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Internet of Things-Based Environmental Health Monitoring Information System: Implementation and Evaluation on Batik Wastewater

Sekar Harum Kurniasih[1]*, Rosidin[2]
[1]Information Systems Study Program, STMIK IKMI Cirebon, Cirebon, Indonesia
Corresponding Author: sekarharumk@gmail.

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ABSTRACT

Batik wastewater contains synthetic dyes and chemicals that may endanger workers and nearby communities, so continuous monitoring is needed. This study developed and evaluated a prototype Internet of Things (IoT) based environmental health monitoring information system for batik wastewater, using an ESP32 microcontroller, pH and Total Dissolved Solids (TDS) sensors, ThingSpeak, and a local web dashboard. A prototype development and descriptive functional evaluation design was used. One batik wastewater sample was observed for about 30 minutes, producing 100 pH entries and 100 TDS entries, together with device operational logs and interface documentation. The sensors were not calibrated, so the readings describe variation only: pH ranged from 7.59 to 11.61 (mean 8.77) and TDS from 0 to 695.36 ppm (median 652.28 ppm). The log contained 228 identifiable status messages, of which 38 (16.7%) indicated successful transmission to ThingSpeak and 190 indicated failure; these are log messages, not the 100 data entries, so the online record was incomplete. Code -401 accounted for 186 failures, and the upload interval, which was probably shorter than the 15 second limit of free ThingSpeak accounts, is the most likely cause, although this was not tested. The prototype fulfilled basic data acquisition and visualization. Longer upload intervals or bulk updates, local buffering with resending, validation rules, and calibration against reference instruments are needed before the data can support environmental health information systems and early warning.

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INTRODUCTION

The batik industry is an important part of Indonesia's economy and cultural heritage, but its production processes also raise environmental health concerns. Dyeing, coloring, wax removal (*pelorodan*), and washing generate wastewater with diverse physical and chemical characteristics. A study in the Ulu Gedong batik center, Jambi, found wastewater samples with a pH of 2.3 and chemical and biological oxygen demand far above the quality standards, while most craftspeople lacked the knowledge and funds to treat their waste (Maryani et al., 2023). Dyes and chemicals used in batik production have also been associated with skin disorders, reduced lung capacity, and visual impairment among workers (Matin et al., 2022). Azo dyes, which are widely used in the textile industry and its derivative products, are linked to skin sensitization, allergic reactions, genotoxic effects, and cancer risk (Ramamurthy et al., 2024).

Polluted water can also cause diarrhea, respiratory illness, and skin diseases in exposed communities (Nishan et al., 2024). Monitoring the characteristics of batik wastewater is therefore part of environmental health efforts, which in Indonesia are regulated, among others, by Minister of Health Regulation No. 2 of 2023 on environmental health (Kementerian Kesehatan Republik Indonesia, 2023). Strongly acidic or alkaline effluent can also irritate the skin and eyes of workers who handle it and can harm aquatic organisms, which is why pH is one of the two parameters monitored here. [Authors to insert: number of batik SMEs or centres in Cirebon and Indonesia and their wastewater practices, from BPS or provincial industry data.]

Conventional water quality monitoring generally relies on sampling and laboratory measurement at specific times. This approach provides accurate information about a sample at the time of measurement, but changes that occur between measurements may go unobserved. From a health informatics perspective, such data gaps limit the ability of environmental health officers to detect risky changes early. A review of 74 studies on environmental health information systems showed that digital technologies such as the Internet of Things (IoT), smart devices, and predictive analytics can generate actionable information and support proactive decisions on environmental health risks, although most evidence comes from high-income countries and low- and middle-income countries still face resource and interoperability constraints (Masimula et al., 2026). IoT integrates sensors, microcontrollers, communication networks, data storage, and digital interfaces so that readings can be transmitted and presented periodically (Laha et al., 2022; Murti et al., 2024). Nishan et al. (2024) developed an IoT-based industrial wastewater monitoring system integrating several water quality parameters, and Forhad et al. (2024) applied real-time monitoring in water treatment plants. The intended users are district environmental health officers, sanitarians at community health centres (puskesmas), whose information systems are still fragmented (Aisyah et al., 2025), and batik SME owners. They would use the data to decide when to take laboratory samples, which production stage to inspect, and how to adjust waste handling.

Potential of hydrogen (pH) and Total Dissolved Solids (TDS) are often used as initial indicators in such monitoring systems. pH indicates the acidity or alkalinity of a solution, whereas TDS reflects the amount of dissolved substances measured in water, usually expressed in parts per million (ppm) (Murti et al., 2024; T.R. et al., 2024). These two parameters cannot capture all types of pollutants, such as dyes, organic matter, or heavy metals, and cannot be the sole basis for judging whether wastewater complies with quality standards. However, sudden changes in pH or TDS can serve as early signals that trigger more complete sampling and laboratory testing. Reported pH of batik wastewater varies widely with the process and dye used, from strongly acidic values of 2.3 in Jambi (Maryani et al., 2023) and 4.32 in a raw wastewater sample used for treatment trials (Rahmadyanti & Febriyanti, 2020) to near neutral values of about 7.2 in the influent of a wastewater treatment plant at a batik center (Triwiswara, 2019), and a chemical oxygen demand of 12,000 mg/L has been reported in untreated batik wastewater (Rahmadyanti & Febriyanti, 2020). This variability makes pH a practical first indicator, whereas TDS gives a quick estimate of dissolved ions. For a health relevant assessment, further parameters such as temperature, conductivity, colour, and chemical oxygen demand would be needed; temperature and conductivity can be measured with low cost modules, whereas colour and chemical oxygen demand generally require laboratory analysis.

The success of an IoT-based monitoring information system depends not only on the sensors' ability to produce readings, but also on measurement reliability, data transmission completeness, and clarity of information presentation. Abu Bakar et al. (2025) emphasized sensor calibration to support measurement reliability, and Leischner et al. (2026) showed the importance of comparing low-cost sensors with reference monitoring stations. Affandi et al. (2026) developed an ESP32-based system that integrates pH, TDS, and turbidity sensors and presents data through a website, while Ariyani et al. (2026) and Zafi et al. (2024) applied ESP32 and TDS sensors for water quality monitoring connected to online services. Other studies extended monitoring with wireless sensor networks, multiparameter dashboards, and fuzzy logic classification (Afif et al., 2026; Axiotidis et al., 2024; Insani & Arifin, 2025; López-Munoz et al., 2024). In the Indonesian context, Ujianti et al. (2025) implemented IoT-based water quality monitoring in coastal areas with historical data storage. Most of these studies emphasize sensor accuracy or dashboard functionality; to our knowledge, few report the proportion of readings that actually reach the online platform, so quantitative transmission success rates are scarce and the completeness found in this study is difficult to benchmark.

These studies demonstrate the technical feasibility of IoT for water quality monitoring. However, few studies have implemented and evaluated such systems on wastewater from small-scale batik industries from an environmental health informatics perspective, that is, by assessing not only device functions but also the completeness and fitness for use of the data for health stakeholders. Evaluations that distinguish locally read data from data actually available on the online platform are also rarely reported, even though this gap determines whether a system can support early risk detection. The novelty of this study lies in this data-completeness-oriented evaluation in a batik wastewater setting. This study therefore implemented an ESP32-based pH and TDS monitoring information system integrated with ThingSpeak and a local web dashboard for batik wastewater. The objectives were to (1) implement an ESP32-based pH and TDS monitoring system for batik wastewater; (2) integrate data transmission and storage through ThingSpeak and information presentation through a local web dashboard; and (3) evaluate the variation in sensor readings and the completeness of data transmission as a basis for assessing the system's feasibility to support environmental health information systems. The contribution is implementational and evaluative; pH and TDS values are treated as initial monitoring indicators and are not used to infer absolute sensor accuracy or the wastewater's compliance with quality standards. The findings are expected to benefit environmental health officers by showing what a low cost monitoring prototype can and cannot support, batik SME owners by indicating how simple self monitoring could be organised, and local governments by identifying the data quality requirements that should be met before IoT monitoring is adopted.

METHOD

This study used an prototype development and descriptive functional evaluation approach, in the form of an engineering case study, to design and evaluate a prototype IoT-based environmental health monitoring information system for batik wastewater. The evaluation focused on four stages of the data flow, namely sensor reading, presentation of measured values, data transmission to the online platform, and data visualization as charts and history. This approach is consistent with IoT-based water quality monitoring systems that

integrate sensors, processing devices, and digital interfaces (Affandi et al., 2026; Nishan et al., 2024). The study evaluated prototype functions and the feasibility of the data flow, not the effectiveness of waste treatment, direct health impacts, or the wastewater's compliance with quality standards. From an environmental health information system perspective, the data flow was assessed against three data quality dimensions commonly used in health information systems (Ghalavand et al., 2024; Syed et al., 2023). Completeness was defined as the number of successful uploads divided by the number of identifiable upload attempts in the operational log. Timeliness, the delay between a reading and its availability online, was not assessed in this study. Validity was defined as the share of readings that are physically implausible for the measured medium, such as a TDS of 0 ppm in wastewater.

The authors built the prototype and programmed the ESP32 in the Arduino IDE; the components used in the final build are described below. The system used an ESP32 as the controller, pH and TDS sensors as reading devices, a Wi-Fi connection for data communication, ThingSpeak for online storage and visualization, and a local web dashboard at the development address localhost:3000. The ESP32 was chosen for its processing capability and Wi-Fi connectivity at low cost, making it suitable for small-scale batik centers with limited resources. [Authors to complete: pH sensor and module model, TDS sensor and module model, power supply, ADC resolution and reference voltage, sampling interval, and upload interval.] [Authors to complete: location, date, production stage, volume, and temperature of the wastewater sample, and whether the probes were placed in a container or in the effluent stream.] The function of each component is summarized in Table 1.

Table 1. System components and their functions

Component	Function
ESP32	Reads sensor outputs, runs the program, and transmits data via Wi-Fi
pH sensor	Produces readings to estimate the acidity or alkalinity of the sample
TDS sensor	Produces an estimate of dissolved solids displayed in ppm
ThingSpeak	Receives, stores, and visualizes sensor data successfully sent to the configured channel
Local web dashboard	Displays pH and TDS values, charts, and data history through a web interface

The system workflow begins with the pH and TDS sensors reading the sample. The ESP32 receives the sensor outputs and processes them according to the embedded program. Readings are displayed on the Arduino IDE Serial Monitor, and the program transmits data to ThingSpeak via Wi-Fi. Data successfully received by the platform can be used for online monitoring, while the local web dashboard presents values, charts, and history according to the data available to that interface. Figure 1 shows the conceptual flow of the system; the values shown in the illustration are examples, not observation data. The program logic is summarized in the pseudo code below.

Pseudo code of the ESP32 program (summary of the workflow above):

1. Connect to the Wi-Fi network.
2. Read the pH and TDS sensors.
3. Print the readings on the Serial Monitor.
4. Attempt to send the readings to ThingSpeak and receive a status code.
5. Print the status code (success or failure code) on the Serial Monitor.

6. Wait for the sampling interval [authors to state the value] and repeat from step 2.

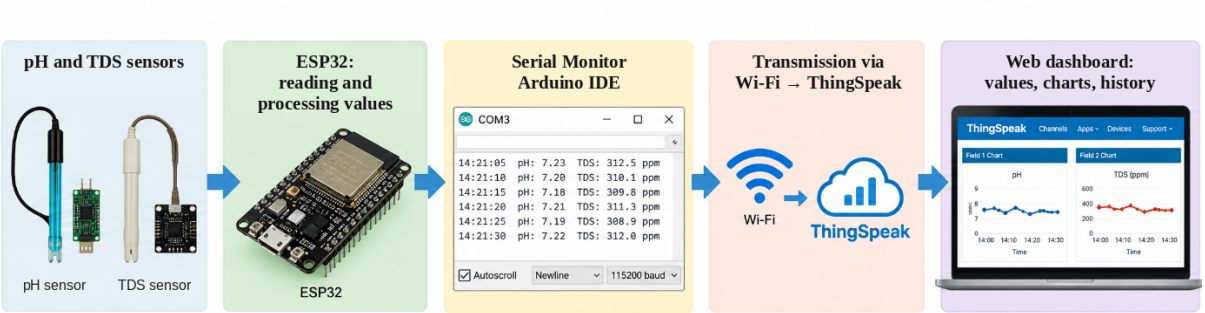


Figure 1. General flow of the IoT-based pH and TDS monitoring information system (conceptual illustration) Values shown in the illustration are examples only and are not observation data.

Local sensor reading and data transmission to ThingSpeak are separate processes. From an environmental health information system perspective, this distinction matters because stakeholders accessing the data online can only see the data that were successfully transmitted. The evaluation therefore separated reading success from transmission success.

The research data consisted of pH and TDS sensor reading records, device operational logs, and visual documentation of the system interface (Table 2). The available records comprised 100 entries each for pH and TDS, obtained in August 2026 over a period of about 30 minutes. These counts indicate the number of records in each dataset but do not by themselves prove that all entries were paired measurements or were successfully sent to ThingSpeak. Timestamps in the records and in Figures 2 and 3 are in UTC; the observation on 18 August 2026 ran from about 04:26 to 04:57 UTC, which corresponds to about 11:26 to 11:57 local time (WIB, UTC+7). [Authors to state: how the 100 entries per parameter were generated (local dashboard database or ThingSpeak export) and how they relate to the 231 reading blocks in the Serial Monitor log.]

Table 2. Data sources and their uses

Data type	Information analyzed	Role in the study
Sensor measurements	pH and TDS values with timestamps	To identify the range and changes in values during testing
System operational log	Local readings and data transmission status	To examine data acquisition and identify transmission problems
Interface documentation	Dashboard views, charts, and data history	To examine visual presentation of information

Data were processed descriptively by examining value ranges, means, medians, standard deviations, time order, record completeness, and consistency with the device operational log. TDS readings of 0 ppm that appeared in some records were not removed because their cause could not be confirmed; they were retained and treated as findings requiring further review. pH and TDS data were compared by time only when timestamp correspondence could be confirmed. Summary statistics excluding the implausible zero values are also reported, and the possible causes of such values (probe out of solution, loose connection, or an ADC reading of 0) are discussed in the Results.

The evaluation was functional and descriptive. The functional evaluation examined whether the ESP32 could read sensor values, display readings on the Serial Monitor, transmit data to ThingSpeak, and present values and visualizations on the dashboard. Data completeness was evaluated by counting successful and failed transmission messages in the operational log and expressing their proportion of all identifiable status messages. Failure messages, including HTTP response -401, were treated as indicating that the corresponding transmission attempt failed, but the cause of failure was not determined from the code alone. Accuracy, absolute error, and relative error were not calculated because no reference values from a comparison instrument or appropriate standard solution were available (Hartanto et al., 2026; Leischner et al., 2026). The evaluation was therefore limited to prototype functions, data presentation, variation in readings, and the observed completeness of data communication. Calibration with standard pH buffer solutions (for example pH 4.01, 6.86, and 9.18) and a TDS reference solution was not performed at this prototype stage, so the readings reported here are raw sensor outputs and should be treated as uncalibrated; calibration and a repeat measurement against a calibrated reference pH meter should be done in the next stage. The TDS module estimates TDS from electrical conductivity, and conductivity depends on temperature (Rebello et al., 2020); temperature was not recorded.

RESULTS AND DISCUSSION

Testing showed that the prototype performed the basic flow of a monitoring information system: it displayed sensor readings on the Arduino IDE Serial Monitor, transmitted data via Wi-Fi to ThingSpeak, and presented pH and TDS values, sensor charts, and data history on the local web dashboard. The results are discussed in terms of sensor readings, data communication completeness, and information presentation, because successful sensor reading does not automatically imply successful data transmission.

The pH data contained 100 entries ranging from 7.59 to 11.61, with a mean of 8.77, a median of 8.46, and a standard deviation of 0.86 (Table 3). The median being lower than the mean indicates a number of high readings pulling the mean upward. Figure 2 shows that pH tended to stay around 8 at the beginning of the observation, rose above 10 in the middle, and then declined with several brief spikes toward the end. Based on the available data, it cannot be confirmed whether this variation was caused by changes in sample characteristics, sensor response, or other measurement factors. The rise from about 8 to above 10 and the later decline within about 30 minutes in a single sample may reflect electrode drift, insufficient stabilization time, or electrical interference rather than real changes in the wastewater, so a repeat measurement with a calibrated reference pH meter is needed.

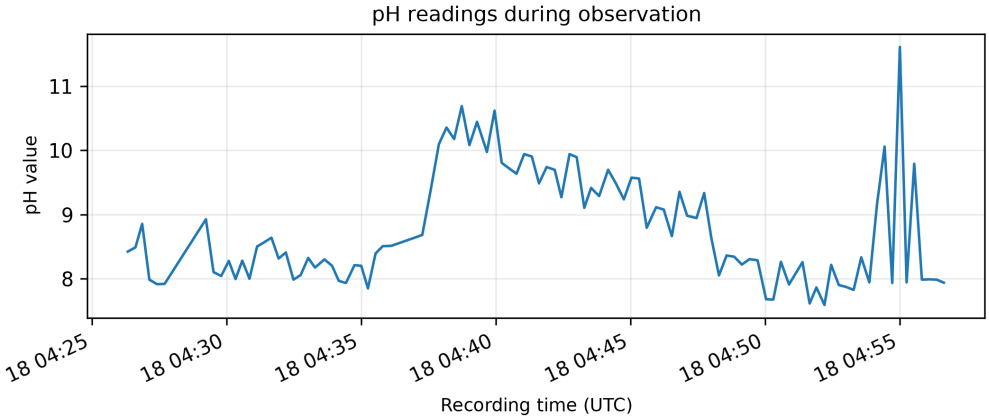


Figure 2. Changes in pH readings during observation Time axis in UTC (local time WIB = UTC+7).

The TDS data also contained 100 entries over the same period. TDS values ranged from 0.00 to 695.36 ppm, with a mean of 628.60 ppm, a median of 652.28 ppm, and a standard deviation of 118.44 ppm. Most values were in the range of about 620–695 ppm, while two entries were 0 ppm (Figure 3). Both zero-value entries were retained in the summary statistics because there was insufficient evidence to determine whether they reflected sample conditions or reading problems. The large standard deviation of TDS was driven by these two entries and by two further transient dips visible in Figure 3, to about 250 ppm near 04:32 UTC and to about 15 ppm near 04:53 UTC, which were also retained. Excluding the two zero values, the mean TDS would be about 641.4 ppm (calculated from the reported mean and number of entries). [Authors to add: median and standard deviation excluding the implausible values.] The zero values may reflect the probe being out of the solution, a loose connection, or an ADC reading of 0, but this could not be verified. TDS modules estimate TDS from electrical conductivity with a fixed conversion factor, commonly about 0.5 to 0.9 depending on the water type, and conductivity changes with temperature (Rebello et al., 2020); temperature was not recorded and the use of temperature compensation could not be confirmed, so the TDS values are uncompensated estimates.

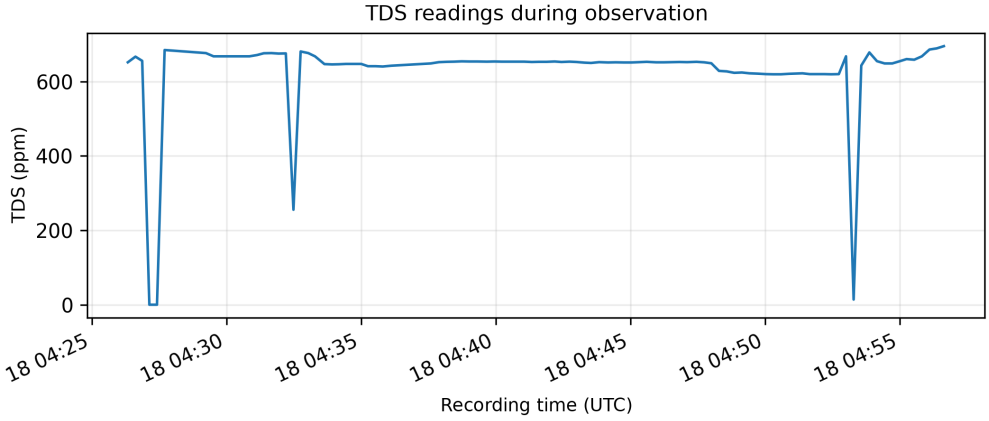


Figure 3. Changes in TDS readings during observation Time axis in UTC (local time WIB = UTC+7).

Table 3. Summary statistics of sensor readings

Statistic	pH	TDS (ppm)
Number of entries	100	100
Minimum	7.59	0.00
Maximum	11.61	695.36
Mean	8.77	628.60
Median	8.46	652.28
Standard deviation	0.86	118.44
Zero-value entries	0	2
Mean excluding zero-value entries	8.77	641.4

Note. The range and standard deviation describe the variation in readings during testing, not sensor accuracy.

From an environmental health perspective, pH readings repeatedly exceeding 10 are the type of event that a monitoring system should flag as a signal for further examination. Batik wastewater can be highly acidic or alkaline depending on the production stage, and such extreme characteristics are associated with risks to workers and the surrounding environment (Maryani et al., 2023; Matin et al., 2022). However, because the sensor had not been calibrated against standard solutions, the value of 11.61 cannot be interpreted as a definitive sample condition. If confirmed with calibrated instruments, such spikes would illustrate the added value of the system, because one-off sampling could easily miss them.

The most important result for the feasibility of the information system is data transmission completeness. The Serial Monitor log contained 231 device reading blocks. In this log, 38 messages indicated successful transmission to ThingSpeak and 190 indicated failure. The failure messages comprised HTTP code -401 (186 times), -301 (3 times), and -304 (once). There were thus 228 identifiable status messages, while the status of the remaining three blocks could not be confirmed (Table 4). In the ThingSpeak Arduino library, code -401 indicates that the point was not inserted, which typically occurs when updates are sent more often than the one update every 15 seconds allowed for free accounts (MathWorks, 2021, 2024), whereas -301 indicates a failed connection and -304 a timeout. If the 231 reading blocks were recorded over a period similar to the 30 minute observation, they correspond to roughly one block every 8 seconds, which is shorter than the 15 second minimum.

Table 4. Status of data transmission to ThingSpeak based on the operational log

Message status	Count	Percentage of identified messages (%)
Transmission succeeded	38	16.7
Transmission failed, code -401	186	81.6
Transmission failed, code -301	3	1.3
Transmission failed, code -304	1	0.4
Total identified messages	228	100.0
Unidentified status	3	–

Note. Percentages are calculated from the 228 identifiable status messages. These figures are message counts in the log, not a measure of transmission success for all CSV entries.

Only about one in six status messages (16.7%) indicated successful transmission, and 97.9% of failures carried code -401. In health information systems, completeness is a data quality dimension that determines whether data can be used for decision-making. If environmental health officers used this system to monitor a batik center remotely, most

readings would not be available to them, and a risky event could occur precisely during a period of missing data. This finding is consistent with a review of environmental health information systems that identified limited infrastructure and interoperability as major barriers in low- and middle-income countries (Masimula et al., 2026), and with studies emphasizing that IoT system performance is determined by the transmission process, not only by the sensors (Axiotidis et al., 2024; López-Munoz et al., 2024). The cause of failure cannot be confirmed from the recorded codes alone, but the upload interval is the most probable cause, because 38 uploads succeeded with the same channel configuration and credentials, which makes those less likely explanations. This explanation was not tested in the present study; a follow up test with an upload interval of at least 15 seconds, or with bulk updates, is needed to show whether completeness improves, together with checks of the network connection and the handling of service responses. Transmission success rates from other ESP32 and ThingSpeak studies were not reported in the studies reviewed here, so the 16.7% completeness cannot yet be benchmarked; future studies should report completeness explicitly.

Table 5 summarizes the data quality indicators defined in the Method.

Table 5. Data quality indicators of the prototype

Dimension	Definition used in this study	Result in this study
Completeness	Successful uploads divided by identifiable upload attempts in the operational log	38 of 228 status messages (16.7%)
Timeliness	Delay between a reading and its availability online	Not assessed
Validity	Share of readings that are physically implausible for wastewater (TDS of 0 ppm)	2 of 100 TDS entries (2.0%); no pH entry outside the 0 to 14 scale

Note. Two further transient TDS dips (about 250 ppm and about 15 ppm) were not counted as implausible because their cause is unknown.

The interface documentation shows that ThingSpeak displayed charts of the data it received (Figure 4), while the local web dashboard provided sensor charts (Figure 5) as well as a summary of pH and TDS values with a historical data menu (Figure 6). Presenting the latest values, trend charts, and measurement history matches the needs of environmental health information system users to monitor current conditions while tracing changes over time (Affandi et al., 2026; Insani & Arifin, 2025). However, the screenshots only support a visual evaluation of the interface and do not prove that all sensor readings were successfully sent to and stored in ThingSpeak.

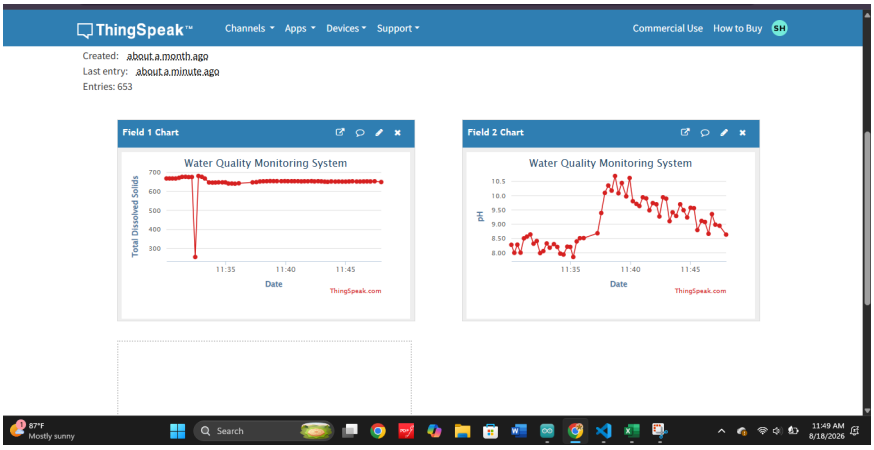


Figure 4. Chart view on ThingSpeak

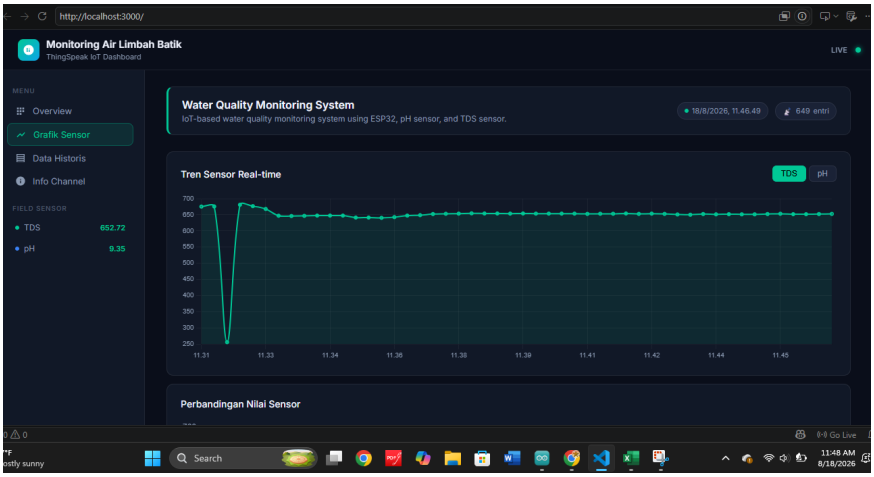


Figure 5. Chart view on the local web dashboard

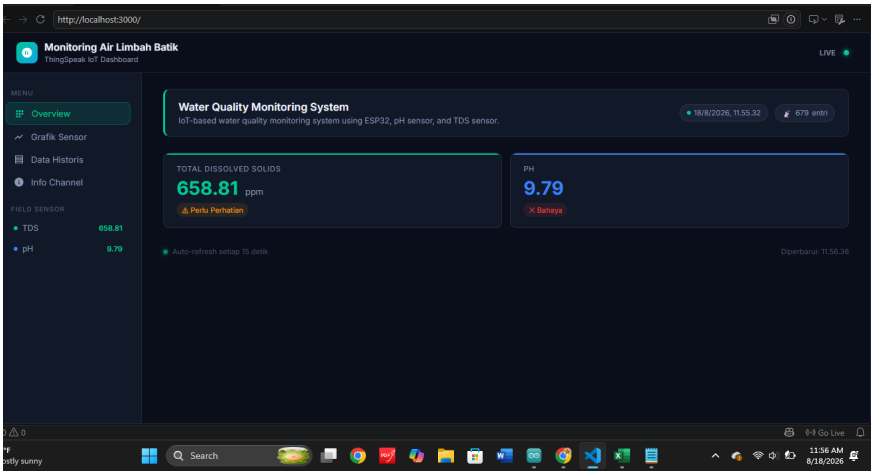


Figure 6. Summary view of the local web dashboard

Overall, the prototype fulfilled the data acquisition and visualization functions but did not yet meet the data completeness and validity requirements needed for use in environmental health information systems. The integration of sensors, a microcontroller, connectivity, and digital interfaces in this study is consistent with IoT-based water quality monitoring approaches (Murti et al., 2024; Nishan et al., 2024; Ujianti et al., 2025). The main contribution of this study lies in an evaluation that separates data read locally from data available online, revealing a gap

that is often hidden when evaluation relies only on the dashboard display. For use within government reporting, the dashboard data could be exposed as structured records (timestamp, parameter, value, unit, and status) through an application programming interface, so that they can be mapped to national health information standards; information systems in Indonesian puskesmas are described as fragmented, with the national system moving towards FHIR based standards and alignment with SATUSEHAT (Aisyah et al., 2025).

These findings have practical implications for developing low-cost environmental health monitoring systems in batik centers. First, the dashboard should include automatic flags for readings outside ranges set by environmental health officers, so that the system acts as an early warning that triggers laboratory sampling. Second, data validation rules are needed to flag implausible values, such as TDS of 0 ppm, before data enter the database. Third, the device should buffer data when transmission fails and resend them once the connection is restored, so that the online record has no gaps. Fourth, the sensors should be calibrated and compared with reference instruments before their results are used for health decisions (Abu Bakar et al., 2025; Hartanto et al., 2026). In practice, environmental health officers would set pH and TDS thresholds on the dashboard, receive an alert when a reading leaves the agreed range, and use the stored history for periodic reporting and for deciding when to take laboratory samples; this workflow was not tested with officers or SME owners in the present study.

This study has several limitations. The observation lasted about 30 minutes in a single test context and therefore does not capture variation in wastewater between days or production stages. No calibration data or reference instrument readings were available, so interpretation is limited to the range and variation of the readings. Only pH and TDS were monitored, whereas the pollutants most relevant to health, such as dyes, heavy metals, and organic matter, require separate testing (Ramamurthy et al., 2024). The results also cannot be used to state whether the wastewater samples met quality standards. In addition, no user evaluation was conducted with environmental health officers or batik SME owners, and power supply, connectivity, and durability under field conditions were not assessed. Temperature was not recorded, and the sensors were not calibrated against standard solutions.

CONCLUSION

This study implemented a prototype IoT-based environmental health monitoring information system for batik wastewater using an ESP32, pH and TDS sensors, ThingSpeak, and a local web dashboard. The system read sensor values, displayed them on the Serial Monitor, and presented values, charts, and reading history, with pH of 7.59–11.61 and TDS of 0–695.36 ppm over about 30 minutes of observation. However, only 16.7% of transmission status messages indicated success, so most of the data were not available online to remote users. These findings confirm that the feasibility of a monitoring system for environmental health cannot be judged solely by its ability to read and display data, but also by the completeness and validity of the data that reach decision-makers. With improved transmission, local data buffering, validation rules, early warning flags, and calibration against reference instruments, this low-cost system has the potential to help environmental health officers and batik businesses detect changes in wastewater characteristics earlier. Because the sensors were not calibrated, the pH and TDS values cannot be interpreted without calibration. The system was tested on one sample for about 30 minutes, so its feasibility for continuous monitoring has not yet been

shown. The most probable technical cause of the failed transmissions is an upload interval shorter than the ThingSpeak limit of one update every 15 seconds for free accounts, and the first fix to be tested is a longer interval or bulk updates. The next step is a multi day field deployment at a batik center with laboratory comparison and calibration.

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CONFLICT OF INTEREST

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

Sekar Harum Kurniasih: Conceptualization, Methodology, Software, Investigation, Data curation, Formal analysis, Visualization, Writing original draft. **Rosidin:** Conceptualization, Methodology, Validation, Resources, Supervision, Writing review and editing. Both authors have read and approved the final manuscript.

GENERATIVE AI STATEMENT

The author(s) declared that generative AI was used in the creation of this manuscript. Claude (Anthropic) was used to translate the manuscript into English, restructure it according to the journal template, add discussion on environmental health informatics, translate the figure labels, and format the citations. This application was conducted in adherence to established ethical guidelines regarding the use and disclosure of generative AI in scholarly research. Each author has provided substantial intellectual contributions to the work, which has been rigorously vetted for accuracy, and the author(s) assume full responsibility for the integrity and final content of the manuscript. Claude (Anthropic) was also used to revise the manuscript in response to reviewer comments. The authors checked all statements and reference details added during revision against the original sources.

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