



EDGE AI-BASED WATER QUALITY MONITORING, PREDICTION AND ALERT SYSTEM

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Abstract:

Safe and clean water is essential for public health, but regular water testing can be time-consuming and difficult to perform in remote areas. This paper presents a low-cost Edge AI-based water quality monitoring system using an ESP32 for real-time on-site monitoring. The system uses sensors to measure pH, Total Dissolved Solids (TDS), turbidity, temperature, and water level. The collected data is processed locally to calculate the Water Quality Index (WQI) and determine the overall water quality status. Based on predefined limits, the system provides immediate alerts using LEDs and a buzzer. The measured data and WQI results can also be transmitted through Wi-Fi to a web dashboard for remote monitoring and record keeping. Local processing reduces dependence on continuous internet connectivity and enables faster detection of abnormal water conditions. The proposed system provides a simple, affordable, and practical solution for real-time water quality monitoring in rural, domestic, and small-scale applications.

Keywords: Edge AI, ESP32, IoT, Water Quality Monitoring, Water Quality Index (WQI), Real-Time Monitoring, LED/Buzzer Alert, Wi-Fi, GSM (Optional).

1. INTRODUCTION

Water quality directly affects human health and the environment. However, water sources can be contaminated by sewage, industrial discharge, agricultural activities, and other pollutants. Regular monitoring is therefore important for detecting unsafe water conditions at an early stage.



Conventional water testing usually requires sample collection followed by laboratory analysis. This process can take time, requires trained personnel, and may not provide immediate information when water quality changes suddenly. These limitations have increased the need for automatic and continuous monitoring systems.

IoT technology provides a practical way to monitor water parameters using sensors, microcontrollers, and wireless communication. Parameters such as pH, total dissolved solids (TDS), turbidity, and water level can be measured and sent to an online platform. However, cloud-dependent systems may experience communication delays or become unavailable when internet connectivity is poor.

The proposed system addresses this issue by performing water-quality processing locally on an ESP32 microcontroller. Sensor readings are used to calculate the Water Quality Index (WQI) and check the measured values against predefined limits.

When an abnormal condition is detected, the ESP32 activates LED and buzzer alerts at the monitoring location. The sensor data and WQI can also be transmitted through Wi-Fi to an IoT dashboard for remote observation and data logging. The proposed system therefore combines local processing, automatic alerting, and remote monitoring in a compact and low-cost platform for real-time water-quality assessment.

2. LITERATURE SURVEY

Bogdan et al. (2023) developed a low-cost IoT system for water-quality monitoring in rural areas. The system measured pH, TDS, turbidity, and temperature and displayed the results through a mobile application. However, it mainly focused on monitoring and did not include Edge AI-based prediction or automatic local control.

de Camargo et al. (2023) reviewed low-cost sensors used for IoT-based water-quality monitoring. The study showed that low-cost sensors can support remote monitoring but also highlighted issues related to sensor accuracy, reliability, calibration, and comparison with reference instruments.

Lal et al. (2024) developed a low-cost IoT system for lake-water monitoring using sensors for turbidity, TDS, temperature, pH, and dissolved oxygen. The system provided real-time monitoring and demonstrated the usefulness of low-cost sensors. However, prediction and local AI-based decision-making were not the main focus.

Essamlali et al. (2024) reviewed the use of machine learning and IoT for water-quality monitoring. The study showed that ML can improve water-quality prediction and classification when combined with sensor data. However, many systems still depend on external computing or communication infrastructure.

Bhati et al. (2024) presented an AI and IoT-based approach for low-cost water-quality monitoring in rural areas. The study demonstrated how sensor data and AI techniques can be combined for



water assessment. However, implementing advanced AI models directly on small microcontrollers remains challenging.

Naloufi et al. (2024) investigated a low-cost IoT system for long-term monitoring of water quality in urban rivers. The study highlighted the importance of sensor stability and reliable communication for continuous monitoring. However, it did not focus on Edge AI-based prediction and automatic control.

Slongo et al. (2024) evaluated low-cost water-quality sensors for real-time measurement. Their work showed that inexpensive sensors can be useful but require proper calibration and validation. This indicates the importance of sensor preprocessing and calibration in embedded water-quality systems.

Faghir Hagh et al. (2024) developed a low-cost LoRa-based optical system for real-time monitoring of water-quality parameters. The work demonstrated the benefits of wireless communication for remote monitoring. However, its sensing approach is different from a multi-sensor ESP32 system with local WQI calculation.

Forhad et al. (2024) developed an IoT-based real-time water-quality monitoring system for water-treatment plants. The system monitored parameters such as pH, dissolved oxygen, TDS, and temperature and supported remote monitoring. However, cloud/IoT monitoring was emphasized more than local Edge AI decision-making.

Kularbphetpong et al. (2025) investigated machine-learning techniques for predicting the Water Quality Index. The study showed that ML models can be used to estimate WQI from water-quality parameters. However, implementing such prediction directly on resource-constrained embedded devices requires lightweight models.

Dharmarathne et al. (2025) reviewed recent applications of machine learning and IoT in water-quality assessment. The study identified ML, IoT sensors, prediction, and real-time monitoring as important developments. It also highlighted practical challenges such as sensor reliability, data quality, and deployment limitations.

Ngwenya et al. (2025) reviewed the use of IoT and machine learning for real-time ambient water-quality monitoring. The study emphasized the potential of combining sensing, communication, and AI. However, real-world deployment still faces challenges related to data quality, network reliability, and system scalability.

Choudhary et al. (2025) used ensemble machine-learning methods for Water Quality Index prediction and applied explainable AI to understand model predictions. The study demonstrates the value of ML for WQI estimation. However, the models are primarily designed for computational environments rather than small embedded platforms.

Yuan et al. (2025) investigated machine-learning methods for improving WQI prediction using long-term water-quality data. The results demonstrated that ML can improve WQI estimation for



different water systems. However, such data-driven models require suitable datasets and are not directly designed for low-cost Edge AI hardware.

Pandey et al. (2026) reviewed machine learning, deep learning, and IoT approaches for water-quality prediction. The study highlighted the growing role of AI and IoT in real-time water monitoring. However, lightweight AI implementation, low-cost hardware, local alerts, and autonomous control remain important areas for further development.

The literature review table comparisons are shown below as Table.1 Literature Review

Table 1 Literature Review

Author(s) & Year	Study / Paper	Method / Tools	Main Limitation	Relevance to Proposed System
Bogdan et al. (2023)	Low-Cost IoT Water-Quality System for Rural Areas	Arduino UNO, Bluetooth, DS18B20, pH, TDS, Turbidity sensors; Mobile App	Lacks Edge AI prediction and autonomous local control.	Establishes feasibility of low-cost multi-sensor IoT. Proposed system extends this with ESP32 & Edge AI.
de Camargo et al. (2023)	Low-Cost Water Quality Sensors for IoT: Systematic Review	Systematic review of sensor types, architectures, reliability & performance	Low-cost sensors suffer from calibration, accuracy & validation issues.	Guides sensor selection while emphasizing essential calibration & validation mechanisms.
Lal et al. (2024)	Low-cost IoT System for Lake Water Quality Monitoring	Real-time lake monitoring via pH, TDS, turbidity, temp sensors & IoT	Focuses purely on monitoring; lacks predictive capability & embedded AI.	Supports real-time monitoring design; proposed system adds WQI prediction & Edge AI control.
Essamlali et al. (2024)	ML and IoT for Water-Quality Monitoring	ML integrated with IoT sensing & water-quality data analytics	Relies on cloud/external servers, inducing latency & connectivity risks.	Motivates shift to ESP32 Edge AI to ensure offline local inference.
Bhati et al. (2024)	AI and IoT for Rural Water Monitoring	Water sensors + AI/IoT techniques for quality assessment	Conventional AI models require resources beyond small microcontrollers.	Highlights the necessity of lightweight ML optimized for ESP32 hardware.
Naloufi et al. (2024)	Long-Term IoT Water-Quality Monitoring	Low-cost sensors & long-term IoT urban river monitoring	Sensor stability & connectivity challenges; lacks Edge AI prediction.	Provides guidelines for reliable long-term sensing; proposed work adds local AI execution.
Slongo et al. / de Camargo et al. (2024)	Evaluation of Low-Cost Sensors for Real-Time Monitoring	Experimental evaluation under controlled and field conditions	Raw low-cost sensor data is highly volatile without calibration.	Directly supports inclusion of pre-filtering & calibration prior to ML processing.
Faghir Hagh et al.	LoRa-Based Optical Water	Optical sensing combined with LoRa	Optical focus & different architecture	Demonstrates low-power remote



(2024)	Monitoring	wireless communication	than multi-sensor microcontrollers.	transmission; complements ESP32 sensing architecture.
Forhad et al. (2024)	Real-Time IoT Water-Treatment Monitoring	IoT remote monitoring with pH, DO, TDS, and temperature sensors	Centered on telemetry/visualization without local autonomous control.	Validates multi-parameter set; proposed system adds local predictive actuation.
Kularbphetong et al. (2025)	Machine Learning for WQI Prediction	ML algorithms applied to water parameters for WQI estimation	Models require heavy datasets & ignore embedded microcontroller deployment.	Establishes ML WQI baseline while motivating lightweight embedded model design.
Dharmarathne et al. (2025)	ML and IoT for Water-Quality Assessment	Comprehensive review of ML/IoT sensing & analytics workflows	Identifies open challenges: sensor noise, generalization, real-time edge execution.	Frames core challenges solved by proposed system (preprocessing + Edge AI).
Ngwenya et al. (2025)	IoT and ML for Ambient Water Quality	Review of integrated sensing, analytics, and network systems	Network latency, scalability, and data reliability constraints.	Reinforces advantage of local Edge AI execution during network drops.
Choudhary et al. (2025)	Ensemble ML & Explainable WQI Prediction	Ensemble ML models and Explainable AI (XAI) for WQI scoring	High computational complexity unsuited for embedded edge nodes.	Demonstrates interpretable WQI scoring; proposed system translates this to lightweight format.
Yuan et al. (2025)	Machine Learning for WQI Optimization	Data-driven ML trained on long-term water quality datasets	Heavy reliance on data quality; lacks hardware implementation.	Motivates robust training set preparation for embedded ESP32 model deployment.
Pandey et al. (2026)	ML, Deep Learning and IoT for Water Quality	Review of ML/DL and IoT architectures for water monitoring	Edge AI, low-cost microcontrollers, local alerts & auto-control remain underexplored.	Directly establishes overall research gap addressed by our proposed integrated platform.

3. METHODOLOGY

Edge AI is structured as a layered pipeline covering sensing, on-device computation, and alerting. The design deliberately excludes predictive control or valve actuation, concentrating instead on fast assessment and communication of water quality. Data flows sequentially from the physical sample through to the remote dashboard, as shown in Fig. 1.

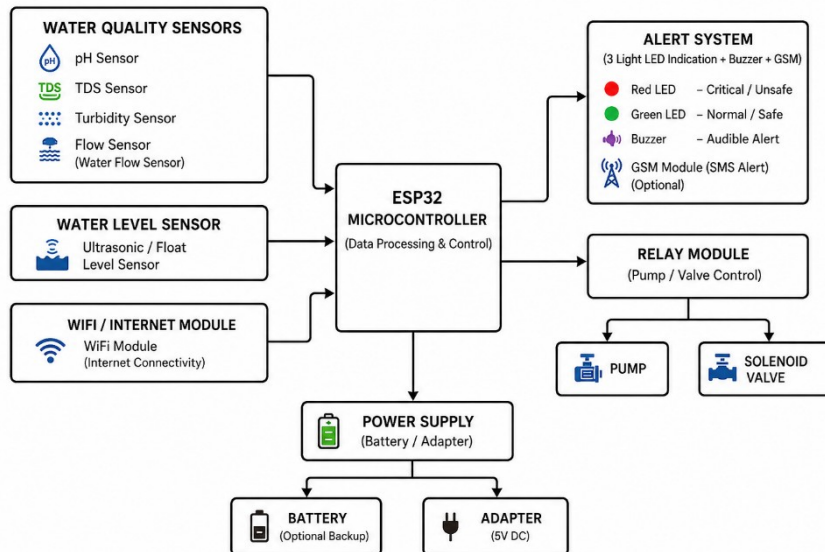


Figure 1 Block diagram of the Edge AI sensing, edge-processing, and alert pipeline.

As the diagram shows, the pipeline is built purely for monitoring and alerting, with pump- and valve-automation left out entirely.

A. Hardware System Design

Processing is handled by an ESP32-WROOM-32E, chosen for its dual-core Xtensa LX6 architecture that supports parallel Free RTOS tasking, its built-in Wi-Fi 4 radio for cloud connectivity, and its generous set of ADC & GPIO pins.

The sensor suite delivers a rounded picture of water quality: a pH E-201C combination electrode with signal-conditioning circuitry measures hydrogen-ion concentration, calibrated against standard buffer solutions at pH 4.01, 6.86, and 9.18.

Total Dissolved Solids are captured with a DF Robot Gravity TDS meter, which applies an AC excitation signal to a conductivity probe to avoid electrode polarization and outputs a voltage proportional to concentration in ppm. Turbidity is sensed optically through an SEN0189 module measuring light scattered at 90 degrees, calibrated against a 100 NTU standard. A hermetically sealed DS18B20 digital sensor, communicating over the One-Wire bus, supplies the precise temperature readings needed to compensate the pH and TDS measurements for thermal drift. Water level is tracked by an HC-SR04 ultrasonic sensor using pulse-echo time-of-flight timing to confirm adequate sensor submersion. The alert hardware itself consists of a high-intensity red LED and an active piezo buzzer each switched through a GPIO-controlled transistor stage for direct on-site audio-visual warning.



B. Data Acquisition and Preprocessing

Firmware is written in C/C++ within the Arduino IDE and split across two Free RTOS tasks. Task 1 runs on Core 0 at a 1 Hz sampling rate; for every analog channel it takes ten rapid ADC samples and averages them to suppress electrical noise. These averaged raw values are then converted to engineering units through pre-derived calibration functions. Both the pH and TDS conversions fold in real-time temperature compensation drawn from the DS18B20 reading to correct for thermal drift inherent to electrochemical sensing, while the turbidity conversion applies a non-linear calibration curve that maps voltage to Nephelometric Turbidity Units. Digital temperature and ultrasonic level values are read directly. All six processed parameters are collected into a shared Sensor Data structure, and a data-ready semaphore flag is raised to hand off to the Edge AI task.

C. Edge AI: WQI Calculation and Classification

The core intelligence lives in Task 2, running on Core 1 and triggered by the data-ready flag. This task computes a Weighted Arithmetic Water Quality Index, a well-established model that folds several disparate readings into one dimensionless potability score. Four parameters feed the index — pH, TDS, turbidity, and temperature — each assigned an ideal value and a weight reflecting its relative importance to health. A sub-index is derived for each parameter from how far the observed value deviates from its ideal, normalised against the corresponding WHO/BIS permissible limit, and the overall WQI is the weighted sum of these sub-indices. The resulting score is then sorted into one of five descriptive bands on a 0–100+ scale: Excellent, Good, Poor, Very Poor, and Unsuitable for Drinking. This entire pipeline completes in microseconds on the ESP32, exemplifying the Edge AI principle of interpreting data locally and instantly, with no cloud round-trip involved.

D. Alert Generation and Cloud Transmission

After classification, a deterministic rule-based safety check runs independently of the WQI band: it compares each parameter against its WHO threshold and separately checks whether the aggregated WQI exceeds 100. Either condition alone is enough to raise an alert flag. The alerting logic is built for fail-safe immediacy — as soon as the flag is set, the ESP32 drives the LED GPIO pin high to light the red indicator and applies a 2 kHz PWM signal to the buzzer pin for an unmistakable audible warning. Because this safety path is entirely local, alert actuation carries zero network-induced delay, even during an outage. At the same time, the processed sensor values, WQI score, and quality category are packaged into a compact JSON payload and sent over Wi-Fi to a cloud broker using MQTT at Quality-of-Service level 1.

E. Cloud and Mobile Dashboard

On the receiving end, a Node-RED flow subscribes to the MQTT topic and parses the incoming JSON stream to populate a live, interactive dashboard: gauge widgets for each parameter, time-series charts for trend viewing, and a prominent WQI dial. Because the interface is web-based, it

can be reached from any phone or computer browser, rounding out the system's dual local-and-remote situational-awareness design.

4. RESULTS

A laboratory prototype was developed to evaluate the proposed water-quality monitoring system. The ESP32, sensor interfaces, and alert components were assembled on a custom PCB. Water samples were tested in a 500 mL beaker, as shown in Fig. 2.

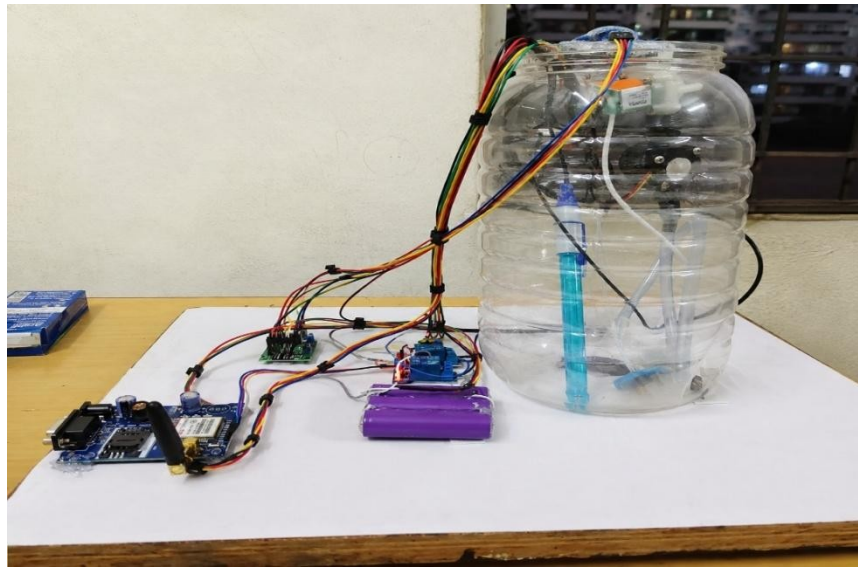


Figure 2 Laboratory prototype of the Edge AI sensing and alert hardware under test.

A. Sensor Calibration and Accuracy

The sensors were calibrated using reference instruments before testing. The pH sensor was calibrated with three buffer solutions and achieved an (R^2) value of 0.998. The TDS sensor showed an accuracy of approximately $\pm 2\%$ when compared with a reference meter. The turbidity sensor achieved an (R^2) value of 0.992 after calibration. The DS18B20 temperature sensor showed an error of less than ± 0.1 °C.

B. WQI and Alert Testing

Three water samples were tested to evaluate the complete system.

- Sample 1 – Tap Water: The measured values were pH 7.2, TDS 145 ppm, turbidity 0.6 NTU, and temperature 24.8 °C. The calculated WQI was 38, classified as Excellent. The green LED remained ON and the buzzer was OFF.
- Sample 2 – River Water: The measured values were pH 8.1, TDS 380 ppm, turbidity 12 NTU, and temperature 22.5 °C. The WQI increased to 145 and was classified as Poor. The red LED and buzzer were activated, and the dashboard displayed the warning status.



- Sample 3 – Contaminated Water: Soil and salt were added to increase contamination. The measured values were pH 8.8, TDS 1250 ppm, and turbidity 55 NTU. The WQI reached 342, classified as Unsuitable for Drinking. The local LED and buzzer alerts were activated, and the dashboard indicated unsafe water.

C. Processing Time and Reliability

The ESP32 processing time was measured using the `micros()` function. The WQI calculation and threshold checking required approximately 85 μ s. Including sensor reading and data averaging, the local response time was approximately 110ms.

The system was also operated continuously for 72 hours without a watchdog reset or observed memory-related failure. MQTT communication was performed in parallel with local processing. The monitoring trends and dashboard results are shown in Fig. 3 and Fig. 4.

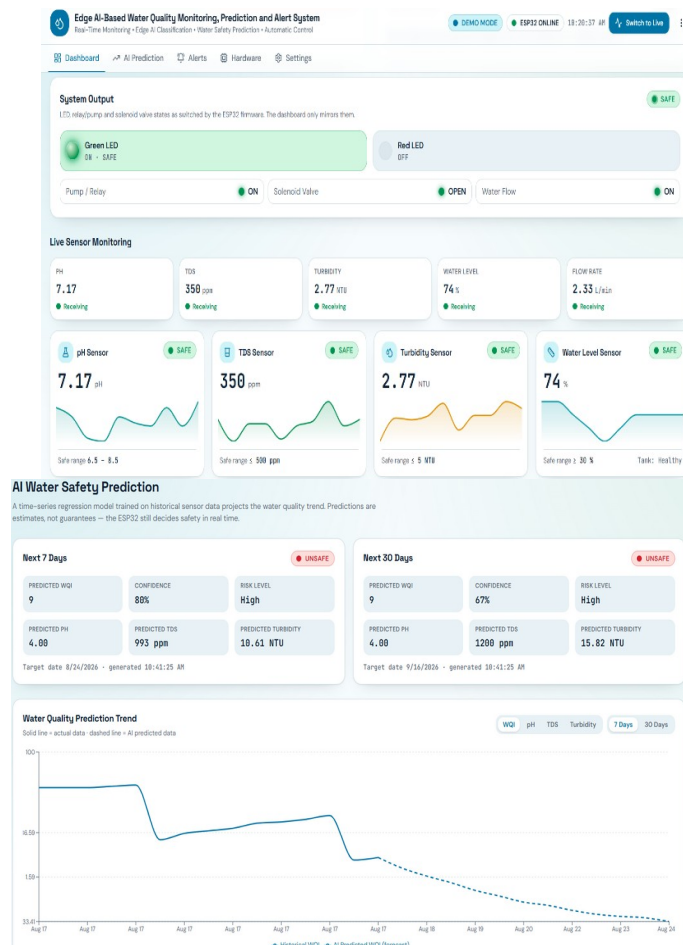


Figure 3 Dashboard trend graphs for TDS, pH, turbidity, temperature, flow, and tank level.

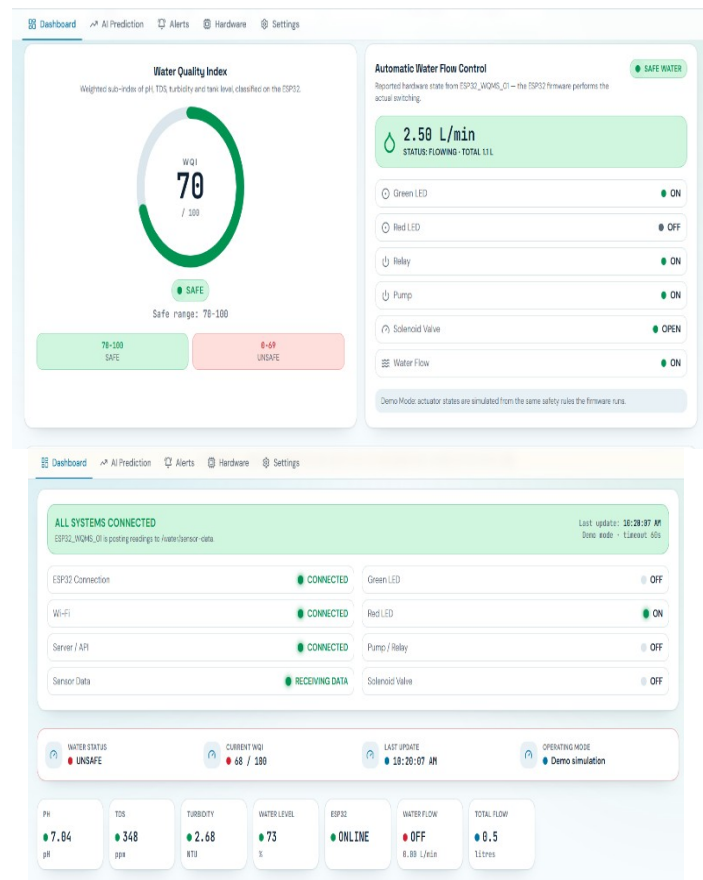


Figure 4 Control-room dashboard showing the latest sensor snapshot and safety prediction.

5. DISCUSSION

The proposed system demonstrates the benefit of processing water-quality data directly at the edge. The ESP32 calculates the WQI locally and can generate an alert without depending on continuous internet access. This improves the response time and allows the basic safety function to continue even when the network is unavailable.

Compared with systems that mainly provide cloud-based monitoring, the proposed approach combines local processing, WQI calculation, and immediate LED and buzzer alerts in one low-cost embedded unit. The WQI also makes the results easier to understand because several measured parameters are represented by a single quality classification.

The ESP32-based design is suitable for portable and low-power applications. However, the present system mainly uses fixed limits and WQI rules. Therefore, it may not identify complex contamination patterns that require machine-learning analysis. Future improvements can address this limitation.



6. CONCLUSION

This paper presented an ESP32-based Edge AI system for real-time water-quality monitoring and alert generation. The system measures multiple water parameters, calculates the Water Quality Index locally, and provides visual and audible warnings when unsafe conditions are detected.

A major advantage of the proposed system is that the basic monitoring and alert functions do not depend on cloud connectivity. Wi-Fi can still be used to send data to an IoT dashboard for remote observation and record keeping. The proposed design is therefore suitable for low-cost and portable water-quality monitoring applications.

Future work will focus on integrating Tiny ML-based anomaly detection, mobile monitoring, solar power, LoRa communication, and long-term water-quality prediction. These improvements can make the system more suitable for remote and large-scale deployments.

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