https://doi.org/10.65646/3cp3es20dpg8n146

A Low-Cost IoT-Enabled Buoy System for Real-Time Detection and Ultrasonication-Based Mitigation of Harmful Algal Blooms in Sri Lankan Freshwater Bodies

RMPKD Gunawardhana
Department of Electrical and Computer Engineering
Faculty of Engineering Technology
The Open University of Sri Lanka, Nawala, Nugegoda
s19003503@ousl.lk

Pamoda Koggala
Department of Electrical and Computer Engineering
Faculty of Engineering Technology
The Open University of Sri Lanka, Nawala, Nugegoda
kmkog@ou.ac.lk

MSS Perera
Department of Electrical and Computer Engineering
Faculty of Engineering Technology
The Open University of Sri Lanka, Nawala, Nugegoda
msper@ou.ac.lk

Abstract— **Harmful algal blooms (HABs) are an increasing threat to drinking-water supply, fisheries and aquatic ecosystems in Sri Lankan reservoirs and urban lakes, yet detection in the country still relies almost entirely on manual sampling and laboratory analysis. This paper presents the design, implementation and experimental evaluation of a low-cost, solar-powered buoy platform that combines real-time water-quality sensing with a non-chemical mitigation mechanism. The buoy integrates pH, turbidity and temperature sensors with a custom-built chlorophyll-a fluorometer built around a 470 nm excitation LED and an OPT101 photodiode, all interfaced to an ATmega328P microcontroller. Sensor data are relayed over a 433 MHz LoRa link to a gateway and displayed on a cloud dashboard, while an ultrasonic transducer array driven by an IR2110/IRF640N H-bridge provides physical algae suppression. Laboratory trials using Beira Lake water showed that algae-contaminated samples produced pH values of 7.20–7.99 against 6.63–6.69 for clear water, and fluorometer readings of 70–78 ADC counts against 58–65 ADC counts for clear water. A three-day ultrasonication trial produced only a modest reduction in turbidity, pH and fluorescence, and LoRa communication remained stable over a 1 km outdoor test link. The results confirm that an affordable sensor–communication–mitigation platform of this kind is technically feasible for early-warning HAB monitoring in resource-limited settings, while also identifying the fluorometer sensitivity and ultrasonic power density as the main areas requiring further development before field deployment.**

I. Introduction

Lakes, reservoirs and rivers supply most of Sri Lanka's drinking water, irrigation and inland fisheries, and their condition is increasingly threatened by harmful algal blooms (HABs). Nutrient loading from agricultural runoff, untreated wastewater and rapid urbanisation, combined with warm tropical temperatures and slow-moving water, creates conditions that favour toxin-producing cyanobacteria [1]. Blooms have been documented in Beira Lake, Kala Wewa and Parakrama Samudraya, with reported consequences including fish kills, discolouration and deterioration of raw water quality for downstream treatment plants.

Present HAB surveillance in the country is largely reactive. Water samples are collected manually and sent to a laboratory for microscopy or toxin assays, a process that is reliable but too slow to support an early warning response; by the time results are available a bloom may already be well established. Several biological and chemical control techniques have been studied at laboratory scale, but no low-cost, continuously operating detection-and-response system is yet in routine use for Sri Lankan water bodies. Critically, no existing platform integrates real-time, multi-parameter water-quality sensing with an automated, non-chemical mitigation response within a single low-cost, field-deployable unit for Sri Lankan reservoirs; existing efforts address detection and mitigation as separate, standalone problems. This paper addresses that integration gap directly.

This paper reports on a fixed buoy prototype developed to close that gap. The buoy combines three water-quality sensors, a purpose-built low-cost chlorophyll-a fluorometer, an automatic ultrasonic

mitigation unit, and a long-range wireless link to a cloud dashboard, all powered from a solar-charged battery. The specific objectives addressed in this work were to (i) identify water-quality parameters that correlate with bloom conditions, (ii) build a waterproof buoy housing capable of carrying the sensing and mitigation hardware, (iii) develop and characterise a low-cost fluorometer for chlorophyll-a estimation, (iv) implement a threshold-triggered ultrasonic control loop for non-chemical algae suppression, and (v) establish a LoRa-based telemetry link to a remote dashboard for continuous monitoring.

II. Related Work

A. Detection and Monitoring Approaches

Manual sampling followed by ELISA or liquid-chromatography assays remains the reference method for confirming cyanotoxin presence, but it is slow, costly and unsuitable for continuous surveillance [4], [5]. Satellite-based remote sensing (MODIS, Sentinel-2, Landsat) enables large-area chlorophyll mapping, but its coarse temporal resolution and sensitivity to cloud cover limit its usefulness for small inland reservoirs [6], [7]. In-situ sensor platforms — typically fixed buoys or barges carrying multiparameter sondes and fluorometers — provide the high-frequency, continuous data needed for early warning, at the cost of biofouling and periodic recalibration [8]. Optical fluorometry is widely used to estimate algal biomass from chlorophyll-a fluorescence around 685 nm and can be extended to phycocyanin detection for cyanobacteria-specific identification, although species-dependent variability means readings must be interpreted as relative rather than absolute concentrations unless independently calibrated [9], [10].

B. Mitigation Techniques

Chemical algaecides act quickly but risk non-target toxicity and sudden toxin release from lysing cells, making them unattractive for sustainable long-term use [3]. Biological methods such as bio-manipulation or bacterial competition are environmentally benign but slow and difficult to predict. Physical methods, including aeration, UV exposure and ultrasonication, avoid chemical residues altogether; ultrasonication in particular disrupts the gas vesicles that keep cyanobacteria buoyant and can rupture cell walls through acoustic cavitation [14], [15]. A field trial at the Per Aru reservoir in Sri Lanka reported 76–85 % algal removal near a 24–58 kHz transducer, with effectiveness decreasing sharply with distance and depth [11], a finding that directly informed the transducer placement strategy adopted in this work. Unlike prior mitigation studies such as the Per Aru trial [11], which evaluated ultrasonication as a standalone intervention without continuous sensing or remote telemetry, the platform presented here closes the loop by triggering mitigation automatically from real-time sensor thresholds and reporting both sensing and mitigation status over a single wireless link.

III. System Design

A. Architecture Overview

The platform is organised as a sensing-and-mitigation buoy node, a LoRa gateway, and a cloud dashboard, as shown in Fig. 1. On the buoy, an ATmega328P microcontroller polls the pH, turbidity, temperature and fluorescence sensors at regular intervals and compares the readings against fixed thresholds associated with bloom conditions. When a threshold is exceeded, the microcontroller activates the ultrasonic driver for a fixed 5–10 minute period, logs

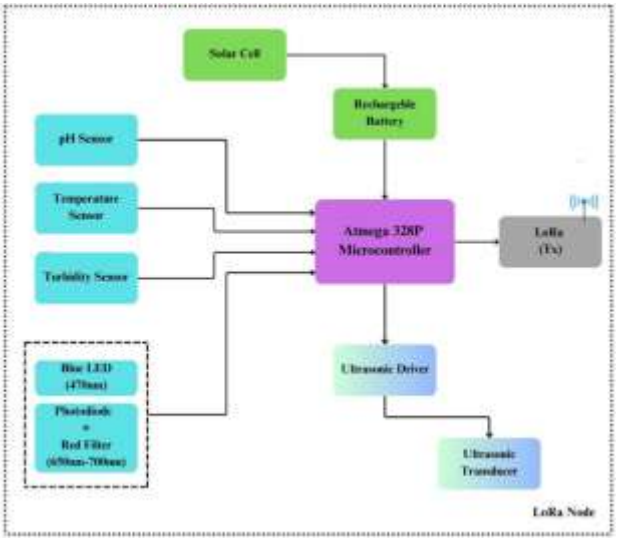


Fig. 1. Block-level architecture of the proposed HAB monitoring and mitigation buoy.

B. Hardware Selection

Component selection was driven by cost, local availability and power budget. Table I lists the principal hardware used in the buoy node. The ultrasonic subsystem, comprising an IR2110 gate driver and an IRF640N H-bridge, was sized to supply approximately 60 V to the transducer array, which was found to be sufficient to generate visible cavitation during bench testing.

TABLE I. KEY HARDWARE COMPONENTS

Component	Model	Role
Microcontroller	ATmega328P	Sensor polling and threshold logic
Temperature sensor	DS18B20	Waterproof 1-Wire temperature (±0.5 °C)
pH sensor	pH0452C	Analogue pH probe
Turbidity sensor	MD0591	Optical suspended-solids sensor
Excitation LED	470 nm blue	Chlorophyll-a excitation source
Photodetector	OPT101	Fluorescence sensing with red filter

Ultrasonic transducer	MD0728, 40 kHz	Physical algae disruption
Gate driver / MOSFET	IR2110 / IRF640N	H-bridge transducer drive
Radio module	SX1278 (433 MHz)	Long-range LoRa telemetry
Battery	4×18650 Li-ion, 4S BMS	Energy storage (14.8 V nominal)

The ATmega328P was selected for its low cost, wide local availability, and sufficient I/O and ADC resolution for the sensor suite, avoiding the added cost and power draw of more capable microcontrollers unnecessary for this application. The 470 nm excitation wavelength and OPT101 photodetector were chosen because chlorophyll-a exhibits strong blue-light absorption with red fluorescence emission near 685 nm, allowing a simple LED–photodiode pair (rather than a laser or spectrometer) to achieve adequate excitation–emission separation at low cost. A 40 kHz drive frequency was selected for the ultrasonic transducer array based on the 24–58 kHz range reported effective for cyanobacterial disruption in the Per Aru field trial [11], balancing cavitation effectiveness against transducer cost and availability.

C. Fluorometer and Ultrasonication Design

Chlorophyll-a absorbs strongly in the blue region and re-emits a fraction of that energy as red fluorescence near 685 nm. The fluorometer therefore excites the water sample with a 470 nm LED and collects the emitted light with an OPT101 photodiode placed behind a red optical filter that rejects the excitation wavelength. The weak photodiode signal is amplified and passed through an RC filter before being digitised by the microcontroller's ADC. The excitation and detection paths are physically separated inside an opaque tube to minimise direct LED leakage and ambient-light interference, which was found during bench testing to be the dominant source of measurement noise.

The ultrasonic subsystem generates a 40 kHz drive signal from the microcontroller's PWM output, which is boosted by the H-bridge driver to excite the transducer array. Multiple transducers were connected in parallel to increase the treated area, following the observation from prior field work that ultrasonic effectiveness falls off quickly with distance from the source [11].

D. Communication and Power

A 433 MHz LoRa link was chosen over Wi-Fi or cellular connectivity because reservoirs and lakes in Sri Lanka are frequently outside reliable network coverage; LoRa's long range and low power draw are well matched to a battery-powered, remotely sited node. The buoy is powered by a 4×18650 lithium-ion pack (14.8 V nominal, 26.64 Wh) charged through a 4S 10 A battery-management module from four parallel-connected 5 V solar cells, with buck converters providing regulated 12 V, 5 V and 3.3 V rails for the ultrasonic driver, sensors and logic circuitry respectively.

IV. Implementation

The ATmega328P was clocked with a 16 MHz crystal and powered from a regulated 5 V rail; the sensor interface and driver circuits were first prototyped on a custom two-layer PCB before being transferred to the final enclosure. The pH and turbidity sensors were calibrated against standard buffer solutions and side-by-side comparisons of clear and algae-laden water; the pH sensor showed a small systematic offset of roughly −1 pH unit relative to the buffer references, which was corrected in software, while the temperature sensor tracked a reference thermometer to within about ±2 %.

The fluorometer went through two design iterations: an initial open black-box configuration used to verify the LED and photodiode circuits independently, followed by a sealed, tube-based optical structure that enclosed both the excitation and detection paths to exclude ambient light. This second iteration produced markedly more repeatable readings and was carried into the final prototype.

All subsystems — sensor interface, fluorometer, ultrasonic driver, LoRa node, power management and battery — were finally integrated into a single waterproof enclosure mounted on a buoyancy ring, with the ultrasonic transducer suspended beneath the platform and the solar panel fixed to the enclosure lid (Fig. 2). Cable glands and sealed wiring were used at all enclosure penetrations to protect the electronics during prolonged water contact.



Fig. 2. Fully assembled buoy prototype with integrated sensing, communication, power and ultrasonication subsystems.

V. Results and Discussion

A. Sensor and Fluorometer Response

The prototype was evaluated using water drawn from Beira Lake alongside groundwater used as a

clear-water reference. Across repeated measurements taken at different times of day, algae-contaminated samples consistently read higher in pH (7.20–7.99) than the clear-water reference (6.63–6.69), which is plausibly consistent with elevated photosynthetic CO_2 drawdown in the presence of algae, although this mechanism was not independently verified via direct CO_2 or biomass measurement and should be treated as a hypothesis rather than a confirmed explanation. Turbidity sensor output was inversely related to particle load, with algae samples producing lower output voltages (3.45–3.86 V) than clear water (3.64–3.91 V) as expected from light scattering by suspended cells.

The fluorometer produced ADC values of 70–78 for algae-contaminated water compared with 58–65 for clear water, corresponding to an average separation of roughly 20%, as summarised in Table II. This is sufficient to distinguish contaminated from clear water, but represents a comparatively narrow margin and may result in limited sensitivity to low or early-stage blooms, particularly before the algal concentration reaches a sufficiently detectable level. Because the unit was not calibrated against a certified laboratory fluorometer, the ADC values should be interpreted as relative fluorescence intensity rather than absolute chlorophyll-a concentration.

TABLE II. SENSOR RESPONSE FOR ALGAE-CONTAMINATED VS. CLEAR WATER

Parameter	Algae water	Clear water
pH	7.45 ± 0.29	6.66 ± 0.02
Turbidity output (V)	3.62 ± 0.16	3.86 ± 0.09
Fluorometer (ADC counts)	70–78 (avg. 74.0)	58–65 (avg. 61.5)

B. Ultrasonication Performance

The ultrasonic transducers were verified using a water-droplet agitation test before being applied to algae-contaminated samples over a three-day exposure period, with pH, turbidity and fluorometer readings logged daily (Table III). All three parameters declined gradually — pH from 7.85 to 7.70, turbidity from 438 to 425 ADC counts, and fluorescence from 78 to 73 ADC counts — but no visually obvious reduction in algal concentration was observed over the same period. This is broadly consistent with the distance-dependent effectiveness reported for the Per Aru reservoir trial [11]: at bench scale, the acoustic power density delivered to the sample volume was evidently too low, and the exposure too short, to achieve substantial cell disruption. Higher transducer power, closer transducer-to-sample coupling and longer treatment cycles are likely needed before ultrasonication alone can be relied on for meaningful in-field bloom suppression.

TABLE III. WATER QUALITY DURING THREE-DAY ULTRASONIC TREATMENT

Day	pH	Turbidity (ADC)	Fluorometer (ADC)
1 (before)	7.85	438	78
2	7.78	432	76
3	7.70	425	73

C. Communication and Power Budget

The LoRa link was tested outdoors between the buoy node and a gateway placed approximately 1 km away. All transmitted packets — containing pH, temperature, turbidity and fluorometer readings — were received without observable corruption or loss during the test window, confirming LoRa as a viable telemetry option for reservoirs beyond the reach of Wi-Fi or cellular coverage. RSSI and SNR were not logged in this trial and are recommended for future characterisation under varying weather and foliage conditions.

Power analysis showed that the sensing, logic and communication load draws approximately 0.5–1 W continuously, giving roughly 20–22 hours of autonomy from the 22.64 Wh usable battery capacity in low-power sensing mode. The ultrasonic subsystem, by contrast, draws 18–20 W, limiting continuous ultrasonication to about one hour per full charge. The 5 V, 200 mA solar array recovers approximately 5 Wh per day under typical sunlight, which is adequate to sustain continuous low-power monitoring but not to fully offset frequent, extended ultrasonication cycles — a trade-off that will need to be reflected in the threshold and duty-cycle logic for any long-term field deployment.

D. Limitations

Three limitations qualify the results reported here. First, the fluorometer was tested only against a small number of grab samples rather than a continuous 24-hour cycle, so the relationship between ADC reading and bloom severity is not yet well resolved. Second, the ultrasonication trial ran for only three days at bench scale and under a fixed transducer power, which is short relative to typical bloom life cycles and insufficient to draw firm conclusions about field mitigation effectiveness. Third, the system has not yet been validated through extended outdoor deployment, so biofouling, wave action and long-term power balance remain open questions.

VI. CONCLUSION AND FUTURE WORK

This work demonstrated a low-cost, solar-powered buoy that combines pH, turbidity, temperature and chlorophyll-a fluorescence sensing with LoRa telemetry and ultrasonic mitigation for harmful algal bloom management in Sri Lankan water bodies. Laboratory testing with Beira Lake water confirmed that the sensor suite can distinguish algae-contaminated water from clear water, that LoRa

communication is reliable over kilometre-scale distances, and that the ultrasonic subsystem operates correctly, although its bloom-suppression effect at the tested power level was modest. Taken together, the results support the feasibility of an affordable monitoring-and-mitigation platform for developing-country deployment, while pointing to fluorometer sensitivity, ultrasonic power density and long-term field validation as the priority areas for continued development.

To the authors' knowledge, this is among the first reported Sri Lankan platforms to combine real-time multi-parameter water-quality sensing, long-range LoRa telemetry, and automated non-chemical (ultrasonic) mitigation within a single low-cost, solar-powered buoy unit, closing the loop between detection and response that prior standalone studies have addressed separately.

Future work will focus on improving fluorometer sensitivity through better optical filtering and higher-grade photodetectors, incorporating a phycocyanin channel for cyanobacteria-specific identification, adding GPS for multi-buoy deployment mapping, applying machine-learning models to historical sensor data for predictive bloom alerts, and conducting extended in-reservoir trials to validate power budgeting and mitigation performance under real environmental conditions.

REFERENCES

[1] L. P. Jayatissa, E. I. L. Silva, J. McElhiney, and L. A. Lawton, "Occurrence of toxigenic cyanobacterial blooms in freshwaters of Sri Lanka," Syst. Appl. Microbiol., vol. 29, no. 2, pp. 156–164, 2006.

[2] M. K. Wimalasena, H. Niroshika, and S. Wasana, "Biological approaches used to control the algal bloom formation in aquatic environments: A review," ResearchGate, 2023.

[3] H. M. Anabtawi, W. H. Lee, A. Al-Anazi, M. M. Mohamed, and A. Aly Hassan, "Advancements in biological strategies for controlling harmful algal blooms (HABs)," Water, vol. 16, no. 2, p. 224, 2024.

[4] I. Y. Massey, P. Wu, J. Wei, J. Luo, P. Ding, H. Wei, and F. Yang, "A mini-review on detection methods of microcystins," Toxins, vol. 12, no. 10, p. 641, 2020.

[5] S. Singh, A. Srivastava, H.-M. Oh, C.-Y. Ahn, G.-G. Choi, and R. K. Asthana, "Recent trends in development of biosensors for detection of microcystin," Toxicon, vol. 60, no. 5, pp. 878–894, 2012.

[6] R. P. Stumpf, T. W. Davis, T. T. Wynne, J. L. Graham, K. A. Loftin, T. H. Johengen, D. Gossiaux, D. Palladino, and A. Burtner, "Challenges for mapping cyanotoxin patterns from remote sensing of cyanobacteria," Harmful Algae, vol. 54, pp. 160–173, 2016.

[7] R. M. Khan, B. Salehi, M. Mahdianpari, F. Mohammadimanesh, G. Mountrakis, and L. J. Quackenbush, "A meta-analysis on harmful algal bloom (HAB) detection and monitoring: A remote sensing perspective," Remote Sens., vol. 13, no. 21, p. 4347, 2021.

[8] B. D. Johnston, K. M. Finkelstein, S. R. Gifford, M. D. Stouder, E. A. Nystrom, P. R. Savoy, J. J. Rosen, and M. B. Jennings, "Evaluation of sensors for continuous monitoring of harmful algal blooms in the Finger Lakes region, New York, 2019 and 2020," U.S. Geological Survey Scientific Investigations Report, 2024.

[9] Deltares, "Evaluation of fluorometers for the in situ monitoring of chlorophyll and/or cyanobacteria," Technical Report.

[10] E. Bertone, A. Chuang, M. A. Burford, and D. P. Hamilton, "In-situ fluorescence monitoring of cyanobacteria: Laboratory-based quantification of species-specific measurement accuracy," Harmful Algae, vol. 87, p. 101625, 2019.

[11] T. Thurkka, N. Anoja, T. Mikunthan, and A. C. Thavaranjit, "Removal of algae by sonicator: A case study from Per Aru reservoir," AGRIEAST: J. Agric. Sci., vol. 14, no. 2, p. 1, 2020.

[12] D. H. Kwon, S. M. Hong, A. Abbas, J. Pyo, H.-K. Lee, S.-S. Baek, and K. H. Cho, "Inland harmful algal blooms (HABs) modeling using internet of things (IoT) system and deep learning," Environ. Eng. Res., vol. 28, no. 1, 2022.

[13] C.-K. Chen and Y.-C. Chen, "Detection of chlorophyll fluorescence as a rapid alert of eutrophic water," Water Supply, vol. 22, no. 3, pp. 3508–3518, 2021.

[14] J. Park, J. Church, Y. Son, K.-T. Kim, and W. H. Lee, "Recent advances in ultrasonic treatment: Challenges and field applications for controlling harmful algal blooms (HABs)," Ultrason. Sonochem., vol. 38, pp. 326–334, 2017.

[15] J. Park, Y. Son, and W. H. Lee, "Variation of efficiencies and limits of ultrasonication for practical algal bloom control in fields," Ultrason. Sonochem., vol. 55, pp. 8–17, 2019.