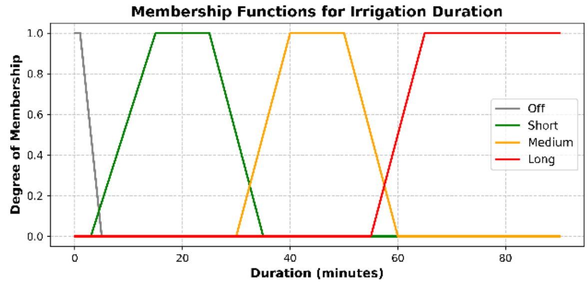

Fig. 6. Watering duration membership function.

tions consist of three categories: cold, medium, and hot, as illustrated in Fig. 5. The cold membership function covers the low-temperature range, where the degree of membership gradually decreases as the ambient temperature increases. The medium category indicates that the temperature is within a normal or comfortable range, neither too cold nor too hot, making it suitable for the growth of tobacco plants. In this category, temperature is often considered a transitional point that bridges the conditions between cold and hot. The hot membership function corresponds to the high-temperature range, where the degree of membership rises sharply once the temperature exceeds the medium threshold.

The cold membership function in Eq. (4) has a value range between 10°C and 25°C, with the membership degree decreasing outside this interval. Within this range, the function gradually reduces the membership degree as the temperature increases, indicating a transition from cold to medium conditions. Temperatures below 10°C are considered to have full membership in the cold category, while values above 25°C are no longer classified as cold. This design ensures a smooth transition in the fuzzy system, thereby preventing abrupt changes between categories.

$$\mu\text{Cold}(x) = \begin{cases} 0 & \\ \frac{x-0}{10} & x < 0 \text{ or } x > 25 \\ 1 & 0 \leq x \leq 10 \\ \frac{25-x}{15} & 10 \leq x \leq 25. \end{cases} \tag{4}$$

Equation (5) defines the medium temperature range between 25°C and 30°C. Within this range, the membership function reaches its peak, representing an optimal environmental temperature condition. Temperatures between 20°C and 25°C gradually increase their degree of membership in the medium category, while values between 30°C and 35°C gradually decrease. The overlapping design with both cold and hot categories enables the fuzzy system to handle uncertainty and ensure smoother temperature transitions.

$$\mu\text{Medium}(x) = \begin{cases} 0 & x < 20 \text{ or } x > 35 \\ \frac{x-20}{5} & 20 \leq x \leq 25 \\ 1 & 25 \leq x \leq 30 \\ \frac{35-x}{5} & 30 \leq x \leq 35. \end{cases} \tag{5}$$

In Eq. (6), the temperature is categorized as hot when it falls within the range of 40°C to 50°C. In the hot category, the membership function gradually increases from 30°C to 40°C, then reaches its maximum value at higher temperatures. Temperatures between 40°C and 50°C have full membership in the hot category, while values above 50°C are no longer included in this category. This design provides a more realistic representation of how high-temperature conditions are perceived in the Mamdani fuzzy logic.

$$\mu\text{Hot}(x) = \begin{cases} 0 & \\ \frac{x-30}{10} & x < 30 \text{ or } x > 50 \\ 1 & 30 \leq x \leq 40 \\ \frac{50-x}{10} & 4 \leq x \leq 50. \end{cases} \tag{6}$$

The outputs used in this drip irrigation system are based on the duration of watering the tobacco plants, which is determined using the membership functions of off, short, medium, and long, as shown in Fig. 6. The duration of watering is calculated based on the results of the fuzzy logic process. It considers input from the soil moisture sensor and the ambient temperature sensor. With this categorization, the system can automatically adjust the watering duration, ensuring that the plants receive the optimal amount of water according to their needs. This approach aims to increase water-use efficiency while maintaining plant health and productivity.

The membership function for the watering duration in the off condition is defined in Eq. (7). This equation indicates that the watering system is categorized as off within the value range of 0 to 5, where the membership degree gradually decreases as the duration increases. For values less than or equal to 0, the membership degree is 1, representing a completely off condition.

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In the range between 2 and 5, the membership degree decreases progressively, while values greater than 5 are no longer classified as off. This design ensures that the Mamdani fuzzy logic can represent the gradual transition from an inactive to an active watering state without abrupt changes.

$$\mu\text{Off}(x) = \begin{cases} 1 & x \leq 0 \\ \frac{2-x}{2} & 0 \leq x \leq 2 \\ \frac{5-x}{3} & 2 \leq x \leq 5 \\ 0 & x > 5. \end{cases} \tag{7}$$

Equation (8) represents the condition for a short watering duration. The membership value ranges from 1 to 35 minutes, which is categorized as short watering for tobacco plants. Within this range, the membership degree gradually increases from 1 to 15 minutes, reaches its peak between 15 and 25 minutes, and gradually decreases until 35 minutes. Values below 1 minute or above 35 minutes are no longer considered part of the short watering category.

$$\mu\text{Short}(x) = \begin{cases} 0 & x < 20 \text{ or } x > 35 \\ \frac{x-1}{14} & 1 \leq x \leq 15 \\ 1 & 15 \leq x \leq 25 \\ \frac{35-x}{10} & 25 \leq x \leq 35. \end{cases} \tag{8}$$

Next, Eq. (9) describes the condition for moderate watering of tobacco plants. The membership values range from 30 to 60 minutes, representing the medium watering duration. Within this range, the membership degree gradually increases from 30 to 40 minutes, reaches its peak between 40 and 50 minutes, and gradually decreases from 50 to 60 minutes. Values below 30 minutes or above 60 minutes are not included in the moderate watering category.

$$\mu\text{Medium}(x) = \begin{cases} 0 & x < 30 \text{ or } x > 60 \\ \frac{x-30}{10} & 30 \leq x \leq 40 \\ 1 & 40 \leq x \leq 50 \\ \frac{6-x}{10} & 50 \leq x \leq 60. \end{cases} \tag{9}$$

The condition for a long watering duration is defined in Eq. (10), with membership values ranging from 55 to 90 minutes. Within this range, the membership degree gradually increases from 55 to 65 minutes and gradually decreases up to 90 minutes. Values below 55 minutes or above 90 minutes are not included in the long watering category. This fuzzy set allows the irrigation system to provide extended watering when soil moisture is low, and temperature conditions require longer irrigation.

$$\mu\text{Long}(x) = \begin{cases} 0 & \\ \frac{x-55}{10} & x < 55 \text{ or } x > 90 \\ 1 & 55 \leq x \leq 65 \\ \frac{90-x}{10} & 65 \leq x \leq 90. \end{cases} \tag{10}$$

TABLE I
FUZZY RULES IN THE RESEARCH.

Temperature	Soil Moisture	Watering Duration
Hot	Dry	Long
Hot	Normal	Short
Hot	Wet	Off
Medium	Dry	Medium
Medium	Normal	Medium
Medium	Wet	Off
Cold	Dry	Short
Cold	Normal	Off
Cold	Wet	Off

Table I presents the fuzzy rules for determining the watering duration of tobacco plants based on readings from the temperature and soil moisture sensors. Temperature values are categorized into three membership functions: hot, medium, and cold, while soil moisture values are classified as dry, normal, and wet. The watering duration, which serves as the output of the fuzzy system, is divided into four levels: long, medium, short, and off. These categories correspond to different irrigation times, enabling the system to adjust the watering schedule according to the combined conditions of temperature and soil moisture.

E. System Validation

The validation stage is essential to ensure that the IoT-based drip irrigation system for tobacco plants operates accurately and reliably. The first validation test involves testing the dataset. The system performance is evaluated by comparing the sensor readings and fuzzy logic output from the Arduino Uno microcontroller with the simulation results obtained using MATLAB software. The data used for validation include soil moisture, air temperature, and watering duration (determined through defuzzification). The purpose of this validation is to assess the consistency between the Arduino-based implementation and the MATLAB simulation. The differences in the output values are analyzed to ensure the system operates within acceptable tolerance limits.

Furthermore, field testing is conducted for one month in tobacco fields. The parameters observed during field testing include the efficiency of water use in tobacco plants by comparing traditional watering methods with the automatic irrigation system. The watering duration is also monitored to determine whether the system can operate in accordance with environmental conditions, including soil moisture and temperature. The system response is evaluated to assess the ability of the automatic irrigation system to respond dynamically to changes in environmental conditions.

Fig. 7. Internet of Things (IoT)-based tobacco drip irrigation system.

III. Results and Discussion

A. System Implementation Results

The research presents the findings from testing the IoT-based drip irrigation system for tobacco plants. The IoT-based drip irrigation system, as shown in Fig. 7, facilitates automated watering by collecting data from soil moisture and DHT11 temperature sensors. When soil moisture readings fall below a predetermined threshold and the surrounding air temperature is within the normal or cool range, the pump is activated, and the system irrigates the plants automatically. The system has been successfully implemented and proven capable of optimizing soil moisture conditions and water delivery according to the specific requirements of tobacco plants. Additionally, farmers can assess soil fertility using an integrated soil pH sensor.

B. Watering Duration Analysis

The outcomes generated from the two input parameters (soil moisture and temperature) and the corresponding irrigation duration reveal variation based on the defuzzification process results. From the results in Table II, it can be seen that the watering duration for tobacco plants, determined using fuzzy logic with soil moisture and ambient temperature parameters, varies based on environmental conditions. A long watering duration is observed when the temperature is high and the soil moisture is low. For example, the condition at 36°C with 28% soil moisture results in a watering duration of 82.5 minutes. For a short watering duration, when the temperature is 37°C and soil moisture is 45%, the output is 15 minutes, classified as short. Meanwhile, under conditions with 62% soil moisture and a temperature of 27°C, the system does not activate, resulting in a watering duration of 0 minute, classified as "off".

TABLE II
Watering Duration Outputs.

Soil Moisture (%)	Temperature (°C)	Watering Duration (minutes)	Category
28	36	82.50	Long
30	31	52.50	Medium
45	37	15.00	Short
47	32	52.50	Medium
25	23	38.88	Medium
27	22	34.33	Short
38	34	52.33	Medium
62	27	0.00	Off

These results are further illustrated in the temperature sensor graph (Fig. 8), soil moisture graph (Fig 9), and watering duration output graph (Fig 10). In Fig 8, temperature variations recorded by the DHT11 sensor in the IoT-based drip irrigation system for tobacco plants are shown. The data are collected hourly each day. The graph indicates a gradual temperature change, starting with cooler conditions in the morning. During the daytime, temperatures in Bojonegoro rise significantly before gradually decreasing in the afternoon and evening. The highest temperature recorded by the DHT11 sensor is 36°C at midday. The DHT11 sensor demonstrates an accuracy of ±2°C when compared with the actual ambient temperature in the tobacco plantation environment.

The graph in Fig. 9 illustrates changes in soil moisture levels as measured by the soil moisture sensor, with data recorded every 15 minutes. The sensor readings range from 15% to 80%, exhibiting various spikes and drops in moisture levels. Readings exceeding 70% and approaching 80% are likely the result of increased

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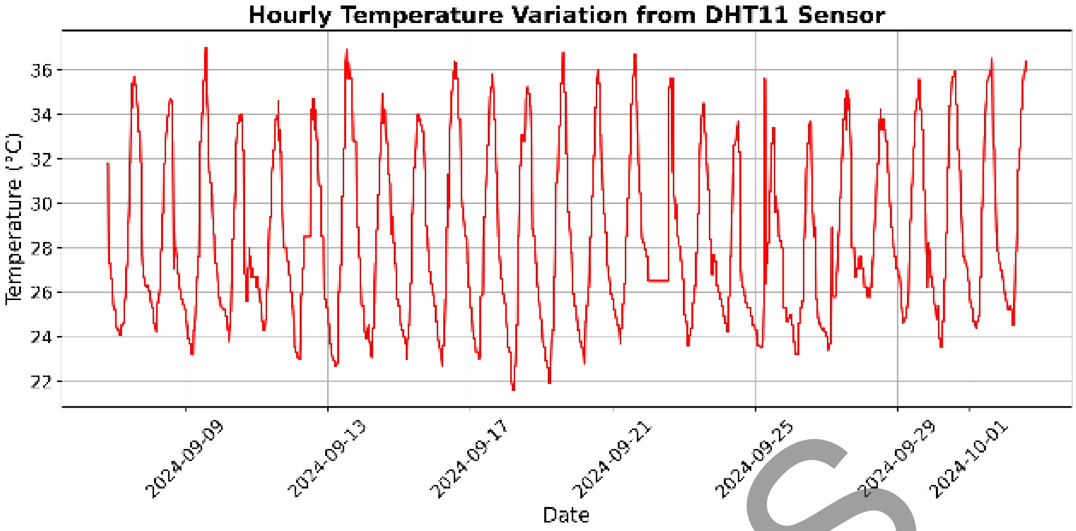

Fig. 8. The recorded temperature historical data.

irrigation or rainfall. Conversely, a drop to 15% is likely attributable to evaporation and water uptake by the tobacco plants.

The graph in Fig. 10 presents the recorded irrigation duration for the tobacco plants. The longest recorded duration is 82.5 minutes, while the shortest was 15 minutes. Over the course of one month, the plants are irrigated a total of 18 times. When irrigation is not required, the recorded duration is 0 minutes.

C. *Water Usage Comparison*

The volume of water used in the drip irrigation system during the watering process can be calculated using Eq. (11). The V is the volume of water used (in milliliters or liters). Then, Q represents the water flow rate or discharge (volume per unit time). Meanwhile, t is the watering duration (in units of time, such as seconds or minutes).

$$V = Q + t \tag{11}$$

By knowing the flow rate and watering duration, the total volume of water delivered to the crop can be accurately determined. In the research, the water volume for each irrigation session is calculated using a constant flow rate of 6.0 mL/min, based on the system's measured output. The amount of water applied to each tobacco plant is determined by the watering duration generated through the fuzzy logic algorithm. The watering volume data for each instance is presented in Table III. The results indicate that, over one month, the total water requirement for each plant is 4,180.26 mL.

TABLE III
WATER VOLUME USED IN INTERNET OF THINGS (IOT)-BASED IRRIGATION SESSIONS.

No	Watering Duration (minutes)	Water Volume (mL)
1	52.50	315.00
2	52.50	315.00
3	46.60	279.60
4	52.50	315.00
5	52.50	315.00
6	38.88	233.28
7	52.50	315.00
8	52.50	315.00
9	35.33	211.98
10	52.50	315.00
11	15.00	90.00
12	82.50	495.00
13	52.50	315.00
14	52.50	315.00
15	52.50	315.00
Total		4,180.26

For comparison, manual watering is performed three times per week during the same growth phase. Based on Table IV, manual watering of tobacco plants for one month requires a total of 6,600 mL of water per plant. Each watering session consumes 550 mL of water and is conducted in the afternoon. This manual watering schedule begins immediately after transplanting the seedlings into the field. The frequency and volume of water used are determined through interviews with local farmers, representing conventional practices during the early vegetative phase.

A comparison of the water volume requirements between the IoT-based drip irrigation system and the traditional manual method is illustrated in Fig. 11.

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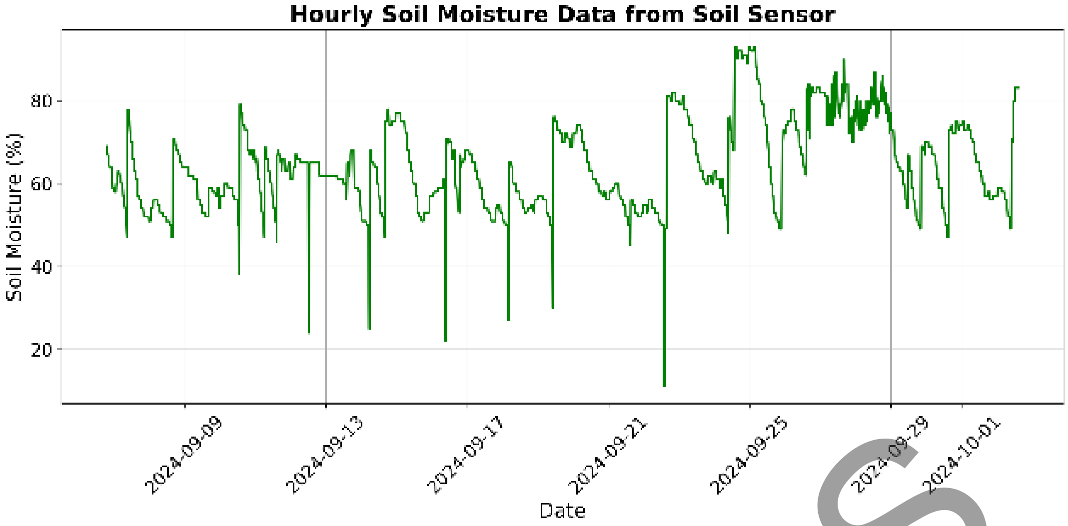

Fig. 9. Historical data of soil moisture recorded by the sensor.

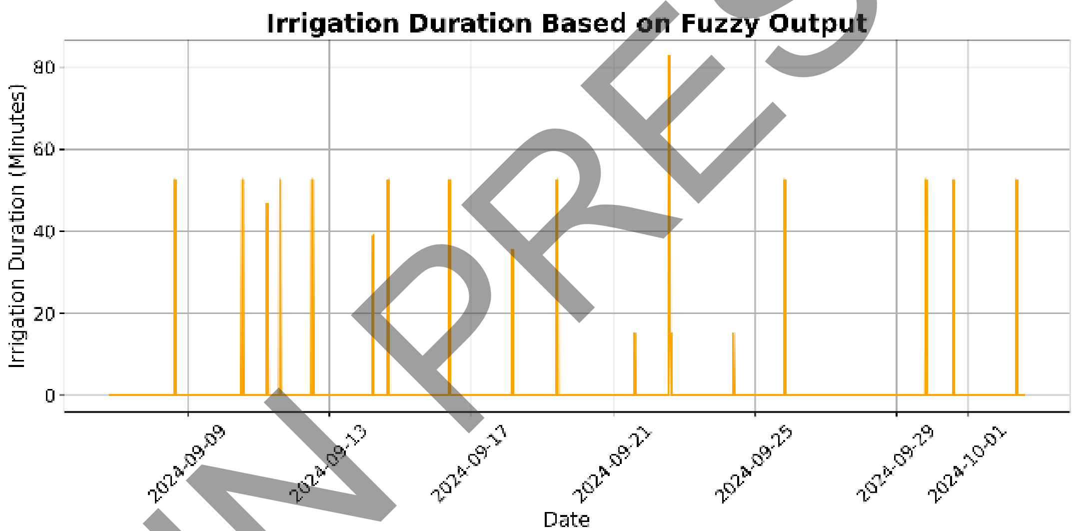

Fig. 10. Recorded irrigation duration based on fuzzy output.

TABLE IV
DATA ON TRADITIONAL WATERING OF TOBACCO PLANTS.

Week	Watering Frequency	Water Volume (mL)	One Week Total (mL)	One Month Total (mL)
1	3 times	550	1,650	1,650
2	3 times	550	1,650	1,650
3	3 times	550	1,650	1,650
4	3 times	550	1,650	1,650
		Total		6,600

Traditional manual watering requires 6,600 mL of water per plant per month, whereas the IoT-based drip irrigation system requires only 4,180.26 mL of water. This result represents 36.67% of water savings. Therefore, the IoT-based drip irrigation system is considered effective in conserving water during the dry season in

TABLE V
WEEKLY GROWTH IN PLANT HEIGHT UNDER TWO WATERING METHODS.

Watering Method	Plant Height			
	Week			
	1	2	3	4
Automatic	6 cm	11 cm	18 cm	28 cm
Conventional	6 cm	9 cm	15 cm	25 cm

TABLE VI
WEEKLY LEAF COUNT OF TOBACCO PLANTS UNDER AUTOMATIC VERSUS MANUAL IRRIGATION.

Watering Method	Number of Leaves			
	Week			
	1	2	3	4
Automatic	2	3	5	6
Conventional	2	3	4	5

tobacco cultivation.

Monitoring the input and output is conducted for one month during the early stages of tobacco growth, specifically after transplanting 35-day-old seedlings in the early vegetative phase. At this stage, tobacco plants require relatively intensive watering due to the active development of their roots and leaves. As the plants mature, both the frequency and volume of watering are gradually reduced. The one-month testing period is relatively short. Therefore, additional testing is recommended until the harvest stage to enhance the validity and reliability of the findings.

D. Growth Analysis of Tobacco Plants

As shown in Table V, observations of tobacco plant growth over a one-month period reveal differences between the automatic drip irrigation method and the conventional manual method in terms of both plant height and leaf count. Under the automatic irrigation method, plant height increases from 6 cm in the first week to 28 cm in the fourth week. In contrast, under the conventional method, plant height also begins at 6 cm in the first week but reaches only 25 cm by the fourth week.

Table VI shows that tobacco plants receiving automatic irrigation grow faster than those under conventional irrigation. Both methods start with two leaves in the first week. However, by the fourth week, plants under automatic irrigation reach six leaves, whereas those under conventional irrigation reach only five leaves. This result indicates that automatic irrigation provides a more consistent water supply, promoting better leaf development. Overall, automatic irrigation enhances plant growth and has the potential to increase crop yield more compared to manual watering methods.

E. System validation

System validation is carried out by comparing the input and output results of the Mamdani fuzzy logic system implemented on the Arduino Uno with simulations conducted using MATLAB software. The purpose of this validation is to determine the optimal irrigation duration for tobacco plants by evaluating the consistency between the outputs from both platforms. The results in Table VII indicate that the average difference in fuzzy output between the Arduino Uno implementation and MATLAB simulations is 0.33. This finding demonstrates that the Mamdani fuzzy logic implementation on the Arduino Uno achieves high accuracy, closely matching the results obtained in MATLAB. The small discrepancy is within acceptable operational tolerance limits and is primarily attributable to the precision constraints of the Arduino's numerical computations. It stems from differences in data types and the resolution of sensor input data when compared with MATLAB simulations. These minor discrepancies do not significantly affect the overall performance of the system [36].

Additionally, statistical testing of the IoT-based drip irrigation system is conducted to evaluate its water-use efficiency compared with manual irrigation. Table VIII presents descriptive statistics of the water volume used in both the automatic and manual systems. As shown in Table VIII, the automatic irrigation system uses an average of 297.32 mL of water per session, with a standard deviation of 83.19 mL, ranging from a minimum of 90 mL to a maximum of 495 mL. In contrast, the manual irrigation method consistently uses 550 mL of water, with no variation (standard deviation = 0). These results indicate that the automatic system not only uses less water on average but also adjusts the water volume according to plant needs, whereas manual irrigation applies a fixed amount regardless of actual requirements.

Next, an independent two-sample t-test is conducted to evaluate this difference further. The null hypothesis (H_0) states that there is no significant difference in the average water volume between the two methods. The results show a t-value of -10.480 and a p-value of 0.000, indicating a statistically significant difference [37]. However, due to the absence of variation in the manual method data (standard deviation = 0), the assumptions of normality and equal variances may not be fully satisfied. Therefore, the results should be interpreted with caution. Nonetheless, the findings sup-

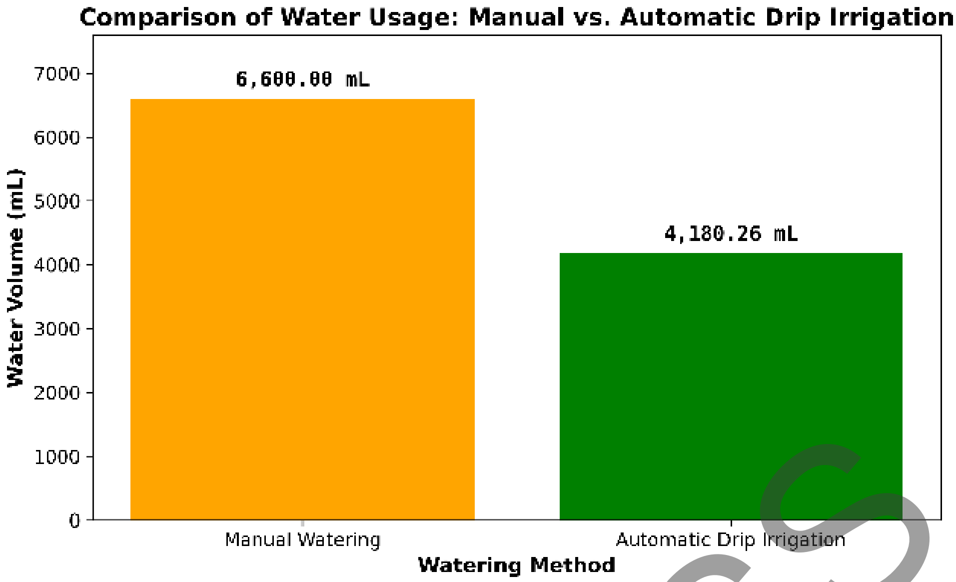

Fig. 11. Comparison of water volume: Conventional versus Internet of Things (IoT)-based irrigation.

TABLE VII
COMPARISON OF FUZZY OUTPUT FROM ARDUINO AND MATLAB.

No	Soil Moisture (%)	Temperature (°C)	Fuzzy (Arduino)	Fuzzy (MATLAB)	Data Difference
1	28	36	82.50	82.80	0.30
2	30	31	52.50	52.20	0.30
3	45	37	15.00	14.85	0.15
4	47	32	52.50	52.20	0.30
5	25	23	38.88	38.08	0.80
6	27	22	35.33	35.50	0.17
7	38	34	52.50	52.20	0.30
		Average Difference			0.33

TABLE VIII
RESULTS OF DESCRIPTIVE STATISTICS OF WATER VOLUME.

Method	Mean (mL)	Standard Deviation (mL)	Minimum Value (mL)	Maximum Value (mL)
Automatic	297.32	83.19	90	495
Manual	550.00	0.00	550	550

port that the automated irrigation system significantly reduces water usage compared to the manual method.

F. Firebase Integration and Monitoring Application

The serialized data are transmitted from the Arduino Uno to the ESP8266 and subsequently sent to Firebase, where they can be accessed in real time. The data uploaded to Firebase include soil moisture, temperature, air humidity, soil pH, and pump output, all formatted in JSON. Transmitting data to Firebase facilitates real-time access for users, as illustrated in Fig. 12. Figure 12 presents the Firebase Realtime Database interface, in which sensor readings are automatically stored and updated. The hierarchical JSON structure simplifies data organization and retrieval while enabling seamless integration with mobile applications for irrigation system monitoring.

Furthermore, the data in Firebase are connected to a smartphone application, enabling real-time monitoring. To store the collected data, it is also saved to Google Sheets. The developed application interface is shown in Fig. 13. The homepage features a menu with options for monitoring each sensor and the pump condition. From each selected menu, sensor readings are displayed according to the current sensor status, allowing users to monitor the drip irrigation system easily.

Figure 14 shows the dashboard of the application. It displays information related to air temperature and

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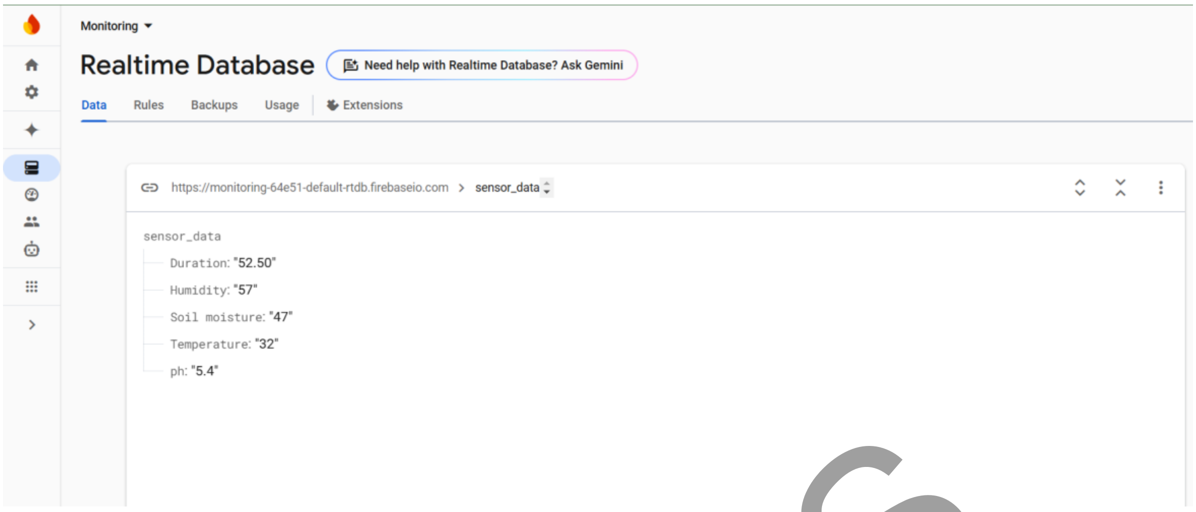

Fig. 12. Real-time Firebase interface for sensor and pump monitoring.

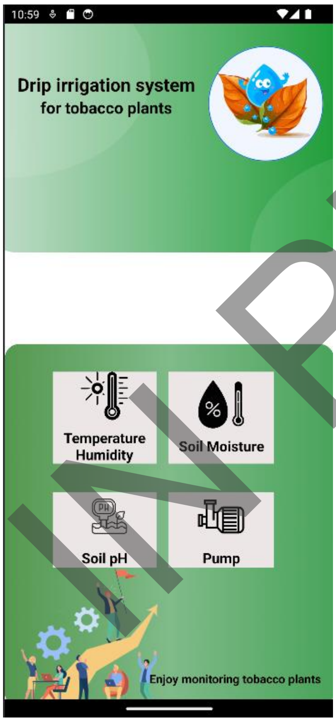

Fig. 13. Homepage of the monitoring application for the drip irrigation system.

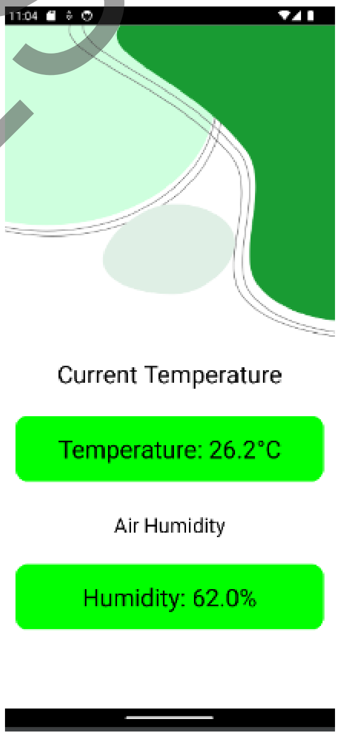

Fig. 14. Dashboard display for DHT11 temperature and humidity sensor.

humidity that farmers can monitor. The application presents sensor data in an informative format.

Figure 15 illustrates the detailed page of sensor readings, where farmers can access real-time data. Each displayed value allows farmers to monitor the moisture condition of the tobacco plant according to actual conditions. The page provides data on soil moisture ranging from 0% to 100%.

In Fig. 16, the detailed page of the soil pH sensor allows farmers to easily monitor soil fertility levels for tobacco cultivation. The displayed values enable

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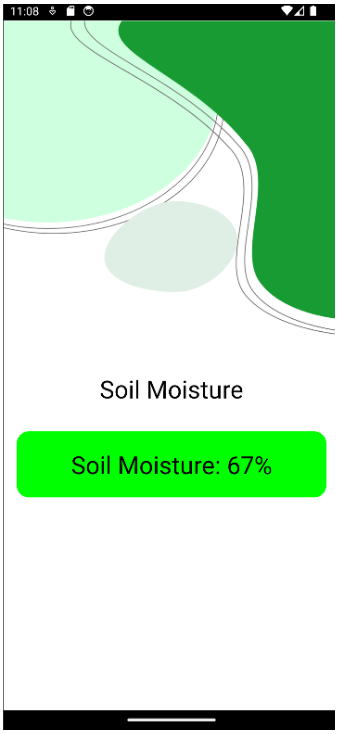

Fig. 15. A real-time soil moisture sensor dashboard in the application.

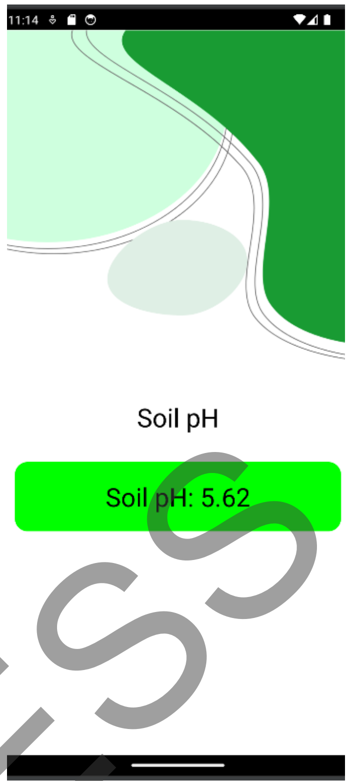

Fig. 16. Dashboard display for soil pH sensor monitoring.

them to take corrective actions if the soil pH is too low, such as applying appropriate fertilizers. Tobacco plants generally thrive in slightly acidic to neutral soil (pH 5.5–6.5). Continuous monitoring helps to ensure optimal nutrient absorption, while corrective measures, such as liming or soil amendments, can be applied promptly when pH deviates from this range.

G. Discussion

As shown in Fig. 17, the tobacco plants are 45 days old from the initial sowing stage when they are transplanted to the field. The soil is tilled and mixed with mud to create a loose texture, enabling the roots to grow more effectively and absorb moisture efficiently. The drip irrigation system is controlled using fuzzy algorithms, producing three distinct output durations: 82.50 minutes (long), 52.50 minutes (medium), and 15 minutes (short). These durations enable more efficient irrigation, tailored to soil temperature and moisture conditions.

Previous studies support the effectiveness of drip irrigation. For example, previous research has reported that drip irrigation on tomato plants saves 10% more water compared to surface irrigation, with a soil moisture threshold of 12% [15]. Similarly, another research has demonstrated that drip irrigation on shallot plants can achieve up to 90% water savings [16]. In comparison, the present research achieves a water-saving rate of 36.67%. The differences in savings can be attributed to variations in plant type, soil characteristics, and the specific fuzzy logic configurations employed.

IV. Conclusion

Conventional irrigation methods for tobacco cultivation, still widely practiced by farmers, often result in excessive water usage, insufficient responsiveness to environmental conditions, and higher manual labor requirements. These inefficiencies can adversely affect the growth and development of tobacco crops. To address these issues, the researchers develop an IoT-based drip irrigation system utilizing the Mamdani fuzzy logic method. The system utilizes one Arduino Uno unit for fuzzy processing, coded directly on the microcontroller, as well as one ESP8266 unit for data transmission to Firebase. The sensors used in the system include a temperature sensor (DHT11), a soil moisture sensor, and a soil pH sensor.

The results demonstrate that the proposed IoT-based drip irrigation system effectively automates and optimizes the irrigation process, achieving a 36.67%

Fig. 17. Field implementation of the Internet of Things (IoT)-based drip irrigation system.

improvement in water efficiency compared with conventional methods. Furthermore, the system exhibits high accuracy, with an average fuzzy output difference of 0.33 between the Arduino Uno implementation and MATLAB simulation. This slight discrepancy confirms the consistency of the Mamdani fuzzy logic implementation across hardware and simulation platforms. In terms of plant growth, under the automatic irrigation method, plant height increases from 6 cm in the first week to 28 cm in the fourth week. Meanwhile, under the conventional method, plant height also starts at 6 cm but reaches only 25 cm by the fourth week. This result indicates that the automated system supports better plant development.

Despite these promising outcomes, the research has several limitations. It is conducted on a small scale and over a short period (one month), without accounting for variable weather conditions, such as rainfall or extreme temperatures. It is also limited to alluvial soil. Sensor performance under extreme conditions and the system’s effectiveness on other soil types remain untested. Future research should expand the system to different crops and soil types, conduct longer-term trials under varying weather conditions, and integrate predictive weather data to improve irrigation efficiency. Testing on diverse soils and multiple seasons will evaluate adaptability, while predictive models can help prevent over- or under-watering and optimize overall crop productivity.

Author Contribution

Designed the IoT-based drip irrigation system concept and research methodology, P. L.; Collected field data from tobacco plantation and IoT sensors, P. L.; Prepared IoT device configurations and analysis tools, P. L.; Conducted data processing and analysis using fuzzy logic, P. L.; Drafted and revised the manuscript until the final version, P. L.; Provided guidance in system design and research methodology as the main supervisor, M. U. H. A. R.; Provided and managed the data as corresponding author, M. U. H. A. R.; Supplied resources and expertise for data processing and analysis, M. U. H. A. R.; Contributed to data processing and analysis, M. U. H. A. R.; Reviewed, corrected, and provided input to improve the quality of the manuscript, M. U. H. A. R.; Supervised the research as the first advisor, M. U. H. A. R.; Provided feedback on research design and methodology as the co-supervisor, S.; Provided literature references and recommendations on research equipment usage, S.; Reviewed, corrected, and provided input to improve the quality of the manuscript, S.; and Supervised the research as the second advisor, S.

Data Availability

The data supporting the findings of this study are available from the corresponding author, M. Udin Harun Al Rasyid, upon reasonable request. Due to the large size and specialized format of the raw IoT sensor data collected from field measurements and the associated system configuration files, these datasets are not stored in a public repository.

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