



Mamdani Fuzzy-Based Soil Fertility Detection Using Moisture and Color Sensors

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ARTICLE INFO

Article History:

Submitted/Received 25 May 2026

First Revised 3 June 2026

Accepted 10 June 2026

Publication Date 30 June 2026

Keywords:

Internet of Things (IoT),

Soil fertility,

Soil moisture sensor,

TCS3200,

Fuzzy Mamdani

ABSTRACT

Soil fertility plays an important role in supporting agricultural productivity and sustainable farming practices. Conventional methods for determining soil fertility, such as visual observation of soil color and manual inspection of soil moisture, are often subjective, inefficient, and less accurate. This study proposes an Internet of Things (IoT)-based soil fertility detection system using a soil moisture sensor and a TCS3200 color sensor to provide real-time and objective soil condition monitoring. The system employs a NodeMCU ESP8266 microcontroller for data acquisition and wireless communication. Sensor data are processed using the Mamdani Fuzzy Inference System (FIS) to classify soil fertility into three categories: fertile, moderately fertile, and infertile. The developed system displays monitoring results locally through an OLED display and remotely through Google Spreadsheet integration for real-time observation. Sensor calibration and field testing were conducted using several soil samples with different moisture and color characteristics. Experimental results showed that the soil moisture sensor achieved an average error rate of 1.57%, indicating good measurement accuracy. Furthermore, the fuzzy-based classification successfully identified soil fertility levels according to the measured parameters. The integration of IoT technology and fuzzy logic provides an effective low-cost solution for precision agriculture applications, particularly for small-scale farming environments. The proposed system is expected to assist farmers in monitoring soil conditions more efficiently, accurately, and continuously.

1. Introduction

Soil fertility is one of the most important factors affecting agricultural productivity and crop quality. Fertile soil provides sufficient nutrients, water availability, and proper physical structure to support optimal plant growth. However, conventional methods for evaluating soil fertility are still widely practiced by farmers, such as visual observation of soil color and manual inspection of soil moisture. These approaches are generally subjective, inefficient, and highly dependent on human experience, especially for large-scale agricultural areas. Therefore, a more accurate, objective, and real-time monitoring system is needed to support modern precision agriculture practices [1], [2].

The development of the Internet of Things (IoT) has significantly transformed agricultural monitoring systems by enabling real-time data acquisition, remote observation, and automated decision-making. IoT technology allows sensor devices to continuously collect environmental data and transmit the information through wireless networks for monitoring and analysis. In precision agriculture, IoT-based monitoring systems have been widely implemented to observe soil moisture, temperature, humidity, nutrient content, and irrigation conditions in order to improve farming efficiency and crop productivity [3], [4], [5].

Among various soil parameters, soil moisture and soil color are important indicators for determining soil fertility. Soil moisture directly affects water availability, nutrient transport, and microbial activity within the soil. Insufficient or excessive soil moisture may negatively influence plant growth and reduce agricultural productivity [6]. Meanwhile, soil color is closely related to organic matter content and mineral composition. Darker soil generally indicates higher organic material concentration and better fertility conditions compared to brighter soil [7]. Therefore, combining soil moisture and soil color measurements can provide a more comprehensive assessment of soil fertility conditions.

Several previous studies have implemented IoT-based systems for soil monitoring and smart agriculture applications. Research conducted by Firmansyah et al. developed an IoT-based soil fertility detection system using fuzzy logic for monitoring agricultural land conditions [8]. Other studies integrated soil moisture sensors with IoT platforms for real-time irrigation monitoring and automatic watering systems [9], [10]. Furthermore, Mamdani fuzzy inference systems have been widely applied in intelligent agricultural systems because of their ability to handle uncertainty and imitate human reasoning in decision-making processes [11], [12].

Despite these advancements, most existing studies primarily focus on soil moisture monitoring, irrigation control, or soil nutrient assessment as independent parameters, while limited attention has been given to integrating soil moisture and soil color information within a unified IoT-based fuzzy decision-making framework for soil fertility evaluation. Therefore, the novelty of this research lies in the

development of a low-cost IoT-based soil fertility detection system that combines soil moisture and soil color sensing with the Mamdani Fuzzy Inference System and real-time cloud monitoring using NodeMCU ESP8266, enabling a more comprehensive and practical assessment of soil fertility conditions for precision agriculture applications [13].

2. Methods

2.1. Research Methods

This study employed an experimental engineering approach to develop an Internet of Things (IoT)-based soil fertility detection system using soil moisture and soil color parameters. The proposed system was designed to provide real-time monitoring and intelligent classification of soil fertility conditions using the Mamdani Fuzzy Inference System (FIS). The research stages included problem identification, hardware and software design, system implementation, sensor calibration, data acquisition, and performance evaluation.

The development process followed the prototyping method, where hardware integration and software testing were conducted iteratively until the system achieved stable monitoring and classification performance. IoT-based monitoring systems have been widely implemented in precision agriculture because they enable continuous environmental monitoring and support more accurate agricultural decision-making processes.

The overall research flow is illustrated in Figure 1.

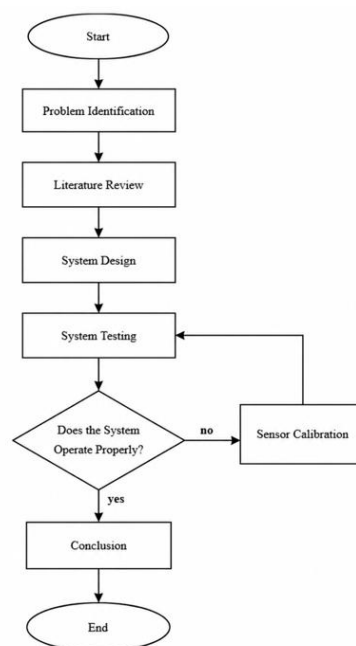


Figure 1: Research flowchart.

2.2. System Architecture

The developed system consisted of several integrated components, including a soil moisture sensor, TCS3200 color sensor, NodeMCU ESP8266 microcontroller, OLED display module, lithium-ion battery, and cloud-based monitoring platform. The architecture of the proposed system is presented in Figure 2.

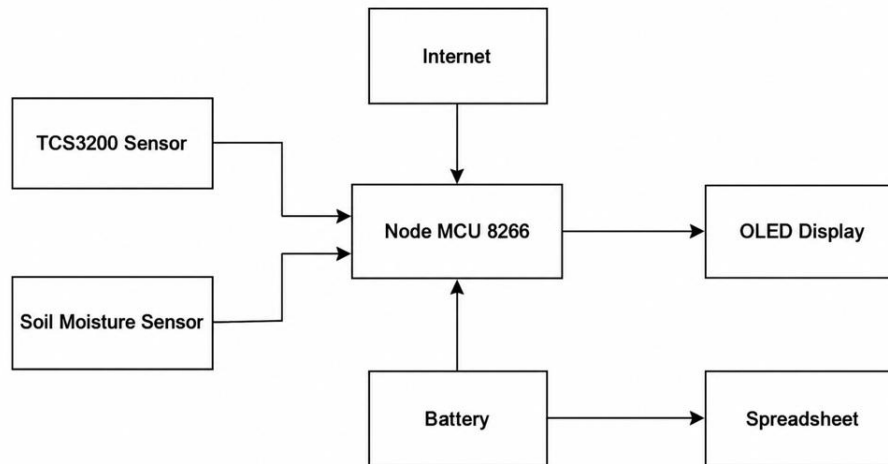


Figure 2: Overall system architecture.

The soil moisture sensor measured soil water content, while the TCS3200 sensor detected soil color characteristics in RGB format. The sensor data were processed by the NodeMCU ESP8266 microcontroller and classified using the Mamdani fuzzy inference method. The classification results were displayed locally on an OLED display and transmitted wirelessly through a Wi-Fi network to Google Spreadsheet for remote monitoring.

The NodeMCU ESP8266 was selected because it provides integrated Wi-Fi capability, low power consumption, and compatibility with IoT-based monitoring systems [13]. The use of cloud-based monitoring platforms allows users to observe soil conditions remotely using smartphones or computers connected to the internet.

2.3. Hardware Design

The hardware configuration consisted of several main components, namely NodeMCU ESP8266, soil moisture sensor, TCS3200 color sensor, OLED display, lithium-ion battery, and jumper cables. Table 1 summarizes the specifications of the hardware components used in this study.

Table 1: Hardware specification.

Component	Specification	Description
NodeMCU ESP8266	Tensilica L106 32-bit, 80 MHz, 4 MB Flash, Wi-Fi 802.11 b/g/n	Main microcontroller for sensor processing and IoT communication
Soil Moisture Sensor	Operating voltage: 3.3–5V DC, analog and digital output	Measures soil moisture level based on electrical resistance
TCS3200 Color Sensor	RGB color detection, 8×8 photodiode array, TTL square-wave output	Detects soil color intensity in RGB format
OLED Display	0.96 inch, 128×64 pixels, I2C interface	Displays real-time monitoring results locally
Lithium-Ion Battery	3.7V rechargeable battery with boost converter	Provides portable power supply for the system
Jumper Cables	Male-to-Male, Male-to-Female, Female-to-Female	Connects electronic components within the system
Internet Connection	Wi-Fi network	Enables real-time cloud-based data transmission
Google Spreadsheet	Cloud-based monitoring platform	Stores and displays sensor data remotely

All electronic components were integrated into a unified hardware system controlled by the NodeMCU ESP8266 microcontroller. The integrated system enabled simultaneous acquisition of soil moisture and soil color data for fertility classification.

Figure 3 illustrates the overall hardware integration of the proposed system.

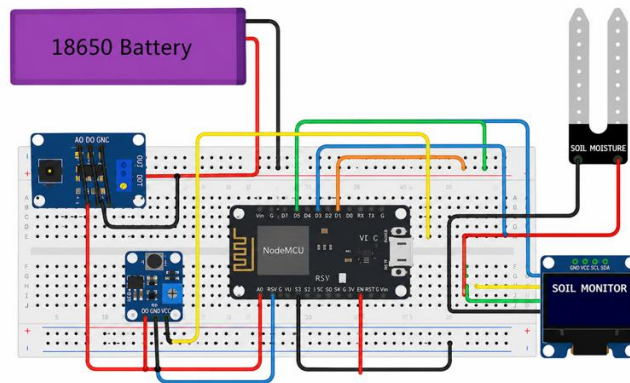


Figure 3: Overall hardware integration.

2.4. Software Design

The software development process involved sensor data acquisition, fuzzy inference implementation, OLED visualization, and cloud-based data transmission. The Arduino IDE platform was used to program the NodeMCU ESP8266 microcontroller.

The software workflow began with reading soil moisture and soil color sensor values. The acquired sensor signals were then converted into digital data and processed using the Mamdani Fuzzy Inference System (FIS) to determine soil fertility status. The classification results were subsequently displayed on

the OLED screen for local monitoring and transmitted to Google Spreadsheet through Wi-Fi communication for real-time remote observation.

The software flowchart used in the developed system is illustrated in Figure 4.

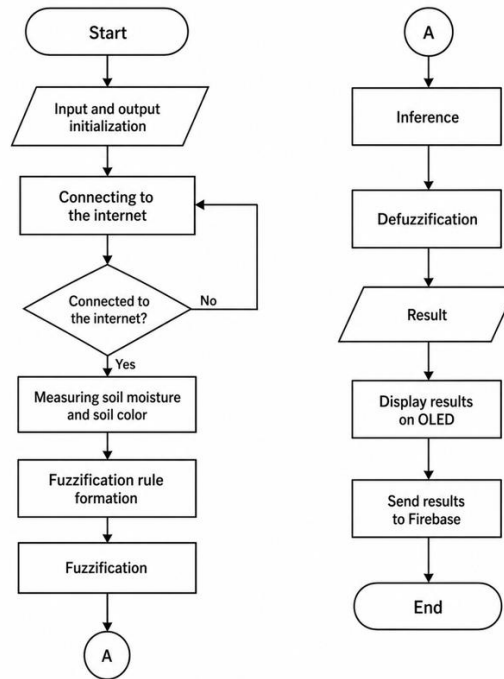


Figure 4: Software design flowchart.

2.5. Mamdani Fuzzy Inference System Design

The Mamdani Fuzzy Inference System (FIS) was implemented to classify soil fertility levels based on soil moisture and soil color parameters. Fuzzy logic was selected because it is capable of handling uncertainty and representing human reasoning in decision-making processes, particularly in agricultural monitoring systems with dynamic environmental conditions [11], [14].

The developed fuzzy system consisted of two input variables and one output variable. The input variables were soil moisture and soil color intensity obtained from the soil moisture sensor and TCS3200 color sensor, respectively. Meanwhile, the output variable represented the soil fertility classification result.

The linguistic variables and fuzzy sets used in this study are summarized in Table 2.

Table 2: Linguistic variables and fuzzy sets

Variable	Type	Fuzzy Sets
Soil Moisture	Input	Dry, Moist, Wet
Soil Color	Input	Bright, Medium, Dark
Soil Fertility	Output	Infertile, Moderately Fertile, Fertile

The soil moisture parameter represented the water content condition of the soil measured in percentage form. Lower moisture values indicated dry soil conditions, while higher values represented wet soil conditions. Soil color intensity was determined using RGB readings generated by the TCS3200 sensor. Darker soil colors generally indicate higher organic matter content and better fertility characteristics [15].

Triangular and trapezoidal membership functions were applied to represent each fuzzy variable. These membership functions were selected because of their simplicity and computational efficiency for embedded systems implementation. The membership function ranges used in the proposed system are presented in Table 3.

Table 3: Membership function ranges.

Variable	Fuzzy Set	Range
Soil Moisture	Dry	0 – 40%
	Moist	30 – 70%
	Wet	60 – 100%
Soil Color	Bright	Low RGB intensity
	Medium	Medium RGB intensity
	Dark	High RGB intensity
Soil Fertility	Infertile	0 – 40%
	Moderately Fertile	30 – 70%
	Fertile	60 – 100%

The membership function models used in this study are illustrated in Figures 5–7.

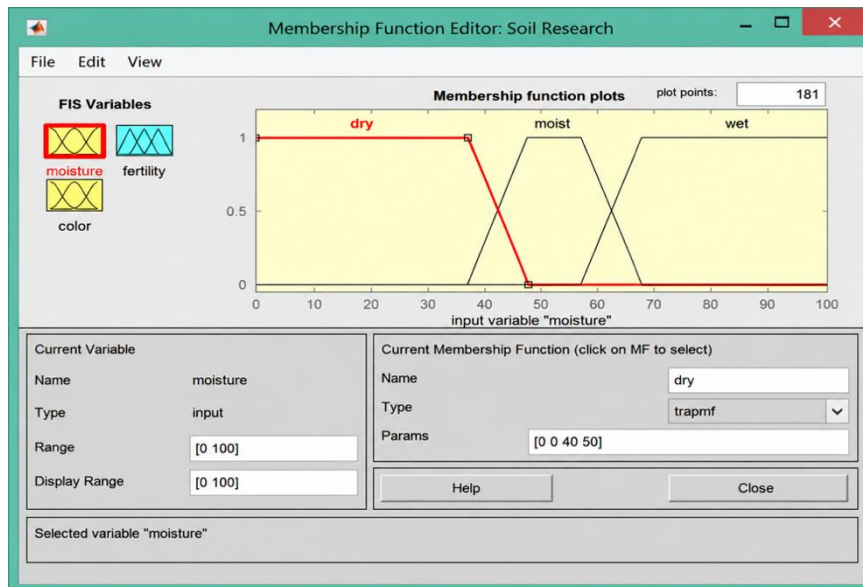


Figure 5: Soil moisture membership function.

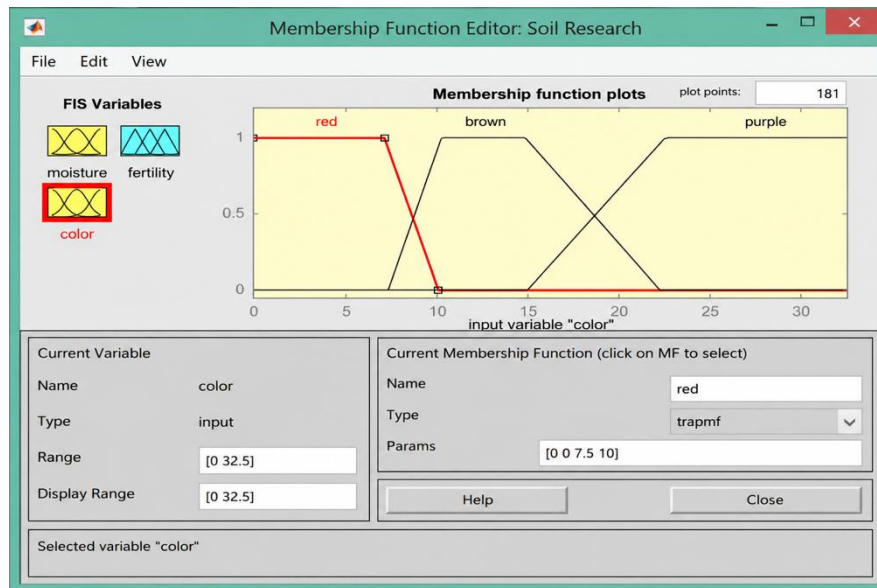


Figure 6: Soil color membership function.

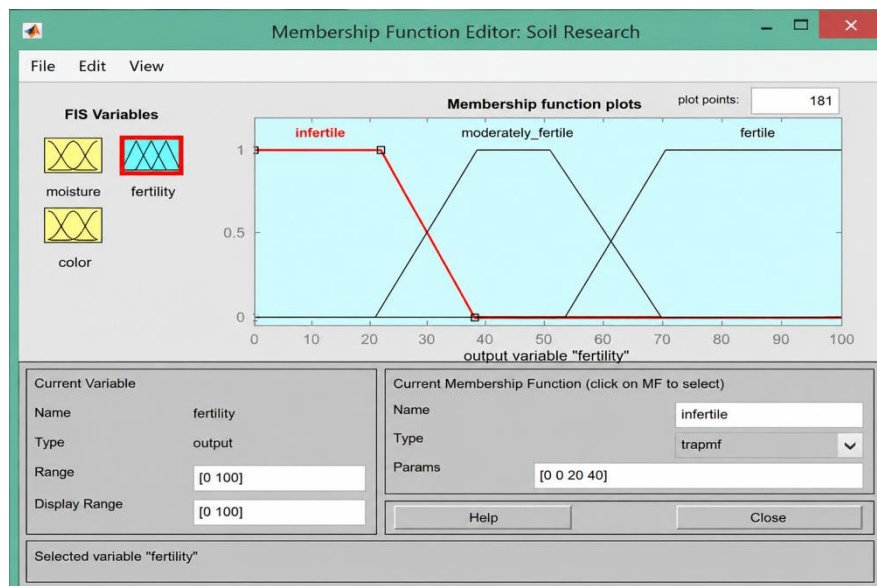


Figure 7: Soil fertility output membership function.

The fuzzy inference mechanism involved fuzzification, rule evaluation, aggregation, and defuzzification processes. During the fuzzification stage, crisp sensor values were transformed into fuzzy membership values according to the predefined membership functions. The fuzzy rules were then evaluated using the Mamdani inference approach.

The fuzzy rule base was constructed using IF–THEN rules derived from soil condition characteristics. The relationship between soil moisture and soil color parameters in determining soil fertility level is presented in Table 4.

Table 4: Mamdani fuzzy rule base.

Soil Moisture	Soil Color	Soil Fertility
Dry	Bright	Infertile
Dry	Medium	Infertile
Dry	Dark	Moderately Fertile
Moist	Bright	Moderately Fertile
Moist	Medium	Moderately Fertile
Moist	Dark	Fertile
Wet	Bright	Moderately Infertile
Wet	Medium	Fertile
Wet	Dark	Fertile

One of the implemented fuzzy rules [16] can be expressed as follows:

$$IF \text{ Soil Moisture} = \text{Wet} \text{ AND } \text{Soil Color} = \text{Dark} \text{ THEN } \text{Fertility} = \text{Fertile} \quad (1)$$

The centroid method was applied during the defuzzification stage to convert fuzzy output values into crisp numerical values representing soil fertility level. The centroid defuzzification equation is expressed as [17]:

$$z^* = \frac{\int \mu(z) \cdot z \, dz}{\int \mu(z) \, dz} \quad (2)$$

where z^* represents the crisp output value and $\mu(z)$ denotes the aggregated membership function.

The Mamdani FIS implementation enabled the proposed system to classify soil fertility conditions automatically based on sensor measurements obtained in real time.

2.6. Testing Procedure

The testing procedure was conducted to evaluate the performance of the proposed IoT-based soil fertility detection system in terms of sensor accuracy, fuzzy classification capability, and real-time data transmission reliability. Prior to field implementation, calibration was performed on both the soil moisture sensor and the TCS3200 color sensor to ensure measurement consistency and stability.

The experimental testing scenario consisted of sensor calibration and field testing under different soil conditions. The soil moisture sensor was evaluated using dry, moist, and wet soil samples, while the TCS3200 color sensor was calibrated using several reference color samples to validate RGB detection performance. Field testing was subsequently conducted using soil samples with varying moisture levels and color characteristics to evaluate the performance of the Mamdani fuzzy classification system. Each sensor underwent 15 testing iterations during the calibration and validation stages to improve measurement reliability and reduce uncertainty.

During field testing, the soil moisture sensor probe was inserted into the soil sample to measure water content, whereas the TCS3200 sensor captured soil color intensity in RGB format. The acquired sensor data were processed using the Mamdani Fuzzy Inference System (FIS) implemented on the

NodeMCU ESP8266 microcontroller to classify soil fertility into infertile, moderately fertile, and fertile categories.

The developed system also evaluated real-time wireless communication performance by transmitting sensor readings and classification results to Google Spreadsheet through Wi-Fi connectivity. Local monitoring was simultaneously provided through the integrated OLED display module.

The measurement error percentage was calculated using Equation (3) [18].

$$Error(\%) = \frac{|Measured\ Value - Reference\ Value|}{Reference\ Value} \times 100 \quad (3)$$

where the measured value represents the sensor output and the reference value denotes the actual soil condition obtained during calibration.

3. Results and Discussion

3.1. Sensor Calibration and Testing Results

Sensor calibration was conducted to evaluate the measurement accuracy and stability of the developed IoT-based soil fertility detection system before field implementation. The calibration process involved the TCS3200 color sensor and the soil moisture sensor under different testing conditions.

The TCS3200 sensor calibration was performed using several origami paper samples with different colors to validate RGB color detection capability. The obtained results demonstrated that the sensor was capable of distinguishing color intensity consistently based on RGB readings. The calibration results of the TCS3200 sensor are presented in Table 5.

Table 5: TCS3200 color sensor calibration results.

No	Color	R	G	B
1	Red	236	151	185
2	Green	215	242	231
3	Blue	169	196	239
4	Yellow	250	242	215
5	Orange	255	227	233
6	Pink	255	229	251
7	Brown	177	134	155
8	Purple	223	179	233
9	Black	105	92	122
10	White	250	249	255
11	Dark Brown	148	112	120
12	Light Brown	198	170	162
13	Dark Gray	121	118	130
14	Light Gray	201	198	205
15	Dark Red	189	104	118

The soil moisture sensor calibration process was conducted to evaluate the accuracy of soil moisture measurements compared with a digital moist meter as the reference instrument. In this process, the soil moisture sensor generated ADC (Analog-to-Digital Converter) values that were converted into percentage values and subsequently compared with the actual moisture values measured using the moist meter. The calibration results are presented in Table 6.

Table 6: Soil moisture sensor calibration results.

No	ADC Value	ADC(%)	MM Scale	MM(%)	Error(%)
1	882	19.50	2.0	20.00	2.50
2	851	23.79	2.4	24.00	0.88
3	812	29.18	2.9	29.00	0.62
4	775	34.30	3.5	35.00	2.00
5	740	39.14	4.0	40.00	2.15
6	703	44.26	4.5	45.00	1.64
7	666	49.38	5.0	50.00	1.24
8	629	54.50	5.5	55.00	0.91
9	592	59.61	6.0	60.00	0.65
10	556	64.59	6.5	65.00	0.63
11	520	69.57	7.1	71.00	2.01
12	484	74.55	7.6	76.00	1.91
13	447	79.67	8.1	81.00	1.64
14	410	84.79	8.6	86.00	1.41
15	374	89.76	9.1	91.00	1.36
Average Error (%)					1.57%

The calibration results indicate that the developed soil moisture sensor demonstrated stable measurement performance with values closely matching the reference moist meter readings. The obtained ADC values exhibit an inverse relationship with soil moisture level, where lower ADC values correspond to higher moisture percentages. Based on the experimental results, the developed soil moisture sensor achieved an average measurement error of 1.57%, indicating reliable performance for real-time soil monitoring applications.

To further analyze the relationship between the ADC values generated by the soil moisture sensor and the normalized soil moisture percentage, a graphical visualization was created based on the calibration results presented in Table 6. As shown in Figure 8, the graph illustrates the inverse relationship between ADC values and soil moisture levels, where lower ADC values correspond to higher soil moisture percentages.

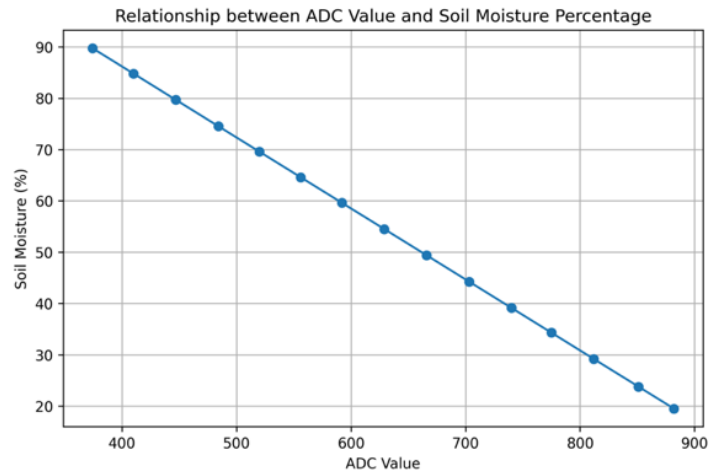


Figure 8: Relationship between ADC value and soil moisture percentage.

Field testing was subsequently conducted using soil samples with different moisture levels and soil color characteristics to evaluate the capability of the developed system under varying environmental conditions. The testing datasets were grouped into dry, moist, and wet soil categories. The experimental results indicate that the proposed system was capable of measuring soil moisture and detecting soil color characteristics consistently under different soil conditions.

3.2. Mamdani Fuzzy Classification Results

The Mamdani Fuzzy Inference System (FIS) was implemented to classify soil fertility levels based on soil moisture and soil color parameters obtained from the soil moisture sensor and TCS3200 color sensor. The fuzzy classification process consisted of fuzzification, rule evaluation, inference, and defuzzification stages to determine the final fertility classification output.

Field testing was conducted using several soil samples categorized into dry, moist, and wet soil conditions. The obtained soil moisture values and RGB color characteristics were processed according to the predefined membership functions and fuzzy rule base presented in the previous section. The testing process aimed to evaluate the capability of the developed system in classifying soil fertility conditions under different environmental parameters.

The dry soil testing results are presented in Table 7.

Table 7: Dry soil testing result.

No	Soil Moisture (%)	RGB Value (R, G, B)	Soil Color	Fuzzy Classification
1	21.5	(198, 134, 66)	Bright Brown	Infertile
2	24.1	(205, 133, 63)	Bright Brown	Infertile
3	27.8	(184, 134, 11)	Yellowish Brown	Infertile
4	29.3	(210, 180, 140)	Bright Brown	Moderately Fertile
5	31.0	(160, 82, 45)	Brown	Moderately Fertile

Based on the results presented in Table 7, dry soil samples generally produced low moisture values and brighter soil color characteristics. These conditions resulted in infertile and moderately fertile classifications due to the low water content and lower indication of soil organic matter.

The moist soil testing results are presented in Table 8.

Table 8: Moist soil testing result.

No	Soil Moisture (%)	RGB Value (R, G, B)	Soil Color	Fuzzy Classification
1	45.3	(139, 90, 43)	Brown	Moderately Fertile
2	48.7	(139, 69, 19)	Brown	Moderately Fertile
3	52.1	(101, 67, 33)	Dark Brown	Fertile
4	55.4	(92, 64, 51)	Dark Brown	Fertile
5	58.2	(123, 63, 0)	Brown	Fertile

The results in Table 8 indicate that soil samples with moderate moisture levels and darker color characteristics tended to produce fertile classifications. Darker soil colors generally indicate higher organic matter content, which contributes to improved soil fertility characteristics.

The wet soil testing results are presented in Table 9.

Table 9: Wet soil testing result.

No	Soil Moisture (%)	RGB Value (R, G, B)	Soil Color	Fuzzy Classification
1	71.4	(78, 53, 36)	Dark Brown	Fertile
2	75.8	(59, 47, 47)	Dark Brown	Fertile
3	80.2	(47, 27, 12)	Blackish Brown	Fertile
4	84.7	(28, 28, 28)	Blackish Brown	Fertile
5	89.5	(0, 0, 0)	Black	Fertile

3.3. IoT Monitoring and System Implementation Results

The implementation of the IoT-based soil fertility detection system was conducted by integrating the soil moisture sensor, TCS3200 color sensor, NodeMCU ESP8266 microcontroller, OLED display, and wireless communication module into a single embedded monitoring device. The developed prototype was designed to perform real-time acquisition, processing, classification, and transmission of soil condition data. The overall prototype implementation adapted from the developed hardware design is presented in Figure 9.

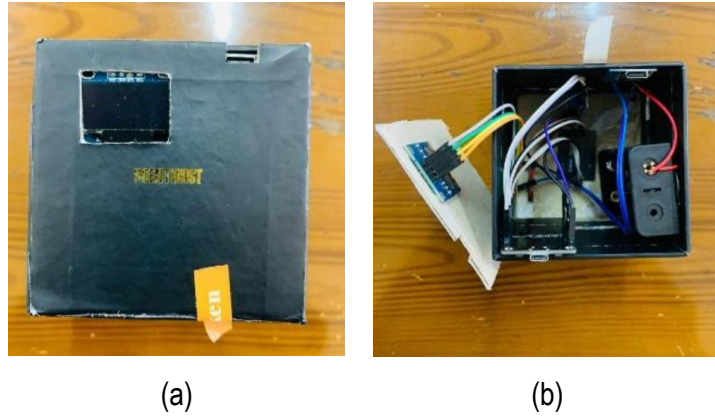


Figure 9: (a) External prototype design of the soil fertility detection system, (b) Internal hardware configuration of the prototype.

The developed prototype consisted of a NodeMCU ESP8266 microcontroller connected to the soil moisture sensor and TCS3200 color sensor as the primary input devices. The soil moisture sensor was utilized to measure soil water content, while the TCS3200 sensor detected soil color characteristics through RGB readings. The obtained sensor data were processed using the Mamdani Fuzzy Inference System (FIS) to determine soil fertility classification categories, namely infertile, moderately fertile, and fertile.

The NodeMCU ESP8266 was selected due to its integrated Wi-Fi capability, enabling real-time communication with cloud-based monitoring platforms. Sensor data and fuzzy classification results were transmitted automatically to Google Spreadsheet through wireless internet communication. This implementation enabled users to monitor soil conditions remotely using smartphones or computers connected to the internet. In addition, the measured data were also displayed locally using a 0.96-inch OLED display for direct field observation.

The system implementation results demonstrated stable hardware integration and reliable real-time monitoring performance during experimental testing. The prototype was capable of continuously acquiring sensor data, processing fuzzy classification, displaying local monitoring information, and transmitting measurement results to the cloud platform without significant communication interruption. The wireless monitoring capability provided practical advantages for precision agriculture applications, particularly for small-scale farming environments requiring efficient and objective soil condition monitoring.

Furthermore, the developed system successfully demonstrated the integration of IoT technology and fuzzy logic methods within a compact embedded platform. The proposed implementation can support early soil fertility detection and assist users in monitoring soil conditions continuously without relying solely on manual observation methods. Overall, the prototype implementation results indicate that the

developed system has significant potential for supporting smart agriculture applications and real-time environmental monitoring systems.

3.4. Comparison with Previous Studies

Although numerous studies have investigated IoT-based agricultural monitoring systems and fuzzy logic applications for soil analysis, most existing works focus on specific parameters such as soil moisture, soil nutrients, irrigation management, or crop recommendation. Therefore, it is important to compare the proposed system with recent related studies to evaluate its relative contribution and practical applicability. The comparison presented in Table 10 summarizes the characteristics and performance of several state-of-the-art studies and highlights the advantages of the proposed system, particularly in integrating soil moisture and soil color sensing with Mamdani Fuzzy Inference System (FIS)-based decision making and real-time cloud monitoring for soil fertility assessment.

Table 10: Comparison of the proposed system with recent related studies.

Reference	Year	Research Focus	Input Parameters	Intelligent Method	Main Findings
[2]	2023	Soil information diagnosis using smartphone-based IoT monitoring	Soil moisture, environmental parameters	Multi-sensor monitoring system	Enabled real-time soil condition monitoring using IoT and mobile devices.
[13]	2022	Soil nutrient detection and fertilizer recommendation	Nitrogen, phosphorus, potassium	Fuzzy Logic	Generated fertilizer recommendations based on soil nutrient conditions.
[19]	2022	Smart agriculture decision support system	Soil pH, nitrogen, phosphorus, potassium	Fuzzy Inference System	Provided crop recommendation according to soil characteristics.
[9]	2024	Intelligent agricultural monitoring and control	Soil moisture and environmental variables	Intelligent control system	Improved monitoring and control of agricultural environments through IoT devices.
[7]	2024	Soil quality monitoring for soybean cultivation	Soil quality parameters	Mamdani Fuzzy Logic	Supported soil quality evaluation for agricultural production.
[10]	2025	Soil nutrient monitoring and control	Soil nutrient parameters	Fuzzy Logic with multi-modal sensors	Enabled real-time nutrient monitoring and management.
[4]	2025	Precision agriculture monitoring system	Soil and crop environmental parameters	IoT-based monitoring	Supported low-cost precision agriculture applications.
Proposed Study	2026	Real-time soil fertility assessment	Soil moisture and soil color	Mamdani Fuzzy Inference System integrated with IoT monitoring	Achieved an average soil moisture measurement error of 1.57% and successfully classified soil fertility into infertile, moderately fertile, and fertile categories through real-time cloud-based monitoring.

Based on Table 10, the proposed system offers a distinct contribution by combining soil moisture and soil color parameters as complementary indicators of soil fertility. Unlike previous studies that primarily emphasized nutrient monitoring or irrigation-related applications, the developed system provides a practical and low-cost approach for real-time soil fertility evaluation. Furthermore, the obtained average measurement error of 1.57% demonstrates the reliability of the sensing mechanism for precision agriculture applications. This combination of dual-parameter sensing, fuzzy-based decision making, and cloud-connected monitoring enhances the practicality of the system for continuous soil condition assessment.

4. Conclusion

This study successfully developed an IoT-based soil fertility detection system using soil moisture and color sensors integrated with the Mamdani Fuzzy Inference System (FIS). The proposed system utilized a soil moisture sensor and TCS3200 color sensor to measure soil moisture levels and soil color characteristics as the primary parameters for soil fertility classification. The NodeMCU ESP8266 microcontroller was implemented to perform data processing and real-time wireless communication for remote monitoring applications.

Based on the experimental results, the developed soil moisture sensor demonstrated reliable performance with an average measurement error of 1.57% compared to the reference moist meter measurements. In addition, the TCS3200 sensor was capable of detecting soil color variations consistently through RGB measurements, enabling effective identification of soil color characteristics associated with fertility conditions.

The Mamdani fuzzy classification system successfully classified soil conditions into infertile, moderately fertile, and fertile categories based on soil moisture and soil color parameters. Experimental testing demonstrated that higher soil moisture levels and darker soil color characteristics generally produced fertile classifications, while lower moisture levels and brighter soil colors tended to produce infertile classifications. The obtained results indicate that the developed fuzzy rule base effectively represented the relationship between environmental soil parameters and soil fertility conditions.

Furthermore, the IoT implementation results demonstrated stable real-time monitoring performance through wireless communication using the NodeMCU ESP8266 platform. Sensor measurements and fuzzy classification results were successfully displayed locally through the OLED module and remotely through cloud-based monitoring platforms. Overall, the developed system has significant potential for supporting smart agriculture applications, particularly for real-time soil monitoring and precision farming environments.

References

- [1] R. Sreeram, S. Adithya Krishna, A. S. Kumar, S. Remya, and Y. Y. Cho, 'Soil moisture monitoring technologies in smart agriculture: A comprehensive review', *Farming System*, vol. 4, no. 2, p. 100189, Apr. 2026, doi: 10.1016/J.FARSYS.2025.100189.
- [2] Y. Wu, Z. Yang, and Y. Liu, 'Internet-of-Things-Based Multiple-Sensor Monitoring System for Soil Information Diagnosis Using a Smartphone', *Micromachines 2023*, Vol. 14, vol. 14, no. 7, Jul. 2023, doi: 10.3390/M14071395.
- [3] I. N. Afifah, 'An IoT-Based Real-Time Soil Moisture Monitoring System for Smart Agriculture Using ESP32', 2026.
- [4] T. S. Kalaivani, T. Kamireddy, and S. Govindakumar, 'IoT-Enabled Soil and Crop Monitoring System Using Low-Cost Smart Sensors for Precision Agriculture', *Engineering Proceedings 2025*, Vol. 118, vol. 118, no. 1, p. 77, Nov. 2025, doi: 10.3390/ECSA-12-26537.
- [5] R. Silvestri, M. Vecchio, M. Pincheira, and F. Antonelli, 'Smart Irrigation with Fuzzy Decision Support Systems in Trentino Vineyards', *Sensors 2025*, Vol. 25, vol. 25, no. 23, Nov. 2025, doi: 10.3390/S25237188.
- [6] R. Silvestri, M. Vecchio, M. Pincheira, and F. Antonelli, 'Smart Irrigation with Fuzzy Decision Support Systems in Trentino Vineyards', *Sensors 2025*, Vol. 25, vol. 25, no. 23, Nov. 2025, doi: 10.3390/S25237188.
- [7] H. Sujadi, M. D. Purwanto, D. Susandi, and I. Marina, 'Development of a Soil Quality Monitoring System for Soybean Cultivation Based on Internet of Things with Mamdani Fuzzy Logic Method', *INCITEST 2024 - Proceedings of the 7th International Conference on Informatics, Engineering, Sciences and Technology*, 2024, doi: 10.1109/INCITEST64888.2024.11121496.
- [8] D. Firmansyah and I. B. G. Dwidasmara, 'Implementasi IoT pada Alat Pendeteksi Kesuburan Tanah Menggunakan Algoritma Fuzzy Logic', *Jurnal Nasional Teknologi Informasi dan Aplikasinya*, vol. 2, no. 2, pp. 333–338, Feb. 2024, doi: 10.24843/JNATIA.2024.V02.I02.P12.
- [9] S. A. Finecomess, G. Gebresenbet, and H. M. Alwan, 'IoT Utilizing an Internet of Things (IoT) Device, Intelligent Control Design, and Simulation for an Agricultural System', 2024, doi: 10.3390/iot5010004.
- [10] A. W. Hakis, A. Latief Arda, and A. Jalil, 'IoT-based Soil Nutrient Monitoring and Control Using Fuzzy Logic and Multi-Modal Sensor Integration', *Journal of Applied Informatics and Computing (JAIC)*, vol. 9, no. 5, pp. 2736–2745, 2025, [Online]. Available: <http://jurnal.polibatam.ac.id/index.php/JAIC>
- [11] K. Jenis Tanaman Pertanian Bagi Petani *et al.*, 'Analysis of Fuzzy Mamdani Implementation in Decision Making of Agricultural Plant Types for Farmers', *Sistemasi: Jurnal Sistem Informasi*, vol. 13, no. 2, pp. 841–850, Mar. 2024, doi: 10.32520/STMSI.V13I2.3612.
- [12] A. Yunan and S. Kurniadi, 'Implementation of Fuzzy Inference Mamdani System Based on Graphic User Interface for the timing of planting rice on rice plants in traditional farming systems in South Aceh district', *Jurnal Inotera*, vol. 6, no. 2, pp. 119–127, Nov. 2021, doi: 10.31572/INOTERA.VOL6.ISS2.2021.ID151.
- [13] R. Madhumathi, T. Arumuganathan, and R. Shruthi, 'Soil Nutrient Detection and Recommendation Using IoT and Fuzzy Logic', *Computer Systems Science and Engineering*, vol. 43, no. 2, pp. 455–469, Apr. 2022, doi: 10.32604/CSSE.2022.023792.
- [14] I. Agustian, B. I. Prayoga, H. Santosa, N. Daratha, and R. Faurina, 'NFT Hydroponic Control

Using Mamdani Fuzzy Inference System', *Journal of Robotics and Control (JRC)*, vol. 3, no. 3, pp. 374–383, Jul. 2022, doi: 10.18196/jrc.v3i3.14714.

- [15] R. R. Poppiel *et al.*, 'Soil Color and Mineralogy Mapping Using Proximal and Remote Sensing in Midwest Brazil', *Remote Sensing 2020, Vol. 12*, vol. 12, no. 7, Apr. 2020, doi: 10.3390/RS12071197.
- [16] E. H. Mamdani and S. Assilian, 'An experiment in linguistic synthesis with a fuzzy logic controller', *Int. J. Man. Mach. Stud.*, vol. 7, no. 1, pp. 1–13, Jan. 1975, doi: 10.1016/S0020-7373(75)80002-2.
- [17] W. Van Leekwijck and E. E. Kerre, 'Defuzzification: criteria and classification', *Fuzzy Sets Syst.*, vol. 108, no. 2, pp. 159–178, Dec. 1999, doi: 10.1016/S0165-0114(97)00337-0.
- [18] J. Fraden, 'Handbook of modern sensors: Physics, designs, and applications', *Handbook of Modern Sensors: Physics, Designs, and Applications*, pp. 1–758, Jan. 2016, doi: 10.1007/978-3-319-19303-8/SAVE-RESEARCH.
- [19] N. R. Zani, 'Design and Development of Soil Nutrients Level Detection System based on Soil Color and pH for Crop Recommendations using Fuzzy Algorithms', *The Indonesian Green Technology Journal*, vol. 11, no. 01, Jun. 2022, doi: 10.21776/UB.IGTJ.2022.011.01.05.