

Aqua Sential: Autonomous UAV-Based Water Quality Monitoring System

Farooq Jaleel^{1*}, Harikrishnan J¹, S Gowrilakshmi¹, Joe Jose¹, Ranjitha Rajan², Praseeda B Nair³

Abstract

The increasing occurrence of waterborne health risks and the presence of harmful microorganisms in freshwater environments highlight the need for rapid and continuous water quality monitoring. Traditional laboratory-based testing methods often require significant time and manual sampling, limiting their ability to provide immediate information about changing environmental conditions. This work presents AquaSential, a low-cost, portable, and UAV-ready water quality monitoring system designed for real-time assessment of freshwater bodies. The proposed system uses an ESP32 microcontroller integrated with temperature, pH, turbidity, and Total Dissolved Solids (TDS) sensors to continuously acquire important physicochemical water quality parameters. The collected sensor data is processed by the ESP32 and transmitted wirelessly through its built-in Wi-Fi capability to a ground station for real-time visualization and analysis. A basic threshold-based risk classification model is used to identify water conditions that may be favorable for potential biological hazards, including harmful freshwater pathogens such as Naegleria fowleri. The sensing unit is powered by a rechargeable Li-Po battery with an integrated charging and protection circuit and is housed in a lightweight, waterproof enclosure suitable for outdoor deployment. The compact and modular architecture enables future integration with autonomous UAV platforms for monitoring remote, inaccessible, and potentially hazardous water bodies. AquaSential provides a cost-effective foundation for continuous environmental surveillance, early risk identification, and future intelligent water quality monitoring applications.

Keywords: Aquasential, UAV, ESP32 microcontroller, temperature, pH, turbidity, total dissolved solids

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INTRODUCTION

Freshwater resources are essential for drinking water, agriculture, industry, and maintaining ecological balance. However, increasing environmental pollution, climate change, and human activities have significantly affected the quality of freshwater bodies, making continuous monitoring more important than ever. Contaminated water can create favorable conditions for harmful microorganisms, including Naegleria fowleri, a free-living amoeba commonly known as the "brain-eating amoeba." Recent advances in embedded systems and wireless communication have enabled the development of low-cost, real-time monitoring solutions. In this work, AquaSential is proposed as a portable, UAV-ready water quality monitoring system that integrates an ESP32 microcontroller with temperature, pH, turbidity, and Total Dissolved Solids (TDS) sensors.

Key Features of AquaSential

AquaSential has several advanced capabilities to provide early warning of risks and real-time monitoring of water quality [1] [10]. It uses a multi-sensor array integrated with an ESP32 microcontroller to continuously monitor important physicochemical parameters like temperature, pH, turbidity and Total Dissolved Solids (TDS). The in-built Wi-Fi of ESP32 allows continuous remote monitoring and quick analysis by processing and wirelessly transmitting the collected sensor data to a ground station. The system performs a basic risk classification using the measured environmental parameters to provide early warnings for conditions that might favor the proliferation of harmful freshwater pathogens, such as *Naegleria fowleri*. The sensing module is powered by a rechargeable Li-Po battery and is housed in a lightweight waterproof 3D-printed enclosure for robust operation in the outdoor environment. The sensing module is enclosed in a lightweight waterproof 3D printed enclosure and powered by a rechargeable Li-Po battery with integrated charging and protection circuit for reliable operation in outdoor environments. Its compactness, low cost and energy efficiency make it suitable for long-term field deployment and future integration with autonomous UAVs for efficient monitoring of lakes, ponds, reservoirs and other remote water bodies [3, 4, 5,7].

Benefits of AquaSential

AquaSential provides an effective, smart and affordable solution to long-term monitoring of freshwater quality. It allows real-time, in-situ measurement of important water quality parameters unlike conventional testing methods that require a laboratory [5]. This significantly reduces the time taken to detect possible contamination. By continuously monitoring temperature, pH, turbidity and Total Dissolved Solids (TDS), the system will be able to detect changes in water quality at an early stage and raise timely warnings for conditions that may be conducive to the growth of harmful pathogens like *Naegleria fowleri*[10]. This allows authorities and environmental agencies to take preventive steps before it becomes hazardous. The wireless communication function of the system can instantly send the sensor data to a ground station without the need for frequent manual sampling, thereby improving the monitoring efficiency. The cost-effective hardware architecture based on the ESP32 microcontroller and inexpensive sensors make the solution economically feasible for large-scale deployment in lakes, ponds, reservoirs, rivers and other freshwater bodies [8]. Its compact and lightweight design and its waterproof 3D printed enclosure ensure reliable operation in harsh outdoor environments and protect the electronics from water and physical damage. AquaSential has been designed to be scalable for the future too. It is light weight and can be mounted on autonomous UAVs enabling rapid monitoring of remote, inaccessible and hazardous water bodies without exposing personnel to unnecessary risks [9]. Unlike conventional IoT-based water quality monitoring systems that primarily focus on fixed monitoring stations or standalone sensing platforms, the proposed AquaSential system integrates real-time multi-parameter sensing, wireless IoT communication, lightweight modular hardware, and future UAV deployment capability into a single portable platform. The system combines temperature, pH, turbidity, and Total Dissolved Solids (TDS) sensing with onboard ESP32 processing and wireless transmission for continuous freshwater monitoring [7]. Furthermore, a threshold-based water quality risk assessment mechanism provides immediate identification of potentially hazardous environmental conditions that may support harmful microorganisms. The compact waterproof enclosure and low-power architecture allow the system to be deployed manually today while remaining suitable for future autonomous UAV integration, providing a flexible and scalable solution for monitoring remote freshwater bodies [10].

LITERATURE REVIEW

Many studies have been conducted on the pathogenic traits of *Naegleria fowleri*, a deadly amoeba that is frequently found in warm freshwater habitats. The study investigated the unknowns surrounding human immune responses to the pathogen and emphasised the molecular pathways causing infection. [7] It highlighted the serious hazards to public health posed by contaminated water sources and the necessity of proactive environmental monitoring. The findings offered a solid biological foundation for the creation of quick and early-warning water quality assessment systems targeted at reducing human exposure to such deadly biological dangers by illustrating the serious health effects and quick course of the infection [1].

Drone technology has been thoroughly examined as a means of gathering physicochemical data and water samples from aquatic environments [2]. The study showed that by offering a quicker, safer, and more effective substitute for traditional boat-based sampling techniques, unmanned aerial vehicles (UAVs) have a great deal of promise to enhance large-scale water monitoring programmes. Nonetheless, a number of drawbacks were noted, such as the comparatively limited number of water samples gathered, poorer sample retrieval success rates, and operational limitations brought on by aviation laws and flight restrictions [2].

The labor-intensive traditional spot-sampling techniques were to be replaced with an automated water sampling system combined with an unmanned aerial vehicle (UAV) [6]. To guarantee precise and dependable sample collection, the suggested system included a specialised automatic locking mechanism that was engaged after stringent field quality control procedures. The study effectively showed how UAVs may automate field operations and expedite water sample procedures, providing an affordable option for data collection in a variety of challenging-to-reach aquatic situations. The results confirmed the practical efficacy and mechanical viability of drone-integrated water collection systems for environmental monitoring applications [6, 7].

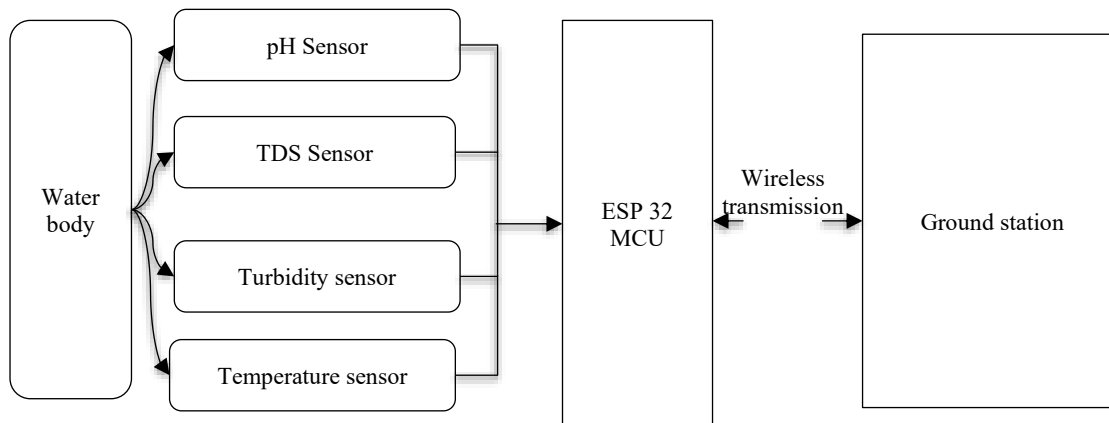
To overcome the spatial constraints and low efficiency of human surface water sampling, an intelligent multirotor UAV-assisted water sample system was created [9]. In order to prevent cross-contamination, the suggested system included lightweight ABS plastic parts and a unique servo-controlled nozzle mechanism that could fill several onboard sample containers while also flushing the system. The study emphasized the benefits of UAV-based sampling over unmanned surface vehicles, especially with regard to coverage, operational flexibility, and accessibility. The results showed a reliable hardware architecture that satisfies conventional environmental monitoring standards, which makes it appropriate for effective water quality evaluation in expansive and intricate aquatic ecosystems [9].

To measure important water quality indicators autonomously and in situ, a UAV-based system with an integrated sensor node was created. Real-time environmental monitoring was made possible by the prototype's incorporation of sensors for electrical conductivity (EC), pH, dissolved oxygen (DO), temperature, and turbidity. The system included an adaptive mechanism that automatically activated water-sampling cartridges based on sensor readings, in addition to continuous data collecting. The work provided a solid technological basis for real-time water quality evaluation and risk categorisation systems by demonstrating the viability of combining live sensor telemetry with physical sample collection on a single aerial platform [6].

For environmental surveillance applications, ESP32 microcontroller-based low-cost Internet of Things water quality monitoring systems have been extensively researched. These systems usually incorporate sensors to measure temperature, pH, turbidity, and Total Dissolved Solids (TDS), and they use wireless communication technology to transmit, monitor, and analyse data remotely. Real-time water quality testing has been demonstrated to be economical, scalable, and effective when ESP32-based sensor networks are used. These investigations back up the choice of the ESP32 microprocessor and related sensor setups for the AquaSential system's development [9, 10]. While prior studies have independently shown the efficacy of sensor-driven water quality monitoring, UAV-based water sampling, and IoT-enabled environmental surveillance, there is still a need for a small and reasonably priced platform that combines wireless data communication, early risk classification capabilities, and real-time physicochemical water quality monitoring. In order to close this gap, the AquaSential system combines an ESP32 microcontroller with sensors for temperature, pH, turbidity, and Total Dissolved Solids (TDS). It also offers the flexibility to be integrated with autonomous UAV platforms in the future to monitor remote freshwater settings [10]. As shown in Table 1, recent studies have explored various UAV-assisted and IoT-based approaches for water quality monitoring, each with distinct advantages and limitations.

Table 1. Summary of previous studies and the proposed monitoring framework.

Study	System	Parameters	Wireless	UAV	Limitation
[2]	UAV sampling	Sampling only	No	Yes	No real-time sensing
[5]	UAV monitoring	pH, EC, DO	Limited	Yes	Expensive
[6]	Fixed monitoring	pH, Turbidity, TDS	Wi-Fi	No	No mobility
[8]	IoT + UAVReady	Temperature, pH, Turbidity, TDS	Wi-Fi	Future-ready	Low-cost portable platform

**Figure 1.** Block diagram of AquaSential.

PROPOSED METHODOLOGY

The proposed methodology for AquaSential is to develop an autonomous, low-cost water quality monitoring system capable of continuous, real-time monitoring of freshwater quality. The system utilizes the ESP32 microcontroller and a set of temperature, pH, turbidity and Total Dissolved Solids (TDS) sensors to measure the main physicochemical parameters affecting water quality and pathogen growth [2]. The ESP32 collects data from the sensors, processes it and wirelessly transmits it to a ground station using its onboard Wi-Fi module where it can be visualized and analyzed in real-time. Based on the measured parameters, a basic risk classification algorithm assesses the quality of the water and generates early warnings in case of unfavorable conditions [9]. The entire sensing unit is powered with a rechargeable Li-Po battery with an integrated charging and protection circuit, and the unit is housed in a lightweight, waterproof 3D-printed casing to enable a reliable operation in aquatic environments. The compact and modular design also allows easy future integration with autonomous UAVs, allowing for efficient monitoring of large, remote and difficult to access water bodies while reducing the need for manual sampling [3, 4, 5, 6]. The overall block diagram of the proposed AquaSential system is shown in Figure 1.

The AquaSential system adopts a systematic approach for real-time water quality monitoring. The entire system runs on a power supply unit which consists of a rechargeable Li-Po battery, charging module and voltage regulation circuit. The main processing unit is a microcontroller ESP32 connected with four water quality sensors, namely temperature, pH, turbidity and Total Dissolved Solids (TDS) [3]. These sensors continuously measure the physicochemical properties of the water and send the measured values to the ESP32 to process the signals and filter the data. The processed information is then transmitted via the built-in Wi-Fi module of the ESP32 wirelessly to a ground station which displays and analyses the sensor readings [4, 5, 6].

A simple risk classification algorithm based on threshold values is used to evaluate the water quality and to give early warnings when the conditions become conducive for possible biological hazards. The sensing module is housed in a lightweight and waterproof container, making it suitable for field deployment and future integration with an autonomous UAV for monitoring large and remote freshwater bodies. The methodology provides a continuous, reliable and cost-effective water quality assessment with reduced need for manual sampling [4] [10].

Table 2. Water quality assessment thresholds.

Parameter	Safe	Moderate risk	High risk
Temperature	20–30°C	30–35°C	>35°C
pH	6.5–8.5	6.0–6.5 or 8.5–9.0	<6 or >9
Turbidity	<5 NTU	5–10 NTU	>10 NTU
TDS	<500 ppm	500–1000 ppm	>1000 ppm

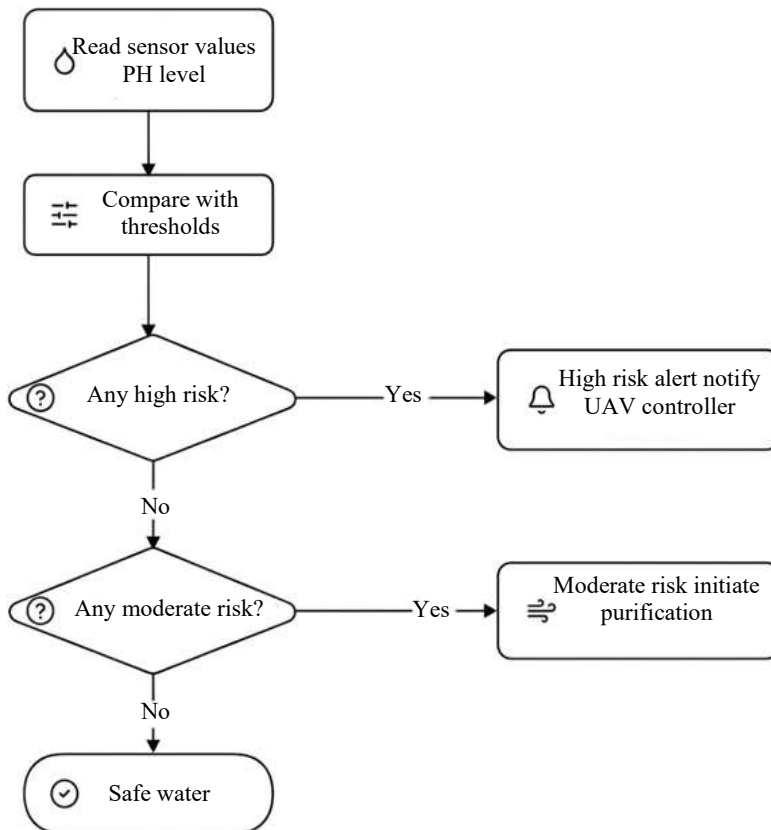


Figure 2. Flowchart of the water quality risk assessment system.

WATER QUALITY RISK CLASSIFICATION

The AquaSential system classifies freshwater conditions into three risk levels based on measured physicochemical parameters. Figure 2 demonstrates the water quality risk assessment and decision-making workflow, where sensor data are analysed against predetermined thresholds to identify water conditions and trigger relevant alarm or purification operations. Table 2 presents the threshold ranges used to classify water quality into safe, moderate-risk, and high-risk categories based on temperature, pH, turbidity, and TDS measurements.

WORKING PRINCIPLE

The AquaSential system begins its operation by deploying the sensing module into the target freshwater body. The temperature, pH, turbidity, and Total Dissolved Solids (TDS) sensors continuously measure the physicochemical properties of the water and generate corresponding analog or digital signals [10]. These signals are collected by the ESP32 microcontroller, which converts, filters, and processes the sensor data to obtain accurate measurements. The processed data is then transmitted wirelessly to a ground station through the ESP32's built-in Wi-Fi module, where it is displayed for real-time monitoring and analysis. Based on predefined threshold values, the system performs a basic risk classification to determine whether the measured water conditions indicate a potential biological hazard,

such as favorable conditions for the growth of *Naegleria fowleri* [1][10]. The entire module is powered by a rechargeable Li-Po battery with an integrated charging and protection circuit, while the waterproof 3D-printed enclosure ensures reliable operation in aquatic environments. The lightweight and compact design also allows the module to be mounted on an autonomous UAV in the future, enabling rapid monitoring of large, remote water bodies [3][4]. The overall working sequence of the AquaSential system is illustrated in Figure 3.

CIRCUIT EXPLANATION

The AquaSential system uses an ESP32 microcontroller as its main brain, handling data collection, processing, and wireless communication. This system gets its power from a 3.7 V Li-Po battery, which is connected to a TP4056 module that makes sure the battery charges safely and doesn't get overcharged or completely drained [6]. The TP4056's output is then sent to an MT3608 boost converter, which creates a stable 5 V power supply for the analog sensors and the ESP32's VIN pin.

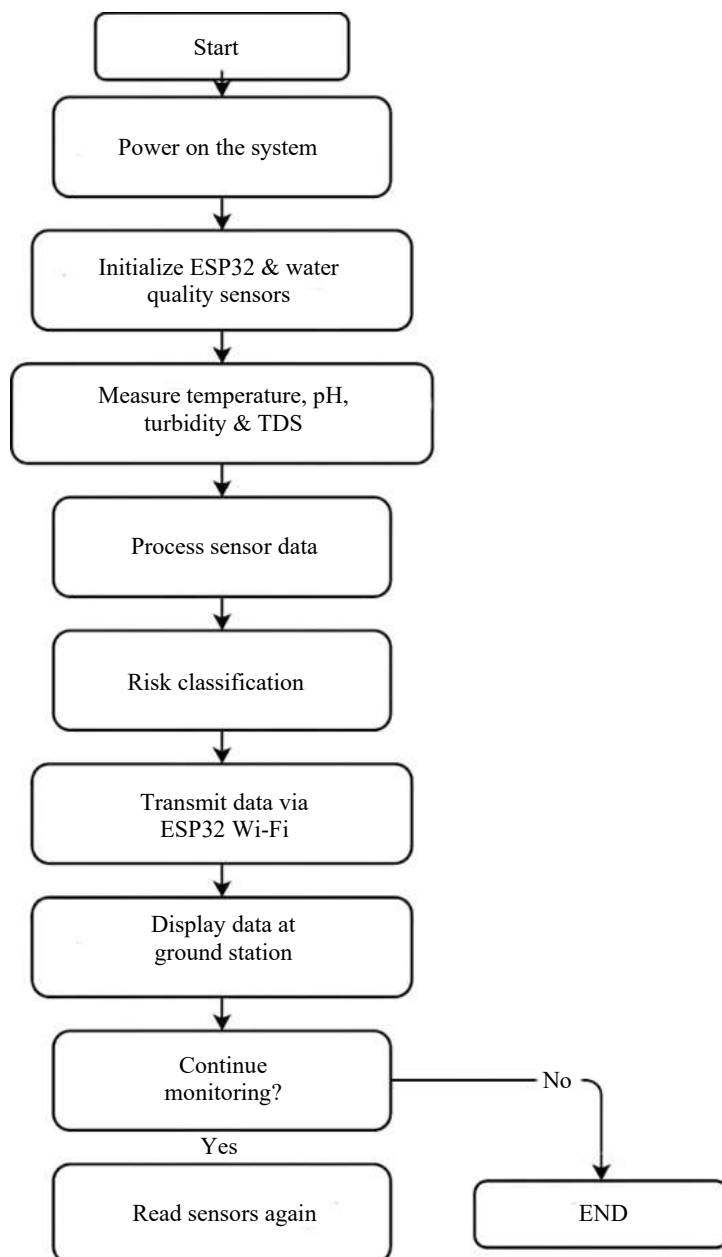


Figure 3. Flow chart of AquaSential.

Finally, the ESP32's built-in voltage regulator takes this 5 V supply and converts it into the 3.3 V logic supply that the microcontroller needs to run its internal circuits. This setup is pretty clever, as it allows the AquaSentinel to work efficiently and reliably, even when running on battery power. The TP4056 module is especially important, since it prevents the battery from getting damaged due to overcharging or deep discharge. And with the MT3608 boost converter generating a stable 5 V supply, the system's analog sensors and ESP32 microcontroller can operate smoothly, without any worries about power fluctuations [4][5]. Overall, the AquaSentinel's power management system is designed to be efficient, reliable, and safe, making it a great choice for applications where battery power is the only option. Whether it's used for monitoring water quality, tracking environmental changes, or something else entirely, this system is sure to provide accurate and reliable data, thanks to its well-designed power management setup. The DS18B20 temperature sensor is connected to GPIO4 of the ESP32. This connection uses a 4.7 k Ω pull-up resistor. The resistor helps the DS18B20 temperature sensor communicate with the ESP32 in a way [6]. The pH sensor gets its power from the 5 V rail. The pH sensor is connected to GPIO34. There is a voltage divider between the sensor and GPIO34. This voltage divider ensures the output voltage from the sensor does not go above the 3.3 V limit of the ESP32's ADC. The turbidity sensor also gets its power from the 5 V supply. The turbidity sensor is connected to GPIO35. This connection lets the ESP32 measure the number of particles suspended in water using the turbidity sensor. The TDS sensor is connected to GPIO32. The TDS sensor uses this connection to measure the number of dissolved solids in water. The TDS sensor shares its power and ground connections, with the DS18B20 temperature sensor, the pH sensor and the turbidity sensor [2] [3]. The circuit connections between the ESP32 microcontroller and the various sensors are shown in Figure 4.

ADVANTAGES

- Continuously measures water quality parameters and provides early warnings of potential biological hazards, enabling faster response to contamination [2][9].
- Transmits data wirelessly to a ground station and features a waterproof, compact design that can be integrated with autonomous UAVs for monitoring remote and inaccessible waterbodies [10].
- The modular design supports future enhancements such as UAV integration, long-range communication (LoRa), and machine learning-based water quality prediction [4].

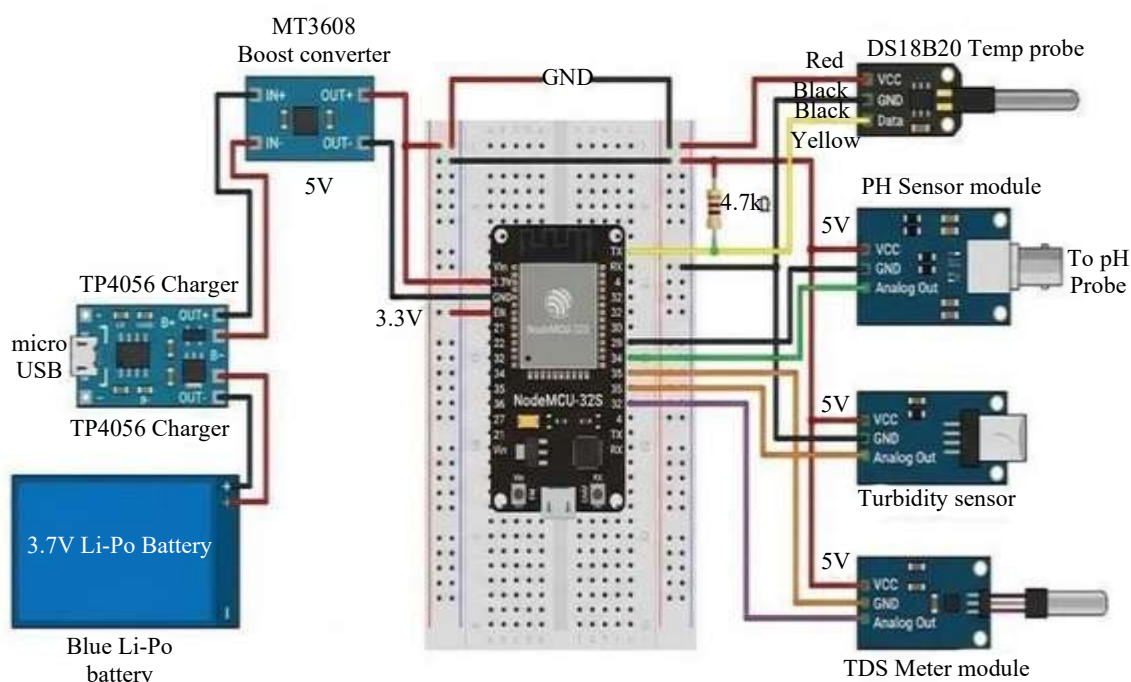


Figure 4. Circuit diagram of aquasentinel.

Table 3. Experimental observations of system components.

Parameter	Observation
Temperature sensor	Stable operation
pH sensor	Continuous monitoring
Turbidity sensor	Fast response
TDS sensor	Stable readings
Wi-Fi	Successful real-time transmission
Battery	Continuous operation during testing
Waterproof enclosure	No water ingress observed

RESULT

The prototype successfully demonstrated stable operation throughout the testing period. Sensor measurements were transmitted to the ground station with negligible communication delay under laboratory conditions. The integrated ESP32 maintained uninterrupted acquisition of all sensor parameters, demonstrating the feasibility of continuous freshwater monitoring. The testing outcomes presented in Table 3 demonstrate the reliable operation of the sensing, communication, power, and enclosure modules.

CONCLUSION

This study presented AquaSential, a portable IoT-enabled freshwater quality monitoring platform that combines low-cost sensing, wireless communication, and future UAV deployment capability. Experimental evaluation demonstrated successful integration of temperature, pH, turbidity, and TDS sensing with real-time data transmission through the ESP32 platform. The proposed threshold-based classification approach provides early identification of potentially hazardous water conditions while maintaining a lightweight and energy-efficient design suitable for field deployment.

The major contributions of this work include the development of a modular low-cost monitoring architecture, wireless real-time environmental surveillance, and a UAV-ready platform capable of monitoring inaccessible freshwater bodies. Future work will focus on integrating autonomous UAV navigation, machine-learning-based water quality prediction, cloud-based data analytics, and long-term field validation under diverse environmental conditions.

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