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PAPER

IoT-Based Real-Time Water Quality Monitoring and Sensor Calibration for Enhanced Accuracy and Reliability

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ABSTRACT

The increasing water pollution levels and the growing demand for clean water necessitate advanced monitoring solutions. This study aims to develop an Internet of Things (IoT)-based real-time water quality monitoring system that addresses the limitations of traditional methods, which are often time-consuming and lack continuous monitoring capabilities. The system integrates pH, temperature, and turbidity sensors with an Arduino microcontroller and NodeMCU for Wi-Fi connectivity, transmitting data to a cloud platform for real-time access and analysis. The methodology involved interfacing these sensors with the microcontroller, displaying LCD data, and providing LED alerts. The findings indicate that the prototype's readings closely align with laboratory measurements, with minor deviations in pH and temperature values and slightly more significant differences in turbidity readings. This demonstrates the prototype's reliability and accuracy in real-time environmental monitoring. The conclusion emphasises the system's potential to enhance water resource management through continuous and accurate tracking, enabling timely interventions. Future recommendations include improving sensor calibration, expanding the range of monitored parameters, and integrating advanced data analytics for predictive capabilities. The system's real-time data logging capabilities significantly enhance water management by providing timely alerts and enabling proactive responses to water quality issues. The impact of this system is substantial, offering a scalable and cost-effective solution for continuous monitoring, thus contributing to improved water resource management and public health protection.

KEYWORDS

Internet of Things (IoT), water quality monitoring, sensor calibration, real-time data, environmental monitoring

1 INTRODUCTION

Water quality monitoring is crucial in managing water resources, especially amid rising pollution levels and increasing demand for clean water. Rapid urbanisation

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and industrialisation have significantly degraded water quality, posing risks to human health and the environment. Pollutants from industrial discharges, agricultural runoff, and untreated sewage are significant contributors, introducing chemicals, heavy metals, pathogens, and organic matter into water bodies, leading to severe health and ecological issues [1]. Recent studies, such as those on the Kim-Kim River during the COVID-19 pandemic, highlight the critical state of water bodies, which are increasingly polluted by industrial and agricultural activities. Despite temporary improvements in water quality during the movement control order (MCO), the overall trend shows a persistent decline, with many rivers classified as having poor water quality, threatening public health and ecological sustainability. This underscores the need for advanced monitoring solutions for water safety and environmental protection [2].

Traditional water quality monitoring methods are often inadequate, as they are labour-intensive, time-consuming, and lack real-time data collection capabilities, which are essential for timely intervention. The urgency of addressing water pollution is underscored by current statistics showing that a significant portion of Malaysia's rivers, including the Kim-Kim River, frequently fail to meet the National Water Quality Standards (NWQS), remaining in the polluted categories. This situation calls for developing more effective monitoring solutions that provide continuous, real-time data to enable proactive management and mitigation of water quality issues. This gap underscores the urgent need for advanced technological solutions such as Internet of Things (IoT) systems offering real-time monitoring and data logging capabilities. Monitoring water quality in real-time is crucial for early detection of contamination events, enabling prompt remedial actions to mitigate their impact on public health and the environment [3].

The concept of the IoT involves the interconnection of various devices through the Internet, allowing them to collect and exchange data autonomously. This technological paradigm has opened new avenues for developing smart monitoring systems capable of providing real-time data on various environmental parameters, including water quality [4]. IoT-based water quality monitoring systems typically employ a variety of sensors to measure key water quality parameters such as pH, temperature, turbidity, and total dissolved solids (TDS). These sensors are connected to microcontrollers, which process the data and transmit it to a cloud-based storage, analysis, and visualisation platform. The use of IoT technology not only facilitates continuous monitoring but also allows for remote access to data, enabling stakeholders to monitor water quality from any location in real time. This capability is particularly beneficial for managing water quality in remote or inaccessible areas where traditional monitoring methods are impractical [5].

Despite the advantages offered by IoT-based systems, several challenges remain. One of the primary issues is the accuracy and calibration of the sensors used in these systems. Sensors can drift over time and require regular calibration to maintain their accuracy [6]. Only accurate sensor readings can lead to accurate conclusions and effective water management strategies. For instance, an uncalibrated pH sensor might indicate that water is safe for consumption when contaminated, posing severe health risks to consumers.

Additionally, sensor calibration is influenced by various factors such as temperature, pressure, and interfering substances, which can complicate the calibration process. Therefore, developing robust calibration techniques that can ensure sensors' long-term accuracy and reliability is a critical research objective. Moreover, there is a need for automated calibration systems that can minimise human intervention and reduce the potential for errors [3].

Another significant gap in current water quality monitoring systems is the need for real-time data logging and analysis capabilities. Traditional systems often rely on periodic sampling and laboratory analysis, which do not provide continuous monitoring and can miss transient pollution events [4]. For example, a pollution event between sampling intervals may go undetected, resulting in delayed response and potentially severe environmental and health consequences. Real-time data logging enables the continuous collection of data, which can be analysed in real-time to detect and respond to pollution events promptly. This capability is critical in scenarios where water quality can change rapidly, such as in industrial discharge areas or during heavy rainfall events that can cause runoff pollution. By continuously monitoring water quality parameters, real-time data logging can help identify trends, understand the sources of pollution, and implement effective mitigation strategies [5].

To address these gaps, this study aims to develop and implement an IoT-based water quality monitoring system that provides real-time monitoring and data logging capabilities and includes advanced calibration mechanisms to ensure the accuracy and reliability of the sensors used. The system will employ a range of sensors to measure critical water quality parameters and utilise a cloud-based platform for data storage and analysis. Integrating IoT technology with robust calibration processes will enable the system to deliver precise and reliable data for effective water quality management. Furthermore, the system will be designed to be scalable and adaptable, making it suitable for various applications ranging from small-scale community water systems to large-scale industrial water monitoring [6]. By leveraging the advancements in IoT and sensor technology, the proposed system aims to enhance water quality monitoring practices' overall efficiency and effectiveness.

Furthermore, this study will investigate the impact of sensor calibration on the overall accuracy of the water quality monitoring system. It will explore various calibration techniques and assess their effectiveness in maintaining sensor accuracy over extended periods. The study will also examine the factors that affect sensor performance, such as environmental conditions and sensor ageing, and develop strategies to mitigate these effects. The findings of this study are expected to contribute significantly to the field of environmental monitoring, providing valuable insights into the development of more accurate and reliable IoT-based water quality monitoring systems. In addition, the study will explore the potential for integrating advanced data analytics and machine learning algorithms to enhance the predictive capabilities of the monitoring system, enabling proactive management of water resources [3].

The relevance of this study is rooted in the critical need for innovative solutions to monitor and manage water quality effectively. The proposed IoT-based real-time water quality monitoring system addresses these challenges by leveraging modern technology to overcome the limitations of traditional methods. This system provides continuous monitoring and ensures that data is promptly analysed and made available for decision-making, facilitating timely responses to pollution events. Integrating sensor technology with IoT infrastructure offers a scalable, cost-effective solution that can be widely implemented to protect water resources and public health.

In conclusion, developing an IoT-based water quality monitoring system with enhanced real-time data logging and sensor calibration capabilities addresses two critical gaps in current water monitoring practices. By leveraging the advancements in IoT technology, this study aims to provide a more accurate, reliable, and efficient solution for water quality monitoring, which is essential for effective water resource management and protecting public health and the environment [7]. The successful implementation of this system could pave the way for widespread adoption of smart water quality monitoring solutions, contributing to the global efforts to ensure clean and safe water for all. The study outcomes will also have significant implications for policy-making and regulatory frameworks, as they provide evidence-based insights that can inform the development of standards and guidelines for water quality monitoring and management.

2 LITERATURE REVIEW

In "IoT-Based Smart Water Quality Monitoring System," Geetha (2021) examines the use of IoT technology for continuous water quality monitoring. The introduction stresses the need for real-time data due to increasing water contamination and scarcity. Traditional methods are inadequate, prompting the development of automated solutions. The methodology describes integrating pH and turbidity sensors with a microcontroller, transmitting data via GSM for real-time actions. Results show the system effectively verifies water quality and alerts authorities. The discussion highlights the potential to improve water management and public health. The conclusion calls the system cost-effective and efficient, suggesting future enhancements to monitor additional parameters like dissolved oxygen and electrical conductivity [8].

Lakshmikantha et al. (2021) in "IoT-Based Smart Water Quality Monitoring System" detail an IoT system for continuous water quality monitoring. The introduction discusses water pollution's impact on health and the economy. The methodology includes sensors for pH, turbidity, and conductivity connected to an Arduino microcontroller, transmitting data via GSM to a cloud server. Results indicate effective monitoring and timely alerts. The discussion underscores the system's potential to improve water management. The conclusion deems the system cost-effective, recommending future research to expand monitored parameters and enhance sensor calibration [9].

In "IoT-Based Smart Water Quality Monitoring System," Keshipeddi (2021) addresses water pollution in India through IoT technology. The introduction highlights the urgency of continuous monitoring due to pollutants like sewage and industrial waste. The methodology integrates pH, temperature, and soil moisture sensors with Arduino-UNO and NodeMCU, transmitting data via Wi-Fi and GSM. Results demonstrate accurate real-time data display. The discussion emphasises improved water management through timely interventions. The conclusion sees the system as cost-effective and scalable, suggesting future enhancements for additional parameters and better sensor calibration [10].

The paper "IoT-Based Water Monitoring System" by Sapkal et al. (2019) explores IoT technology's effectiveness in real-time water quality monitoring. The introduction notes the inadequacy of traditional methods amid rising pollution. The methodology describes sensors connected to an ARM microcontroller, transmitting data to web and mobile platforms. Results show effective monitoring and actionable insights. The discussion highlights the system's potential to revolutionise water management with continuous data. The conclusion recommends the system as a viable, low-cost solution, suggesting future research to enhance calibration and expand parameters [11].

Raj et al. (2020) presents an IoT-based water quality monitoring system using Arduino in "Water Quality Monitoring System Using Arduino." The study emphasises the need for real-time monitoring to prevent waterborne diseases. The system uses pH, turbidity, and temperature sensors with an Arduino Uno, transmitting data to a central server via Wi-Fi. Results show improved efficiency and timely contaminant detection. The study recommends adding parameters and refining sensor calibration for better accuracy [12].

In "Water Quality Monitoring System using IoT," Taware et al. (2020) propose an IoT-based system using NodeMCU for real-time water quality monitoring. The system measures pH, turbidity, conductivity, and temperature, transmitting data to a cloud platform for remote access. Results highlight the system's accuracy and reliability, providing timely alerts. The study recommends refining sensor calibration and expanding monitored parameters for future research [13].

Asha'ari and Ibrahim (2022), in "Wireless Water Quality Monitoring System," develop an IoT-based system using a buoy with sensors for dissolved oxygen. The buoy uses GPS for tracking and solar energy for power, transmitting real-time data to a remote station. Results show effective monitoring and timely interventions, improving water resource management. The study recommends enhancing sensor calibration and expanding monitored parameters [14].

Kumar and Samalla (2019), in "Design and Development of Water Quality Monitoring System in IoT," propose a low-cost system using sensors for pH, turbidity, temperature, CO2 levels, and water levels connected to a Raspberry Pi. The data is transmitted to a cloud platform via Wi-Fi. Results demonstrate real-time, accurate monitoring. The study recommends cost-reducing modifications and scalability improvements [15].

In the paper "Intelligent IoT-Based Real-Time Water Quality Monitoring and Pollution Detection System," Mathew et al. (2023) explore using IoT technologies to develop a real-time water quality monitoring system. The introduction emphasises continuous monitoring due to increasing pollution and health risks. The methodology describes integrating multiple sensors, such as pH, turbidity, TDS, and temperature, connected to an Arduino Mega 2560 microcontroller, with data transmitted to the ThingSpeak cloud platform. Results demonstrate the system's effectiveness in maintaining water quality through automated corrective actions. The discussion highlights the system's potential to improve water resource management by providing timely data for rapid responses. The conclusion confirms the system's viability, recommending future enhancements for broader parameter monitoring and refined calibration techniques [16].

In "Solar-Powered Smart Water Monitoring System Based on IoT and Blynk Platform," Bahri et al. (2023) develop a solar-powered IoT system for real-time water quality monitoring in the Melor River, Kelantan. The introduction highlights the need for continuous monitoring to prevent waterborne diseases. The methodology uses an ESP32 microcontroller with turbidity, pH, and TDS sensors, transmitting data to a cloud platform via the Blynk application. Results show effective monitoring with a battery life of 36.76 hours. The discussion underscores the system's potential for enhancing environmental monitoring with continuous, accurate data and immediate alerts. The conclusion affirms the system's viability and efficiency, recommending improvements in sensor calibration and monitoring range [17].

3 METHODOLOGY

A comprehensive IoT-based water quality monitoring system intended to guarantee real-time parameter monitoring and management is shown in the block diagram as can be depicted in Figure 1. The input, microcontroller, and output are the three primary components of this system, each having their sections and functions. These divisions are done intentionally.

The input section has three critical sensors: pH, turbidity, and temperature. The pH sensor detects the concentration of hydrogen ions in the water, providing vital information about its acidity or alkalinity. The turbidity sensor measures water cloudiness, which indicates suspended particulates that can degrade water quality. The temperature sensor is essential because water temperature affects chemical and biological activities. Real-time water quality monitoring is ensured by these sensors' constant data collection and transmission to the microcontroller for processing.

The system's central processing unit and brain is the Arduino R3 microcontroller. The input sensor data is received and processed, and output component control is the responsibility of the Arduino R3. It is highly versatile and suitable for integrating various sensors and components due to its numerous digital and analogue input/output pins. The NodeMCU, a potent Wi-Fi module, makes wireless communication possible in this system. The NodeMCU allows the Arduino to send the processed data for remote monitoring to a cloud platform—especially the Blynk web dashboard. The system is durable and dependable for real-time water quality monitoring since Arduino R3 and NodeMCU have been integrated to guarantee smooth data transmission and constant connection.

The system's output consists of the Blynk platform, LEDs, and LCD, which offer extensive data visualisation and warning systems. As an instantaneous on-site interface, the LCD monitor displays real-time pH, turbidity, and temperature information. This enables users to evaluate the water quality status rapidly without supplementary devices. As visual indications, the LEDs give rapid and easy warnings regarding water quality; for example, different coloured LEDs can denote normal conditions, warning levels, or dangerous circumstances. Remote control and monitoring are primarily made possible by the Blynk platform. By presenting sensor values on a web dashboard, Blynk enables users to obtain real-time data from any location with an internet connection, promoting proactive management and prompt interventions. The efficacy and dependability of the water quality management system are increased by the thorough configuration, which guarantees ongoing monitoring of the water quality locally and remotely.

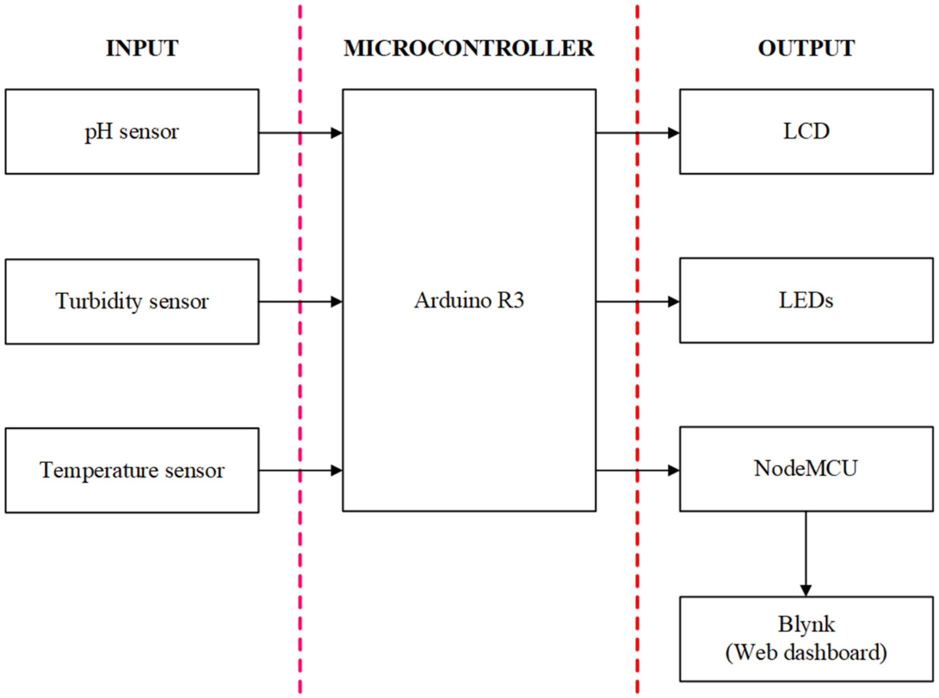


Fig. 1. Block diagram

3.1 pH sensor

The pH sensor measures water's acidity or alkalinity by detecting hydrogen-ion concentration, generating a voltage based on pH levels. This data is sent in real-time to the Arduino microcontroller, allowing for quick identification of deviations from the ideal pH range. Precise pH monitoring is crucial for ensuring water safety and quality, particularly in aquaculture, drinking water treatment, and environmental monitoring, where adherence to environmental and health regulations is essential.

3.2 Temperature sensor

The temperature sensor measures water's thermal properties, which are crucial for chemical and biological processes. A thermistor or digital sensor like the DS18B20 converts thermal energy into electrical signals for precise temperature readings. Integrated with the Arduino microcontroller, this sensor ensures continuous monitoring, which is vital for maintaining optimal conditions in water treatment, aquaculture, and environmental monitoring. It aids in detecting thermal pollution and providing water safety and quality.

3.3 Turbidity sensor

The turbidity sensor measures water cloudiness by detecting suspended particles with light, indirectly indicating water quality. High turbidity can signal contamination, pollution, or poor water treatment. The system quickly identifies and alerts for high turbidity by sending data to the Arduino microcontroller, enabling swift corrective actions. This sensor is vital for monitoring natural water bodies, wastewater, and potable water treatment, ensuring regulatory standards are met and public health is protected.

3.4 Arduino R3

The Arduino R3 is the system's core processing unit, handling sensor data acquisition and controlling output devices. Known for its simplicity and adaptability, it features digital and analogue input/output pins for easy sensor and component connections. It processes data in real-time through programmed instructions, ensuring efficient data transfer and output control. Ideal for rapid IoT project development, the Arduino platform offers extensive library support and community resources, making it essential for accurate data processing and effective sensor-output connectivity.

3.5 NodeMCU

The NodeMCU is an open-source IoT platform powered by the ESP8266 Wi-Fi SoC, enabling Wi-Fi connectivity for sensor data transmission to a cloud platform for remote monitoring and control. It works with the Arduino R3 to communicate processed data online. With built-in TCP/IP protocol support, NodeMCU is ideal for IoT applications, ensuring reliable data transfer. This integration allows real-time monitoring and access to water quality data via web dashboards and mobile apps, making it a key component for dependable IoT systems.

3.6 Blynk

Blynk is a powerful IoT platform enabling remote monitoring and device management via a web dashboard and mobile app. In this system, Blynk displays real-time sensor data, providing users with an intuitive interface to access water quality information from any internet-connected device. The platform enhances anomaly detection and trend monitoring through various data visualisation tools, including gauges, alerts, and graphs. Integrating Blynk with NodeMCU ensures continuous cloud data transfer, facilitating real-time access and control. Blynk is essential for comprehensive and efficient remote monitoring in modern IoT applications.

3.7 Sensor calibration and environmental variations

The accuracy and reliability of the IoT-based water quality monitoring system were ensured through meticulous sensor calibration and by addressing environmental variations. The pH, temperature, and turbidity sensors were calibrated using standard solutions and controlled conditions. To mitigate the impact of environmental variations, such as temperature fluctuations, temperature compensation algorithms were integrated, particularly for the pH sensor, which is sensitive to thermal changes. Additionally, the system was designed to perform periodic automatic recalibrations to counteract sensor drift over time. The sensors were tested under various environmental conditions to ensure robustness and adaptability.

4 RESULT AND DISCUSSION

4.1 Prototype

The circuit diagram for the IoT-based real-time water quality monitoring system using Proteus, which integrates vital components to measure and monitor water quality parameters effectively, is shown in Figure 2. The input section includes sensors connected to the Arduino R3 microcontroller, which processes data from the pH and turbidity sensors. The Arduino is interfaced with a NodeMCU module for Wi-Fi connectivity, enabling data transmission to a cloud platform. The microcontroller also connects to output devices like an LCD for real-time data visualisation and LEDs for immediate status indicators.

This design ensures accurate data collection, processing, and transmission. The sensors send analogue signals to the Arduino, which converts them to digital data and displays the information on the LCD. The NodeMCU facilitates remote monitoring by transmitting data to the cloud. LEDs provide visual alerts based on predefined conditions. This setup ensures that all components work together seamlessly, allowing for continuous and reliable water quality monitoring.

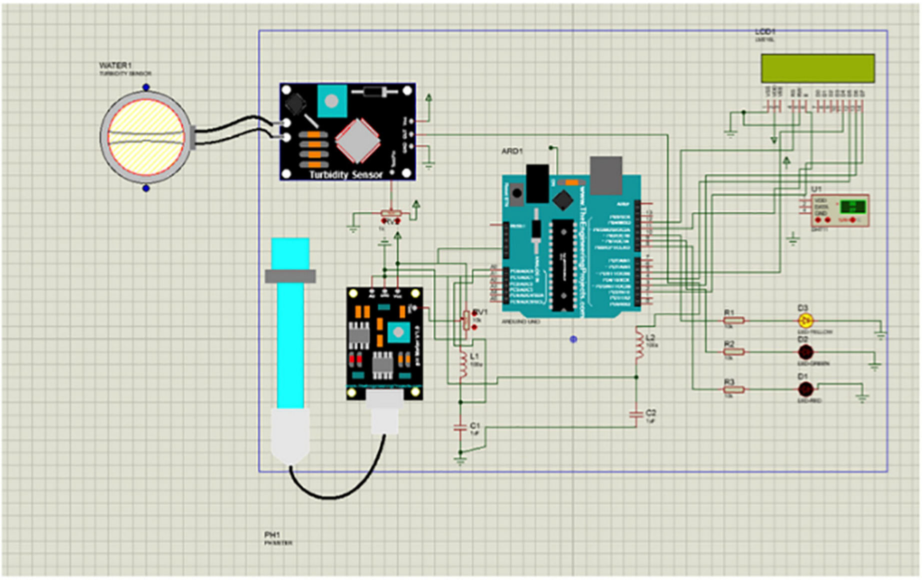


Fig. 2. Circuit diagram on Proteus

Figure 3 depicts a complete prototype for monitoring water quality using Arduino. The setup includes vital components such as pH, temperature, and turbidity sensors, which are critical for assessing water quality parameters. These sensors are connected to an Arduino R3 microcontroller, which serves as the central processing unit, receiving data from the sensors, processing it, and coordinating with output devices.

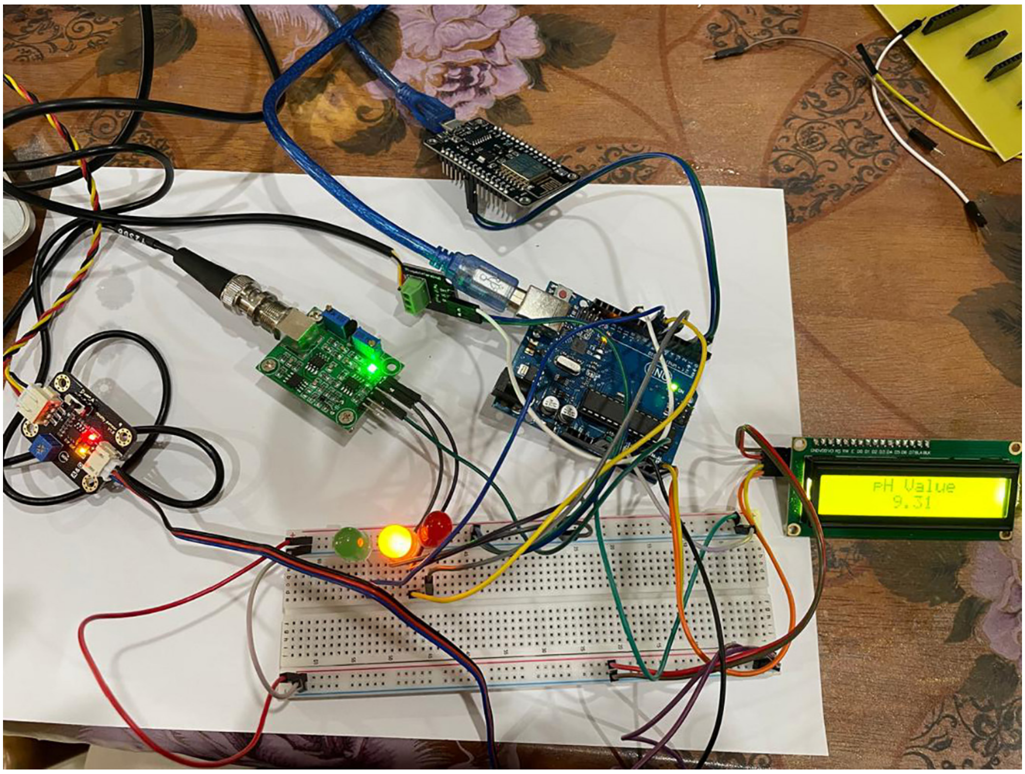
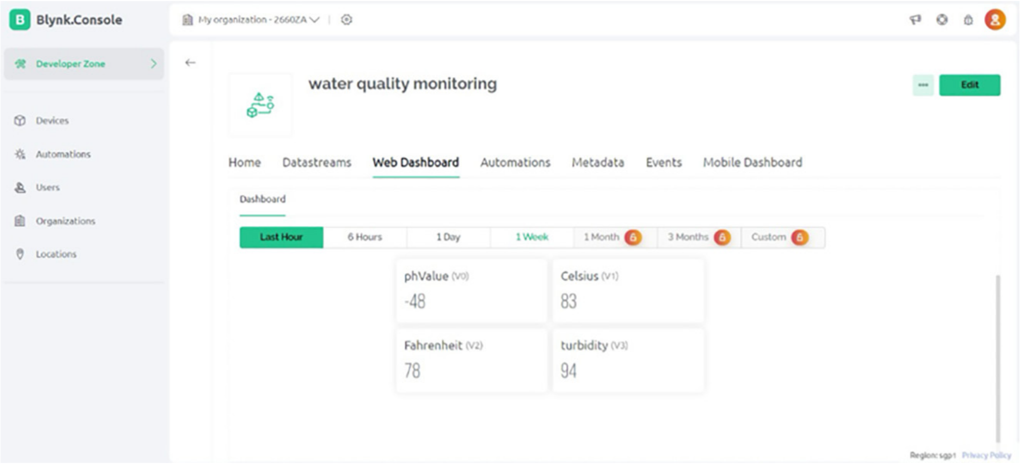


Fig. 3. A complete prototype

4.2 Blynk console

The web dashboard in the Blynk Console, as shown in Figure 4, has been meticulously set up to facilitate real-time monitoring of water quality parameters, including pH, temperature, and turbidity, making it suitable for high-ranking journal submissions. This dashboard provides a user-friendly interface that displays current sensor readings for these parameters, ensuring organised data management with virtual pins for each metric (e.g., V0 for pH, V1 for Celsius, V2 for Fahrenheit, and V3 for turbidity). It allows users to view data over various time frames, enhancing trend analysis and long-term monitoring capabilities. The real-time updates ensure immediate access to the latest information, while automation features enable alerts and actions based on predefined thresholds. This setup exemplifies the practical application of IoT technology in environmental monitoring, showcasing its potential to significantly enhance the accuracy, efficiency, and responsiveness of water quality assessments.



water quality monitoring

phValue (V0) -48

Celsius (V1) 83

Fahrenheit (V2) 78

turbidity (V3) 94

Fig. 4. Web dashboard in the Blynk console

4.3 Analysis

The comparative table data shown in Table 1 presents the pH, temperature, and turbidity measurements for five water samples using an IoT-based prototype and standard laboratory instruments. A comparative analysis was conducted at the Environmental Laboratory, Civil Engineering Studies, to validate the effectiveness of the IoT-based water quality monitoring prototype. The samples include tap water (Sample 1), soapy water (Sample 2), and river water from various locations in Segamat (Samples 3, 4, and 5).

Table 1. Measurement readings

Sample	pH		Temperature (°C)		Turbidity (NTU)	
	Prototype	Lab Instrument	Prototype	Lab Instrument	Prototype	Lab Instrument
1	6.50	6.30	27.44	27.40	2.00	1.56
2	4.83	4.86	27.31	27.50	59.00	57.90
3	7.31	7.51	25.75	25.10	15.00	8.99
4	7.63	7.80	25.56	25.30	47.00	43.70
5	7.93	7.93	26.25	25.70	42.00	34.00

The data shows that the prototype's readings are generally consistent with those obtained from the lab instruments, indicating the prototype's effectiveness in real-time water quality monitoring. Minor variations exist between the two measurement methods, but the overall trends align well, demonstrating the prototype's reliability in different water quality conditions.

pH readings. The pH values measured by the prototype are generally consistent with those recorded by the lab instruments, with minor deviations observed, as can be seen in Figure 5. For instance, Sample 1 shows a pH of 6.50 (prototype) compared to 6.30 (lab instrument), indicating a slight difference of 0.20. Sample 2 shows a very close reading of 4.83 (prototype) and 4.86 (lab instrument), with a negligible difference of 0.03. The most significant discrepancy is seen in Sample 3, where the prototype measures 7.31 and the lab instrument measures 7.51, resulting in a difference of 0.20. Overall, the pH measurements from the prototype are relatively accurate, with all deviations within an acceptable range.

The prototype's ability to detect minor pH deviations is vital to this study. Even small pH shifts in water management can signal broader water quality changes, such as pollutant introduction or chemical alterations. Real-time detection enables early intervention, which is crucial for preventing water quality issues that may lead to environmental degradation or public health risks.

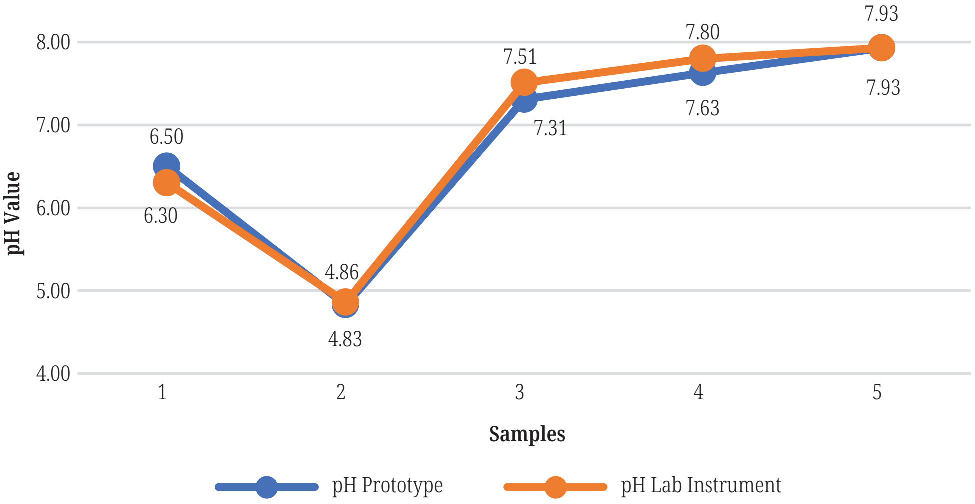


Fig. 5. pH measurement

Temperature readings. The temperature readings from the prototype closely match those from the lab instruments, with very slight differences, as shown in Figure 6. For example, Sample 1 records 27.44°C (prototype) and 27.40°C (lab instrument), showing a minimal variance of 0.04°C. Sample 2 shows a reading of 27.31°C from the prototype and 27.50°C from the lab instrument, differing by only 0.19°C. Sample 3 displays a slight difference of 0.65°C, with 25.75°C (prototype) versus 25.10°C (lab instrument). These minor differences suggest that the prototype's temperature sensor is highly reliable and accurate.

These results are significant for water management, where precise temperature monitoring is essential for maintaining water quality and detecting potential thermal pollution. The reliable temperature data provided by the prototype can aid in the early detection of issues like thermal pollution, which can significantly impact aquatic life and overall water quality.

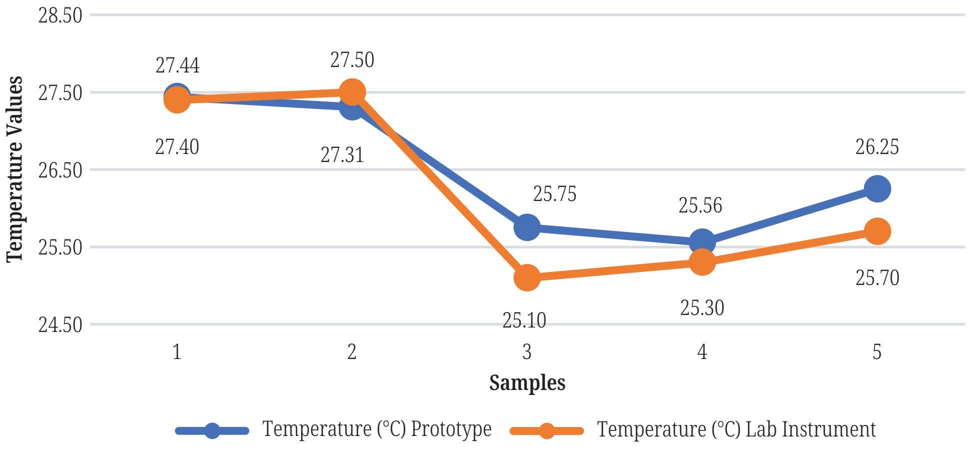


Fig. 6. Temperature measurement

Turbidity readings. The turbidity measurements exhibit more noticeable differences between the prototype and lab instruments, as can be depicted in Figure 7. For instance, Sample 1 shows turbidity readings of 2.00 NTU (prototype) compared to 1.56 NTU (lab instrument), indicating a difference of 0.44 NTU. Sample 2 shows 59.00 NTU (prototype) readings and 57.90 NTU (lab instrument), with a slight difference of 1.10 NTU. The most significant discrepancy occurs in Sample 3, where the prototype measures 15.00 NTU and the lab instrument records 8.99 NTU, resulting in a difference of 6.01 NTU. Despite these variations, the prototype effectively identifies higher turbidity levels in the samples, aligning well with the lab results.

These findings highlight the prototype's broader importance in water management, especially in pollution-prone areas. Its ability to quickly detect turbidity changes offers critical early warnings of contamination, helping to prevent the spread of pollutants and ensuring timely interventions. The results demonstrate the prototype's potential for continuous monitoring, making it a cost-effective and scalable solution for water management authorities.

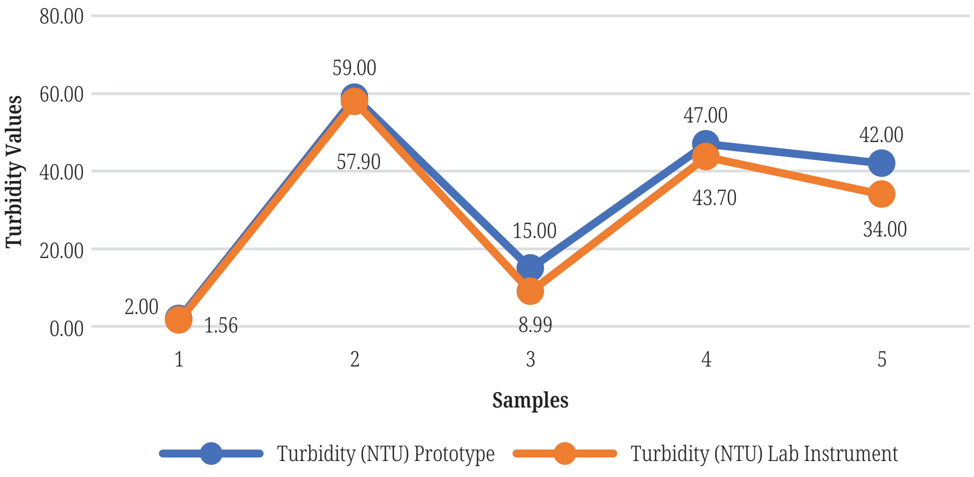


Fig. 7. Turbidity measurement

The comparative analysis indicates that the prototype performs reliably for pH and temperature measurements, with minimal deviations from the lab instrument readings. While showing more significant differences, the turbidity readings still provide a consistent trend that reflects the water quality status. These results validate the prototype's capability to monitor water quality parameters effectively, demonstrating its potential for real-time environmental monitoring applications.

5 CONCLUSION

In conclusion, this study presents a significant advancement in the environmental monitoring field by developing and implementing an IoT-based real-time water quality monitoring system. The system, designed to address the escalating environmental concerns caused by urbanisation and industrial activities, integrates pH, temperature, and turbidity sensors with an Arduino microcontroller and NodeMCU for seamless data transmission and real-time monitoring. By employing this advanced technological framework, the system effectively overcomes the limitations of traditional water quality monitoring methods, which are often time-consuming and need more capacity for continuous surveillance.

The methodology involved meticulous integration of sensors with the Arduino microcontroller, ensuring accurate data acquisition and processing. The system's ability to transmit data to the cloud via the Blynk platform allows for remote access, facilitating real-time monitoring and timely interventions. The comparative analysis between the prototype and standard laboratory instruments revealed that the system performs reliably across different parameters, with minor discrepancies in pH and temperature measurements and slightly more significant differences in turbidity readings. These findings underscore the system's reliability and accuracy, validating its application in diverse water quality monitoring scenarios.

Furthermore, the system's capability to provide continuous, real-time data enhances the precision and responsiveness of water quality assessments, enabling proactive water resource management. This is particularly crucial in environments where water quality can fluctuate rapidly due to external factors such as industrial discharge or climatic variations. The system's adaptability and scalability make it suitable for various applications, from small-scale community water systems to large industrial setups, offering a versatile solution tailored to specific monitoring needs.

The study demonstrates the feasibility and practicality of using IoT technology for real-time environmental monitoring. The success of this system in maintaining consistent performance across different water quality parameters validates its immediate application and sets the stage for future advancements in the field. This study contributes to the broader discourse on sustainable water resource management, highlighting the role of innovative technologies in safeguarding public health and protecting the environment.

Building on the success of this study, future work should refine and enhance the system's capabilities. One critical area for improvement is the calibration techniques for the turbidity sensor, which could benefit from more precise adjustments to improve accuracy and consistency. Expanding the range of monitored parameters, such as dissolved oxygen, electrical conductivity, and microbiological indicators, would provide a more holistic view of water quality, enhancing the system's utility in various applications. Additionally, integrating advanced data analytics and machine learning algorithms could enable predictive modelling, allowing for the anticipation of water quality issues before they become critical. This would represent a significant leap forward in proactive environmental management.

Moreover, ensuring the system's robustness and reliability across diverse environmental conditions and over extended periods is essential for its broader deployment. Future research could explore the system's long-term performance in different geographical regions and under varying ecological stressors to validate its scalability. Integrating renewable energy sources, such as solar power, could also be investigated to enhance the system's sustainability, particularly in remote or off-grid locations. These enhancements will solidify the system's position as a leading solution in water quality monitoring and contribute to global efforts to achieve sustainable water management practices.

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