Adaptive Nutrient Management for Vegetable Cultivation: A Fuzzy Rule-Based Approach

Sry Dhina Pohan
Information System
Universitas Nahdlatul Ulama Indonesia
Jakarta Pusat, Indonesia
dhinapohaninfosys@unusia.ac.id

Muhammad Arwani
Agro-Industrial Technology
Universitas Nahdlatul Ulama Indonesia
Jakarta Pusat, Indonesia
m.arwani@unusia.ac.id

Abstract—The availability of foodstuffs, especially vegetables in Indonesia, is highly dependent on seasonal changes, making it necessary to implement precision agriculture to improve the efficiency of vegetable cultivation. The accuracy in fulfilling plant nutrient requirements is a key factor in the effectiveness of vegetable cultivation, hence a nutrient solution irrigation control system is essential. The main challenge in developing such a control system is the variation in the duration of nutrient solution irrigation, which is highly dependent on soil fertility levels and the environmental conditions of the vegetable cultivation area. This research proposes a fuzzy rule-based algorithm to determine irrigation duration based on temperature, air humidity, soil moisture, and light intensity. The fuzzy algorithm is implemented in the nutrient solution irrigation control system through a wireless sensor network (WSN). This research resulted in the design of an application for the nutrient solution irrigation control system in vegetable plant growth, capable of determining irrigation duration accurately and clearly with the implementation of the fuzzy rule-based algorithm, resulting in an irrigation duration of 48 seconds/500ml categorized as long for nutrient solution irrigation. The fuzzy rule-based algorithm was tested using Mean Square Error (MAPE) based on the irrigation duration results, yielding an error percentage of 0.25%, which is considered highly accurate in conducting nutrient solution irrigation for vegetable plants. This automated control system has the potential to increase vegetable crop productivity by minimizing fertilizer and water wastage.

Keywords—Control System, Fuzzy Rule-based, Irrigation, Nutrient Solution, Precision Farming

I. INTRODUCTION

Global food demand is projected to increase significantly by 50% by 2050 due to population growth [1]. On the other hand, global warming is triggering climate shifts that greatly impact soil fertility, leading to a decline in food productivity. This is evident in recent years, where agricultural land, particularly for vegetable crops, has seen a 20-25% decrease in productivity [2].

The availability of foodstuffs, especially vegetables, is essential to meet the needs of the population. Vegetable cultivation is highly dependent on the availability of water and nutrients to ensure timely harvesting. Currently, the availability of water and nutrients is heavily influenced by extreme climate changes and the limitation of subsidized fertilizers, making precision agriculture increasingly necessary [3]. One application of precision agriculture is the nutrient irrigation control system to ensure efficient vegetable plant growth [4]. Plant growth is influenced by temperature and humidity, which can result in inadequate nutrient intake, necessitating the use of nutrient solutions in liquid form for easier absorption by plants compared to solid fertilizers, which are more difficult for plants to decompose. The main factor in determining a plant's ability to absorb nutrients [5] is the relative acidity or pH of the water and solution [6].

Another issue is that the scheduled duration of nutrient solution irrigation does not consider soil fertility levels and environmental conditions, which can hinder plant growth. Therefore, a system is needed that can control nutrient irrigation by considering several indicators such as soil fertility and environmental conditions. The application of algorithms in the control system for automating plant nutrient solution irrigation based on variations in soil fertility and environmental conditions can thus increase vegetable crop productivity. Various algorithms can be utilized to develop a plant nutrient

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irrigation control system [7], such as fuzzy logic, artificial neural networks, genetic algorithms, harmony search algorithms, bat algorithms, firefly algorithms, and others [8]. These algorithms have been used to build system models that can provide the best solutions for irrigation scheduling by analyzing datasets [9].

One popular algorithm is fuzzy logic with a rule-based foundation, known as fuzzy rule-based, which has membership functions allowing for the automation of water or nutrient solution irrigation for vegetable plants. The rules in the fuzzy algorithm are programmed into Arduino and Wi-Fi nodes [10], which are used as connections to control nutrient solution irrigation, where the system can store data and display irrigation information [11]. The application of the fuzzy algorithm has been proven to influence the quality of vegetable plant growth, as shown by several growth parameters such as the number of leaves, leaf area, and plant height [12]. In vegetable cultivation, nutrient solution irrigation is one of the key factors affecting plant growth and yield [13]. Nutrient solutions are crucial for ensuring that plants receive all the necessary nutrients for growth and producing high-quality fruits, leading to optimal yields [14]. Optimal growth can be achieved by monitoring soil moisture to regulate the absorption needs of the nutrient solution. Irrigation with nutrient solutions can increase yields by 11.1-17.4%, enhance nutrient uptake, and improve fruit quality [15].

Therefore, the development of an intelligent and adaptive control system for nutrient solution irrigation can help increase resource use efficiency, improve crop productivity, and reduce environmental impact [16]. Conventional irrigation is done on a scheduled basis, so the nutrient supply received by the plants sometimes does not meet their needs. The application of an irrigation control system in the research [17] has been proven to increase resource efficiency and crop productivity.

A key factor in vegetable plant growth is the proper nutrition tailored to the growth stage, ensuring regular harvests. Precision agriculture can address this challenge through the implementation of reliable algorithms in control systems. This research adopts a fuzzy system design for automatic irrigation of agricultural land, prioritizing areas with dry and semi-arid geographic conditions [18]. The novelty of this research lies in applying nutrient solution irrigation duration to vegetable crop fields based on the concept of automatic irrigation with a fuzzy system design. Data acquisition of input variables such as air humidity, soil moisture, temperature, and light intensity is carried out using wireless-based sensors [19]. The type of fuzzy membership used is triangular, which is employed to compare error values in nutrient solution irrigation as inputs to the fuzzy logic rule base [20]. The output of the fuzzy logic is the duration and timing of irrigation, depending on the field's plant needs [21]. The fuzzy-based control system works to provide the right amount of nutrients during plant growth, thereby improving harvest quality [22]. The adoption of the fuzzy rule-based algorithm in nutrient solution irrigation for plants can easily monitor several factors such as soil moisture, air humidity, environmental temperature, and light intensity as the basis for nutrient irrigation. Therefore, the fuzzy rule-based control system for vegetable crop nutrient irrigation, which is simple and reliable, can be a better alternative control system and can be widely implemented.

II. METHOD

A. Experimental Site

The research was conducted in the province of North Sumatra, in the city of Padangsidimpuan, located at approximately 1°22' - 1°30' North Latitude and 99°16' - 99°24' East Longitude, with an elevation of 350 meters above sea level. The region has a tropical climate with relatively high rainfall ranging between 2,000-3,000 mm throughout the year, with peak rainfall occurring from October to December. The average temperature in this city ranges between 28°C and 29°C, with the highest

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temperature reaching around 33°C. Relative humidity is also quite high, reaching around 90% during most months, making the conditions quite hot and humid.

B. Experimental Crops and Nutritions

The research was conducted on the *Intan* variety of tomato plants, with each fruit weighing 70 grams. The cultivation area used for the tomato plants measured 2.5 meters by 5 meters. The tomatoes were cultivated for 30 days, with data collection intervals set at 1 minute per 3 drips, and irrigation was carried out daily from 05:30 to 07:00 Western Indonesia Time (WIB). During days 1-7, the tomato seeds were sown, and the seedlings were monitored until they developed leaves and grew tall enough to be transferred to 35x35 cm polybags. There were two groups of tomato plants, with a total of 20 plants. The first group of 10 plants was watered using an automatic nutrient solution irrigation system, while the second group of 10 plants was watered manually as a control. On days 10-20, the tomato seedlings were irrigated using a nutrient solution containing 6.33% C-organic, 3.26% N, 4.11% P2O5, 3.45% K2O, 60.3 ppm Fe, 255.11 ppm Mn, 276.47 ppm Cu, 253.02 ppm Zn, 5.16 ppm Co, 3.48 ppm Mo, and 127.11 ppm B, with an irrigation dosage of 3-5 cc/liter [15].

C. Sensor Data Acqusition

Sensor data acquisition is carried out to support the irrigation of nutrient solutions for tomato plants, with stages adopted based on the Internet of Things (IoT) architecture for agriculture. The IoT architecture stages include the data collection and transfer layer, the network layer, the service layer, and the application layer [23]. The data collection layer accommodates sensor nodes or wireless sensor networks on each sensor, which are useful for controlling cultivation. The sensors used include temperature and humidity sensors, soil moisture sensors, and light intensity sensors. These three sensors are connected to the ESP32 microcontroller, then programmed and configured in the Arduino IDE. The program results in the Arduino IDE are integrated through a wireless sensor network (WSN) with Wi-Fi or the internet, which can provide data in the form of sensor data information, as the wireless sensor network gateway can transmit data via the internet gateway [24]. The sensor data on tomato plant growth is collected in the service layer, where data processing such as data visualization, data analysis, storage, and data protection is performed. After all processes are completed, the application layer, operated by the end-user, can monitor and control various processes in the automatic nutrient solution irrigation system. The Sensor Data Acquisition for Plant Nutrient Solution Irrigation can be seen in Figure 1[25].

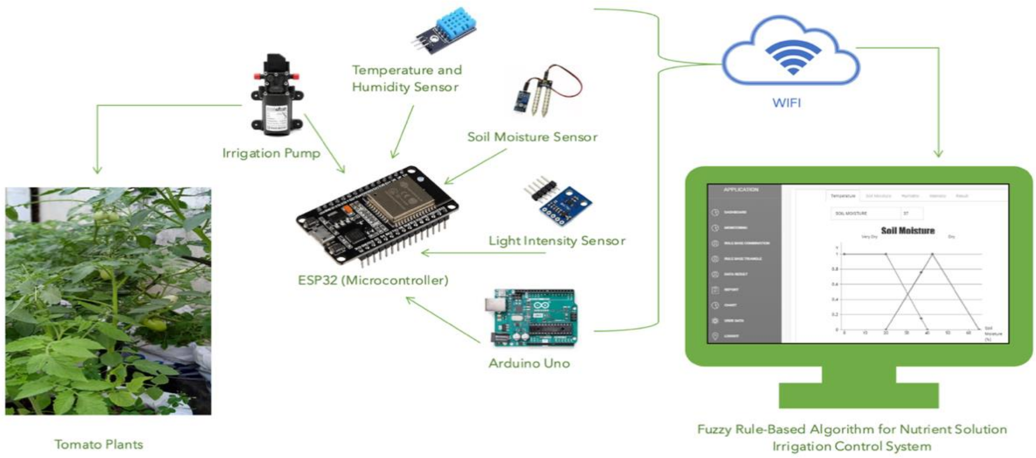

Figure. 1. Sensor Data Acquisition for Plant Nutrient Solution Irrigation

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D. Fuzzy Rule-Based Algorithm

The Fuzzy Rule-Based Algorithm is used to determine the irrigation duration of nutrient solutions for tomato plants. The fuzzy rule-based system is adopted from fuzzy logic algorithms, which involve several processes such as fuzzification, rule application, aggregation, and defuzzification. The purpose of these processes is to configure the fuzzy system model [26]. Fuzzy Set Theory provides a new form of knowledge representation known as membership functions, which rely on the accumulated data. This data is then represented through fuzzy numbers that correspond to verbal statements presented in a parametric form [27]. One of the membership functions applied is the triangular fuzzy function, which facilitates easier data interpretation and more efficient computational calculations [28]. The triangular fuzzy function with A[x], specifically A (a,b,c; 1) with the membership function μ[x] [29], is illustrated in Figure 2.

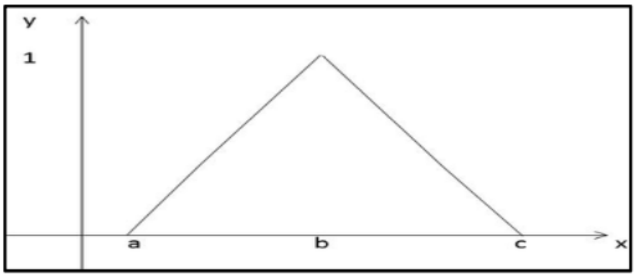

Figure 2. Fuzzy Triangular Membership Function

With the triangular membership function A[x], denoted as A (a, b, c; 1), it is explained that:

1) "a" is the start point or left endpoint, marking the beginning boundary of the fuzzy set where the membership value starts increasing from zero (0).
2) "b" is the peak point or the top of the triangle where the membership value reaches 1, indicating that the element is fully included in the fuzzy set.
3) "c" is the end point or right endpoint, marking the end boundary of the fuzzy set where the membership value starts decreasing back to zero (0).

With the formula for the triangular membership function as follows [29]:

$$\mu[x] = \begin{cases} 0, & x \leq a \ or \ x \geq c; \\ (x-a)/(b-a) & a \leq x \leq b; \\ 1, & x = b; \\ (c-x)/(c-b) & b \leq x \leq c. \end{cases} \quad (1)$$

The formula for the triangular membership function is applied to represent concepts that are not too precise based on parameter data from sensors collected over 30 days on tomato plants, including temperature, humidity, soil moisture, and light intensity. The application of fuzzy logic determines the duration of nutrient solution irrigation, which can be categorized as Short, Very Short, Medium, Long, or Very Long. The Fuzzy Sets variables can be seen in Table 1:

Table 1
Variabel Fuzzy Sets

X_1	Range (x_1)	X_2	Range (x_2)	X_3	Range (x_3)	X_4	Range (x_4)
Very Cold	0-12.5	Very Dry	0-40	Very Low	0-35	Dark	0-2,000
Cold	6.25-25	Dry	20-65	Low	17.5-55	Rather Dim	1,000-5,000
Normal	20-30	Normal Wet	60-80	Normal	50-70	Normal	3,000-10,000
Hot	27.5-45	Wet	75-90	High	65-85	Bright	9,000-30,000
Very Hot	40-50	Very Wet	87.5-100	Very High	80-100	Very Bright	25,000-60,000

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In the variables Temperature (x_1), Soil Moisture (x_2), Humidity (x_3) dan Light Intensity (x_4), each variable has five fuzzy sets. When combined, this results in 625 rules. These rules are used to determine the irrigation duration for nutrient solutions in tomato plants. The membership for each fuzzy set variable is described in Figure 3.

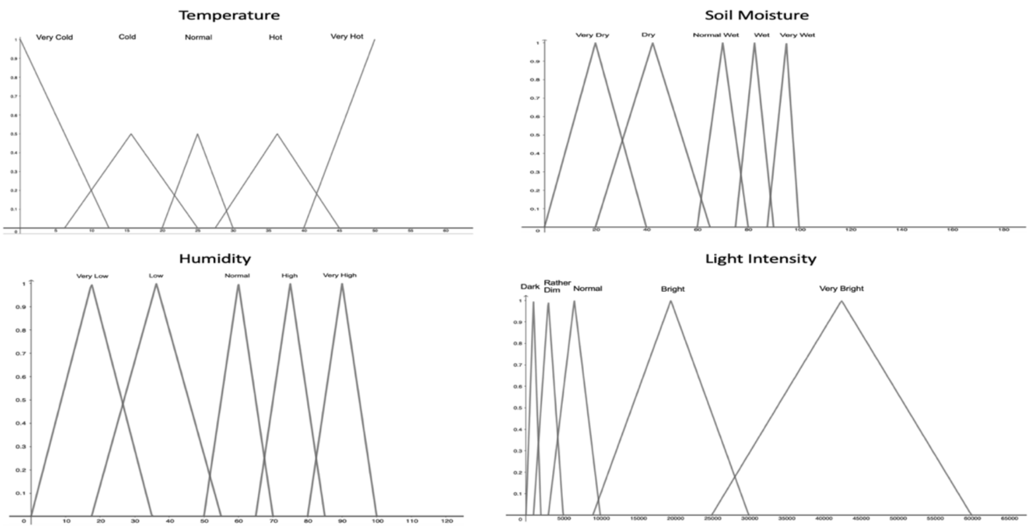

Figure 3. Fuzzy Set Variable Membership

III. RESULTS AND DISCUSSION

Components and materials needed for data acquisition and the development of a fuzzy rule-based control system for nutrient solution irrigation of plants. The method used involves applying a fuzzy rule-based algorithm with a triangular membership function to determine the irrigation duration for nutrient solutions for the plants. Data acquired with the support of a wireless sensor network was successfully collected daily over the course of one month. The sensor acquisition data can be seen in Table 2.

Table 2.
Sensor Acquisition Data

Time	Temperature	Soil Moisture	Humidity	Intensity
01/06/24 05.30	27.030001	50	72. 112235	2,965
02/06/24 06.59	29.001121	57	75.400602	5,244
03/06/24 06.51	30.100232	32	77.003356	5,282
04/06/24 05.35	24.220011	61	71	3,609
05/06/24 05.24	26	53	82.329999	2,990
06/06/24 05.29	23.004921	76	79.111001	3,108
07/06/24 05.39	22.111056	65	88.000099	2,954
08/06/24 05.25	21.300029	67	90.190901	2,941
09/06/24 05.29	23.333408	74	79.005059	3,683
10/06/24 05.37	24.221004	61	85.009999	2,979
11/06/24 05.49	27.004011	54	73.019999	3,655
12/06/24 05.30	26.000262	55	74	3,643
13/06/24 05.53	24.210044	58	76.155506	3,628
14/06/24 05.56	23.233001	59	78.299999	3,619
15/06/24 05.57	22	64	74.166090	3,552
16/06/24 06.00	21.200229	65	75	3,544
17/06/24 06.02	22.311101	67	76.222302	3,533
18/06/24 06.03	26.222222	70	75.233099	3,155
19/06/24 06.05	25.133099	71	77.299451	3,145
20/06/24 06.07	24.333331	72	79	3,131
21/06/24 06.08	21.290879	75	81.004599	3,110

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22/06/24 06.13	22.400111	74	80.044432	3,112
23/06/24 06.15	23	73	79.288766	3,130
24/06/24 05.26	25.343447	64	74.143333	2,110
25/06/24 06.18	21	66	89.177799	2,949
26/06/24 06.59	30.334311	37	76.001288	5,192
27/06/24 06.46	30	78	54.120099	5,180
28/06/24 06.39	22.753331	68	77.345550	3,524
29/06/24 06.50	20.900074	80	40	5,030
30/06/24 05.47	21.964449	75	82.111056	3,108

Sensor data is selected and then normalized so that it can be used as input for the fuzzy rule-based algorithm. The stages of the Fuzzy Rule-Based process are fuzzification, rule application, implication, aggregation, and defuzzification.

A. Fuzzification

Fuzzification is the process of converting crisp input values into fuzzy values based on membership functions. The data acquired through sensors, such as (x_1 = 27.030001), (x_2 = 50), (x_3 = 72.112235), and (x_4 = 2,965), are input into the system and calculated using the triangular fuzzy membership function. The calculation is performed based on the provisions of Table I for the fuzzy set variables as follows:

1) Temperature

$\mu_{Verycold}$ (27.030001) = 0 (as it is outside the very cold value range)
μ_{Cold} (27.030001) = 0 (as it is outside the cold value range)
$\mu_{Normal}(27.030001) = \frac{30-27.03}{30-27.5} = 0.792$
$\mu_{Hot}(27.030001) = \frac{27.03-27.5}{40-27.5} = 0.056$ (2)
$\mu_{Veryhot}$ (27.030001) = 0 (as it is outside the very hot value range)

The highest membership degree for temperature = 27.030001 is in the normal category with a value of 0.792.

2) Soil moisture

$\mu_{VeryDry}$ (50) = 0 (as it is outside the very dry value range)
$\mu_{dry}(50) = \frac{65-50}{65-40} = 0.6$ (3)
$\mu_{normalwet}$ (50) = 0 (as it is outside the normal wet value range)
μ_{Wet} (50) = 0 (as it is outside the wet value range)
$\mu_{VeryWet}$ (50) = 0 (as it is outside the very wet value range)

The highest membership degree for soil moisture = 50 is in the dry category with a value of 0.6.

3) Humidity

$\mu_{VeryLow}$ (72.112235) = 0 (as it is outside the very low value range)
μ_{Low} (72.112235) = 0 (as it is outside the low value range)
μ_{Normal}(72.112235) = 0 (as it is outside the normal value range)
$\mu_{High}(72.112235) = \frac{85-72.112235}{85-65} = 0.643$ (4)
$\mu_{VeryHigh}$(72.112235) = 0 (as it is outside the very high value range

The highest membership degree for humidity = 72.112235 is in the high category with a value of 0.643

4) Light Intensity

μ_{Dark} (2965) = 0 (as it is outside the dark value range)
$\mu_{Ratherdim}(2965) = \frac{5000-2965}{5000-3000} = 0.702$

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$$\mu_{Normal}(2965) = \frac{6000-2965}{6000-3000} = 0.568 \quad (5)$$

μ_{Bright} (2965) = 0 (as it is outside the bright value range)

$\mu_{VeryBright}$ (2965) = 0 (as it is outside the very bright value range)

The highest membership degree for light intensity = 2965 is in the high category with a value of 0.702

The results indicate that the temperature is in the normal phase, soil moisture is in the dry phase, humidity is in the high phase, and light intensity is in the rather dim phase. The graph of these four variables is shown in Figure 4.

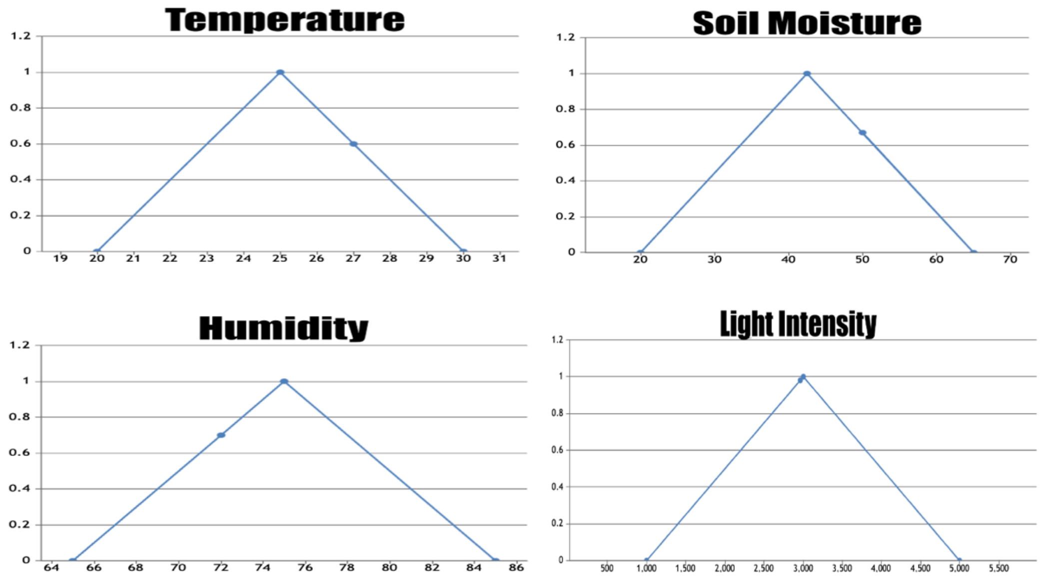

Figure 4. Graph of the Sensor Variable Conditions

B. Rule Application

Rule application is the process of establishing predetermined fuzzy rules based on fuzzy input data, which includes data acquired from sensors and fuzzy variable datasets, to produce fuzzy values that can determine the category of irrigation duration for the plant nutrient solution. A total of 625 fuzzy rules have been compiled; however, the rules listed are those that closely approximate the fuzzy variable dataset and are selected based on the five categories of irrigation for the plant nutrient solution. The fuzzy rules applied based on each irrigation category are as follows:

1) If temperature is normal and soil moisture is dry and humidity is high and light intensity is rather dim then Duration drip nutrition is Long
2) If temperature is normal and soil moisture is very dry and humidity is high and light intensity is normal then Duration drip nutrition is Very Long
3) If temperature is normal and soil moisture is normal wet and humidity is high and light intensity is rather dim then Duration drip nutrition is Medium
4) If temperature is normal and soil moisture is wet and humidity is normal and light intensity is normal then Duration drip nutrition is Short
5) *If temperature is cold and soil moisture is wet and humidity is dry and light intensity is normal then duration drip nutrition is Very Short*

C. Implication

Implication is the process that connects the premise (condition) of a rule with the conclusion derived from the rule's result. Implication determines the extent to which the

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conditions set in the rule affect the outcome. From the statement, "If temperature is Normal and soil moisture is Dry and humidity is High and light intensity is Rather Dim, then Duration Drip is Long," the results can be determined using the triangular membership function. The implication stage, with the IF-THEN rules, is based on the data from the temperature, soil moisture, humidity, and light sensors. The statements in the implication are obtained through rule evaluation and adjustment of the sensor data variables as follows:

1) Rule 1: Duration is long x_1 :0.792 (normal) , x_2: 0.6 (Dry) , x_3: 0.643 (High), x_4 : 0.702 (Rather Dim)
2) Rule 2 : Duration is very long does not meet the criteria because soil moisture is not very dry (membership degree 0)
3) Rule 3 : Duration is medium does not meet the criteria because soil moisture is not normal wet (membership degree 0)
4) Rule 4 : Duration is short does not meet the criteria because soil moisture is not wet (membership degree 0)
5) Rule 5 : Duration is very short does not the criteria because temperature is not cold (membership degree 0)

D. Defuzzification

Defuzzification is the process of converting the fuzzy values resulting from aggregation into a precise crisp value. The purpose of defuzzification is to produce a final decision that can be practically applied. Defuzzification is performed using the centroid method, which calculates the center of the area of the fuzzy curve formed from the aggregation result. The irrigation duration for the nutrient solution in plants is calculated by determining the membership degree, which is 0.6, and the value range for each irrigation duration category. The value ranges for each nutrient solution irrigation duration category are as follows: Long [36, 48, 60], Very Long [48, 60, 72], Medium [24, 36, 48], Short [12, 24, 36], and Very Short [0, 12, 24]. For the Long category [36, 48, 60], the nutrient solution irrigation duration is applied using the following triangular membership function equation:

$$\mu Long(x) = \begin{cases} \frac{x-36}{48-36}; & 36 \leq x \leq 0 \\ \frac{60-x}{60-48}; & 48 \leq x \leq 60 \\ 0; & out\ of\ range \end{cases} \quad (6)$$

The defuzzification result using the centroid method is obtained by converting fuzzy values into crisp values to determine the nutrient solution irrigation duration. The equation for the centroid method is as follows:

$$Centroid = \frac{\int_a^b x.\mu_{Long}(x)dx}{\int_a^b \mu_{Long}(x)dx} \quad (7)$$

In the centroid method, the duration is determined by dividing the value range of the Long category into two parts: the first part, where $a = 36, b = 48$, and the second part, where $a = 48, b = 60$. The calculation is performed by integrating the membership function $\mu_{Long}(x)$ over the entire range, as explained below:

$$\int_{36}^{48} \mu_{Long}\ (x)dx = \int_{36}^{48} x.\frac{x-36}{12}dx = \frac{1}{12}\left[\frac{x^3}{3} - 18x^2\right]_{36}^{48} = 264$$

$$\int_{48}^{60} \mu_{Long}\ (x)dx = \int_{48}^{60} x.\frac{60-x}{12}dx = \frac{1}{12}\left[\frac{x^3}{3} - 30x^2\right]_{48}^{60} = 312$$

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$$Total = 264 + 312 = 576$$

$$\int_{36}^{48} \mu_{Long}\ (x)dx = \int_{36}^{48} \frac{x-36}{12} dx = \frac{1}{12}\left[\frac{x^2}{2} - 36x\right]_{36}^{48} = 6$$

$$\int_{48}^{60} \mu_{Long}\ (x)dx = \int_{48}^{60} \frac{60-x}{12} dx = \frac{1}{12}\left[\frac{x^2}{2} - 60x\right]_{48}^{60} = 6$$

$$Total = 6 + 6 = 12$$

$$Centroid = \frac{576}{12} = 48 \quad (8)$$

As a result, the final crisp value from the defuzzification process for nutrient solution irrigation duration in plants yields a duration of 48 seconds for the Long irrigation category.

The application result of the fuzzy rule-based algorithm for irrigating the nutrient solution in tomato plants via a web-based platform can be seen in Figure 5.

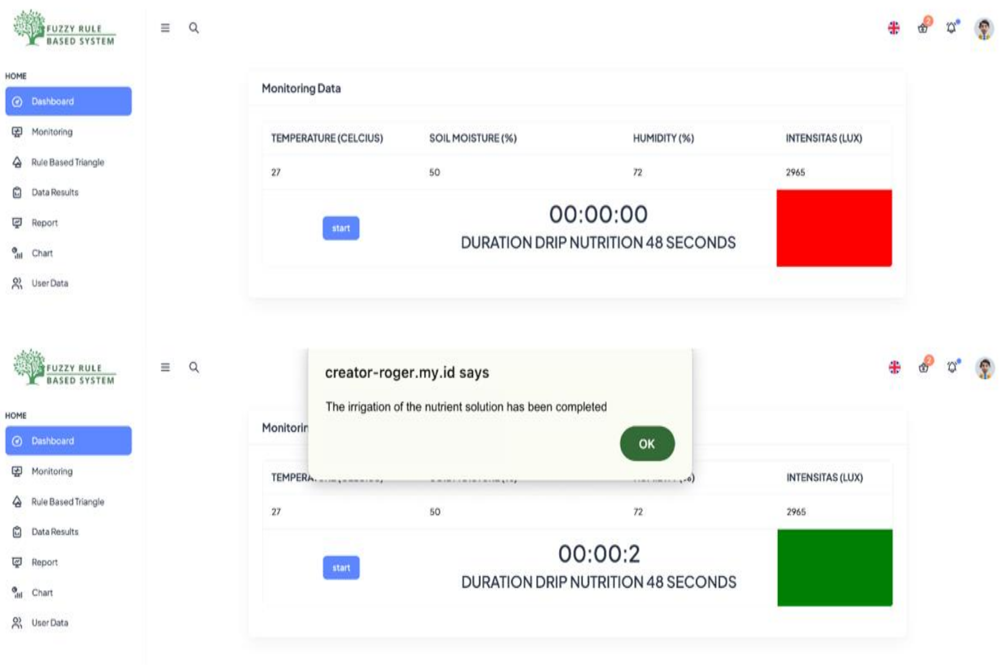

Figure 5. Fuzzy Rule-Based Application for Nutrient Solution Irrigation

The results of nutrient solution irrigation on tomato plants, including the duration and volume of the nutrient solution, based on the variables Temperature (x_1), Soil Moisture (x_2), Humidity (x_3) dan Light Intensity (x_4) can be seen in Table 3.

Table 3.
Nutrient Solution Application Results

X_1	X_2	X_3	X_4	Duration Drip/ Seconds	Volume Of Nutrient Solution
27.030001	50	72. 112235	2,965	48	500 ml
29.001121	57	75.400602	5,244	60	600 ml
30.100232	32	77.003356	5,282	60	600 ml
24.220011	61	71	3,609	36	400 ml
26	53	82.329999	2,990	48	500 ml
23.004921	76	79.111001	3,108	36	400 ml
22.111056	65	88.000099	2,954	36	400 ml
21.300029	67	90.190901	2,941	36	400 ml

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23.333408	74	79.005059	3,683	48	500 ml
24.221004	61	85.009999	2,979	48	500 ml
27.004011	54	73.019999	3,655	48	500 ml
26.000262	55	74	3,643	48	500 ml
24.210044	58	76.155506	3,628	48	500 ml
23.233001	59	78.299999	3,619	48	500 ml
22	64	74.166090	3,552	36	400 ml
21.200229	65	75	3,544	36	400 ml
22.311101	67	76.222302	3,533	36	400 ml
26.222222	70	75.233099	3,155	36	400 ml
25.133099	71	77.299451	3,145	36	400 ml
24.333331	72	79	3,131	36	400 ml
21.290879	75	81.004599	3,110	36	400 ml
22.400111	74	80.044432	3,112	36	400 ml
23	73	79.288766	3,130	36	400 ml
25.343447	64	74.143333	2,110	36	400 ml
21	66	89.177799	2,949	36	400 ml
30.334311	37	76.001288	5,192	60	600 ml
30	78	54.120099	5,180	24	300 ml
22.753331	68	77.345550	3,524	36	400 ml
20.900074	80	40	5,030	12	200 ml
21.964449	75	82.111056	3,108	36	400 ml

E. Fuzzy Rule-Based Testing

The fuzzy rule-based algorithm's performance in determining nutrient solution irrigation duration for tomato plants was assessed using Mean Absolute Percentage Error (MAPE). MAPE evaluates predictive models by calculating the error between predicted and actual values as a percentage. The results from testing the fuzzy rule-based algorithm provide an overview of the range between the predicted model values and the actual values of nutrient solution irrigation on tomato plants. The equation for MAPE is as follows [1]:

$$MAPE = 100\frac{1}{n}\sum_{t=1}^{n}\left|\frac{At-Pt}{At}\right| \quad (9)$$

The application of the fuzzy rule-based method using triangular membership functions can be utilized to determine the duration of nutrient watering, providing flexible decision-making in uncertain environmental conditions such as variations in temperature, humidity, and light intensity. The method can be considered accurate, as indicated by a low MAPE value. The fuzzy rule-based method has undergone repeated testing with various conditions and input variables, resulting in consistency that closely meets the needs of plants in different environmental conditions. The results of the nutrient solution irrigation duration testing can be seen in Table 4.

Table 4.
Results Of Nutrient Solution Irrigation Duration Testing

Duration Drip	**Duration Drip System (Seconds)**	**Manual Duration Drip (Seconds)**	**Error Absolute Percentage**
Long	48	48	0,00
Very Long	60	60	0,00
Very Long	60	60	0,00
Medium	36	35	2,78
Long	48	48	0,00
Medium	36	36	0,00
Medium	36	36	0,00
Medium	36	36	0,00
Long	48	48	0,00

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Long	48	48	0,00
Long	48	47	2,08
Long	48	48	0,00
Long	48	48	0,00
Long	48	48	0,00
Medium	36	36	0,00
Medium	36	36	0,00
Medium	36	36	0,00
Medium	36	36	0,00
Medium	36	36	0,00
Medium	36	36	0,00
Medium	36	36	0,00
Medium	36	36	0,00
Medium	36	36	0,00
Medium	36	36	0,00
Medium	36	35	2,78
Very Long	60	60	0,00
Short	24	24	0,00
Medium	36	36	0,00
Very Short	12	12	0,00
Medium	36	36	0,00
MAPE			0.25 %

The results presented in Table IV show the irrigation duration by comparing the duration drip system data as predicted data and the manual duration drip as actual data, with errors ranging from 0% to a maximum of 2.78%. The total calculation of the Error Absolute Percentage resulted in a value of 0.25%. This indicates high accuracy, as most of the predicted durations closely match the actual durations.

IV. CONCLUSION

The data acquired through the wireless sensor network for variables such as temperature, soil moisture, humidity, and light intensity provided critical information for nutrient delivery to vegetable plants. The fuzzy rule-based process, starting with fuzzification and ending with defuzzification, effectively determined the nutrient solution irrigation duration. Specifically, the system determined an irrigation duration of 48 seconds with a nutrient solution volume of 500 ml, which can be absorbed by the plants. The fuzzy rule-based algorithm demonstrated a high accuracy with a Mean Absolute Percentage Error (MAPE) of 0.25%, indicating a very low error rate. This accuracy is considered excellent and suggests that the fuzzy rule-based system can effectively automate irrigation, enhancing resource efficiency and crop productivity. The practical benefits include improved water and nutrient usage, leading to better fruit quality and reduced environmental impact. Future research could explore the integration of additional environmental variables to further improve prediction accuracy and conduct comparative studies with other predictive models to benchmark the system's performance. Overall, the fuzzy rule-based control system for nutrient irrigation is a reliable and effective solution that can be widely implemented in precision agriculture.

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