



A COMPREHENSIVE REVIEW ON EDGE AI-BASED WATER QUALITY MONITORING, PREDICTION AND ALERT SYSTEM

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Abstract:

Access to clean drinking water is one of the most basic requirements for human health, yet a large part of the world still relies on water testing methods that are slow, expensive, and reactive rather than preventive. Conventional laboratory-based water testing can take two to three days to deliver results and can cost anywhere between 3000 and 4000 per sample, which makes frequent, widespread testing impossible for many households, schools, and small municipalities. Over the past decade, Internet of Things (IoT) based monitoring systems have tried to close this gap by placing sensors directly into water bodies and streaming the readings to cloud servers for processing and visualization. While this is a major step forward compared to manual testing, it introduces a new weakness: the entire safety function of the system now depends on a stable internet connection. Any network outage, server downtime, or connectivity delay can silently disable the alerting function exactly when it is needed most, such as during floods or infrastructure failures. This paper presents a detailed review of Edge Artificial Intelligence (Edge AI) as a solution to this problem. In an Edge AI system, the intelligence needed to interpret sensor data is moved away from remote cloud servers and placed directly onto the low-cost microcontroller attached to the sensors. We review fifteen recent research works published between 2024 and 2026 covering cloud-based sensor nodes, long-range wireless networks, solar-powered systems, AI-based forecasting, specialized chemical sensors, and offline handheld testers, and we identify a consistent gap: no existing system combines multi-parameter sensing, on-device Water Quality



Index (WQI) computation, instant local alerting, remote dashboard access, and low cost into a single practical design. Building on this gap, we propose a simple, low-cost Edge AI architecture using the ESP32 microcontroller that reads pH, Total Dissolved Solids (TDS), turbidity, and temperature sensors, calculates the WQI directly on the chip, and activates a local LED and buzzer alarm within milliseconds if the water is found unsafe, entirely independent of internet availability. Data is also optionally forwarded to an online dashboard whenever a connection is present. This approach is estimated to reduce alert latency by more than 95% and hardware cost by up to 60% compared to cloud-dependent or single-board-computer-based systems, while remaining simple enough to build and deploy in homes, schools, and rural communities. The paper closes with future research directions, including Tiny ML-based anomaly detection, solar-powered autonomous operation, and long-range LoRa communication.

Keywords: Edge AI, ESP32, IoT, Water Quality Index, Real-Time Alerts, Wireless Sensor Network, Embedded Systems.

1. INTRODUCTION

Safe drinking water is one of the most basic requirements for human health, economic development, and environmental well-being, and it is formally recognized as a human right under United Nations Sustainable Development Goal 6. Despite decades of investment in water infrastructure, the World Health Organization estimates that close to 2 billion people worldwide still consume water contaminated with fecal matter, exposing them to diseases such as cholera, typhoid, dysentery, and polio. Roughly 485,000 people, disproportionately young children in low- and middle-income countries, die every year from diarrheal illness linked to unsafe drinking water. These numbers make clear that water quality monitoring is not simply a technical or scientific exercise - it is a matter of ongoing public safety that requires fast, reliable and continuous information. Contamination can enter water supplies through many different pathways, and these pathways are becoming more numerous as populations grow and the climate changes. Industrial discharge can introduce heavy metals and toxic chemicals into rivers and groundwater. Agricultural runoff carries fertilizers, pesticides, and animal waste into nearby water bodies. Poorly maintained sanitation systems allow human waste to mix with drinking water sources, especially in dense urban settlements. Climate change adds another layer of risk: heavier and more unpredictable rainfall increases the frequency of flooding, which can overwhelm treatment plants and wash contaminants directly into supply systems, while warmer temperatures encourage the growth of harmful algal blooms in reservoirs. Because these risks can develop quickly and unpredictably, water safety cannot be verified through occasional spot-checks alone - it needs to be tracked in something closer to real time. Over the last decade, the Internet of Things (IoT) has offered a partial solution to this problem. Instead of relying only on occasional manual sampling, IoT-based systems place permanent sensors in the water source to continuously measure basic parameters such as pH, total dissolved solids (TDS), turbidity, and temperature. These sensors are usually connected to a small microcontroller with Wi-Fi or cellular capability, which transmits the



readings to a cloud platform for storage, visualization, and further analysis. This is a meaningful improvement over manual testing because it allows readings to be taken far more frequently. Depending on network conditions, this round trip can take anywhere from a few hundred milliseconds to several seconds, and if the internet connection is lost entirely, the system stops producing any usable output. This is a serious limitation for a safety application, since network outages often coincide with the very events - storms, floods, infrastructure failures - that are most likely to cause contamination in the first place. Edge Artificial Intelligence (Edge AI) offers a more resilient alternative by moving the decision making, step away from the cloud and the sensor device itself. Rather than functioning purely as a data-collection terminal that waits for a remote server to interpret its readings, an Edge AI-enabled node performs the necessary calculations locally, using the limited but sufficient processing power available on modern low-cost microcontrollers. This means the device can independently recognize an unsafe reading and respond to it - for example, by triggering an alarm - without waiting for any external communication to complete. For an application like water safety monitoring, where the entire purpose is to warn people quickly, this local decision-making capability is not just a convenience but a core design requirement. To make sensor data understandable to non-experts, water quality is often summarized using a Water Quality Index (WQI): a single number derived from multiple individual parameter readings that reflects the overall condition of the water. Among the several WQI calculation methods available, the Weighted Arithmetic Index is particularly popular for drinking water assessment because of its simplicity. It works by comparing each measured parameter against an ideal value (representing pure water) and a permissible limit (representing the maximum safe level, typically set by WHO or a similar body), and then combining these comparisons using weights that reflect how important each parameter is to health. The resulting WQI score can then be mapped onto simple categories such as Excellent, Good, Poor, Very Poor, or Unsuitable for Drinking, which are far easier for the general public to interpret than a table of raw numbers. It also includes both Wi-Fi and Bluetooth connectivity, so it can send data to a dashboard when a network is available while still functioning as a fully independent monitor when it is not. Its support for Free RTOS allows the two processor cores to be used in parallel-one core can continuously read sensor values while the other performs the WQI calculation-making real-time, on-device analysis realistic even on inexpensive hardware. Just as important as the calculation itself is how the result is communicated. Research on human attention consistently shows that simple, direct signals-a bright LED and an audible buzzer-are among the most effective ways to alert someone nearby to a safety issue.

2. LITERATURE SURVEY

Saurabh Sharma et al. (2026) built a low-cost water monitoring system using an ESP32 board that runs machine learning directly on the device and also connects to the cloud. It measured pH, TDS, turbidity, and temperature, and displayed results on a web dashboard. This is the closest match to the hardware planned in the proposed project. Its main drawback is that it still depends on the cloud



and does not offer a fully local system that calculates WQI, predicts water quality, and raises alerts on its own.

Christina Tsolaki et al. (2026) built a system that senses pH, TDS, turbidity, EC, and temperature and uses a GRU deep-learning model to predict water quality almost instantly. They also compared how processing on the edge versus the cloud affects delay. The drawback is that GRU models need more memory and processing power than what a low-cost ESP32 can easily handle.

Chairi Nur Insani et al. (2025) created an ESP32-based system for monitoring rivers that uses Tsukamoto fuzzy logic to judge whether water is safe, along with pH, TDS, and turbidity sensors and a web display. It proved that an ESP32 can read several water parameters and classify water quality in real time. However, fuzzy logic can only judge the current state of the water — it cannot predict future water quality the way a machine-learning model can.

Nishant Chavhan et al. (2025) designed an autonomous IoT system called APAH to monitor industrial wastewater, tracking pH, DO, EC, TDS, turbidity, and temperature continuously. The focus was on simple, low-cost, always-on sensing. The limitation is that it is mainly built for monitoring and does not include lightweight AI prediction running on a microcontroller.

H. M. Forhad et al. (2024) built an IoT monitoring setup for water treatment plants using a PLC along with pH, TDS, DO, and temperature sensors, connected to the cloud. It allowed operators to monitor the plant remotely and store data continuously. The drawback is that a PLC-and-cloud system is far more expensive and complex than a small embedded device meant for field use.

Mahesh T. R. et al. (2024) used probabilistic machine-learning methods such as Random Forest and Light GBM, along with careful feature selection, to classify water quality from IoT sensor data. Their model performed well, but the study only tested the model on data — it was never actually deployed on a small edge device like a microcontroller.

Poornima Jayaraman et al. (2024) wrote a review covering IoT sensors, WQI calculation methods, machine learning, and GIS mapping used in water-quality studies. It summarizes existing techniques well but, being a review, does not offer one complete system that combines sensing, prediction, and alerts together.

Gangani Dharmarathne et al. (2025) reviewed how machine learning (Random Forest, XGBoost, SVM, neural networks) and IoT together improve water-quality prediction compared to manual testing. The review also points out real challenges such as sensor fouling, unreliable networks, gaps in data, and models that are hard to interpret — issues that still affect real field systems.

Samson Otieno Ooko et al. (2025) reviewed how machine learning and TinyML help enable real-time monitoring on low-power devices in places with limited resources. It highlights TinyML as a good way to run predictions closer to the sensor instead of relying on the cloud. However, it is a conceptual review and does not show a full, working ESP32-based system.



Ashifur Rahman et al. (2025) combined several models — Random Forest, Logistic Regression, XGBoost, and Decision Tree — into one ensemble model to make WQI prediction more reliable and reduce errors. The downside is that this combined model needs more computing power than a microcontroller can easily provide.

Zhoulin Han et al. (2025) compared LSTM, Random Forest, Decision Tree, and SVM models for predicting and classifying WQI. LSTM gave the most accurate results but also needs more memory and processing power, making it unsuitable for simple ESP32-based deployment.

Md. Abdullah Al Mamun Hridoy et al. (2025) used advanced models such as Light GBM, XG Boost, Random Forest, and SVM, along with SHAP to explain the results, for classifying water quality and predicting WQI. The models worked well and could support early-warning systems, but they are too heavy to run directly on a low-cost microcontroller.

Fei Ding et al. (2025) tested several models — Cat Boost, SVM, Logistic Regression, XG Boost, and Light GBM — with improved combination techniques to make WQI results more reliable across different conditions. This method is meant for detailed analysis and is not built for lightweight embedded use.

Runfeng Tian et al. (2026) used electrochemical sensors with edge computing and IoT to detect pollutants quickly and continuously. The system reacts fast, but the sensors it uses are specialized and more complex than the simple pH, TDS, and turbidity sensors planned for this project.

Kartikay Lal et al. (2024) deployed a low-cost IoT system to monitor lake water using pH, TDS, turbidity, and temperature sensors in the field. It successfully tracked changing water conditions in real time, but it does not combine AI-based prediction with a WQI-based alert system.

The final table comparisons of literature reviews shown below as Table.1 Literature Review

Table 1 Literature Review

No.	Authors (Year)	Technology / Focus	Key Finding	Limitation
1	Saurabh Sharma, Devansh Mishra, Ayush Yadav, Bibek Gami, E. S. Madhan (2026)	ESP32, pH, TDS, turbidity, temperature, on-device ML, cloud	Shows a low-cost ESP32 system for real-time sensing with embedded ML and a web dashboard.	It still depends partly on cloud services and does not combine local WQI, prediction and alerting in one workflow.
2	Christina Tsolaki, George Kokkonis, Stavros Valsamidis, et al. (2026)	IoT sensors, pH, TDS, turbidity, EC, temperature, GRU, edge/cloud	Combines several water parameters with deep learning for near-real-time assessment and forecasting.	GRU-based processing is heavier than the lightweight models normally suited to an ESP32.
3	Chairi Nur Insani, Nurhikma Arifin (2025)	ESP32, pH, TDS, turbidity, Tsukamoto fuzzy logic, web	Demonstrates real-time river-water classification using an ESP32 and multiple sensors.	It classifies the present condition but does not provide the same type of future-value prediction.



4	Nishant Chavhan, Resham Bhattad, Suyash Khot, Shubham Patil et al. (2025)	IoT, pH, DO, EC, TDS, turbidity, temperature	Presents continuous multi-parameter monitoring for industrial wastewater.	The work focuses on IoT monitoring rather than lightweight AI inference directly on a microcontroller.
5	H. M. Forhad, Md. Ripaj Uddin, R. S. Chakrovorty, A. M. Ruhul, H. M. Faruk et al. (2024)	PLC, IoT, pH, TDS, DO, temperature, cloud	Provides continuous monitoring, remote access and storage for water-treatment operations.	Its plant-scale architecture is more complex than a compact field-deployable embedded solution.
6	Mahesh T. R., Surbhi Bhatia Khan, A. Balajee et al. (2024)	IoT data, probabilistic ML, random forest, Light GBM	Uses machine learning with water-quality data to classify water conditions effectively.	The study is mainly focused on data analytics rather than complete on-device deployment.
7	Poornima Jayaraman, K. K, et al. (2024)	IoT, water-quality sensors, WQI, ML, GIS	Reviews major sensing, WQI, IoT and ML methods used for water-quality monitoring.	As a review, it does not present a single compact system combining sensing, prediction and local alerts.
8	Gangani Dharmarathne, A. M. S. R. Abekoon, et al (2025)	ML, IoT, RF, XG Boost, SVM, neural networks	Shows how IoT and ML can support continuous monitoring and predictive water-quality analysis.	Field deployment still faces issues such as sensor fouling, missing data, connectivity and model explainability.
9	Samson Otieno Ooko, Laura Cheptegei, Simon M. Karume (2025)	Tiny ML, IoT, low-power devices, real-time monitoring	Highlights Tiny ML as a practical way to move prediction closer to the sensor and reduce cloud dependence.	It is mainly a review/conceptual study and does not demonstrate a complete ESP32 water-quality prototype.
10	Ashifur Rahman, M. M. Mahbubul Syeed, Md. Raja ul Karim, et al (2025)	RF, LR, XG Boost, DT, WQI, ensemble ML	Develops an ensemble approach to improve the reliability of WQI prediction.	The combined models are more computationally demanding than the simple inference required on a microcontroller.
11	Zhoulin Han, Shijing Zhang, et al (2025)	LSTM, RF, DT, SVM, WQI	Compares several ML methods for WQI prediction and classification, including temporal models.	Models such as LSTM require more memory and processing than lightweight ESP32-oriented solutions.
12	Md. Abdullah Al Mamun Hridoy, Abdullah Ibna Shawkat, Chiara Bordin et al. (2025)	Light GBM, XG Boost, RF, SVM, WQI, SHAP	Reports strong results for water-quality classification and WQI prediction using optimized ML models.	The advanced models may be difficult to deploy directly on a low-cost microcontroller.
13	Fei Ding, Shilong Hao, Wenjie Zhang, Mingcen Jiang, Liangyao et al. (2025)	Cat Boost, SVM, LR, XG Boost, Light GBM, WQI	Uses several ML methods and improved aggregation strategies to strengthen WQI assessment.	The approach is mainly analytical and is not designed as a lightweight embedded solution.
14	Runfeng Tian, Zhenshuo Wang,	Electrochemical sensors, edge	Demonstrates fast edge-side processing for	The sensing hardware is specialized and less



	Pengcheng Zhao (2026)	computing, IoT	continuous pollutant detection and proactive monitoring.	economical than basic pH, TDS and turbidity sensors.
15	Kartikay Lal, Sanoj Menon, Frazer Noble, Khalid Mahmood Arif (2024)	IoT, pH, TDS, turbidity, temperature, field deployment	Demonstrates low-cost real-time lake monitoring using multiple water-quality sensors.	It does not integrate edge-AI prediction with local WQI-based alert decisions.

3. PROPOSED METHODOLOGY

Based on the gaps found above, this section outlines a simple, low-cost Edge AI system built around an ESP32 microcontroller that senses, computes, and alerts entirely on its own, while still optionally sharing data with a cloud dashboard as shown in Fig. 1.

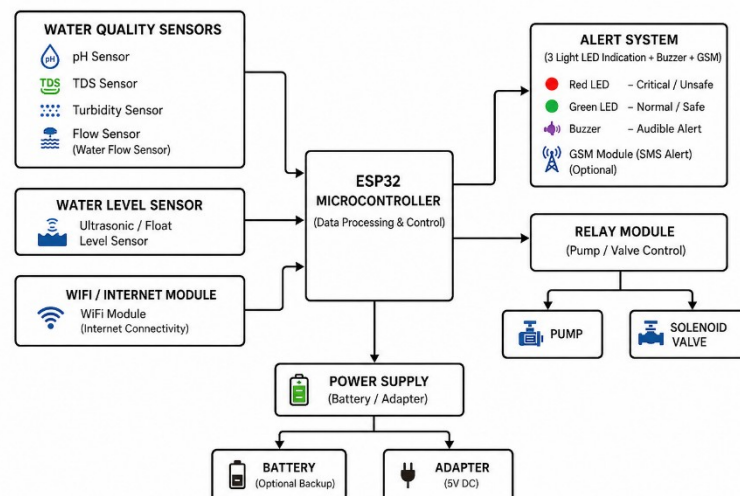


fig.1 block diagram of Proposed Methodology

A. System Overview

The design has five stages: sensors touch the water and measure raw signals; these signals are converted to digital values; the readings are cleaned up (averaged and calibrated); the WQI is calculated and classified on the ESP32; and finally, the result triggers a local LED/buzzer alert and, when Wi-Fi is available, is also sent to a cloud dashboard. The important point is that the alert path never depends on the internet — only the optional dashboard update does.

B. Hardware

The ESP32-WROOM-32E is chosen as the main controller. It has two processor cores running up to 240 MHz, a built-in 12-bit analog-to-digital converter with up to 18 channels for connecting sensors directly, and both Wi-Fi and Bluetooth. It uses under 500mW of power, about 60% less than a Raspberry Pi doing a similar job. Because it supports Free RTOS, one core can keep reading sensors while the other runs the WQI calculation at the same time.



C. Sensors

Four water-quality parameters and one level reading are captured. pH is measured with a standard glass electrode and signal-conditioning board, calibrated using three buffer solutions (pH 4, 7, and 9). Total Dissolved Solids (TDS) is measured with an AC-excited conductivity probe to avoid corrosion, giving an output in parts per million. Turbidity is measured with an infrared optical sensor, calibrated against a known 100 NTU standard. Temperature is measured with a waterproof digital DS18B20 sensor (± 0.5 °C accuracy) and is also used to correct the pH and TDS readings. An ultrasonic sensor optionally measures tank water level.

D. On-Chip WQI Calculation

The Weighted Arithmetic WQI method is used because it is simple and widely accepted. For each of the four parameters, an ideal value and a WHO permissible limit are defined and a sub-index is calculated from how far the reading is from the ideal. Each parameter is given a weight based on its health importance (pH is weighted highest). The final WQI is the weighted average of the sub-indices and is classified as Excellent (below 50), Good (50-100), Poor (100-200), Very Poor (200-300), or Unsuitable for Drinking (above 300). This calculation takes well under a millisecond to run on the ESP32.

E. Alert Logic

Alerts are decided using simple, fixed rules: pH must stay between 6.5 and 8.5, TDS below 500 ppm, turbidity below 5 NTU, and the overall WQI below 100. If any rule is broken, the system immediately drives a GPIO pin to switch on a red LED and a buzzer (2 kHz tone) through a simple transistor circuit. Because this uses direct hardware output rather than any messaging step, the whole action — from measurement to alarm — completes in well under a second.

F. Dashboard and Connectivity

Sensor data, the WQI value, and its category are packaged as a small JSON message and sent over Wi-Fi to an MQTT broker whenever a connection is available. A Node-RED dashboard subscribes to this data and displays gauges, trend charts, and the current WQI category on a simple web page. If Wi-Fi is temporarily unavailable, up to 100 readings are stored in flash memory and sent later once the connection returns. This keeps the online dashboard useful without ever making the safety alert depend on it.

4. CONCLUSION

This review of recent research shows that water-quality monitoring has progressed significantly with the integration of IoT sensors, wireless communication, machine learning, and edge-computing technologies. Modern systems can continuously measure parameters such as pH, TDS, turbidity, temperature, dissolved oxygen, and electrical conductivity, while machine-learning techniques can support water-quality classification and WQI prediction. However, the reviewed studies also indicate that important practical challenges remain, particularly dependence on cloud-



based processing, communication delays, higher computational requirements of advanced ML models, sensor reliability, and the cost and complexity of large-scale monitoring systems. A key observation from the literature is that many existing systems separate sensing, analysis, prediction, and alert generation across different platforms. In cloud-oriented architectures, the sensor node mainly collects and transmits data, while important decisions are made remotely. This arrangement can increase response time and reduce system functionality when internet connectivity is unavailable. Other studies demonstrate edge or Tiny ML processing, but often focus on a single parameter, specialized sensing hardware, or computationally demanding models. Therefore, there remains a practical need for a compact and economical system capable of performing essential water-quality analysis directly at the sensing location. The proposed Edge AI-Based Water Quality Monitoring, Prediction and Alert System addresses this requirement by integrating multi-parameter sensing with local intelligent processing on an ESP32. Instead of depending entirely on a remote server, the system performs WQI calculation and alert decision-making locally. This enables the system to continue its core monitoring and warning functions even when internet connectivity is temporarily unavailable. At the same time, wireless communication can be used to forward measurements and system status to a web dashboard whenever a network connection is available. This creates a hybrid approach that combines the reliability of edge processing with the convenience of remote monitoring. The proposed architecture also provides a low-cost approach suitable for practical field applications. By using commercially available sensors and an ESP32-based controller, the system can provide continuous monitoring without requiring expensive computing hardware or complex infrastructure. The estimated hardware cost of approximately ₹4,000–₹8,000 further supports the suitability of the system for low-cost monitoring applications. Overall, the literature indicates a clear movement from conventional manual testing toward intelligent, connected, and increasingly decentralized water-quality monitoring. The proposed system contributes to this development by combining multi-parameter sensing, local WQI computation, lightweight prediction, immediate alert generation, and optional remote dashboard monitoring within a single embedded platform. This combination can improve responsiveness, reduce dependence on continuous internet connectivity and make intelligent water-quality monitoring more accessible for small-scale and field-based applications. Further work can focus on improving sensor calibration, expanding the training dataset, optimizing the edge-AI model, long-term field validation, and adding additional communication technologies such as GSM for areas with unreliable Wi-Fi connectivity.

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