A Soil Moisture and pH Monitoring System with a Flexible Monopole Antenna Based on IoT for Agricultural Applications

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Abstract – This study aims to address the limitations of manual monitoring in the agricultural sector by designing an Internet of Things (IoT)-based soil moisture and pH monitoring system. The device is designed around an ESP32 Wroom-U microcontroller integrated with an agricultural sensor array (soil pH and soil moisture sensors), an OLED display, a battery management system, a step-down DC-DC converter, and a relay connected to a DC irrigation pump. The primary focus of this study is the integration of a flexible monopole antenna made of Polydimethylsiloxane (PDMS) to extend the wireless data transmission range of the microcontroller. Using the Research and Development (R&D) method, the antenna was designed and simulated for the 2.4 GHz frequency band. Data collection was conducted through two distinct approaches: technical characterization of the antenna performance using simulated return loss and Voltage Standing Wave Ratio (VSWR) metrics, followed by empirical field sampling. The sensor data collection methodology involved periodic analog sampling, calibration via linear regression formulas, and logging environmental variables. Field test results prove that the use of the flexible external PDMS antenna significantly increases the transmission range up to 521.59 meters, which is 17 times farther than a standard built-in antenna. Furthermore, the IoT system successfully transmitted the gathered sensor data to the ThingSpeak cloud platform at sampling intervals of 15 to 30 seconds with highly stable connectivity. This research provides an efficient, robust, and adaptive communication infrastructure solution for the development of smart farming.

Keywords: Smart agriculture, IoT, Soil moisture, Soil pH, Monopole antenna

I. INTRODUCTION

Agriculture is a vital sector for humanity because it provides for basic needs, namely food and spices. Agriculture often serves as a driving force for a country's economy. However, many farmers still rely on manual labor to manage their farms, and most farmers typically own large tracts of farmland. Meanwhile, the adoption of technology in agriculture can boost productivity and improve the quality of crops [1].

One example of a crop that requires special attention is the shallot onion. According to research, red onions are crops that require ample water; if they experience drought, they become susceptible to stress. Furthermore, infrequent watering can cause red onions to grow slowly, which may lead to wilting and even death [2]. Another study also suggests that red onion plants have shallow roots and are highly dependent on soil moisture in the topsoil layer. It also notes that soil moisture content is directly proportional to the plant's health, height, and number of leaves [3]

In addition to shallots, agricultural crops such as rice also require careful attention to soil pH and soil texture. Rice plants require neutral soil pH (6.0–7.0) and moist soil for optimal growth. If the soil pH is below 6, liming must be performed to restore the soil's pH to neutral [4]. Meanwhile, shallots grow best in soil with a pH of 5.6–7.0, which falls within the slightly acidic to neutral range. Soil with a pH below 5.5 tends to contain excessive amounts of aluminum (Al), which is toxic and can inhibit plant growth [5].

Water is the most essential element for all life on Earth. Most living organisms need it, including humans, animals, and plants. In addition, plants require water to absorb nutrients through their roots. However, the availability of water in the soil that can be reached by plant roots is very limited; therefore, it is necessary to measure the moisture content in the soil to prevent the soil from drying out, which can lead to plant death [6], If this occurs, human intervention is required to meet the plants' water needs. To facilitate measurement and monitoring, technology integrated with the internet—commonly known as the Internet of Things (IoT)—is required.

Many smart devices have been developed for modern agriculture, such as pest repellents, pest detectors, and leaf quality meters; and through the IoT, crops can now be monitored entirely via the internet [7]. The development of technology integrated with the internet or the Internet of Things (IoT) is essential in modern agriculture to simplify human labor and ensure the sustainability of cultivated plants. Additionally, the application of technology in agriculture enables real-time data collection and processing, allowing farmers to make quick and accurate decisions regarding plant conditions, moisture levels, and other factors. If this technology is equipped with actuators, farming operations can even run automatically without further human intervention.

Thus, modern IoT-based agriculture not only boosts productivity but also supports sustainable and environmentally friendly farming practices. Antennas and the Internet of Things (IoT) are two closely interrelated concepts, as antennas play a supporting role in internet systems. In IoT technology, antennas are the optimal choice for extending range and offer superior performance characteristics for data transmission. Additionally, the ease of integrating antennas provides a significant advantage in IoT applications [8]. However, the limited range of the built-in antenna found on microcontrollers poses a challenge in operating an IoT device, where long-range coverage is required for implementation; thus, an external antenna paired with an ESP32 Wroom-U microcontroller can serve as a solution to this problem.

The antenna designed in this study operates at a frequency of 2.4 GHz, which falls within the Industrial, Scientific, and Medical Band, commonly known as the ISM band. The selection of the ISM band aims to synchronize data on the ESP-32U microcontroller, which also operates at 2.4 GHz, and because the ESP-32U features Wi-Fi and Bluetooth capabilities that can transmit sensor data to a web server [9]. IoT is utilized for data transmission via a Wi-Fi network by having sensors read soil moisture levels in plants; these sensors then transmit the data through an ESP32 Wroom-U microcontroller, which forwards it over the internet. From there, the data is routed through the ThingSpeak web server for processing.

The choice of a flexible substrate material is intended to enable the antenna to be used on various surfaces, even uneven ones. A monopole antenna was selected because it is suitable for agricultural applications, as it features a wide bandwidth and can operate at low frequencies [10]. Additionally, when an antenna is printed on a flexible substrate, it tends to exhibit stable performance on both flat and curved surfaces, which is crucial for wearable devices or IoT systems that can be attached to uneven surfaces [11]. The antenna material uses Polydimethylsiloxane (PDMS). This material is used because PDMS has organic properties based on silicon. What is interesting about PDMS is that it is gas-permeable, stable, and performs better than rigid substrates such as FR-4 [12].

This research is expected to lead to the development of new methods for monitoring soil moisture that are more efficient, accurate, and easy to implement in agriculture [13]. The design of a flexible antenna with sensors could be a promising alternative, as it is expected to offer increased sensitivity and the potential for this antenna to be utilized in advancing modern agriculture [14].

II. METHODS

This research approach employs the Research and Development (R&D) method, which aims to develop a product through a systematic, planned process. This method begins with a needs analysis and problem identification, followed by the product design and development process. Subsequently, testing and evaluation are conducted to ensure that the resulting product is viable and aligns with the research objectives.

This study outlines the research design to be implemented. There are two research designs focused on antennas and IoT systems. The research steps and antenna design are shown in Figure 1, and the IoT system design is shown in Figure 2.

The antenna design process begins with determining the design, materials, and initial parameters. These decisions are tailored to the intended operating conditions, which are open-field environments, such as rice paddies and plantations. Once these parameters are determined, the next step involves designing and simulating the antenna using CST Microwave Studio software; if the results do not meet the targets, the design is re-optimized, but if the results are satisfactory, the process proceeds to the physical fabrication stage. After the physical antenna is fabricated, a series of laboratory and field tests is conducted, and the results are then analyzed to conclude (see Figure 1).

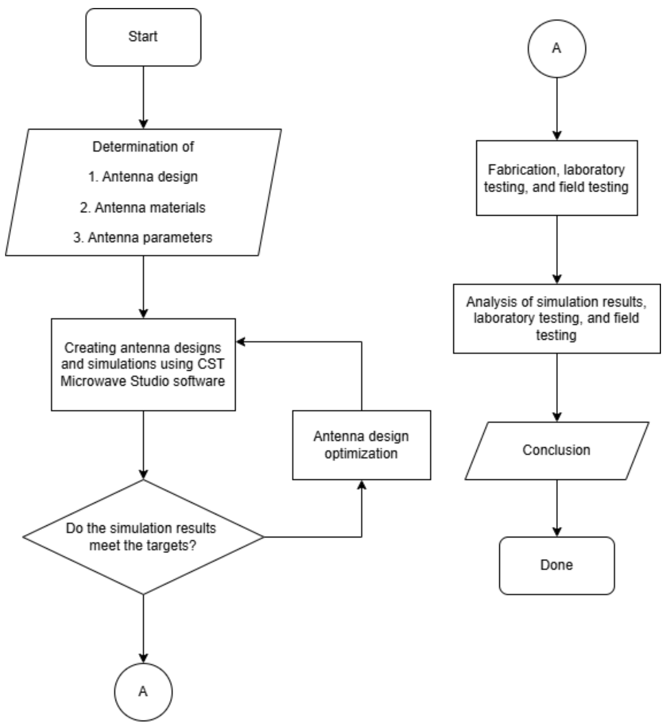

Figure 1. The flowchart of antenna design

There are formulas for designing antennas, starting with the following wavelength formula:

$$\lambda = \frac{c}{f} \quad (1)$$

Information:
λ is Wavelength (m)
f is Frequency (Hz)
c is Constant wave speed (Velocity)

To calculate the length of the antenna transmission line, use the following formula:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-\frac{1}{2}} \quad (2)$$

where, ε_{eff} is Effective dielectric constant, ε_r is variable of Relative dielectric constant (permittivity). h is Thickness or height of the dielectric substrate. W is Width of the microstrip conductor line. The length of the designed antenna can be calculated using the following formula:

$$L = \frac{c}{4 \times f \times \sqrt{\varepsilon_{eff}}} \quad (3)$$

where, L is Physical length of the resonator or antenna, c is Speed of light in a vacuum (≈ 3×10^8 meters per second). f is Operating center frequency (in Hertz), and ε_{eff} is Effective dielectric constant (permittivity) of the substrate material

The IoT system development process is integrated with the antenna. The initial steps include selecting the components to be used, designing the electrical system, and calibrating the sensors until the desired level of accuracy is achieved. The calibrated sensors include pH sensors and soil moisture sensors; this is done so that, under real-world conditions, the sensors can accurately and precisely read the conditions. Once the sensors are accurate, the IoT system is integrated with the antenna for field testing. The testing is conducted by calculating the transmission distance of the system, which is then connected to the ThingSpeak web platform to automatically collect data until the process is complete.

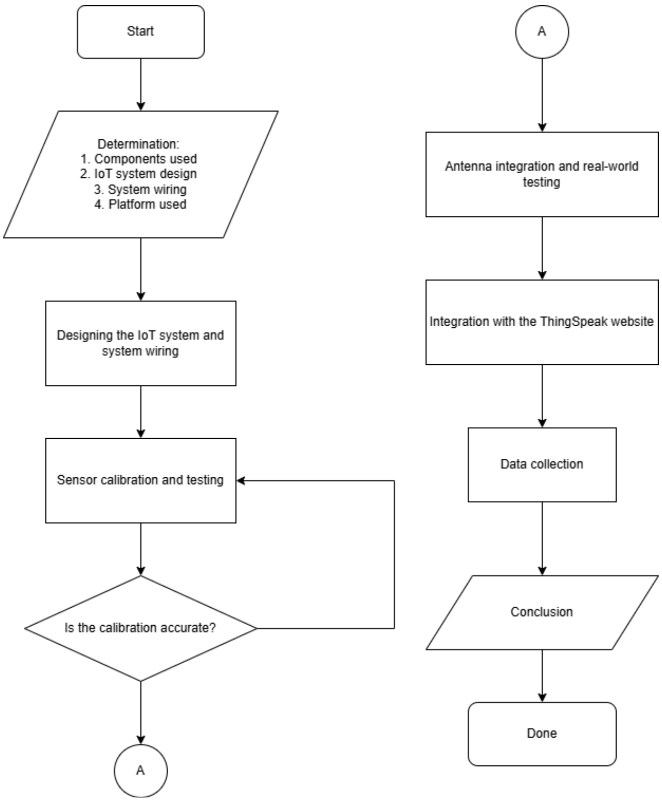

Figure 2. IoT system design flowchart

The process of collecting antenna parameter data involves two main stages: software simulation and field-based physical transmission testing. The first stage uses CST Microwave Studio software to simulate and extract antenna characteristics, including Return Loss (S_{11}), Voltage Standing Wave Ratio (VSWR), bandwidth, gain, and radiation patterns in the E-Plane and H-Plane. The second stage involves measuring Wi-Fi transmission distance to test the maximum real-world signal range, where this test compares four device scenarios: the use of the built-in internal antenna of the ESP32 Wroom-U module, the built-in internal antenna of the ESP32 Wroom-S, and a combination of both modules (ESP32 Wroom-U and ESP32 Wroom -S) in Figure 3, each integrated with a flexible monopole antenna.

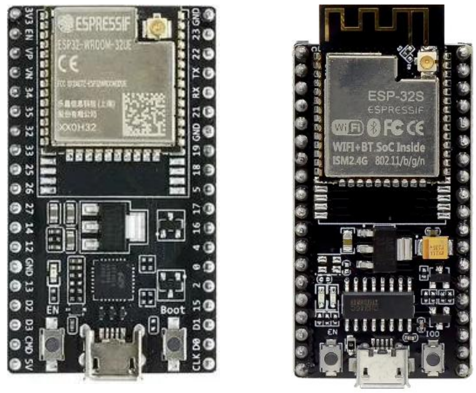

Figure 3. ESP32 Wroom-U and ESP32 Wroom-S Microcontrollers

Meanwhile, data collection for the Internet of Things (IoT) system focused on sensor functionality, network performance monitoring, and testing the devices under real-world conditions. Sensor data collection included readings of soil moisture percentage (%) along with categorization of its condition (dry, moist, wet), as well as measurements of soil acidity on a pH scale of 0–14.

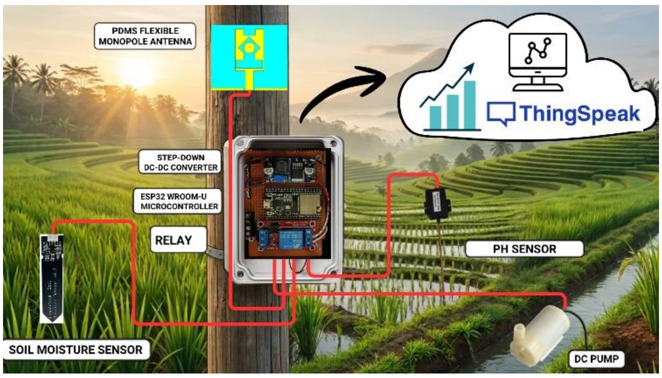

Figure 4. IoT system soil moisture with ThinkSpeak

Data from both sensors is then sent to the ThingSpeak server to analyze parameters related to current environmental conditions as shown in the Figure 4. Once transmitted, the website displays the results as a graph to facilitate data processing. In addition, system performance measurements were conducted to evaluate the impact of using an external antenna on Wi-Fi transmission range and connection stability. These performance measurements evaluate the extent to which implementing an external antenna design can optimize line-of-sight (LoS) range expansion and maintain Wi-Fi connection stability amid signal fluctuations. In the final stage, all hardware and software were tested directly in a real-world rice field ecosystem to assess the system's reliability in measuring environmental parameters under actual weather and terrain conditions.

III. RESULT AND DISCUSSION

A. Antenna Simulation Results

A monopole antenna is an antenna with a single conductive element for transmitting the signal. The microstrip antenna used in this study is a printed monopole antenna fabricated using Printed Circuit Board (PCB) technology, consisting of a conductive patch element mounted on a substrate. The function of the conductive element is to transmit waves, while the substrate serves as a layer of material designed to block or slow the transfer of energy—such as heat, sound, or electricity—from one area to another (insulation). The monopole antenna was chosen because it has a simple design and is suitable for small devices.

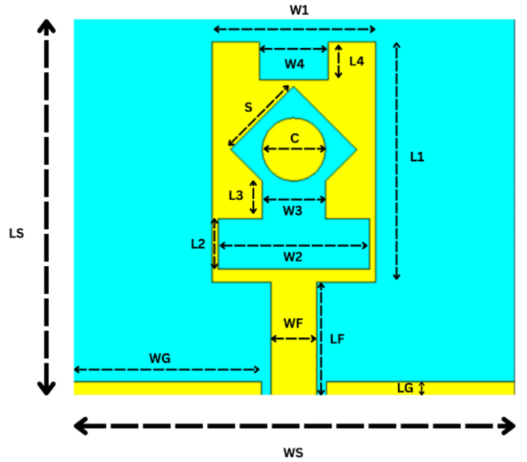

Figure 5. Antenna design system IoT soil moisture with ThinkSpeak

Table 1. Parameter antenna soil moisture with ThinkSpeak

Parameter	Value	Parameter	Value
WS	35	L2	4
LS	30	W2	12
WF	3.6	L3	4
LF	9	W3	5
L1	19	L4	3
W1	13	W4	5.5
WG	20.05	S	5
LG	1.1	C	2.5

The physical characteristics and dimensional parameters of the antenna are listed in Table 1. The antenna device designed in this study has geometric dimensions of 30 × mm × 35 mm and a total thickness of 4.07 mm, which includes the substrate layer and the conductor elements. A distinctive feature of a monopole antenna is that the patch and ground plane are located on the same layer, as shown in Figure 5. This single-layer structure significantly affects the antenna's impedance matching, which in turn determines the magnitude of the return loss

Return loss is the portion of power that is reflected back to the source due to impedance mismatch. This reflected power is referred to as antenna reflection loss. Return loss is measured in decibels (dB), which is the ratio of the reflected power to the transmitted power

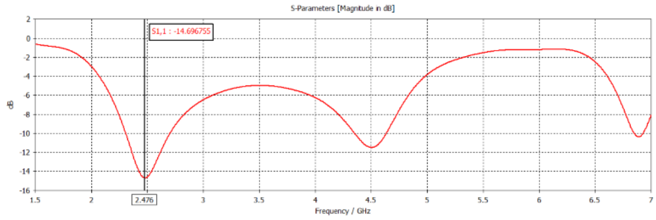

Figure 6. Return loss antenna soil moisture with ThinkSpeak

An antenna is said to be capable of transmitting and receiving data if its return loss is greater than -10 dB. As shown in the simulation in Figure 6, the designed antenna has a return loss of -14.69 dB at a frequency of 2.476 GHz; therefore, the designed antenna meets the requirements for an antenna.

Success in achieving this reflection loss value directly affects the overall efficiency of the designed antenna system. This is closely related to the Voltage Standing Wave Ratio (VSWR) parameter, which serves as a measure of power efficiency in the transmission line and indicates how efficiently power is reflected back to its source. An optimal VSWR is less than 2; if it exceeds this value, it indicates an impedance mismatch that can cause overheating, power loss, and potential damage.

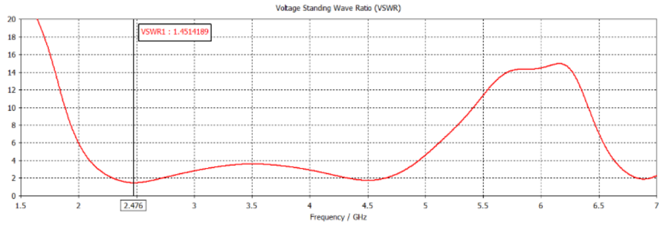

Figure 7. VSWR soil moisture with ThinkSpeak

The VSWR results in Figure 7 show that the designed antenna achieves a VSWR value of 1.45 at an operating frequency of 2.4 GHz. These results indicate that the antenna meets good design criteria, since its minimum VSWR value—which must be below the standard threshold to achieve sufficient efficiency—is within the range of < 2.

With a value of 1.45, it can be concluded that the reflected power is very small, indicating that the power transmission from the transmission line to the antenna is efficient. This optimal power efficiency ensures that signals can be transmitted and received with excellent quality. On the other hand, this performance must also be supported by sufficient bandwidth to ensure that data transfers run smoothly

Bandwidth is a measure of the frequency bandwidth used to quantify the amount of data transmitted within a given time interval, typically expressed in bits per second (bps). This frequency bandwidth is essential to ensure that the antenna can support all subchannels in Wi-Fi communication without significant signal loss. Bandwidth can be calculated using the formula:

$$BW = \frac{f2 - f1}{fc} \times 100\% \quad (4)$$

$$fc = \frac{f2 + f1}{2} \quad (5)$$

where, *BW* is Bandwidth, *f1* is the starting frequency at -10 dB *f2* is the ending frequency at -10 dB, *fc* is Frequency cut off

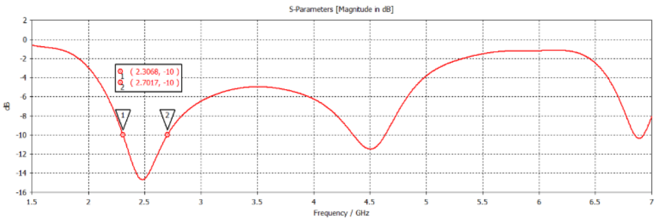
Figure 8. Bandwidth soil moisture with ThinkSpeak

Based on the bandwidth measurement results in Figure 8, the designed antenna falls into the wide-bandwidth category when calculated using Equations (4) and (5), with a bandwidth of 394 MHz, which is equivalent to 15.77% of the center operating frequency of 2.4 GHz. This frequency bandwidth exceeds the IEEE standard for 2.4 GHz Wi-Fi channels, which only requires approximately 100 MHz. This demonstrates that the antenna design has high frequency tolerance in the event of frequency shifts caused by environmental factors or manufacturing tolerances.

This high bandwidth value demonstrates that the antenna is capable of handling large volumes of data on the Wi-Fi spectrum. Signals within that range are then optimally directed through gain parameters. Gain is a measure of how effectively an antenna focuses electromagnetic waves in a specific direction. The higher the gain value, the more effectively the antenna focuses the waves in that direction.

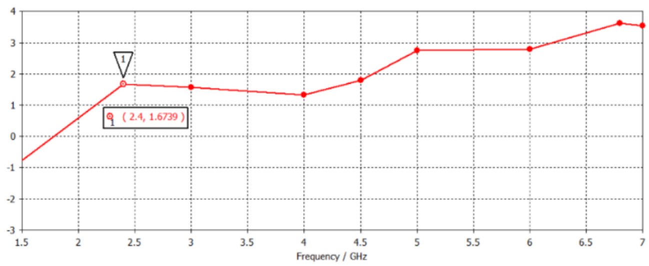
Figure 9. Gain soil moisture with ThinkSpeak

Figure 9 shows an antenna designed to have a low gain of 1.67 dBi. However, low gain is directly proportional to a wider radiation pattern (omnidirectional). Since the designed antenna is a monopole type, the low gain is not an issue. In this case, the gain meets the characteristics expected for a monopole antenna. The combination of the monopole antenna's shape and its gain directly determines how the signal is distributed in free space. These directional distribution parameters are specifically represented by the radiation pattern

The radiation pattern defines the spatial distribution of the energy emitted by an antenna, serving as a visual map of its directional characteristics. It typically maps the intensities of the electric field (E-plane) and magnetic field (H-plane) in the far-field region. By analyzing this distribution, the orientation and focus of the antenna's radiated power can be precisely determined..

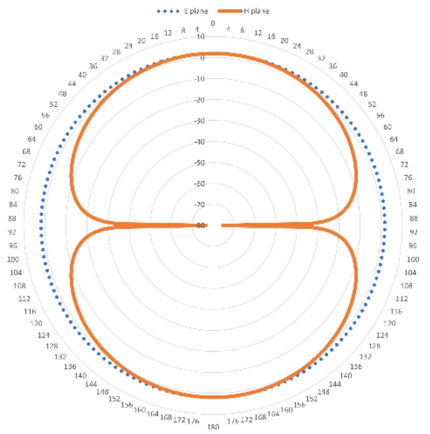
Figure 10. Radiation pattern

The results show that the designed antenna has a radiation pattern consistent with that of a monopole antenna, namely an omnidirectional radiation pattern as shown in Figure 10. This pattern allows the antenna to emit waves in all directions. This omnidirectional characteristic is confirmed by the radiation pattern plots in the elevation plane (E-Plane) and the azimuth plane (H-Plane).

In the H-plane, the radiation pattern forms a nearly perfect circle, indicating that the signal strength is evenly distributed across all horizontal angles. This is highly advantageous for this application, as the antenna does not need to be specifically aimed at the signal source to achieve a stable connection.

B. Antenna Fabrication

The antenna fabrication process begins with the preparation of a PDMS substrate, which starts by mixing the two main materials—Sylgard 184 Silicone Elastomer Base and Sylgard 184 Silicone Elastomer Curing Agent—in a 10:1 ratio. The two materials are then stirred for 5–10 minutes and poured into a pre-prepared mold. The material placed in the mold is then heated to a temperature of 50 °C to 70 °C, so that the two materials can harden while remaining flexible. As shown in Figure 11.

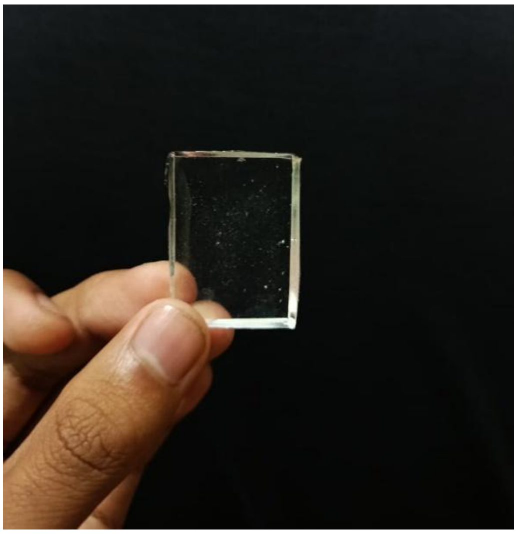
Figure 11. PDMS Fabrication Results

Subsequently, the copper tape is cut precisely based on the pre-designed antenna dimensions to serve as the conductive patch material. In the final assembly stage, the patterned copper patch is positioned securely between the top and bottom PDMS layers. This multi-layer configuration encapsulates the conductive element within the flexible PDMS substrate to ensure mechanical durability.

C. Antenna Range Testing

The use of an external antenna differs from relying solely on the microcontroller's built-in antenna. It has been demonstrated that adding a custom-designed antenna can increase the data transmission range, as shown in Table 1.

Table 2. Comparison results among microcontrollers

Comparison	Range results (meters)
ESP32 Wroom-U	34.08
ESP32 Wroom-U + external antenna	521.59
ESP32 Wroom-S	386.58
ESP32 Wroom-S + external antenna	433.94

The table shows that an external antenna can extend the data transmission range, particularly for the ESP32 Wroom-U microcontroller, which can transmit data up to 521 meters.

D. Sensor Calibration and Testing

The measurement of moisture levels begins with the calibration of the soil moisture sensor, which starts by reading the Analog-to-Digital Converter (ADC) values generated based on three soil condition parameters: dry, moist, and wet. Once the ADC values are obtained, the data is then grouped according to soil condition categories

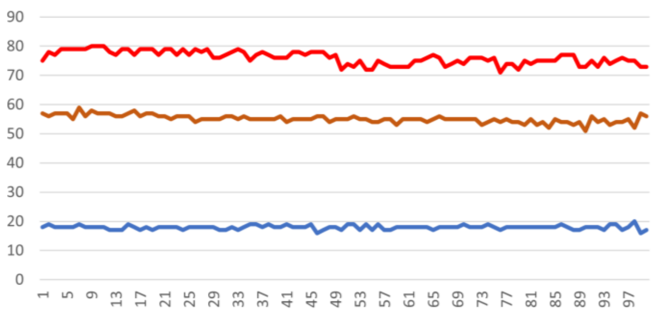

Figure 12. Soil moisture with ThinkSpeak (red: wet, brown: moist, blue: dry)

Testing shows consistent stability in the humidity sensor readings under all conditions, as illustrated in the graph in Figure 12. Under dry conditions, the sensor reads stably within the range of 16%–20% without any fluctuations outside that range. This consistency is also evident in humid conditions within the 55%–66% range, as well as in wet conditions within the 73%–80% range, where all sensor readings are deemed accurate and do not deviate from the percentage parameters of each respective category

Table 3. Average soil moisture

Soil Conditions	Average
Dry	17,93
Damp	55,13
Wet	76,10

The consistency between the sensor output data and the field results under these three conditions indicates that the data-reading system is operating accurately and has a sufficient level of linearity for implementation in automatic control systems, as shown by the average humidity sensor readings in Table 2.

The pH calibration process is performed in the same way as soil moisture sensor calibration, namely by using ADC readings. The first step in calibrating the pH sensor is to test it using pH buffer solutions with pH levels of 4.01, 6.86, and 9.18. Next, for each pH sample tested, the ADC values are recorded from the smallest to the largest and entered into Excel. This data will later be used to create a scatter plot in Excel.

After creating the scatter plot, the next step is to add a trendline and a linear fit, which will generate an equation to convert the ADC values into pH values; this equation will then be programmed into the microcontroller.

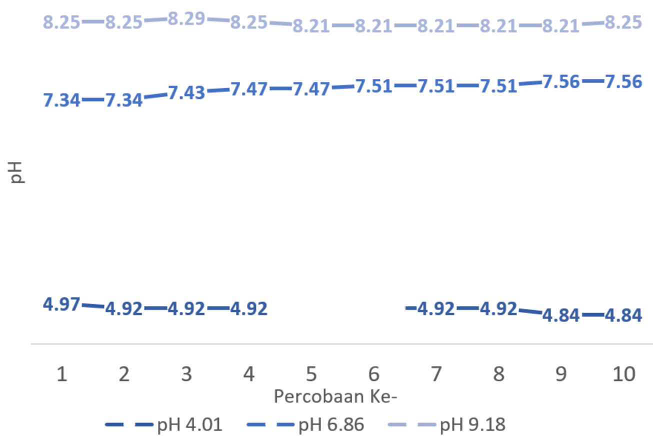

Figure 12. pH sensor calibration

The results of the study show that the sensor provides similar readings at every pH setting. In addition, the results demonstrate a high degree of consistency across 10 test repetitions. As shown in Figure 13, the system is capable of maintaining highly stable readings under all test conditions, despite differences or variations between the measured values and the standard buffer values.

Based on the tests that have been conducted, as shown in

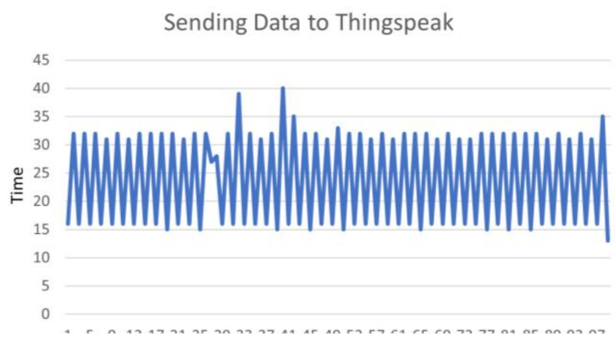

Figure 13. Sending data to Thingspeak

the graph in Figure 14, which illustrates how much time the system takes to send data to the Thingspeak website.

The results show that the IoT system successfully retrieved and transmitted data via the Thingspeak web platform every 15 to 30 seconds. In addition, the decision-making process for the automatic pump system was found to be accurate and efficient, as expected

IV. CONCLUSION

Based on the results of the research conducted, it can be concluded that:

1. The soil moisture and pH monitoring system integrated with a flexible monopole antenna based on IoT for agriculture has been deemed successful as expected. The system has functioned well, and both sensors—the pH sensor and the soil moisture sensor—are considered sufficiently effective in their measurements. Additionally, the microcontroller module has functioned well in making decisions regarding the activation of the actuator, specifically the pump used for irrigation. The designed antenna has also met all criteria as a monopole antenna operating at a frequency of 2.4 GHz.
2. The device is designed to use an ESP32 Wroom-U microcontroller integrated with several components, such as a battery, a step-down DC-DC converter, a relay, an OLED display, a soil pH sensor, a soil moisture sensor, and a DC pump, making it a highly suitable system for agricultural applications. Additionally, to achieve a wide coverage area, the inclusion of an external PDMS monopole antenna is considered effective for data transmission. The readings from the various sensors also exhibit high accuracy. These can be monitored directly via the OLED display mounted on the system enclosure.
3. Devices integrated with the IoT system have seen an increase in efficiency. This is because monitoring no longer requires looking directly at the OLED display on the device; instead, data can be viewed via the website. Data transmission in the IoT system is considered accurate because the website consistently receives data every 15 to 30 seconds

REFERENCES

[1] G. Sushanth and S. Sujatha, "IOT Based Smart Agriculture System," *2018 Int. Conf. Wirel. Commun. Signal Process. Networking, WiSPNET 2018*, vol. 5, no. 6, pp. 838–842, 2018, doi: 10.1109/WiSPNET.2018.8538702.

[2] N. I. Lestari and D. U. Siswanti, "Physiological and Anatomical Responses of Red onion (Allium cepa L.) to Drought Stress after Biofertilizer Application," *J. Biodjati*, vol. 9, no. 2, pp. 359–372, 2024, doi: 10.15575/biodjati.v9i2.38613.

[3] R. Fauziah, A. D. Susila, and E. Sulistyono, "Budidaya Bawang Merah (Allium ascalonicum L.) pada Lahan Kering Menggunakan Irigasi Sprinkler pada berbagai Volume dan Frekuensi," *J. Hortik. Indones.*, vol. 7, no. 1, pp. 1–8, 2016, doi: 10.29244/jhi.7.1.1-8.

[4] D. M. Sari, Jumardi, and N. Rasyid, "Protoptype Pengairan Sawah dan Monitoring Kualitas PH Tanah Berbasis IOT Padi merupakan komoditas tanaman pangan penghasil beras yang memegang peranan penting dalam kehidupan ekonomi Indonesia . Beras sebagai makanan pokok sangat sulit digantikan oleh bah," vol. 5, no. 2, pp. 240–251, 2022.

[5] R. D. Rima, N. Firmawati, L. Elektronika, and J. Fisika, "Rancang Bangun Prototipe Sistem Kontrol pH Tanah Untuk Tanaman Bawang Merah Menggunakan Sensor E201-C," vol. 7, no. 1, pp. 63–68, 2018.

[6] G. Civeira, "Introductory Chapter: Soil Moisture. We are IntechOpen , the world ' s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %," *Intech*, pp. 1–3, 2019, [Online]. Available: http://dx.doi.org/10.1039/C7RA00172J%0Ahttps://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics%0Ahttp://dx.doi.org/10.1016/j.colsurfa.2011.12.014

[7] N. T. Atanasov, B. N. Atanasov, and G. L. Atanasova, "Flexible Wearable Antenna for IoT-Based Plant Health Monitoring," *Electron.*, vol. 13, no. 15, 2024, doi: 10.3390/electronics13152956.

[8] Sneha, P. Malik, R. Sharma, U. Ghosh, and W. S. Alnumay, "Internet of Things and long-range antenna's; challenges, solutions and comparison in next generation systems," *Microprocess. Microsyst.*, vol. 103, no. February 2021, p. 104934, 2023, doi: 10.1016/j.micpro.2023.104934.

[9] S. Gómez-Gijón *et al.*, "Printed RFID sensing system: The cost-effective way to IoT smart agriculture," *Comput. Electron. Agric.*, vol. 232, no. April 2024, p. 110116, 2025, doi: 10.1016/j.compag.2025.110116.

[10] M. J. N. A. Sirojuddin, N. Nurhayati, R. R. H. P. A. Tjahyaningtijas, and F. Baskoro, "Antena Monopole Ultra Wide Band (UWB) untuk Aplikasi Ground Penetrating Radar (GPR)," *J. Tek. Elektro*, vol. 11, no. 1, pp. 88–98, 2022, doi: 10.26740/jte.v11n1.p88-98.

[11] A. A. Ibrahim, H. A. Mohamed, M. A. Abdelghany, and E. Tammam, "Flexible and frequency reconfigurable CPW-fed monopole antenna with frequency selective surface for IoT applications," *Sci. Rep.*, vol. 13, no. 1, pp. 1–13, 2023, doi: 10.1038/s41598-023-34917-y.

[12] S. Morris, A. R. Chandran, N. Timmons, and J. Morrison, "Design and performance of a flexible and conformal PDMS Dipole antenna for WBAN applications," *Eur. Microw. Week 2016 "Microwaves Everywhere", EuMW 2016 - Conf. Proceedings; 46th Eur. Microw. Conf. EuMC 2016*, pp. 84–87, 2016, doi: 10.1109/EuMC.2016.7824283.

[13] A. Raza, R. Keshavarz, and N. Shariati, "Precision Agriculture: Ultra-Compact Sensor and Reconfigurable Antenna for Joint Sensing and Communication," *IEEE Trans. Instrum. Meas.*, vol. 73, no. August, pp. 1–13, 2024, doi: 10.1109/TIM.2024.3350126.

[14] M. T. Khan, X. Q. Lin, C. Zhe, and A. Saboor, "Design, analysis and validation of a microstrip patch antenna with enhanced coupling for leaf moisture sensing: an IoT approach," *Front. Phys.*, vol. 12, no. May, pp. 1–13, 2024, doi: 10.3389/fphy.2024.1402326.