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IoT-Based Embedded System for Monitoring Peatland Methane, Humidity, and Temperature to Support SDG 13

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ABSTRACT

Objective: *This study aims to develop and evaluate an Internet of Things (IoT)-based embedded system for real-time acquisition, monitoring, and visualization of methane concentration, air humidity, and temperature data in peatland environments. The system is designed to support environmental monitoring and climate change mitigation efforts in line with SDG 13 (Climate Action).* ***Method:*** *The proposed system integrates a TGS2611 methane sensor and a DHT22 temperature–humidity sensor with a NodeMCU ESP8266 microcontroller equipped with Wi-Fi connectivity. Measurement data are displayed locally on a 20×4 LCD and transmitted wirelessly to a server. A MySQL database stores the collected data, while a web-based monitoring platform developed using HTML, CSS, JavaScript, and PHP enables real-time visualization and remote access to environmental measurements.* ***Results:*** *The developed IoT-based embedded system successfully acquired, transmitted, stored, and displayed methane concentration, temperature, and humidity data from peatland environments in real time. The integration of wireless communication and web technologies enabled continuous environmental monitoring, providing accurate and accessible measurement information to support effective environmental management and decision-making.* ***Novelty:*** *This study presents an integrated IoT-based embedded monitoring system that combines methane gas detection, environmental sensing, wireless communication, cloud-based data storage, and web visualization into a single platform for peatland monitoring. The proposed system offers an efficient and cost-effective solution for continuous environmental observation, contributing to greenhouse gas monitoring and sustainable peatland management to support SDG 13 (Climate Action).*

INTRODUCTION

Peatland is a source of methane gas emissions (Evans et al., 2021; Mander et al., 2025; Strack et al., 2019; Zhang et al., 2023). Methane gas is one of the gasses that contribute to the greenhouse effect (Filonchyk et al., 2024; Kanna et al., 2024; Kwilinski et al., 2024; Li et al., 2023). Methane gas concentration measurement in peatland uses two methods, namely, the analytical method and the sensors-based measurement method (Gu et al., 2022; Salimian, 2024; Sugavaneshwaran et al., 2024; Swain et al., 2024). The analytical method typically uses a gas analyzer (GA) or gas chromatography (GC) while the sensors-based measurement method uses methane sensors, TGS2611 or MQ-4 (Xu et al., 2023).

The analytical procedure of methane measuring is that methane gas emitted by peatland is trapped by closed-chamber measurement (CCM) (5). The shape of CCM is rectangular or cylindrical with specific dimensions (Abdollahi et al., 2025; Dimitrijević et al., 2023; Gunduz & Demircan, 2022). The CCM has a surface area proportional to methane gas emission flux (Lupascu et al., 2020). Furthermore, Methane gas trapped by CCM is sampled and measured by GA or GC to obtain the value of methane concentration. The advantages of measuring methane concentration by GA or GC are that the measurement result is more accurate due to either GA or GC being traced with a standard measuring instrument, and it has a calibration certificate, which guarantees that the measurement result can be trusted. However, the measurement of gas concentration by GA or GC has weaknesses: that are measurement cannot be carried out directly in the field, is unportable, not continuous, the result data of measurement cannot be saved automatically, requires personnel who have special skills in operating GA or GC, and high measurement cost (Oni et al., 2023). On the other hand, sensors-based gas concentration measurement offers portability, continuous measurement, and automatic data saving, but may not always match the accuracy of the analytical method (Chew et al., 2025; Kaloumenou et al., 2022; Machín & Márquez, 2025; Sugriwan & Soesanto, 2017).

Practically, the measurement of gas concentration not only offers high accuracy but also can be operated directly (portable devices) and continuously, and the result data of measurement can be acquired digitally. This condition can be fulfilled by sensors-based gas concentration measurement (Ainur Rahma et al., 2024). The advantages of sensors-based gas concentration measurement are that they are easy to design and fabricate, the electronics supporting devices are available in online marketplaces at affordable prices, they are easy to operate, and the result data of measurement can be monitored via 20x4 character LCD, PC/laptop monitor or monitored via internet platforms like web or smartphone. The challenge is how the sensors-based gas concentration measurement has similar results to the analytical measurement method (Yang et al., 2022). The practical advantages of the sensors-based gas concentration measurement highlight the potential of the system in revolutionizing environmental monitoring.

To meet the requirements of proven sensors-based gas concentration measurement, we have developed a measurement system as an embedded data acquisition system that is combined with an IoT platform. The TGS2611 and MQ-4 are methane gas sensors interfaced with the node MCU ESP8266, which is a microcontroller and Wi-Fi module. Methane concentration, temperature, and humidity are three parameters that are transmitted to the computer server using HTTP protocol. Temperature and humidity are the supporting data that show environmental parameters. The concentration of methane is displayed on web pages utilizing HTML, CSS, JavaScript, and PHP as front-end and back-end programming. In this paper, we will describe the IoT embedded system for data acquisition and monitoring methane concentration, temperature, and humidity in peatland. Our system ensures the accuracy and reliability of the data, providing a secure and trustful solution for environmental monitoring. The stress on the reliability and security of the system reassures the audience about the quality of the research and the potential of the system in ecological monitoring.

RESEARCH METHOD

Development of IoT-based Embedded System for Data Acquisition and Monitoring Measurement Data Methane Concentration, Humidity, and Temperature on Peatland consists of four main stages namely development of hardware systems, development of software systems, calibration of data acquisition systems, and testing IoT-Embedded systems. Development of hardware systems arranges all electronic devices that are involved in IoT-embedded systems, among other things, methane module sensors, temperature and humidity sensors, Node MCU ESP8266, 20x4 character I2C LCD, including power supply unit (Isnaini et al., 2024). The main task of developing software systems is to program Node MCU ESP8266 as a readable data sensor from TGS2611 and display it to 20x4 characters I2C LCD and IoT platforms. The calibration of data acquisition involves a detailed process where we verify whether the value of the concentration of methane can be read by the data acquisition device accurately, ensuring the system's accuracy and reliability. Finally, the testing of IoT-embedded systems involves a series of tests to ensure that the entire data acquisition system operates properly, including tests for data accuracy, system stability, and response time (Kanakaraja et al., 2021).

Development of hardware system

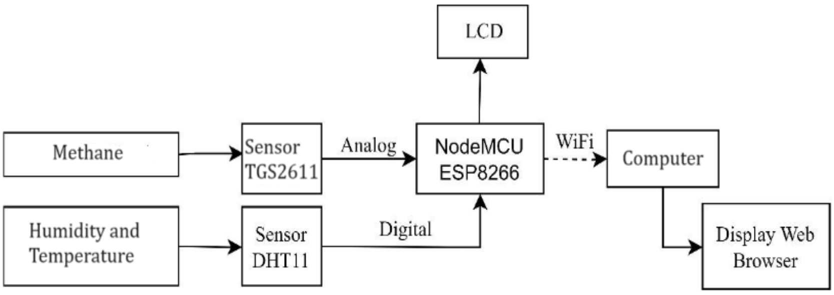

Figure 1. Hardware block diagram

Hardware development involves the power supply unit, TGS2611, MQ4, node MCU ESP2611, 20x4 characters LCD I2C, and personal computer/laptop. The power supply unit is an electrical component that generates voltage and current to supply energy to all hardware systems. TGS2611 and MQ-4 are methane sensors. DHT22 is a digital humidity and temperature sensor. Node MCU ESP8266 is a microcontroller and Wi-Fi module that arranges an interfacing sensor to the personal computer/laptop via HTTP protocol. The 20x4 characters LCD I2C device displays the value of sensors. TGS2611 or MQ-4, DHT22, node MCU ESP8266, power supply unit, and 20x4 character LCD I2C shape a client-side on IoT-embedded systems. The personal computer/laptop serves as a server to load the data that is sent from the client side, and it also provides a user interface for monitoring and controlling the system (Wall et al., 2021). The hardware block diagram is shown in Figure 1.

The wiring connection between TGS2611 (or MQ-4), DHTT, and node MCU ESP8266 is figured in Figure 2. TGS2611 has four pins: Vcc, GND, data output, and NC (no connection). Vcc on TGS2611 relates to Vcc in node MCU ESP8266, GND on TGS2611 relates to GND in node MCU ESP8266, too, and the data output of TGS2611 relates to pin A0 in node MCU ESP8266. For DHT22, the Vcc and GND on DHT22 relate to Vcc and GND in node MCU ESP8266, whereas the pin data on DHT22 relates to GPIO12 (pin D6) in node MCU ESP8266. 20x4 character LCD I2C uses a two-wire interface that uses serial data (SDA) and clock (CLK) in both DHT22 and node MCU ESP8266, while Vcc and GND on DHT22 and node MCU ESP8266 relate together.

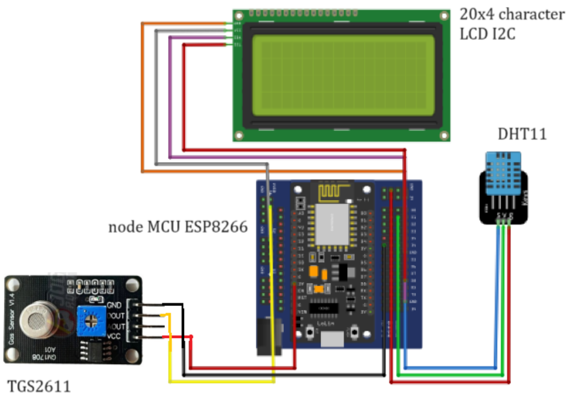

Figure 2. Wiring connection to the hardware systems

Development of software systems

The first thing in the development of software systems is to ensure that we have installed some software, including XAMPP as local host server scripting, Notepad++ as text editor, and Arduino IDE (integrated development environment) as software to program Node MCU ESP266. XAMPP is a powerful software package that contains Apache, MySQL (or Maria DB), Pearl, and PHP. The initial letter on XAMPP, X, shows that it can operate cross-platform, either in the Windows or Linux operating systems (Hošek & Spiwok, 2016). Notepad++ is a light and free software as a source code editor to write program code that supports several programming languages under Windows environments. Likewise, with Arduino IDE, this software is for writing, compiling, and uploading the code of a program to Node MCU ESP8266. Originally, Arduino IDE was made available for Arduino microcontroller families; however, it can also be used to program Node MCU ESP8266 in a few small steps.

To prepare for the development of software and systems in IoT-embedded systems, we must open and activate the XAMPP by pressing the 'start' button on the XAMPP control panel. If the XAMPP control panel is active, it will be marked with some number of PID(s) and Port(s) on the XAMPP control panel. The following preparation was creating a folder in the htdocs folder to accommodate all file programs that are made to regulate transmission data in IoT-embedded systems, pictures, and some software drivers. We named this folder ‘multisensor’. The final preparation is to apply Notepad++ as a text editor, and we treat Notepad++ as a workspace by choosing the ‘multisensor’ folder from htdocs.

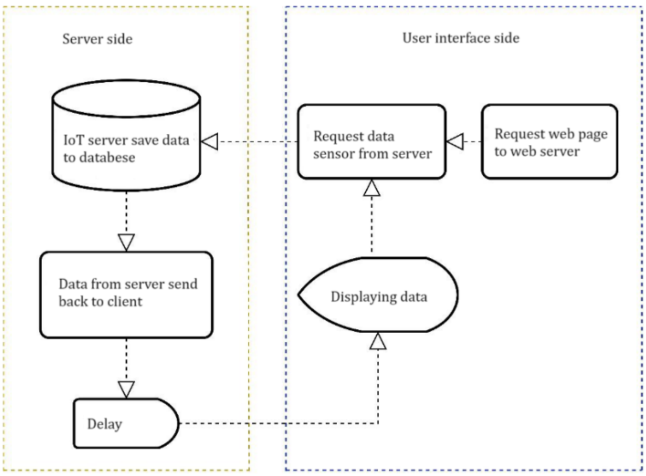

Figure 3. Block diagram of system IoT software

Figure 3 is a block diagram for the IoT software system. To implement the software system in Figure 3, first, we develop a simple web page using Bootstrap 4. Bootstrap 4 is a software package from CSS that can be used to develop the web as simply as possible. On the bootstrap page, scroll down until found the starter template. We copy this template and paste it into the current work on Notepad++ as a text editor, and we save the file by the name index.php. If we look at the appearance of the Bootstrap 4 template on the browser, we will see the Hello, world. The appearance of the web page is very far from what was expected. We will edit this ‘Hello, world’ display as desired to show the values of methane concentrations.

We present the web page in three columns for temperature (in degrees Celsius, 0C), humidity (in percent, %), and methane concentration (in part per million, ppm), respectively. Figure 4 shows the appearance of the designed web page. It is important to note that the web page is in the form of a static web, which means the value of temperature, humidity, and concentration of methane is zero, as written in the previous program code. What is needed is the display in Figure 4. Both the temperature, humidity, and methane concentration values display real-time values as the values read by the sensor. For this purpose, we must prepare a database that accommodates real-time values from sensors.

To provide the database that accumulates the data, we create a database by opening new windows on a browser like Chrome and typing localhost/phpmyadmin/. Then we enter it, and we will go to the home page of PHPMyAdmin. We created a new database under the name dbmultisensor and a new table under the name tb_sensor with columns of 4 for ID, temperature, humidity, and methane concentration. We set the id in the first row with data type integer (INT), auto increment, and primary index. The second row for temperature with data type is decimal and length of character 10,2. The third row for humidity with data type is an integer, and the fourth row for methane concentration, which we set as data type, is double.

The web page in Figure 4 is static, with values of temperature, humidity, and methane concentration zero since the web page cannot access the database. We desire that the value of zero on temperature, humidity, and methane concentration will vary according to the value read by the sensor of DHT22 and TGS2611. Below is the source code in JavaScript to change the temperature, humidity, and methane values to become dynamic.

```
<script type="text/javascript">

        $(document).ready(function(){
                setInterval(function(){
                        $("#checktemperature").load("checktemperature.php");
                        $("#checkhumidity").load("checkhumidity.php");
                        $("#checkmethane").load("checkmethane.php");
                }, 1000);
        });
</script>
```

The source code above, responsible to change the id=checktemperature in PHP code <h2> 0 </h2>. Furthermore, we do the same thing for humidity by replacing id = check humidity and id = check methane for humidity and methane concentration. To load the display data on Figure 4 automatically, we must prepare the document that id #checktemperature in index.php must match with checktemperature.php in the PHP file that is saved in htdocs XAMPP. The same things with id #checkhumidity and id #checkmethane must be matching with checkumidity.php and checkmethane.php in the PHP file in htdocs XAMPP.

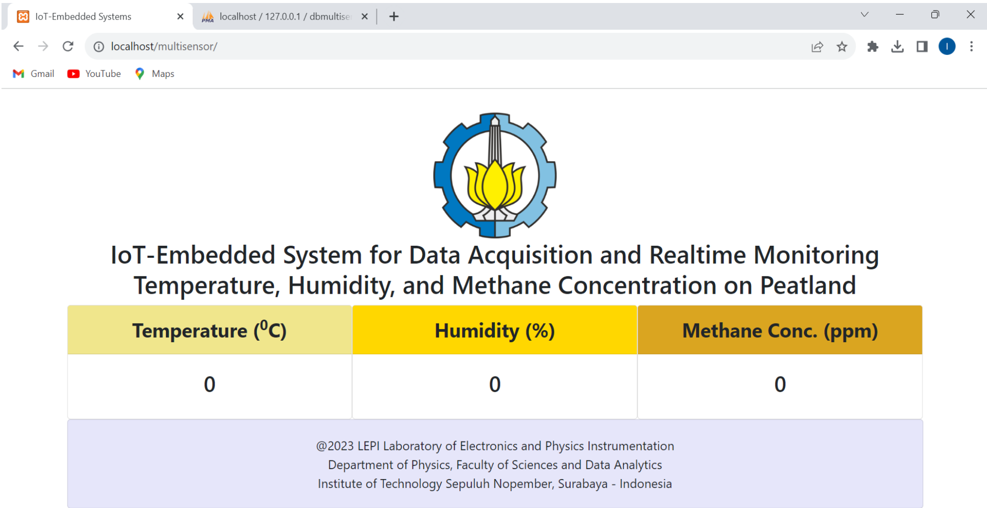

Figure 4. Initial software development for web display

In Arduino IDE, we write program code to ensure that the output of sensors can be read by node MCU ESP8266, to calculate sensor characteristics equation, to display parameter value of the sensor on 20x4 character LCD, and to send them to computer server via HTTP protocol. The program procedure in the Arduino IDE is to add the I2C Wire and LCD libraries and determine the LCD type (LCD_I2C address, column, row) (Tu'u et al., 2019). The next step is to add a library for the Wi-Fi network. The next step is to determine the pin for the DHT22 and define objects for DHT22. Variables for Wi-Fi SSID and Wi-Fi password are declared, and host/server variables containing the web, localhost, or domain name are provided. The sensor characteristic equation is declared by defining constants for gradient (a) and intercept (b) according to the sensor transfer function that satisfies the linear equation (Ariadi et al., 2018). Next is to activate the serial, the LCD I2C, and the DHT22 sensor. The program procedure should also provide a connection to Wi-Fi and check whether the connection is successful or not. If successful, the temperature, humidity, and methane gas concentration values are read by the microcontroller. The internal ADC in the NodeMCU ESP8266 converts the ADC value from the output voltage of the TGS2611 sensor into BCD code and returns it to a return voltage with the characteristic equation of the TGS2611 sensor. The temperature and humidity values detected by the DHT22 and the methane concentration values displayed in the serial monitor are also displayed on the I2C LCD.

The program mechanism for sending data from the NodeMCU ESP8266 to the server computer using the Arduino IDE is to initialize the web server port with a value of 80. The connection on the web server is checked whether it is connected to the server computer or not. If connected, sensor data is sent to the database. The next step is to determine the link address to send data to the database, which contains the https://ip address/name of the database/name of the file, and this address is executed by the program. The final stage is to read the response if the data sent from the Node MCU ESP8266 was sent successfully.

RESULTS AND DISCUSSION

Results

Realization of fabrication IoT-embedded systems consists of four parts, namely the TGS2611 methane sensor circuit, DHT22 digital humidity and temperature circuit, node MCU ESP8266 module, and display unit 20x4 character LCD I2C (Montoya et al., 2021). This system, shown in Figure 5, is a measuring instrument system that can measure the concentration of methane gas in ppm, temperature in degrees Celsius, and humidity in percentage (%). The system must calibrate the TGS2611 methane sensor. Calibration is a process of comparing measured values from sensors, typically in voltage, with the truth value from standard measuring devices. In this work, we calibrate two methane sensors, TGS2611 and MQ-4, and we obtain a calibration equation for TGS2611 and MQ-4, as shown in Table 1.

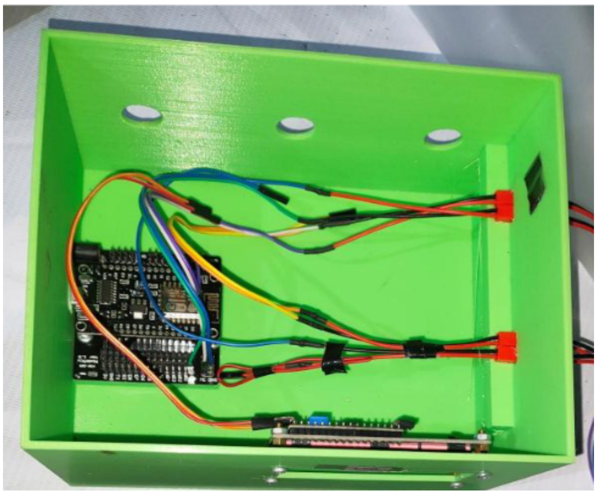

Figure 5. Realization of IoT-embedded system as a measuring device

Table 1. The characteristics of TGS2611 and MQ-4 sensors

Sensor	Characteristic Equations
TGS2611	$V = 0{,}5611 \ln(n) - 2{,}2641$
MQ-4	$V = 0{,}4034 \ln(n) - 1.0710$

Where:
V = voltage (volt)
n = methane concentration (part per million, ppm)

DHT22 has been compared with standard measuring instruments such as the Digital Thermohydrometer. The result of the temperature calibration of DHT22 is shown in Table 2. We compare temperatures from 20 0C to 30 0C that are measured by a digital thermohydrometer, and we compare humidity from 40 %RH to 80 %RH. The result of humidity calibration of DHT22 is shown in Table 3. For the parameter of air temperature in Table 2, we have the uncertainty of measurement on confidence level 95% and coverage factor k = 2, so the error is 2,1 °C. From the calibration results in Table 1, the DHT22 can be used in an IoT-embedded system because the temperature value is similar to the standard measuring instruments.

Table 2. Calibration temperature of DHT22

Temperature Measured by Digital Thermohydrometer (^{0}C)	Corrections (^{0}C)	Temperature Measured by DHT22 (^{0}C)
20	-0.03	20.03
23	-0.02	23.02
25	-0.01	25.01
27	-0.01	27.01
30	0.00	30.00

For the air humidity parameter, measurement uncertainty has been obtained, expressed at a confidence level of 95% with a coverage factor k=2, k indicates 95% confidence and the error results obtained are 3.8% RH. The calibration results obtained values from the measuring instruments made of 40.30%, 50.20%, 60.30%, 68.70%, and 77.40%. The calibration results show that the DHT22 can be used because it is comparable to standard measuring instruments.

Table 3. Calibration humidity of DHT22

Humidity Measured by Digital Thermohydrometer (%RH)	**Corrections (%RH)**	**Humidity Measured by DHT22 (%RH)**
40	-0.30	40.30
50	-0.20	50.20
60	-0.30	60.30
70	+1.30	68.70
80	+2.60	77.40

Referring to Tables 2 and 3, we plot the values on each table to obtain calibration equations for DHT22 for both temperature and humidity, as shown in Table 4.

Table 4. Calibration equations of DHT22 for temperature and humidity

Parameters	**Calibration Equations**
Temperature	$V = 2{,}4\,T + 17{,}8$
Humidity	$V = 9{,}27\,RH + 31{,}57$

Where:
V = voltage (volt)
T = Temperature (0C)
RH = Relative humidity (%RH)

The next step is to test the measuring system. The purpose of this test is to find out whether the sensor system can work with high performance or not. The system would be tested with two platforms, the first being a biogas digester and the second being a tofu waste processing system. In the biogas digester, the TGS2611 and DHT22 sensors are placed in the gas storage vehicle, and tests on tofu waste processing are performed. The biogas digester comes from cow dung, while the tofu waste used is the liquid discarded from the processing results. Both tests on the biogas digester and tofu waste are intended to mimic peat soil. The similarity between the methane gas monitoring system in peatlands and methane gas produced from biogas digesters or tofu waste is the method of trapping methane gas. The difference is that in peatlands, the gas produced is usually trapped using closed chamber measurements, whereas in biogas digesters and yearly waste, the gas is captured in a storage vehicle. The arrangement of monitoring systems in biogas digesters and tofu waste is shown in Figure 6.

(a) (b)

Figure 6. Monitoring of methane gas. (a) biogas digesters, (b) tofu waste storage vehicles.

The result of testing temperatures, humidities, and methane concentrations is shown in Table 5. Temperature and humidity in storage vehicles of biogas digesters tend to be constant at values of 29,8 0C and 70%. However, temperature and humidity in the tofu waste platform change significantly in the range of 30,4 0C to 30,8 0C and 70% to 78%. The data observed in Table 5 is temperature, humidity, and voltage data produced by the TGS2611 or MQ-4 sensor. The voltage data is displayed on the serial monitor and 20x4 character LCD I2C. The methane concentration value is in line with the sensor characteristic equation shown in Table 1, where the methane concentration is obtained by the equation:

$$V = 0{,}5611\, ln(n) - 2{,}2641 \quad (1)$$

$$n = e^{(V+2{,}2641)/0{,}5611} \quad (2)$$

Table 5. Testing temperature, humidity, and methane concentration in biogas digester and tofu waste

	Biogas Digester				Tofu Waste			
No.	**T (^{0}C)**	**RH (%)**	**V (volt)**	**Methane (ppm)**	**T (^{0}C)**	**RH (%)**	**V (volt)**	**Methane (ppm)**
1.	29.8	70	2.63	6138	30.4	70	1.73	1234
2.	29.8	70	2.62	6030	30.4	71	1.87	1584
3.	29.8	70	2.62	6030	30.5	72	2.11	2430
4.	29.8	70	2.62	6030	30.5	73	2.37	3862
5.	29.8	70	2.61	5924	30.5	74	2.75	7602
6.	29.8	70	2.60	5819	30.6	74	2.86	9249
7.	29.8	70	2.60	5819	30.7	75	2.86	9249
8.	29.8	70	2.60	5819	30.6	76	2.87	9415
9.	29.8	70	2.58	5615	30.8	77	2.88	9584
10.	29.8	70	2.60	5819	30.8	78	2.88	9584

The IoT-embedded system for monitoring temperature, humidity, and concentrations of methane is implemented in peatland. The display of all parameters refers to two modes: localhost display and web page display. The fundamental difference between localhost and web page display is that localhost does not require an internet connection, while web pages require a domain and hosting. The second difference is that on a local host, the scripting server is assisted by XAMPP, while on the web, it does not require XAMP. Figure 7 below is a display on localhost/web, which displays temperature, humidity, and methane concentration data.

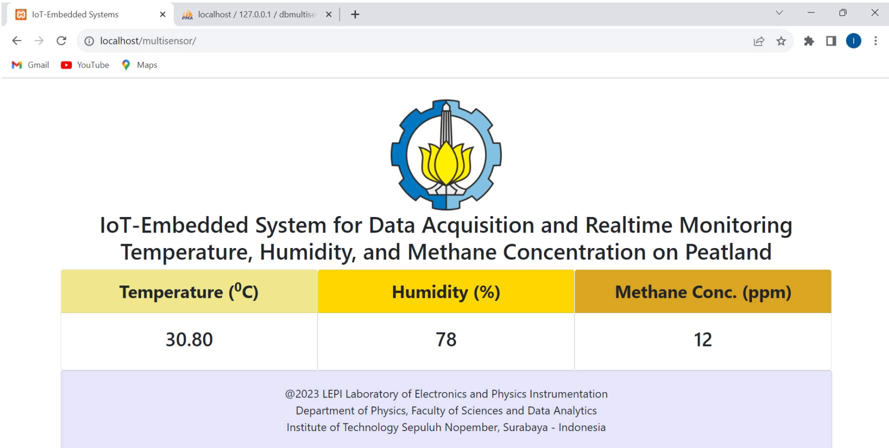

Figure 7. Displaying of temperature, humidity, and methane

Discussion

The developed IoT-based embedded system demonstrated reliable performance in acquiring and monitoring methane concentration, temperature, and humidity data in real time. The integration of the TGS2611 methane sensor, DHT22 temperature–humidity sensor, and NodeMCU ESP8266 enabled stable data acquisition, wireless transmission, and online visualization through both localhost and web-based platforms. The calibration results confirmed that the sensing devices produced measurements comparable to standard instruments, indicating that the proposed system is sufficiently accurate for environmental monitoring applications. These findings demonstrate the feasibility of combining low-cost embedded technologies with IoT communication to support continuous environmental observation.

The system evaluation using biogas digesters and tofu wastewater storage successfully simulated methane-generating environments similar to peatlands. The monitoring results showed relatively stable environmental conditions in the biogas digester, while greater variations in methane concentration, humidity, and temperature were observed in the tofu wastewater system due to differences in biological decomposition processes. The successful transmission and visualization of measurement data through a MySQL database and web interface indicate that the developed platform can support remote monitoring without requiring direct field observation. Such capabilities are particularly valuable for peatland monitoring, where continuous measurements are often required in remote and difficult-to-access locations.

From a broader perspective, the proposed system contributes to sustainable environmental management by providing a practical tool for monitoring greenhouse gas emissions from peatlands. Continuous observation of methane concentration, together with temperature and humidity, can support researchers and environmental authorities in identifying emission patterns, evaluating peatland conditions, and developing evidence-based climate mitigation strategies. The integration of IoT technology with web-based data visualization also enhances the accessibility of environmental information, thereby supporting SDG 13 (Climate Action) through improved environmental monitoring, early detection of ecological changes, and sustainable management of peatland ecosystems.

CONCLUSION

Fundamental Finding: This study successfully developed an IoT-based embedded system capable of acquiring, monitoring, and displaying real-time data on methane concentration, temperature, and humidity in peatland environments. The integration of the TGS2611 (or MQ-4) methane sensor, DHT22 sensor, and NodeMCU ESP8266 demonstrated stable performance in environmental monitoring. The system effectively transmitted measurement data to a web-based platform, enabling continuous observation through local and online interfaces. In addition, the compact and portable design facilitates installation in enclosed peatland chambers and other environmental monitoring sites. **Implication:** The proposed system provides an efficient and cost-effective solution for continuous environmental monitoring and greenhouse gas observation. Real-time access to methane, temperature, and humidity data can support researchers, environmental managers, and policymakers in monitoring peatland conditions, assessing greenhouse gas emissions, and implementing evidence-based climate mitigation strategies. Consequently, this research contributes to the achievement of SDG 13 (Climate Action) by strengthening the application of IoT technology for sustainable environmental monitoring. **Limitation:** The system was evaluated under limited environmental conditions and focused on monitoring three environmental parameters. The testing was primarily conducted in peatland simulation settings, biogas digesters, and tofu wastewater processing environments. Therefore, further validation under diverse peatland ecosystems and long-term field deployment is required to comprehensively evaluate system reliability and performance. **Future Research:** Future studies should integrate additional environmental sensors, such as carbon dioxide (CO_2), soil moisture, atmospheric pressure, and pH sensors, to provide a more comprehensive peatland monitoring system. Further research is also recommended to implement cloud computing, artificial intelligence, and predictive analytics for early warning systems, long-term environmental assessment, and improved climate change mitigation strategies.

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AUTHOR CONTRIBUTIONS

Iwan Sugriwan contributed to the conceptualization of the study, system design, hardware development, methodology, software integration, formal analysis, validation, manuscript drafting, and project administration. **Melania Suweni Muntini** contributed to the research methodology, sensor calibration, data acquisition, validation of the measurement system, interpretation of the results, and critical review of the manuscript. Yono **Hadi Pramono** contributed to the development of the web-based monitoring platform, database management, visualization of the monitoring results, manuscript editing, and final proofreading. All authors have read, reviewed, and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

CONFLICT OF INTEREST STATEMENT

The authors confirm that there are no conflicts of interest, either financial or personal, that may have influenced the content or outcome of this study.

ETHICAL COMPLIANCE STATEMENT

This manuscript complies with research and publication ethics. The authors affirm that the work is original, conducted with academic integrity, and free from any unethical practices, including plagiarism.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors acknowledge the use of digital tools, including AI-based technologies, as support during the research and writing process of this article. Specifically, AI-based language assistance tools were used for improving grammar, language clarity, and manuscript organization. ANSYS software was employed for numerical simulation and structural analysis of the floating fiber embankment model. All outputs generated with digital assistance were critically evaluated, verified, and revised by the authors to ensure academic rigor, accuracy, and compliance with ethical publication standards. The final responsibility for the content, interpretation, and conclusions of this manuscript rests entirely with the authors.

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