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Domestic Wastewater Quality Information System Integrated with the Internet of Things

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ABSTRACT

Real-time information on domestic wastewater quality is essential for Wastewater Treatment Plant (WWTP) operators to monitor treatment performance and ensure compliance with environmental quality standards. In Indonesia, domestic wastewater discharge must comply with regulations established by the Ministry of Environment and Forestry regarding domestic wastewater quality standards. However, conventional monitoring methods based on periodic sampling and laboratory analysis are often time-consuming, costly, and unable to provide continuous information. Therefore, an efficient real-time monitoring system is required to support wastewater management. This research aims to develop a sustainable domestic wastewater quality monitoring system integrated with the Internet of Things (IoT). The study adopted a research and development (R&D) approach to design and implement the monitoring device. The developed system consists of three main subsystems: a solar power system, a multi-parameter sensor system, and an IoT communication platform. The sensors measure several key parameters including temperature, pH, turbidity, dissolved oxygen (DO), and total dissolved solids (TDS). Measurement data are processed by an ESP32 microcontroller and transmitted to the ThingSpeak platform for real-time monitoring. Experimental results indicate stable sensor performance with an average standard deviation of approximately 0.03. The solar-powered design enables autonomous and sustainable operation in wastewater treatment environments.

I. INTRODUCTION

Rapid population growth, massive urbanization, and changes in modern lifestyles have significantly contributed to the increase in domestic wastewater volume [1], [2], [3], [4], [5], [6]. Domestic wastewater originates from household activities such as bathing, washing, cooking, and sanitation. It generally contains organic matter, chemical pollutants, pathogenic microorganisms, and nutrients such as nitrogen and phosphorus. If not managed properly, domestic wastewater can degrade environmental quality, pollute surface and groundwater resources, and pose significant risks to public health [5], [7]. In many urban areas, the increase in domestic wastewater discharge has become a major environmental concern because untreated wastewater can reduce water quality and disrupt aquatic ecosystems.

In many regions, particularly in developing countries, domestic wastewater management systems still face various limitations. Uneven wastewater treatment infrastructure, low public awareness of the importance of wastewater management, and limited monitoring resources are key factors contributing to continued environmental pollution.

Rivers, drainage channels, and other water bodies often serve as final disposal sites for domestic wastewater without adequate treatment. This condition leads to water quality degradation, which is commonly indicated by increased levels of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and decreased dissolved oxygen (DO) concentrations.

From a regulatory perspective, wastewater quality management is an important requirement to ensure environmental sustainability. In Indonesia, the government has established wastewater quality standards through Minister of Environment and Forestry Regulation concerning Domestic Wastewater Quality Standards, which regulates several key parameters including pH, BOD, COD, TSS, oil and grease, and ammonia. Wastewater discharged into the environment must meet these standards to prevent environmental pollution. However, monitoring compliance with these standards often remains limited due to the lack of continuous monitoring systems and the reliance on periodic laboratory testing. As a result, violations of wastewater quality standards may occur without being detected promptly.

Monitoring domestic wastewater quality is therefore a crucial step in pollution control and environmental protection efforts. Information on wastewater quality parameters is needed to evaluate the level of pollution, assess the effectiveness of wastewater treatment systems, and ensure compliance with government-established environmental regulations [8]. However, the monitoring methods that are widely implemented today still rely on conventional techniques involving manual sampling and laboratory analysis. Although these methods can provide accurate results, they require relatively long processing times, high operational costs, and are unable to provide continuous real-time information regarding wastewater conditions [9].

The limitations of conventional monitoring systems often result in reactive rather than preventive decision-making in wastewater management. Pollution is frequently detected only after environmental quality has significantly deteriorated. In addition, monitoring data are often fragmented across different institutions, making it difficult to conduct integrated data analysis or develop data-driven environmental management policies. Therefore, a new approach is required to provide rapid, accurate, and sustainable monitoring of domestic wastewater quality.

Advances in information and communication technology, particularly the Internet of Things (IoT) [10], provide significant opportunities to improve wastewater quality monitoring systems. IoT is a technological concept that enables physical devices such as sensors, controllers, and actuators to be interconnected via the internet, allowing them to automatically collect, transmit, and process data. In the context of water quality monitoring, IoT technology allows sensors to be installed directly at wastewater sources or treatment facilities to measure specific water quality parameters continuously and in real time.

The integration of water quality sensors with IoT technology enables direct and continuous collection of wastewater quality data without intensive human intervention [11]. Key parameters such as pH, temperature, turbidity, conductivity, and dissolved oxygen can be monitored automatically and transmitted through wireless networks to a central server. The collected data can then be stored in a database, visualized through monitoring dashboards, and analyzed to support faster and more accurate decision-making for wastewater management.

A domestic wastewater quality information system integrated with IoT functions not only as a monitoring tool but also as an environmental data management platform[12]. Through this system, water quality information can be accessed by multiple stakeholders including local governments, wastewater treatment plant managers, researchers, and the general public according to defined access rights. Such transparency can improve environmental accountability and encourage broader participation in maintaining environmental quality.

Furthermore, the implementation of IoT-based monitoring systems also enables the development of early warning systems for potential pollution events. When monitored parameters exceed the permitted wastewater quality thresholds defined by environmental regulations, the system can automatically generate alerts or notifications to responsible authorities. This capability allows mitigation measures to be implemented more quickly before environmental pollution spreads and causes wider ecological impacts. Such an approach aligns with the principles of preventive environmental management and sustainable development.

However, the development of an IoT-based domestic wastewater quality information system also presents several technical challenges. These include the selection of reliable sensors capable of operating in harsh wastewater environments, ensuring the stability of wireless data communication systems, maintaining data security, and integrating hardware and software components into a robust monitoring platform. Additionally, the system must be capable of handling large volumes of environmental data and presenting information in a format that is easily understood by users with diverse technical backgrounds.

In the Indonesian context, the implementation of IoT-based wastewater monitoring systems is becoming increasingly important due to growing pressure on water resources resulting from population growth and rapid urban development. Many urban and peri-urban areas still face challenges related to sanitation infrastructure and effective wastewater management. A monitoring system capable of providing real-time information on wastewater quality conditions can serve as a strategic tool for the government in monitoring regulatory compliance, improving wastewater treatment performance, and supporting environmental policy formulation.

Furthermore, integrating domestic wastewater quality monitoring systems with IoT technology also supports the development of smart city and smart environment initiatives [13]. Within the framework of sustainable development, the application of digital technology in environmental monitoring is considered an important indicator of urban technological advancement. Such systems can also be integrated with other smart city platforms, enabling more comprehensive and data-driven environmental management.

Based on this background, the development of a Domestic Wastewater Quality Information System Integrated with the Internet of Things represents an innovative solution to overcome the limitations of conventional wastewater monitoring systems [14]. By providing real-time, accurate, and sustainable monitoring capabilities, the proposed system is expected to support more effective wastewater management, improve compliance with environmental quality standards, and contribute to environmental protection efforts and the improvement of community quality of life. Therefore, the research and development of this system is highly relevant to addressing the challenges of domestic wastewater management in the digital era.

II. METHOD

The resulting information system implements several sensors, including temperature, pH, dissolved oxygen (DO), total dissolved solids (TDS), and turbidity sensors to monitor the quality of domestic wastewater in real time. Each sensor is connected to an ESP32 microcontroller board, which functions as the main processing unit for collecting and converting sensor measurements into digital data. The ESP32 processes the electrical signals generated by the sensors and displays the measurement results on a liquid crystal display (LCD). In addition, the ESP32 transmits the collected data to a cloud platform through a wireless internet connection. The IoT system in this research was designed using several main components, namely a microcontroller, a wireless router, and the ThingSpeak platform. The ESP32 board was selected because it has integrated Wi-Fi capability, allowing it to connect directly to the internet through a router and support real-time data transmission [15]. The ThingSpeak platform was used as the cloud-based data visualization and storage system because it provides convenient monitoring, graphical visualization, and remote access to sensor data through computers or mobile devices. To support sustainable operation in outdoor wastewater treatment environments, the monitoring system was powered using a solar energy subsystem. The solar power system consists of a photovoltaic solar panel, a maximum power point tracking (MPPT) solar charge controller (SCC), and a rechargeable battery. The MPPT SCC optimizes the energy harvested from the solar panel and regulates the charging process to ensure stable power supply and extend battery life [16], [17], [18]. The performance of the developed technological device was evaluated using statistical indicators including the coefficient of determination (R^2), Root Mean Square Error (RMSE) [19], [20], [21], and Mean Absolute Percentage Error (MAPE)[22] to assess the accuracy and reliability of the sensor measurements.

This study adopted a Research and Development (R&D) approach consisting of several stages, including system design, hardware development, sensor programming, system integration, and performance testing. The research process began with identifying the required hardware components, including sensors, microcontroller modules, power supply systems, and communication devices. After determining the required components, programming was carried out for each sensor to enable simultaneous data acquisition from pH, temperature, turbidity, TDS, and DO sensors. Subsequently, a software program was developed to integrate all sensor readings and display the measurement results on the LCD interface.

The next stage involved designing the solar panel structure and electrical panel system to ensure ergonomic installation and protection of electronic components in outdoor environments. After the hardware assembly was completed, the integrated system was tested through repeated measurements to evaluate the performance of the monitoring device. The testing process was conducted iteratively to ensure that the developed system achieved the expected operational performance and data reliability.

Sensor calibration was conducted using the volumetric method with three repeated measurements for each parameter. The calibration data were then validated using statistical evaluation methods including the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE) [23]. Sensor readings were considered valid if the value of R^2 approached 1, RMSE approached 0, and MAPE was less than 10%. These validation criteria were used to ensure that the developed monitoring system provides accurate and reliable measurements for domestic wastewater quality monitoring. Table 1 shows the targeted achievement indicators from the research results.

Table 1. Targeted Achievement Indicators

Work method	Targeted achievement indicators
1. Validation results of performance measurements of pH, TDS, turbidity, DO, and temperature sensors	$R2 \approx 1$; $RMSE \approx 0$; dan $MAPE < 10\%$.
2. The LCD is capable of displaying data on the results of measuring the quality of domestic liquid waste from each sensor.	Yes
3. Sensor measurement data can also be monitored via Android or computer.	Yes
4. The electrical panel system is capable of charging the battery	Yes

The technological device developed for the IoT-integrated domestic wastewater quality information system to support sustainable monitoring is illustrated in Figure 1. The system architecture consists of three main components, namely the solar panel system, the electrical control panel, and the sensor monitoring unit. The solar panel converts solar radiation into direct current (DC) electrical energy, which is then distributed to a solar charge controller (SCC) located inside the electrical panel. The SCC regulates the energy flow to the battery and the electrical load, ensuring stable operation and extending battery lifetime. The MPPT-based SCC was selected because it maximizes the power output from the photovoltaic system and improves charging efficiency.

The block diagram of the developed monitoring system is shown in Figure 2. The electrical panel integrates several key components including the SCC, battery, ESP32 microcontroller, LCD display, and wireless router. The sensors are installed outside the electrical panel and protected using waterproof enclosures to ensure durability in wastewater environments. Each sensor converts environmental parameters into electrical signals which are transmitted to the ESP32 microcontroller for processing and visualization on the LCD.

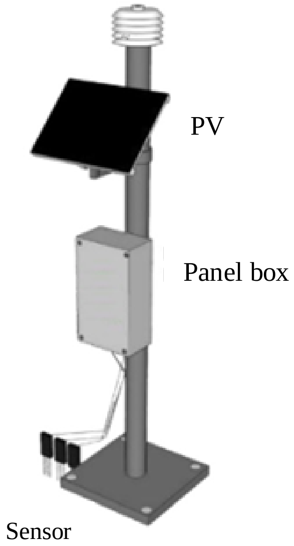


Figure 1. Illustration of the technology device that will be produced

The ESP32 also establishes an internet connection through the router by configuring the router's SSID and password in the program code. Once connected, the ESP32 automatically transmits the sensor measurement data to the ThingSpeak cloud server, allowing wastewater quality monitoring to be performed remotely through Android devices or personal computers.

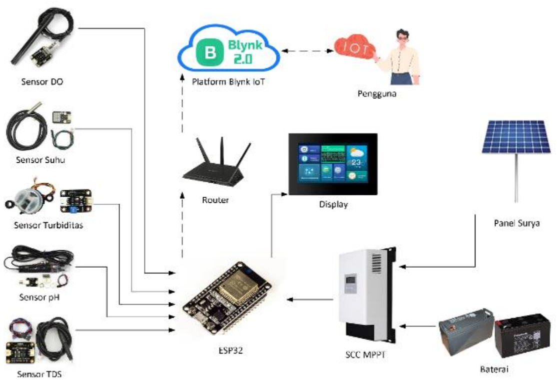


Figure 2. Research block diagram

III. RESULT AND DISCUSSION

The result of this research is a domestic wastewater quality information system technology device integrated with the Internet of Things (IoT) as shown in Figure 3. The developed device is designed to assist Wastewater Treatment Plant (WWTP) operators in monitoring wastewater quality in real time. Through continuous monitoring, operators are able to identify changes in wastewater conditions and take appropriate corrective actions to ensure that treated wastewater meets environmental quality standards. The main parameters measured in this system include temperature, acidity (potential hydrogen – pH), total dissolved solids (TDS), dissolved oxygen (DO), and turbidity. Therefore, the developed technological device is equipped with several waterproof sensors including a temperature sensor (DS18B20), a pH sensor (DFRobot Analog pH Sensor/Meter Kit V2), a TDS sensor (DFRobot Analog TDS Sensor), a turbidity sensor (DFRobot Analog Turbidity Sensor), and a DO sensor (DFRobot Analog Dissolved Oxygen Sensor). The integration of IoT technology is achieved through the implementation of an ESP32 microcontroller board which functions as the main data acquisition and processing unit. The ESP32 is capable of connecting to the internet network through a router and transmitting sensor measurement data to a cloud-based monitoring platform. The measurement results can be visualized and accessed remotely through computers or mobile devices, enabling real-time monitoring of wastewater quality conditions. In addition, the technological device is supported by a solar power subsystem which allows the monitoring system to operate independently without relying on grid electricity. The use of solar panels makes the system portable and suitable for installation in various wastewater treatment ponds such as aeration ponds, facultative ponds, and other treatment units. Figure 3 illustrates the overall design of the IoT-integrated domestic wastewater quality information system developed in this study.

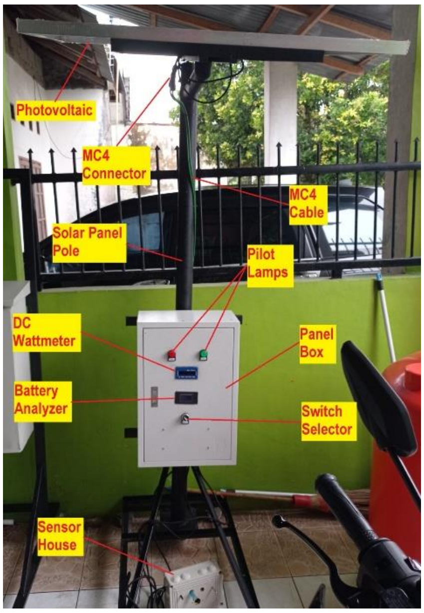


Figure 3. Design of an IoT Integrated Domestic Wastewater Quality Information System

In this research, a 2-inch diameter galvanized iron tube and several pieces of angle iron were designed to support the solar panel and the electrical panel box so that the system structure can stand stably under outdoor environmental conditions as shown in Figure 3. The solar panel used in this study is a monocrystalline type with a maximum capacity of 120 Wp (watt peak). Based on its specifications, the solar panel is capable of producing a maximum voltage of 19.2 V and a maximum current of 6.25 A under optimal solar radiation conditions. An MC4 connector is used to connect the solar panel to a Maximum Power Point Tracking (MPPT) Solar Charge Controller (SCC) located inside the electrical panel box. The electrical panel box used in this system has dimensions of 40 × 60 × 20 cm^3. The MPPT SCC functions to optimize the power output from the solar panel and regulate the charging process to the battery, thereby improving charging efficiency and extending battery lifespan. The electrical panel box in this study is also equipped with a selector switch that functions to connect or disconnect the power supply to the system. The status of the system is indicated by an indicator light, where the green light indicates that the system is connected and the red light indicates that the system is disconnected. Furthermore, a DC wattmeter is installed to measure the current, voltage, and power output from the battery used by the monitoring system load. Meanwhile, the Peacefair PZEM-015 battery analyzer is used to monitor battery parameters including current, voltage, power, impedance, internal resistance, usage time, remaining charge, and battery capacity. This monitoring mechanism allows the system to evaluate energy consumption and ensure stable power supply during operation.

Figure 4 shows the internal components of the electrical panel used in the IoT-integrated domestic wastewater quality monitoring system. The panel contains several important components including a DC miniature circuit breaker (MCB-DC), an MPPT SCC, four battery cells equipped with a battery management system (BMS), an inverter, an AC MCB for ESP32 protection, a sensor module interface, and connector terminals. The solar panel is connected to the 30A 12/24V MPPT SCC using a 2 × 2.5 mm^2 cable through a 2P 10A DC MCB. The SCC is then connected to the battery using another 2P 10A DC MCB through a 2 × 2.5 mm^2 cable. The battery pack used in this system consists of four LiFePO4 battery cells with a capacity of 30 ampere-hours (AH) at 3.20 V connected in series to produce a total voltage of 12.8 V with a capacity of 30 AH. This configuration ensures compatibility with the MPPT SCC which requires a minimum operating voltage of 12 V.

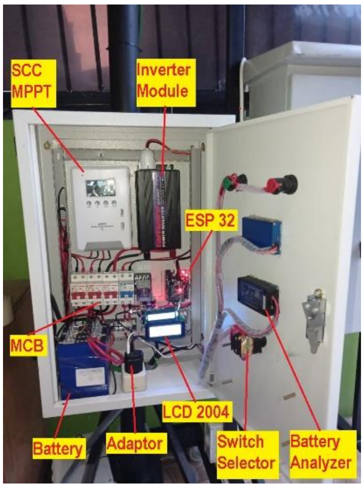
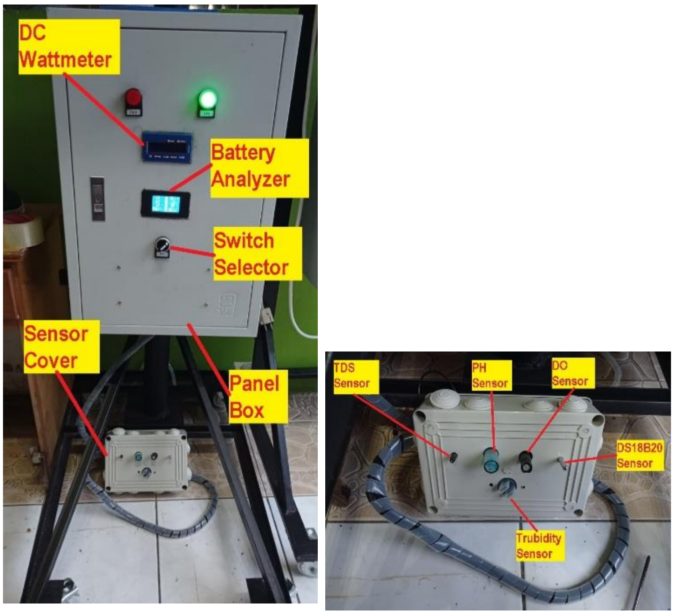


Figure 4. Electrical Panel Box Components Design Results

The battery system is equipped with a Battery Management System (BMS) that protects the battery from overcharging, overdischarging, and excessive current conditions. This protection mechanism improves battery durability and operational safety. The battery is connected to a 1000-watt pure sine wave inverter using a 2 × 10 mm^2 cable in order to convert direct current (DC) electricity from the battery into alternating current (AC) electricity required by certain system components. The selection of cable sizes in this system was based on current carrying capacity considerations. A 2 × 2.5 mm^2 cable was used between the solar panel and the SCC because it can carry approximately 10–20 A of current, which is sufficient for the maximum solar panel current of 6.25 A. Meanwhile, a 2 × 10 mm^2 cable was used between the battery and inverter because the cable can carry currents of approximately 50–70 A, ensuring safe operation for high-power loads.

Figure 5(a) shows the physical configuration of the electrical panel box and the sensor module used in the IoT-based domestic wastewater monitoring system. Several sensor cables connected to the electrical panel box are organized using a 2-meter spiral wrapping band to improve cable management and protect the wiring from environmental disturbances. During wastewater quality measurements, the sensor module is placed directly on the surface of the wastewater so that the sensors can measure water quality parameters in real conditions. The sensor module is equipped with several waterproof sensors as shown in Figure 5(b). These sensors include a temperature sensor (DS18B20), a pH sensor (DFRobot Analog pH Sensor/Meter Kit V2), a TDS sensor (DFRobot Analog TDS Sensor), a turbidity sensor (DFRobot Analog Turbidity Sensor), and a DO sensor (DFRobot Analog Dissolved Oxygen Sensor). The sensor module is also equipped with a floating mechanism designed to maintain the stability of the sensor box on the wastewater surface. Each sensor is positioned through dedicated openings in the float and the sensor enclosure to ensure direct contact with the wastewater while preventing the module from sinking. This floating design improves the practicality of the monitoring system and enables the device to be deployed in various wastewater treatment ponds.



(a) (b)

Figure 5. Sensor Display on Domestic Wastewater Quality Information System (a) Panel Box and Sensor Box, (b) Sensor Box

Testing of each sensor was conducted using well water placed in a container as a preliminary testing medium to evaluate the stability of sensor readings. Each sensor was tested continuously for 26 minutes and 24 seconds, starting from 10:10:17 AM to 10:36:41 AM, resulting in a total of 100 measurement samples. Figure 6 shows the graph of temperature sensor measurement results. The temperature readings ranged from a minimum value of 29.7°C to a maximum value of 29.8°C, resulting in a measurement range of only 0.1°C. Statistical analysis using the standard deviation formula produced a standard deviation value of 0.03, indicating that the temperature sensor demonstrates high measurement stability and reliability.

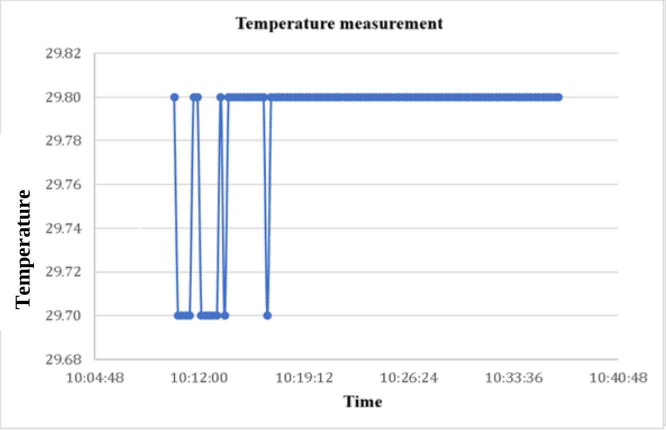


Figure 6. Graph of Temperature Sensor Test Results on Well Water

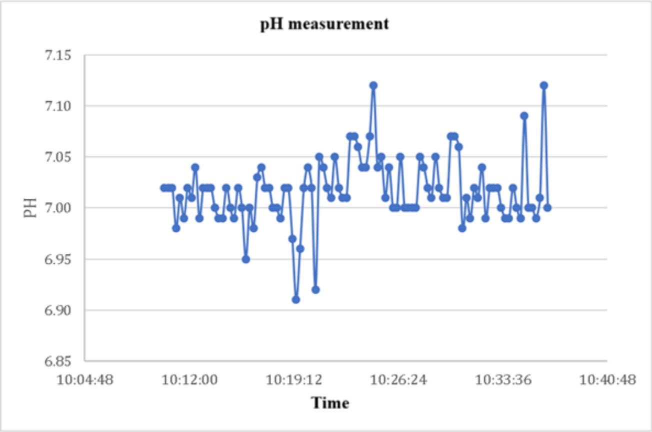


Figure 7. Graph of PH Sensor Test Results on Well Water

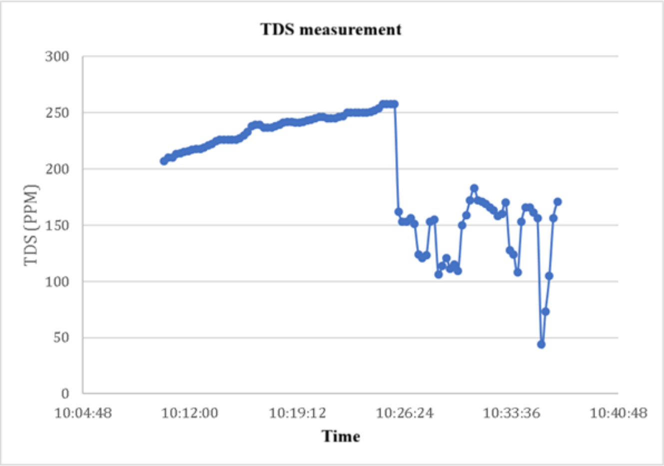


Figure 8. Graph of TDS Sensor Test Results on Well Water

Figure 7 presents the results of pH sensor measurements obtained during the testing period. The graph shows minor fluctuations in pH values with a maximum value of 7.12 and a minimum value of 6.91, resulting in a measurement difference of 0.21. The calculated standard deviation of the pH measurement results is also approximately 0.03. This small deviation indicates that the pH sensor provides stable measurements and is suitable for monitoring domestic wastewater acidity levels in real-time monitoring applications.

Figure 8 shows the results of TDS sensor measurements conducted on the well water sample. Based on the graph, a significant decrease in TDS values occurred at 10:26:01 where the measured value dropped from 258 ppm (at 10:25:45) to 162 ppm. During the first observation period (10:10:17 – 10:25:45), the TDS measurement values ranged between 207 ppm and 258 ppm with a standard deviation of 13.96. Meanwhile, during the second observation period (10:26:01 – 10:36:41), the measured TDS values ranged between 105 ppm and 183 ppm with a standard deviation of 22.95. These results indicate that the TDS sensor exhibits relatively higher variation compared to other sensors. The high deviation may be influenced by environmental factors such as suspended particles, conductivity fluctuations, or interference from other dissolved substances in the water. Therefore, periodic recalibration and sensor maintenance are recommended to ensure measurement accuracy when the system is implemented in real wastewater treatment environments. Despite this limitation, the overall monitoring system successfully demonstrates the capability to perform continuous multi-parameter wastewater quality monitoring and transmit measurement data through the IoT platform.

IV. CONCLUSION

Based on the results and discussion, it can be concluded that the developed Internet of Things (IoT)-based domestic wastewater quality monitoring system is capable of measuring several important wastewater parameters including temperature, turbidity, pH, dissolved oxygen (DO), and total dissolved solids (TDS) in real time. The measurement data are successfully processed by the ESP32 microcontroller and displayed locally through the LCD as well as transmitted to the ThingSpeak cloud platform, allowing users to monitor wastewater quality remotely via Android devices or personal computers. The integration of multi-parameter sensors, wireless communication, and cloud-based data visualization demonstrates that the proposed system can provide continuous monitoring of wastewater conditions. The experimental results show that several sensors, particularly the temperature and pH sensors, exhibit stable measurement performance with a standard deviation of approximately 0.03, indicating good measurement consistency. However, the TDS sensor shows relatively higher variation during testing, suggesting that periodic calibration and maintenance are necessary to maintain measurement accuracy when deployed in real wastewater environments. In addition, the implementation of a solar-powered subsystem enables the monitoring device to operate autonomously and sustainably in outdoor wastewater treatment facilities without relying on grid electricity. Overall, the proposed system provides a practical solution for supporting wastewater treatment plant (WWTP) operators in monitoring domestic wastewater quality more efficiently and enabling faster decision-making in maintaining compliance with environmental quality standards. For future research, the system can be further developed by integrating advanced features such as early warning systems, dedicated monitoring dashboards, and artificial intelligence-based data analytics to support predictive analysis and intelligent decision-making in wastewater management.

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