Internet of things-based fuzzy controller for automatic irrigation and NPK nutrient monitoring of grapes

Moechammad Sarosa[1], Septriandi Wirayoga[1], Mila Kusumawardani[1], Dimas Firmanda Al Riza[2], Yunia Mulyani Azis[3]
[1]Department of Electrical Engineering, State Polytechnic of Malang, Malang, Indonesia
[2]Department of Biosystems Engineering, Faculty of Agricultural Technology, Universitas Brawijaya, Malang, Indonesia
[3]Department of Management, Sekolah Tinggi Ilmu Ekonomi Ekuitas, Bandung, Indonesia

Article Info

Article history:

Received Dec 16, 2024
Revised Oct 3, 2025
Accepted Oct 20, 2025

Keywords:

Fertilizer
Fuzzy
Grape
Internet of things
Watering

ABSTRACT

Grape cultivation has gained increasing attention due to its short growing period and the high market value of its sweet, refreshing fruits. However, achieving optimal growth requires precise environmental and nutrient management, which can be challenging under conventional farming practices. This research aims to develop an automatic watering system that integrates soil moisture and nutrient monitoring to optimize grape cultivation. The system utilizes Nitrogen Phosphorus Potassium (NPK) sensors, soil moisture sensors, and a camera for growth observation, all connected through the internet of things (IoT) for remote monitoring via Android devices. A fuzzy logic controller is implemented to regulate watering duration based on environmental conditions such as temperature and humidity. Experimental results show that the system effectively adjusts watering duration to approximately six seconds when the temperature is between 25–32 °C and humidity is around 60%. The DS18B20 temperature sensor achieved an average error rate of only 0.12%, while the humidity sensor demonstrated 0.2% error, indicating high accuracy levels of 99.8%. Despite minor limitations related to internet stability and sensor calibration, the system demonstrates strong potential for commercial-scale smart farming applications, promoting resource-efficient and data-driven grape cultivation.

Corresponding Author:

Septriandi Wirayoga
Department of Electrical Engineering, State Polytechnic of Malang
Malang, East Java, Indonesia
Email: yoga.septriandi@polinema.ac.id

1. INTRODUCTION

The cultivation of grape vines is starting to be carried out by the community because the potential results are very tempting. A short cultivation period is a factor because the fruit can be harvested and enjoyed immediately. The various types of grape seeds on the market are also of interest to cultivators in getting the desired fruit, ranging from the level of sweetness, the thickness of the flesh, and the crispness of the fruit or seedless fruit. Problems arise because grape cultivation requires special handling; several factors must be considered to get optimal growth results, whereas grape cultivation requires proper watering and attention to the climate [1], [2]. Some stages that must be considered in grape cultivation include land preparation, planting holes, planting, fertilising, watering, loosening the land, and pruning. Among these processes, fertilisation and watering are key to the success of vine cultivation as they will determine the growth and fruiting of the vines [3]. The main factors affecting successful grape cultivation include grape variety, but for the same cultivar, bunch thinning and agrotechnical practices also cause significant differences.

Watering in both the vegetative and generative growth phases should be constant, sufficient, and not waterlogged because even though grapevines need a lot of water, the roots of grapevines rot easily at the beginning of their growth [4]. Vineyard irrigation consumes large amounts of water for sustainability and production of quality grapes [5]. Vineyard irrigation must be improved to meet the growing demand for wine worldwide. Improper tracking of grape growth has compromised the production of quality grapes. Research to address the problem of vineyard irrigation has been conducted using an automated wireless water management system (AWWMS) for vineyard growth using the internet of things. This system regulates wireless sensors installed in the soil by collecting real-time information, including soil moisture, air humidity, and ambient temperature, which are then forwarded to a cloud server through an IoT gateway to decide whether or not to water the soil [6]-[8].

Accurately estimating crop water uptake rates is crucial for effective irrigation scheduling. Despite its importance, real-time monitoring of plant water uptake for irrigation guidance has not been previously documented [9]. This research developed introduces a smart irrigation system that utilizes real-time soil moisture data, enabling dynamic estimation of plant water uptake based on the spatial patterns of soil moisture distribution. Additionally, a central irrigation controller collects plant water uptake information to determine the optimal irrigation amount for each watering cycle [10].

Soil type can affect the amount of grape production but does not significantly affect its quality. Wines of the same variety grown on two very different soils in the same area could not be distinguished in replicated taste tests [11]. Soil depth, drainage and water-holding capacity are more important than soil composition [12]. Wines grown in irrigated vineyards in warm regions have a higher pH than those grown in more extraordinary, non-irrigated places. Wines made from irrigated grapes are generally of lower quality than wines made from the same grape varieties grown without irrigation in cooler regions. The timing of harvesting irrigated grapes is crucial for achieving the necessary balance between sugar, acid and flavour [13].

Previous research found that the watering system still did not add the nutrients plants need, so plant growth must be monitored directly by observing the plants. Based on these problems, this research proposes an internet of things-based automatic watering system with fuzzy control and monitoring of Nitrogen, Phosphorus, and Potassium (NPK) nutrients as an indication of the nutrient content in the soil [14], [15]. Fuzzy logic is required to determine the amount of nutrients that must be injected into the soil. Integrated supervision through internet-based cameras to monitor plant conditions and growth rates can be accessed through Android applications. Automatic watering with the proper nutrients and time according to plant needs will increase plant growth so plant growth phases can be passed optimally. Monitoring plant growth using images taken from cameras can help farmers monitor plants remotely without having to observe directly coming to the location of the plant [16].

2. METHOD

This section describes two main topics in the research method, namely the system block diagram and the fuzzy system to be used. The system block diagram is used to illustrate the relationship between components as a whole, providing a clear understanding of the structure of the designed system. While the fuzzy system used explains the workflow of the system, from input to output, to ensure each step runs according to the predetermined rules.

2.1. System block diagram

The system design is described in a block diagram, as shown in Figure 1; several components are used in this system, such as temperature sensors, humidity sensors, and NPK sensors, to read the environmental conditions of plants. The sensors are read by an Arduino Nano microcontroller and sent to the Raspberry Pi mini-computer to be processed using fuzzy logic as a reference to get the number of nutrients needed by plants and stored in Firebase so that it can be read by Android devices using IoT technology. The nutrient value obtained determines the amount of fertilizer given when watering. The nutrient pump delivers fertilizer to the watering solution, while the water pump performs watering when soil moisture shows a lack of water. The Raspberry Pi also takes pictures of the plants using the camera periodically or according to the user's request and displays them on the Android device.

In detail, the function of each component and its role as an input or output of the system is explained as follows:

a. The soil moisture sensor is used to detect the level of water intensity in the soil (moisture). This sensor consists of a probe that passes current through the soil and then reads its capacitance to obtain a moisture level value [17].
b. The DS18B20 temperature sensor is utilized to monitor soil temperature. It features a waterproof probe that is inserted into the soil, which serves as the cultivation medium for grape plants [18].

c. NPK sensor used to measure soil fertility level [19].
d. The camera module observes the condition of the plants and transmits images to the Android application.
e. The microcontroller functions to process all incoming data, execute commands based on the programmed instructions, and notify grape farmers via the Android application [20].
f. A relay is used to drain the electric current in the water pump so that the water pump valve will open when there is an electric current flowing.
g. The water pump is used to water the grape vines when they reach a particular condition according to the programme that has been created.
h. Android smartphones are used as an interface to display sensor and camera data that can be accessed by grape farmers [21].

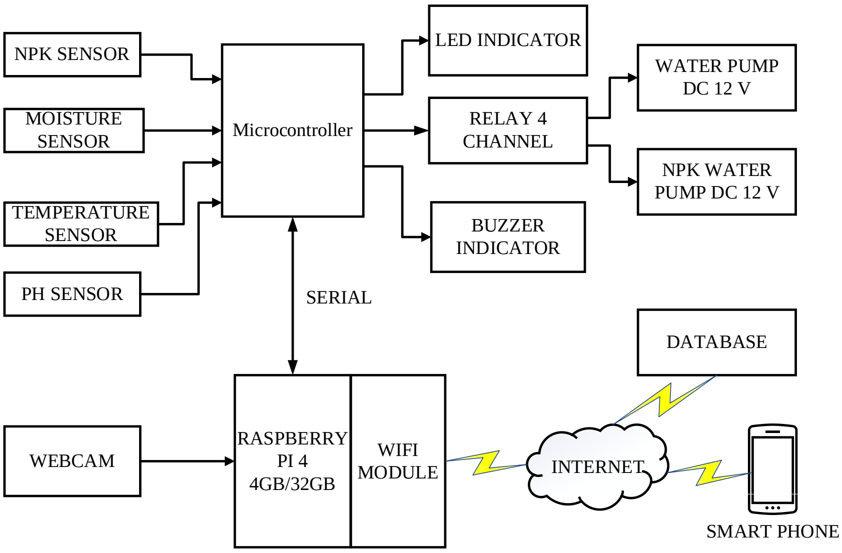

Figure 1. System block diagram

After the system is activated, the system will read the sensors and send the data to the microcontroller to be processed using fuzzy logic. Then, the soil moisture level will be tested. If the moisture is less than the specified value, the watering pump is activated until the soil moisture value is sufficient. In addition, the sensor reading data is sent to Firebase, which can then be read using the application on an Android device. The system is also equipped with a camera to take pictures of plants and send them to Firebase to monitor their progress using an Android device. The history menu provided in the application helps the system to know the history, starting from the results of sensor readings and images of plants that have been recorded using the camera.

The following is a description of each process designed based on the flowchart from Figure 2:

– The soil moisture sensor sends data to the microcontroller and is processed using fuzzy logic then the system automatically waters the plants according to the programme created based on the conditions and needs of the plants read on the sensor.
– The temperature sensor sends data to the microcontroller and is processed using fuzzy logic in combination with the soil moisture sensor to perform watering commands according to the needs of the grape plants.
– The NPK sensor sends data related to the content of nitrogen, phosphorus, and potassium in the soil which will then be processed by the microcontroller using fuzzy methods which will produce outputs in the form of the required nutrient levels based on soil content.
– RS485 Modbus module is used as a data converter from the NPK sensor into serial data which will then be processed by the microcontroller.
– Relay functions as a connector and circuit breaker used to control the water pump in the on or off state.
– Webcam is used to monitor the condition of grape vines by sending images that can be accessed through an android device.

- All data from sensors processed through the microcontroller will be uploaded and stored in the Firebase database which can be accessed through the Android application.
- The output of the system produces automatic watering that is adjusted to the needs of plants based on the measured temperature and humidity sensor values and the dose of plant nutrition needs based on age and measured NPK nutrient content values.

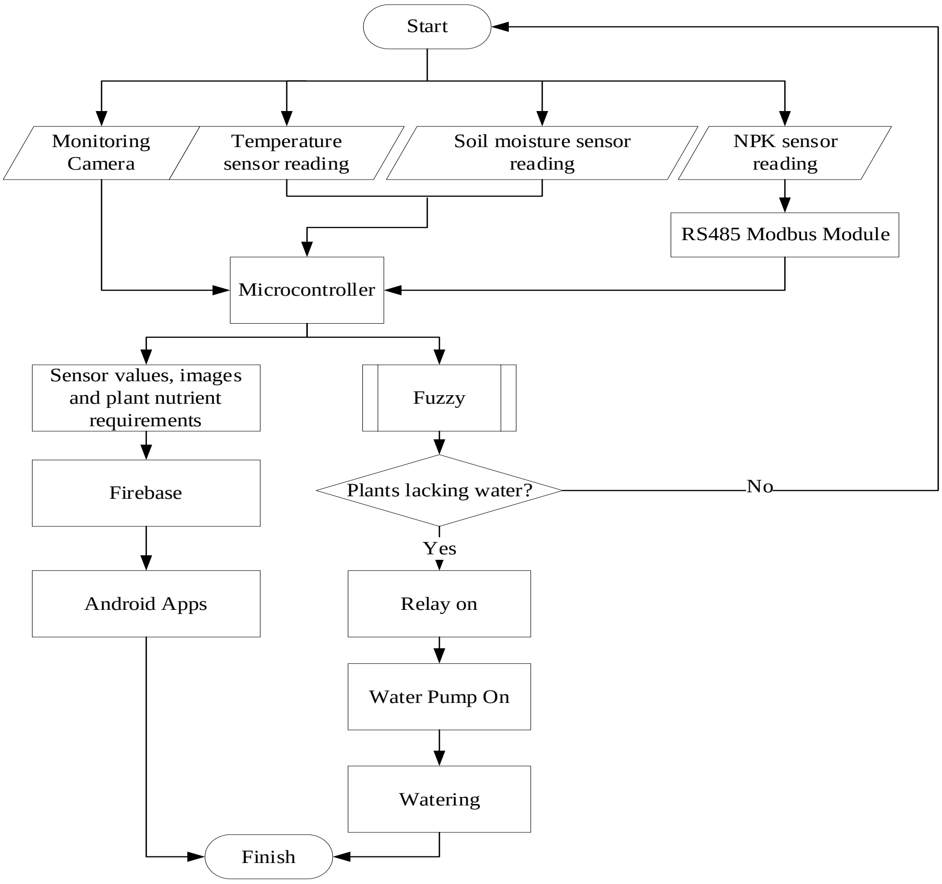

Figure 2. System flowchart

2.2. Use of fuzzy logic

The system typically operates using fuzzy logic to determine the nutrient requirements of plants based on sensor readings. In this study on irrigation systems, a fuzzy controller employing the Mamdani method is utilized. The output from the fuzzy system serves to determine the watering duration, based on input values such as temperature and humidity conditions of grape plants. The steps below outline how the Mamdani fuzzy method is applied to address the irrigation needs of grapevines [22]. The step is determining the crisp or firm value of the sensor that is grouped into a fuzzy set [23]. The following is Table 1, which consists of linguistic variables and their associated fuzzy sets.

Table 1. Fuzzy set

Variable type	Variable name	Fuzzy set	Value range
Input	Temperature (ºC)	Cold	0-25
		Normal	23-31
		Hot	29-50
	Soil moisture (%)	Dry	0-40
		Damp	30-70
		Wet	60-100
Output	Watering duration (seconds)	Short	0-5
		Medium	7-10
		Long	8-20

Rule-based fuzzy controllers operate by determining outputs in response to specific input conditions through the use of "if-then" logic rules [24] as follows: "The rule takes the form "If X is A, then Y is B," where A and B represent linguistic values assigned within the defined ranges of variables X and Y, respectively [25]. The statement "X is A" is the antecedent or premise, while the statement "then Y is B" is the consequent or conclusion. The basic rules applied to the grapevine watering system are shown as follows:

a. When the temperature is low and the soil is dry, the watering time should be extended.
b. When the temperature is low and the soil has moderate moisture, a medium watering duration is applied.
c. When the temperature is low and the soil is already wet, a short watering time is sufficient.
d. When the temperature is in a normal range and the soil is dry, the watering duration should be long.
e. When the temperature is normal and the soil moisture is moderate, a medium watering period is appropriate.
f. When the temperature is normal and the soil is wet, only a short watering is needed.
g. When the temperature is high and the soil is dry, a long watering time is required.
h. When the temperature is high and the soil is moderately moist, a medium watering duration is suitable.
i. When the temperature is high and the soil is already wet, the watering should be brief.

Determination of the range of normal temperature fuzzy set values is based on ideal conditions for grape plants with values of 23-31 ºC. The soil moisture value is obtained from journal references for ideal soil moisture conditions. In the output variable, the duration of watering is determined based on experiments on how long the duration of watering has an effect on soil conditions in a damp or wet state. So that the watering duration range is determined for a minute 0-5 seconds can increase soil moisture by 10-15%, duration 7-10 seconds increases soil moisture around 20-40% and duration 8-20 seconds increases soil moisture >40%.

3. RESULTS AND DISCUSSION

In this section will display the results of the research in the form of tools used and the calibration results of each sensor used. The sensors calibrated in this study are NPK, temperature, and soil moisture sensors which will later become a set of members in fuzzy. After calibration, a thorough system test will be carried out.

3.1. Hardware result

As shown in Figure 3, all components are integrated with the microcontroller, which serves as the central unit for data processing. It processes the input data and executes commands based on the programmed instructions. The following is a description of the picture including: 1) camera Logitech webcam C310, 2) NPK container, 3) water pump DC, 4) field board, 5) hardware container, 6) DS18B20 type temperature sensor, 7) NPK sensor, 8) soil pH sensor, 9) capacitive soil moisture, and 10) another water pump DC.

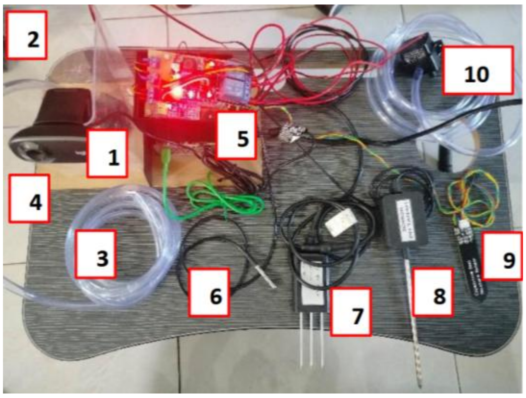

Figure 3. Tools used

3.1. Sensor testing and calibration

In this research, several tests were carried out on each sensor to evaluate their performance in monitoring environmental and soil parameters relevant to grape cultivation. These tests were essential to determine how accurately the sensors could measure real-world conditions compared to standard measuring instruments. The percentage error and accuracy of each sensor can be calculated using (1), (2):

$$\text{Percentage error} = \frac{\text{(difference between sensor and measuring instrument)}}{\text{(measuring instrument value)}} \times 100\% \quad (1)$$

$$\text{Sensor accuracy percentage} = 100\% - \text{(average error percentage)} \quad (2)$$

Testing the NPK content in the soil of the planting media using the NPK sensor compared to the NPK measuring instrument using the 2 1 fertilizer Meter+pH Meter is presented in Table 2. Based on the test data, the concentrations of N, P, and K show variations that affect the category of measurement results. At low concentrations (N=0, P=0, and K=0), the device indicates Too Little results with an estimated percentage of 0%, while at very high concentrations (N=181, P=247, and K=90), the results are Too Much with a rate of 90%. Ideal conditions occur in the medium concentration range, for example, at N=138, P=49, and K=69, with an approximate percentage of 65%. The Ideal concentration range provides stable values between 50% and 70%, indicating the optimum nutrient level for plant growth. This variation reflects the tool's ability to accurately measure crop nutrient requirements and provide recommendations for soil conditions.

Table 2. Testing the value of the NPK sensor compared to the NPK measuring instrument

No sampling	N (ppm)	P (ppm)	K (ppm)	Measurement tools	
				Retrieved	Estimated percentage (%)
1	1	0	0	Too Little	0
2	51	18	25	Too Little	20
3	77	27	38	Ideal	50
4	117	42	58	Ideal	60
5	138	49	69	Ideal	65
6	177	155	217	Ideal	70
7	192	159	223	Too Much	85
8	181	247	90	Too Much	90

Table 3 is the soil moisture sensor used in this system is the capacitive soil moisture v1.2. Calibration of this sensor is performed by comparing its readings with those obtained from a reference device, the pH+Moisture Meter, to ensure accuracy in measuring soil moisture levels. The following is a table of the results of comparing measuring instruments and sensors. Based on the test data, the sensor and measuring instrument show almost identical results with a minimal difference, which is only 1 in one sample, namely when the sensor value is 29 compared to the measuring instrument 30. The highest error value was recorded at 3.33%, while for the other nine measurements, the error value was 0%. This results in a meagre average error value of 0.33%. These results indicate that the sensor has an excellent and consistent level of accuracy in measurement compared to measuring instruments. Thus, the sensor can be trusted for similar measurement applications in this system. The temperature sensor, named the DS18B20 sensor, is calibrated by comparing the instrument's temperature measurement using a hygrometer with the temperature sensor measurement. Table 4 presents the results of the temperature sensor value comparison.

Table 3. Soil moisture sensor value comparison results

No	Sensor	Measurement tools	Difference (measuring tools-sensor)	Error value (%)
1	10	10	0	0
2	19	19	0	0
3	29	30	1	3.33
4	40	40	0	0
5	50	50	0	0
6	60	60	0	0
7	70	70	0	0
8	80	80	0	0
9	90	90	0	0
10	100	100	0	0
Average error value				0.33

The sensor and measuring instrument show similar measurement results from the test data, with a slight average difference. The highest error value occurred in the fifth sample with an error of 2.558%, while the lowest error value was recorded in the tenth sample with only 0.042%. Most of the measurements had error values below 1%, reflecting a good level of precision between the sensor and the measuring instrument. The average error value of 0.530% indicates the measurement system has high accuracy. Thus, the sensor is reliable for measurement applications with a minimal margin of error.

Table 4. Comparison of temperature sensor values with measuring instruments

No	Sensor	Measurement tools	Difference (measuring tools-sensor)	Error value (%)
1	32.25	32.2	0.05	0.155
2	31.62	31.6	0.02	0.063
3	31.56	31.5	0.06	0.190
4	31.37	31.4	0.03	0.095
5	30.87	30.1	0.77	2.558
6	30.31	30.2	0.11	0.364
7	29.81	29.5	0.31	1.050
8	29.56	29.4	0.16	0.544
9	24.56	24.5	0.06	0.244
10	23.81	23.8	0.01	0.042
Average error value				0.530

The soil pH sensor was calibrated by comparing its readings with those obtained from a pH+Moisture Meter, serving as the reference instrument. Table 5 displays the comparison results between the soil pH sensor and the reference device. Based on the test data, the sensor demonstrated good agreement with the reference measurements, yielding an average error of 1.568%. The highest error occurred in the third sample with a value of 7.317%, while the lowest error of 0% was found in the first, fourth, and seventh samples. Most measurements have an error below 5%, indicating the sensor has a pretty good accuracy. The most significant difference is only 0.23, which suggests that the difference between the sensor and the measuring instrument is within acceptable limits. Overall, the sensor system is reliable enough for measurements with decent accuracy.

Table 5. Comparison results of soil pH sensor test

No	Sensor	Measurement tools	Difference (measuring tools-sensor)	Error value (%)
1	12.71	12.71	0	0
2	8.07	7.9	0.17	2.151
3	1.9	2.05	0.15	7.317
4	0.18	0.18	0	0
5	5.16	5.2	0.04	0.769
6	5.23	5	0.23	4.6
7	4.05	4.05	0	0
8	3.29	3.3	0.01	0.303
9	4.88	4.9	0.02	0.408
10	7.39	7.4	0.01	0.135
Average error value				1.568

3.2. Automatic watering system testing

The automatic watering system is tested by directly monitoring the grape vines. The watering in question is of two types: watering water and watering NPK nutrition. Watering works by having a limit value for the temperature sensor, which will turn on the buzzer when the temperature reaches the lower limit of 20 °C and the upper limit of 32 °C. The sensor that triggers watering, watering water is triggered by a soil moisture sensor with a value of less than 20% and watering NPK nutrition is triggered by an NPK sensor with an N value of less than 51 ppm, a P value of less than 18 ppm, and a K value of less than 25 ppm. Table 6 shows the test results of the automatic watering system with varying soil moisture factors.

Table 6. Testing results of automatic watering system

No	N (mg/kg)	P (mg/kg)	K (mg/kg)	Humidity (%)	Pump A water (on-off)	Pump B nutrition (on-off)	Duration (s)
1	1	0	0	4	On	On	7
2	1	0	0	70	Off	On	6
3	58	20	28	10	On	Off	4
4	56	20	28	10	On	Off	3
5	113	40	56	79	Off	Off	0

The nutrient and soil condition monitoring system is tested by directly monitoring the grape vines. Monitoring is carried out periodically to test the monitoring system of nutrients and soil conditions. Nutrient monitoring in question measures three macronutrients: Nitrogen, Phosphorus, and Potassium. The soil conditions in question are soil moisture, temperature, and pH. Table 7 shows the test results of nutrient monitoring, including Nitrogen, Phosphorus, and Potassium.

Table 7. Test results of monitoring nutrients and soil conditions

No	Time	N (mg/kg)	P (mg/kg)	K (mg/kg)	Moisture (%)	Temperature (°C)	pH	Pump A	Pump B
1	21 July 2024 18:01	121	43	60	66	24.19	9.25	0	0
2	22 July 2024 21:34	113	40	56	79	23.69	12.57	0	0
3	23 July 2024 11:06	58	20	28	84	24.75	7.51	0	0
4	24 July 2024 04:09	56	20	28	84	23.44	1.48	0	0
5	24 July 2024 13:25	0	0	0	4	28.37	14	1	1

Based on the test data, there were variations in N, P, and K values related to soil moisture, temperature and pH conditions. On 21-24 July 2023, the levels of N, P, and K decreased significantly, from 121-43-60 mg/kg to 0-0-0 mg/kg at the last measurement. Soil moisture was initially stable in the range of 66-84% but drastically decreased to 4% on 24 July 2023 at 13:25, with a rise in temperature to 28.37 °C and pH reaching 14. These extreme conditions triggered the activation of Pump A and Pump B, indicating that the automation system was working in response to critical situations. This data suggests a close relationship between soil parameters and the system's response to environmental changes. Figure 4 displays the recorded results of monitoring soil conditions and nutrient levels through the Android application. Testing was carried out on three different smartphone models—Samsung A50s (version 10.0), Samsung A30s (version 10.0), and Redmi Note 8 Pro (version 9.0). The survey results indicated that the application functioned properly and was compatible across all tested devices.

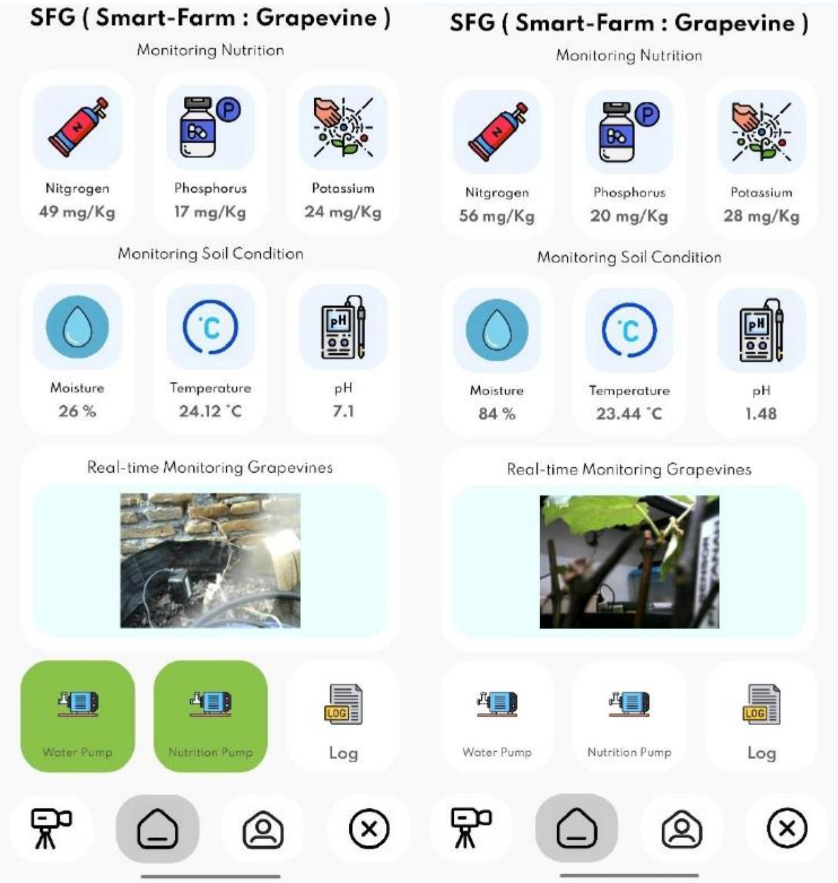

Figure 4. Results of monitoring soil conditions and nutrients through the Android app

4. CONCLUSION

The results of the testing indicate that the automatic watering system for grapevines is effective, delivering an average watering time of approximately 6 seconds when temperatures range between 25–32 °C and soil moisture levels are around 60%. Over a 21-day observation period, grapevine A, which was watered manually, showed an average growth of about 2.5 cm, while grapevine B, which was irrigated automatically, exhibited greater growth with an average increase of 5.3 cm. Providing nutrients according to the needs of the plants based on age was shown to increase the effectiveness of growth, with a significant increase in plant length. The accuracy of the sensors used is very high, with 99.44% for the DS18B20 temperature sensor, 99.874% for the capacitive soil moisture sensor, and the NPK sensor readings showing good performance, especially after being tested with urea, SP-36, and KCl fertilizers for N, P, and K, respectively.

However, several challenges were encountered during implementation, such as the relatively high cost of initial system setup, especially for farmers with limited resources, and reduced reliability of sensor readings under extreme weather or inconsistent network conditions. Despite these obstacles, the system shows strong potential for smart agricultural practices. For future development, it is recommended to conduct large-scale field testing across different environmental conditions and grape varieties to validate scalability and robustness. It is hoped that grape growers in Indonesia can adapt and utilise this technology to improve grape productivity and quality sustainably.

FUNDING INFORMATION

The researchers express their gratitude to the Directorate General of Research Enhancement and Development, Ministry of Education, Culture, Research, and Technology for the grant provided with Decree Number 72/SPK/D.D4/PPK.01.APTV/III/2024 and Agreement/Contract Number 6910 /PL2/TU/2024.

AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Moechammad Sarosa	✓			✓					✓			✓	✓	✓
Septriandi Wirayoga			✓		✓		✓		✓		✓			
Mila Kusumawardani		✓								✓				
Dimas Firmanda Al Riza						✓				✓				
Yunia Mulyani Azis	✓							✓		✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
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Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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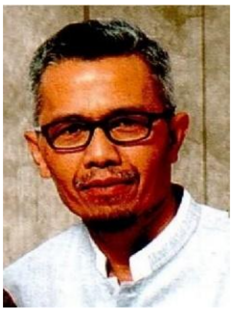
BIOGRAPHIES OF AUTHORS



Moechammad Sarosa obtained his bachelor's degree from Université de Nancy I, France, in 1990. He later completed both his master's and doctoral studies in Electrical Engineering at the Bandung Institute of Technology in 2002 and 2007, respectively. Currently, he holds a position as a lecturer and professor in computer science and electrical engineering at the State Polytechnic of Malang. His research areas include information and communication technology, artificial intelligence, mobile computing, embedded systems, and the internet of things (IoT). He can be contacted at email: msarosa@polinema.ac.id.

Septriandi Wirayoga earned his Bachelor's degree in Electrical Engineering from the Faculty of Engineering, Universitas Brawijaya, in 2014, followed by a Master's degree in Electrical Engineering from the Faculty of Engineering, Institut Teknologi Sepuluh Nopember (ITS) Surabaya, in 2016. He is currently a junior lecturer in the Department of Electrical Engineering at the State Polytechnic of Malang (Politeknik Negeri Malang). His expertise covers microstrip antennas, communication signaling, and microcontroller-based systems. He can be contacted at email: yoga.septriandi@polinema.ac.id.

Mila Kusumawardani obtained her Master of Engineering (M.T.) degree in Electrical Engineering from Brawijaya University, Malang, Indonesia, in 2010. She currently serves as a lecturer in the Digital Telecommunications Networks Study Program, under the Department of Electrical Engineering at the State Polytechnic of Malang. She can be contacted at email: mila.kusumawardani@polinema.ac.id.

Dimas Firmanda Al Riza earned his Doctoral degree in Bio-sensing Engineering from Kyoto University, Japan, in 2019, with support from the LPDP Presidential Scholarship. By 2022, he had authored over 70 scientific publications, including several papers published in reputable Q1 international journals. In 2021, he was honored with the Young Researcher's Academic Encouragement Award by the Japanese Society of Agricultural Machinery and Food Engineers (JSAM) for his academic contributions. He currently heads the Mechatronics Laboratory for Agro-industry Tools and Machinery in the Department of Agricultural Engineering, Faculty of Agricultural Technology, Universitas Brawijaya. He can be contacted at email: dimasfirmanda@ub.ac.id.

Yunia Mulyani Azis completed her Master's degree in Mathematics at Universitas Pendidikan Indonesia in 2004 and received her Doctorate in Learning Technology from Universitas Negeri Malang in 2013. In her daily life, she teaches Business Mathematics, Statistics and Research Methodology courses. She has written several books on Business Mathematics. She has received several research grants from the Ministry of Education, Culture, Research, and Technology, Republic of Indonesia. Her current research interest is in the field of blended learning. She can be contacted at email: yunia.mulyani@ekuitas.ac.id.