FPGA-Based Real-Time Water Quality Monitoring and Classification System Using Multi-Sensor Data Processing

P. Yamini Sri[1], M. Pavani[2], N. Pravallika[3]
[1,2,3]*Department of Electronics and Communication Engineering, Vasireddy Venkatadri Institute of Technology, Andhra Pradesh, India*

***Abstract*—Access to clean and safe water is essential for public health, agriculture, and industrial applications. Conventional water quality monitoring systems based on microcontrollers suffer from limitations such as low processing speed, sequential operation, and reduced accuracy. To address these challenges, this paper presents an FPGA-based real-time water quality monitoring and classification system using multi-sensor data processing.**

The proposed system integrates multiple sensors, including pH, turbidity, temperature, and Total Dissolved Solids (TDS), to continuously monitor water quality parameters. Sensor data is acquired through an external Analog- to-Digital Converter (ADC) and processed in parallel using FPGA architecture, enabling high-speed and efficient computation. The system classifies water quality into different categories based on predefined threshold values aligned with standard guidelines.

Furthermore, the processed data is transmitted using an ESP32 Wi-Fi module to the ThingSpeak cloud platform, enabling real-time remote monitoring and data visualization. A web-based interface and LCD display pro- vide both remote and local access to water quality information.

Experimental results demonstrate improved performance in terms of processing speed, accuracy, and real-time responsiveness compared to conventional systems. The proposed system offers a scalable, cost-effective, and reliable solution for modern water quality monitoring applications.

***Index Terms*—FPGA, Water Quality Monitoring, Real-Time Systems, ESP32, ThingSpeak, Multi-Sensor Data Processing, IoT, Environmental Monitoring**

I. INTRODUCTION

Access to clean and safe water is a fundamental requirement for human health, agriculture, and industrial development. However, rapid urbanization, industrial discharge, and environmental pollution have significantly de- graded water quality across the globe. Contaminated water resources pose serious health risks and environmental challenges, emphasizing the need for efficient monitoring systems [6, 15].

Conventional water quality monitoring techniques primarily depend on manual sampling and laboratory-based analysis. These approaches are time- consuming, costly, and unsuitable for continuous real-time monitoring [1]. Moreover, delayed analysis can lead to late detection of contamination, reducing the effectiveness of preventive measures [25].

Recent advancements in the Internet of Things (IoT) have enabled the development of smart water quality monitoring systems. These systems use various sensors to measure parameters such as pH, turbidity, temperature, and Total Dissolved Solids (TDS), and transmit the data to cloud platforms for real-time analysis [11, 22]. Cloud platforms such as ThingSpeak allow visualization and storage of sensor data, enabling remote monitoring through web-based interfaces [5, 19].

ESP32-based systems have gained significant attention due to their low cost, integrated Wi-Fi capability, and efficient performance in IoT applications. These systems facilitate seamless communication between sensor nodes and cloud platforms, improving accessibility and scalability of monitoring solutions [2, 9]. However, most existing IoT-based systems rely on microcontrollers, which operate sequentially and face limitations in processing speed and handling multiple sensor inputs simultaneously [12, 26].

To overcome these limitations, Field Programmable Gate Arrays (FP- GAs) provide an efficient alternative due to their parallel processing capability and high computational speed. FPGA-based systems can process multiple sensor data streams simultaneously, resulting in faster response time and improved accuracy [7, 18]. This makes them highly suitable for real-time environmental monitoring applications.

In this work, an FPGA-based real-time water quality monitoring and classification system is proposed. The system integrates multiple sensors for continuous data acquisition and utilizes FPGA for high-speed parallel processing. The processed data is transmitted using an ESP32 Wi-Fi module to the ThingSpeak cloud platform for real-time visualization. Additionally, a web-based interface and LCD display are used for both remote and local monitoring.

The proposed system aims to deliver a scalable, accurate, and real-time solution for water quality monitoring by combining FPGA-based processing with IoT-enabled communication.

II. LITERATURE REVIEW

Several research works have been carried out in the field of water quality monitoring using IoT and embedded systems. Traditional systems mainly rely on microcontrollers and wireless sensor networks for data acquisition and transmission.

Bhardwaj et al. [1] developed an IoT-based water quality monitoring system that uses sensors to measure parameters such as pH and turbidity. However, the system suffers from limited processing capability due to the use of microcontrollers.

Nasirudin et al. [2] proposed an ESP32-based monitoring system that transmits sensor data to cloud platforms like ThingSpeak for real-time visualization. Although the system provides remote access, it lacks high-speed data processing and efficient multi-sensor handling.

Sarkar et al. [15] introduced a smart environmental monitoring system using IoT, which improves data accessibility but still relies on sequential data processing, leading to latency issues.

Hota et al. [7] presented an FPGA-based environmental monitoring sys- tem that utilizes parallel processing to improve performance. However, the system lacks cloud integration and user-friendly interfaces.

Kumar et al. [11] developed a smart water monitoring system with IoT integration, but the system's accuracy and scalability are limited due to hardware constraints.

From the literature, it is observed that while IoT-based systems pro- vide remote monitoring capabilities, they suffer from processing delays and limited accuracy. On the other hand, FPGA-based systems offer high-speed processing but often lack IoT integration. Therefore, there is a need for a hybrid system that combines FPGA-based parallel processing with IoT-enabled communication.

The proposed system addresses these limitations by integrating FPGA for high-speed data processing with ESP32 and ThingSpeak for real-time cloud-based monitoring.

2.1Comparison of Existing Systems

Table 1: Comparison of Existing Systems and Proposed System

System	Platform	Processing	IoT Support	Performance
Bhardwaj et al.	Arduino	Sequential	Yes	Moderate
Nasirudin et al.	ESP32	Sequential	Yes	Moderate
Sarkar et al.	IoT + MCU	Sequential	Yes	Moderate

Hota et al.	FPGA	Parallel	No	High
Kumar et al.	IoT System	Sequential	Yes	Moderate
Proposed System	FPGA + ESP32	Parallel	Yes	Very High

2.2 Performance Analysis Using 3D Bar Graph

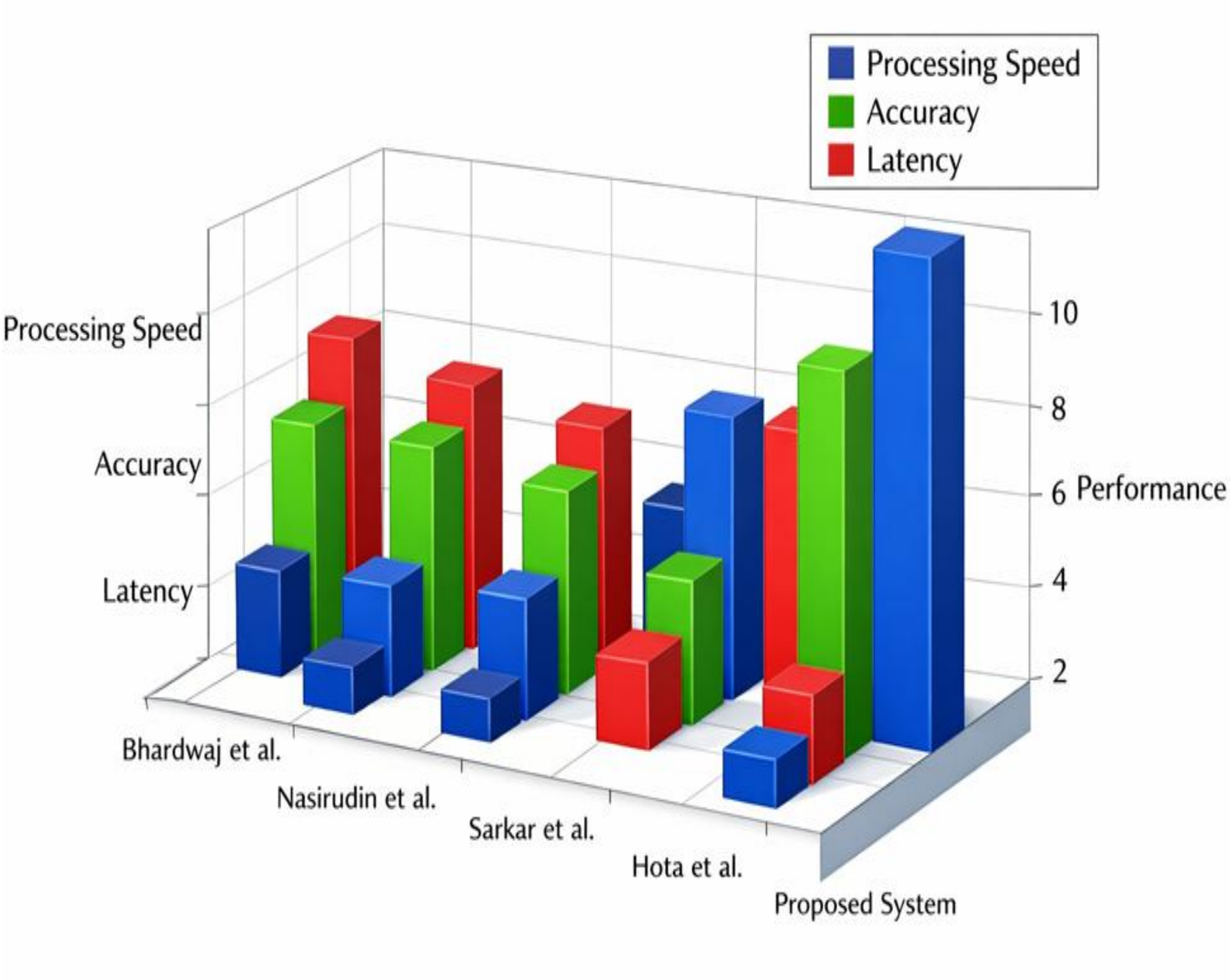

Figure 1: 3D Bar Graph Comparing Processing Speed, Accuracy, and Latency of Existing Systems and Proposed FPGA-Based System

The 3D bar graph illustrates the performance comparison between exist- ing microcontroller-based systems and the proposed FPGA-based system. It is observed that the proposed system achieves significantly higher processing speed and accuracy while reducing latency due to parallel data processing. The integration of IoT further enhances system functionality by enabling real-time remote monitoring.

III. PROPOSED SYSTEM

The proposed system is an FPGA-based real-time water quality monitor- ing and classification system that integrates multi-sensor data acquisition, high-speed processing, and IoT-based communication. The system is de- signed to overcome the limitations of traditional microcontroller-based sys- tems by utilizing parallel processing capabilities of FPGA.

3.1 System Architecture

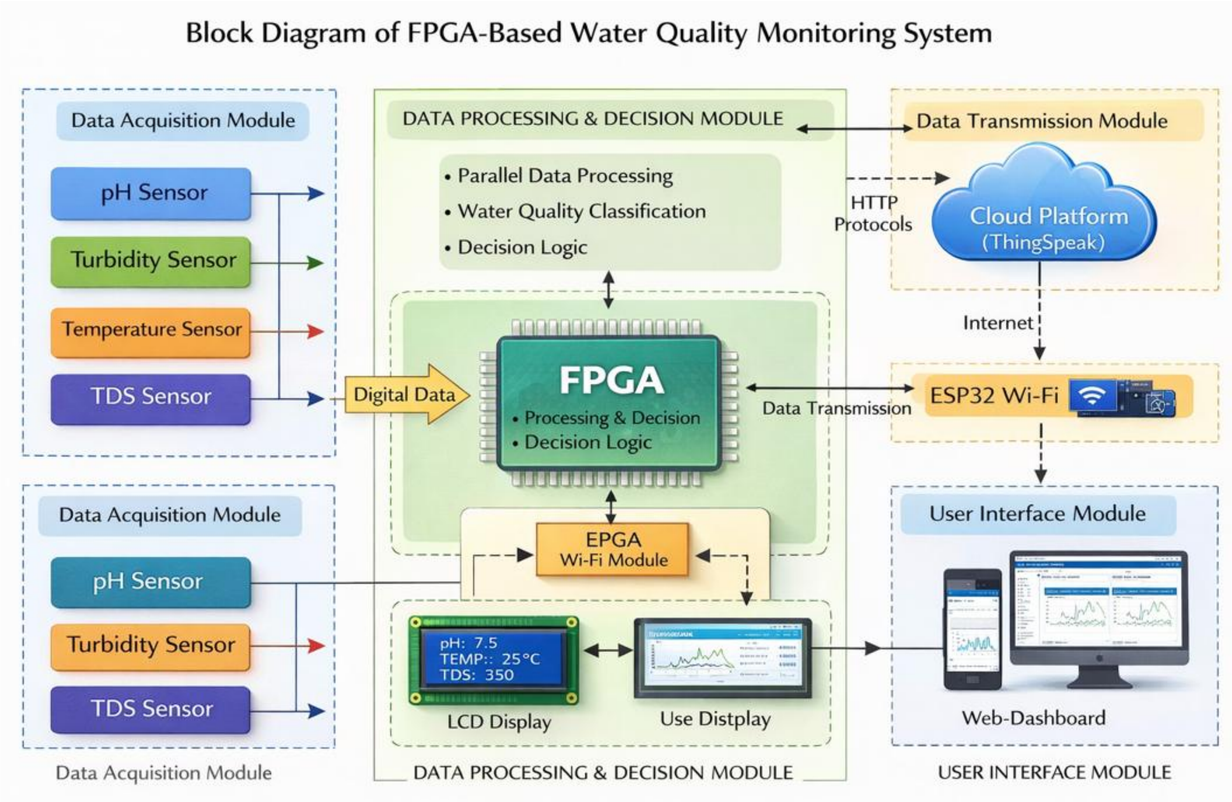

Figure 2: Block Diagram of FPGA-Based Water Quality Monitoring System

The system consists of four major modules: Data Acquisition, Data Processing, Data Transmission, and User Interface.

3.2 Data Acquisition Module

This module collects real-time data from various water quality sensors, including pH, turbidity, temperature, and Total Dissolved Solids (TDS). The sensors generate analog signals, which are converted into digital form using an Analog-to-Digital Converter (ADC). The digitized data is then fed into the FPGA for further processing.

3.3 Data Processing and Decision Module

The FPGA performs high-speed parallel processing of sensor data. Each parameter is compared against predefined threshold values based on standard water quality guidelines. A decision-making logic is implemented to classify water quality into categories such as safe, moderate, or unsafe. The use of parallel architecture significantly reduces latency and improves system efficiency.

3.4 Data Transmission Module

The processed data is transmitted to the cloud using an ESP32 Wi-Fi module. The ESP32 enables communication between the FPGA and the ThingSpeak platform using HTTP protocols. This allows real-time data visualization and remote monitoring through web-based interfaces.

3.5 User Interface Module

The system provides both local and remote user interfaces. Locally, an LCD display connected to the FPGA shows real-time sensor values and water quality status. Remotely, a web-based dashboard displays graphical and numerical data, enabling users to monitor water conditions from anywhere. The integration of FPGA with IoT ensures a scalable, efficient, and real- time monitoring solution suitable for environmental and industrial applications.

IV. METHODOLOGY

The proposed FPGA-based water quality monitoring system follows a structured approach for real-time data acquisition, processing, classification, and transmission. The system integrates multiple sensors with FPGA and IoT modules to achieve high-speed and accurate monitoring.

4.1 System Working Principle

The overall working of the system consists of four main stages: Data Acquisition, Data Processing, Classification, and Data Transmission.

4.2 Data Acquisition

Multiple water quality sensors, including pH, turbidity, temperature, and Total Dissolved Solids (TDS), are used to collect real-time environmental data. These sensors generate analog signals proportional to the measured parameters. An external Analog-to-Digital Converter (ADC) is used to con- vert these analog signals into digital form. The digital data is then provided as input to the FPGA.

4.3 Data Processing

The FPGA acts as the core processing unit of the system. It processes all incoming sensor data simultaneously using parallel processing architecture. Each sensor value is continuously monitored and compared with predefined threshold values based on standard guidelines. This parallel execution significantly reduces processing delay and improves system efficiency compared to traditional microcontroller-based systems.

4.4 Water Quality Classification

The processed sensor values are evaluated using a rule-based classification system. Based on the number of parameters within safe limits, water quality is categorized into four levels:

- Excellent: All parameters are within safe limits
- Good: Any three parameters are within acceptable limits
- Average: Any two parameters are within acceptable limits
- Poor: Less than two parameters are within acceptable limits

This classification ensures a simple yet effective decision-making mechanism for real-time applications.

4.5 Data Transmission

The processed data is transmitted to the cloud using the ESP32 Wi-Fi module. The ESP32 communicates with the ThingSpeak platform through HTTP protocols. This enables real-time data visualization, storage, and remote monitoring via web interfaces.

4.6 User Interface

The system provides both local and remote user interfaces. Locally, an LCD display connected to the FPGA shows real-time sensor readings and classification results. Remotely, a web-based dashboard displays graphical and numerical data for user monitoring. Alerts are generated when any parameter exceeds the predefined safe limits.

4.7 Algorithm for Water Quality Classification

1. Initialize FPGA system and sensors
2. Read sensor values (pH, Temperature, Turbidity, TDS)
3. Convert analog signals into digital data using ADC
4. Process all sensor data in FPGA using parallel architecture
5. Compare each parameter with predefined threshold values
6. Count the number of parameters within safe limits
7. Classify water quality as follows:
   - All parameters safe → Excellent
   - Three parameters safe → Good
   - Two parameters safe → Average
   - Less than two safes → Poor
8. Transmit processed data to ESP32 module
9. Send data to ThingSpeak cloud for visualization
10. Display results on LCD and web interface
11. Repeat the process continuously for real-time monitoring

4.8 Flowchart Representation

The flowchart illustrates the complete working process of the system, starting from sensor data acquisition to classification and cloud transmission. It highlights the continuous and real-time nature of the system operation.

V. RESULTS AND ANALYSIS

The proposed FPGA-based water quality monitoring system was suc- cessfully implemented and tested in a real-time environment. The system integrates multiple sensors with FPGA and ESP32 to achieve accurate, fast, and continuous monitoring.

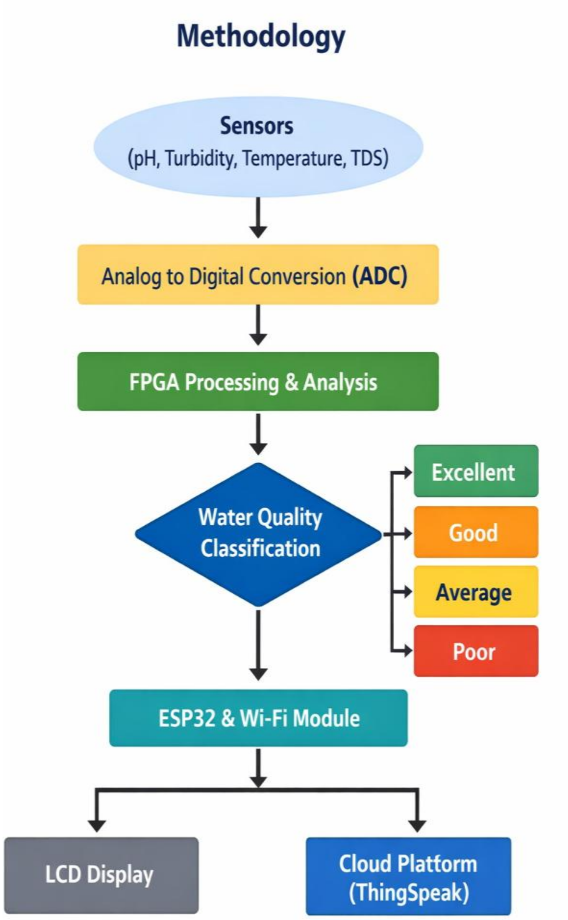

Figure 3: Flowchart of Water Quality Monitoring and Classification Process

5.1 Hardware Prototype Implementation

The complete hardware setup includes FPGA (Artix-7 board), pH sensor, turbidity sensor, temperature sensor, and TDS sensor integrated through ADC and interfaced with ESP32.

The prototype demonstrates stable operation with real-time data acqui- sition and processing. The FPGA efficiently handles multiple sensor inputs

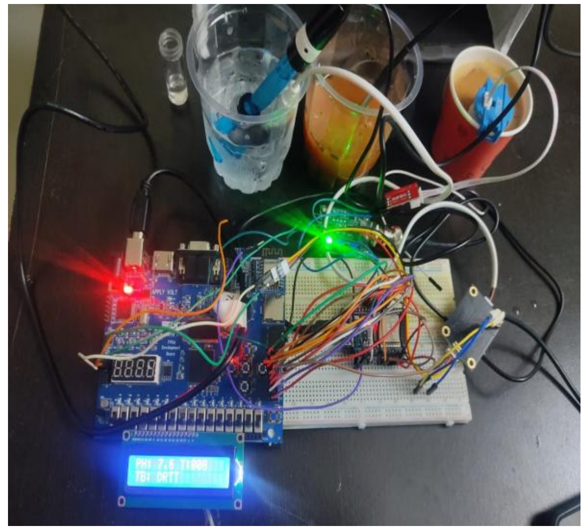

Figure 4: Experimental Setup of FPGA-Based Water Quality Monitoring System simultaneously.

5.2 LCD Display Output

The real-time processed data is displayed on an LCD connected to the FPGA.

Observed Output:

- pH Value: 7.4 (Neutral Range)
- Temperature: 25°C (Approx.)
- Water Status: Drinkable (DRTT indication)

This confirms that the system can provide instant local feedback without internet dependency.

5.3 Web-Based Monitoring Interface

A web-based dashboard was developed to visualize real-time data trans- mitted via ESP32.

Sample Observations:

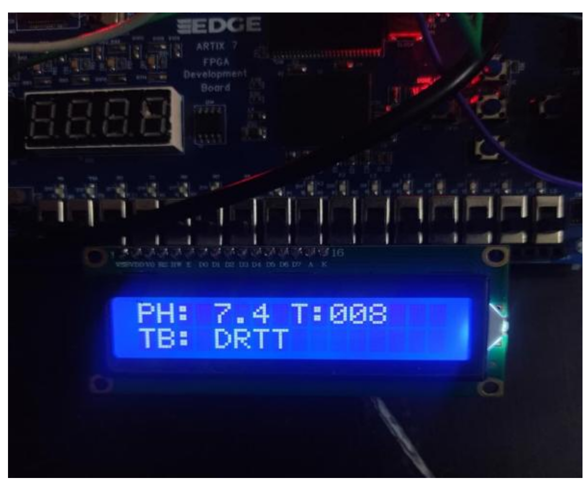

Figure 5: LCD Display Showing Real-Time Water Parameters

- pH: 7.0 – 7.8 (Optimal Range)
- TDS: 45 – 116 ppm (Good Quality)
- Turbidity: 5 – 6 NTU (Clear Water) The dashboard provides:
- Live data updates
- Clean and intuitive UI
- Real-time monitoring capability

5.4 System Performance Evaluation

The system performance was evaluated based on processing capability and real-time response.

Figure 6: Web Dashboard Showing Real-Time Sensor Values

Figure 7: Web Dashboard with Updated Water Quality Parameters

Parameter	Microcontroller System	Proposed FPGA System
Processing Speed	Low	High
Accuracy	Moderate	High
Latency	High	Low
Real-Time Monitoring	Limited	Excellent

Table 2: Performance Comparison of Systems

5.5 Discussion

The experimental results clearly demonstrate that the proposed FPGA-based system provides superior performance compared to conventional microcontroller- based systems. The integration of ESP32 and web-based monitoring enables real-time remote access, while FPGA ensures high-speed processing and ac- curacy. The system successfully achieves reliable water quality classification and monitoring in real-time conditions.

VI. CONCLUSION

This paper presented an FPGA-based real-time water quality monitoring and classification system using multi-sensor data processing. The system successfully integrates multiple sensors such as pH, turbidity, temperature, and Total Dissolved Solids (TDS) with FPGA to achieve high-speed and accurate data processing.

Unlike conventional microcontroller-based systems, the proposed design utilizes FPGA’s parallel processing capability, which significantly reduces latency and improves overall system performance. The integration of the ESP32 Wi-Fi module enables seamless transmission of processed data to the ThingSpeak cloud platform, allowing real-time remote monitoring.

The experimental results demonstrate that the system provides reliable and accurate water quality assessment. The LCD display offers local monitoring, while the web-based dashboard ensures remote accessibility. The system effectively classifies water quality into different categories based on standard threshold values.

Overall, the proposed system provides a scalable, cost-effective, and efficient solution for real-time water quality monitoring suitable for environ- mental, agricultural, and industrial applications.

VII. FUTURE SCOPE

Although the proposed system demonstrates efficient performance, sev- eral enhancements can be implemented in future work:

- Integration of additional sensors such as dissolved oxygen and conduc- tivity for more comprehensive analysis

- Implementation of machine learning algorithms for intelligent water quality prediction
- Development of a mobile application for enhanced user accessibility
- Integration with cloud-based analytics for long-term data analysis and reporting
- Power optimization using low-power FPGA architectures and renew- able energy sources
- Expansion of the system for large-scale water monitoring networks

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the Depart- ment of Electronics and Communication Engineering for providing the nec- essary resources and support to carry out this project. Special thanks to the project guide for their valuable guidance and continuous encouragement throughout the development of this work.

REFERENCES

[1] S. Bhardwaj et al., "Real-Time Water Quality Monitoring System Using IoT," IJERT, 2020.
[2] M. Nasirudin et al., "IoT-Based Water Quality Monitoring Using ESP32," IEEE IoT Conference, 2021.
[3] K. A. Delin and S. P. Jackson, "The Sensor Web: A New Instrument Concept," IEEE Internet Computing, 2001.
[4] Xilinx Inc., "Artix-7 FPGA Data Sheet," 2022.
[5] MathWorks, "ThingSpeak IoT Platform Documentation," 2023.
[6] World Health Organization, "Guidelines for Drinking-water Quality," 2017.
[7] B. K. Hota et al., "FPGA-Based Environmental Monitoring System," IEEE Trans. Industrial Electronics, 2020.
[8] A. Kumar and G. Hancke, "Energy Efficient Monitoring Using WSN," IEEE Sensors Journal, 2014.
[9] Espressif Systems, "ESP32 Technical Reference Manual," 2022.
[10] S. R. Madeti and S. N. Singh, "IoT for Aquaculture Monitoring," IEEE Systems Journal, 2017.
[11] P. Kumar et al., "Smart Water Monitoring Using IoT Sensors," Elsevier Procedia, 2019.
[12] R. N. Mahajan and M. N. Patil, "FPGA-Based Sensor Data Processing System," IEEE Conference, 2018.
[13] J. Gubbi et al., "Internet of Things (IoT): A Vision," Future Generation Computer Systems, 2013.
[14] D. Evans, "The Internet of Things: How the Next Evolution of the Internet is Changing Everything," Cisco, 2011.
[15] S. Sarkar et al., "Assessment of Water Quality Using IoT," IEEE Access, 2020.
[16] A. S. Al-Fuqaha et al., "Internet of Things: A Survey," IEEE Commu- nications Surveys, 2015.
[17] N. Kumar and P. Sinha, "Real-Time Data Processing Using FPGA," IEEE Embedded Systems, 2019.
[18] Y. Zhou et al., "Parallel Processing Using FPGA for Sensor Networks," IEEE Transactions, 2018.
[19] T. H. Luan et al., "Cloud-Based IoT Monitoring Systems," IEEE Cloud Computing, 2015.
[20] M. Li et al., "Sensor Data Fusion in IoT Systems," IEEE Sensors Jour- nal, 2019.
[21] S. K. Panda et al., "Design of Smart Water Quality System," Springer, 2021.
[22] R. Rajalakshmi and S. Devi Mahalakshmi, "IoT for Smart Environment Monitoring," International Journal, 2016.
[23] H. Kopetz, "Real-Time Systems Design Principles," Springer, 2011.
[24] A. R. Al-Ali et al., "IoT-Based Smart Monitoring Systems," IEEE, 2017.
[25] P. S. Chauhan and M. K. Shukla, "Water Pollution Monitoring Using Sensors," Elsevier, 2020.
[26] S. V. Patil and S. R. Patil, "Embedded Systems for Environmental Mon- itoring," IEEE, 2018.
[27] L. Da Xu et al., "Internet of Things in Industries: A Survey," IEEE Transactions on Industrial Informatics, 2014.