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Design and development of an IoT-based intelligent water quality management system for aquaculture

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Abstract

Water quality is generally known to directly affect the health and growth rate of aquatic organisms and determines the success of any aquaculture fish production. However, water quality problems are difficult to detect early in aquaculture production facilities, largely because it requires a high level of technical understanding of the physio-chemical properties of water. In this research, an IoT-based intelligent water quality management system for aquaculture was designed and developed to monitor temperature, pH, and turbidity. ESP32 Microcontroller programmed with the C programming language was used to implement the smart control module which received data from the sensors and transmitted to a cloud database. A web application was also developed which enabled real-time monitoring and control of the system by a user from anywhere in the world, via any internet-connected device. Alarms and notifications could be received via WhatsApp Messenger. The system demonstrated capacity to improve the efficiency and productivity of aquaculture production.

Keywords: Aquaculture, Water quality, IoT, Aquatic organisms

Introduction

Aquatic organisms, like any living organism, survive and thrive under some specific environmental conditions. It is generally known that the growth of aquatic life and successful aquaculture production depends largely on the quality of water in which the livestock is bred [1, 2]. However, of all the challenges confronting aquaculture development, effective water quality management for aquaculture production are about the most critical. Water quality directly affects the health and growth rate of fish. Simply put, a pond with good water quality will produce more and healthier fish than a pond with poor water quality. Water quality problems are also the most difficult to address in aquaculture production, largely because it requires a high level of expertise and technical understanding of the physio-chemical and biological properties of water such as temperature, pH, turbidity, salinity, ammonia, and oxygen content as it pertains to the fish being cultured, to effectively detect issues, monitor, and improve water quality. This level of knowledge and skill is not easily or readily available to most fish farmers in developing countries. The existing methods of water quality management in aquaculture present its own challenges to the fish farmer. The farmer cannot easily keep track of critical water quality parameters as they are difficult to monitor and measure under the traditional method which basically relies on intuition of the farmer to determine when to treat the water, without concrete empirical data backing up the decision. Where more scientific means are sought, the farmer must rely on periodic collection of water samples which are then sent to a laboratory to be tested by an expert. This process is usually tedious, labour intensive, and elongates the response time for the farmer to take remedial action, if issues with water quality are detected from the tests. The use of hand-held water test kits, while being an improvement, does not effectively solve the challenge, as it still relies on a manual process of sample collection and testing. As a result of these challenges, water quality issues in most aquaculture production farms are only detected and addressed after the negative consequence on the fish stock has occurred or begins to visibly manifest on the fish stock. The effect of this challenges is manifested in high mortality rate of the fish stock, and slow growth rate of the surviving fish, thereby resulting in low productivity, profitability, or outright loss to the farmer, with corresponding negative impact of food and nutritional security for the general population.

The emergence of new technologies, such as the development of advanced electronic sensors and embedded systems, smart internet-enabled devices, automation, and artificial intelligence, present new opportunities for remarkable innovations in agriculture. Several research works have been conducted and several more are ongoing worldwide to tailor these emerging technologies towards solving the problems pertaining to agriculture and food production globally [3]. This has heralded the development of 'smart agriculture' technologies, driven by smart sensors, the internet of things (IoT), machine learning, with real-time data collection and big data analytics, that address some of the critical and long-standing challenges in agriculture, with the potential to tremendously improve the level of agricultural output [2].

The main questions to be investigated in this research are as follows:

- How can the internet of things (IoT) and smart automation technology be effectively applied to measure, monitor and control water quality parameters in fish farming?
- How well can an IoT-based fish farming water quality management system help to improve productivity in aquaculture through reduced fish mortality rate and faster fish growth rate?

To this end, the main objectives of this research are as follows:

- To design and implement IoT sensor network and control module to measure and monitor selected water quality parameters and transmit the captured data via the internet to a cloud database.
- To develop and implement an algorithm to analyse captured data and recommend and implement defined actions based on data, via suitable actuators connected to the system.
- To test and evaluate the performance of the proposed system.

Literature review

Water quality with respect to aquaculture refers to all the physical, chemical, and biological properties of water that makes it usable for the purpose of breeding and producing fish. Water quality variables include all characteristics of water that influence the survival, reproduction, growth, production, or management of fish in any way [4, 5]. Several research works been undertaken to understand the physical and chemical qualities of water that are critical to successful aquaculture, as a lack of understanding results in poor growth and high feed conversions or, at worst, total loss of all fish in the pond [6–9]. There are many water quality variables of interest in fish culture that describe the physio-chemical state of the pond water. These variables include temperature, salinity, pH, total alkalinity, total hardness and calcium, dissolved oxygen, carbon dioxide, ammonia and nitrate, turbidity, chlorine, heavy metals content, etc. However, only a few variables are significant, which should be given critical attention to control water quality to some extent by management techniques [10].

Temperature

In aquaculture, temperature is the most important physical property of water as it affects all chemical and biological processes. Fish are cold-blooded organisms, and they assume almost the same temperature as their surroundings. Physiological processes such as respiration, feeding, metabolism, reproduction, growth, and general behaviour are influenced by temperature. Temperature also in a way influences other water quality parameters, particularly the presence of dissolved gases such as dissolved oxygen, carbon dioxide, and nitrogen [5]. As a rule, the rates of chemical and biological reactions double for every 10oC rise in temperature. The implication of this is that metabolism in fish and consumption of oxygen progresses twice as fast at 30oC than at 20 °C [4]. Warm water fish such as catfish and tilapia, which are commonly grown in Nigeria (and Africa at large), grow best at temperatures between 25 °C and 32 °C [4]. A temperature of 29 °C is considered optimum [11]. Fish, however, have poor tolerance to sudden changes in temperature. Temperature changes by as little as 5 °C could be fatal to fish [4]. In large-scale aquaculture systems, controlling water temperature is not practical. However, temperature measurement can provide useful insight to predict the level of physiological and biological activities going on in the water.

Turbidity

Turbidity refers to the number of suspended solids in water, and it affects the passage of light into the water. The greater the number of suspended solids in the water, the murkier it appears and the higher the measured turbidity value. The major source of turbidity in open waters is typically phytoplankton, which are microscopic floating plants that dwell on the surface of water. Other sources include clay and silt build-up, erosion, and leftover feed and fish waste dissolved in the water [4, 12]. Turbidity is widely measured in nephelometric turbidity units (NTU), which is a measure of how light is scattered by suspended particulate material in the water. Usually, turbidity is measured to give an estimate of the total suspended solids (TSS). Acceptable range of turbidity levels for optimum aquaculture production has been found to be between 25 and 80 mg/L [5]. The impact of turbidity on fish growth has varying consequences depending on the cause of turbidity in water. Turbidity caused by microscopic organisms such as phytoplankton and zooplankton may not be directly harmful to the fish, as phytoplankton produces oxygen (via photosynthesis). They also use up ammonia produced by fish as a nutrient source. Phytoplankton and zooplankton also provide an important food source for fries and fingerling sized fish [11]. Turbidity caused by suspended fish wastes are dangerous as they contribute excess nitrogen or ammonia to the system. This waste could affect the fish gills and promote the growth of harmful bacteria in the water which accelerates fish mortality [11].

pH

pH is a measure of the hydrogen ion concentration, which expresses whether a solution is acidic or basic in reaction. It is expressed mathematically as the negative logarithm of the hydrogen ion concentration [13].

$$\mathrm{pH} = -\mathrm{Log}_1 0[\mathrm{H}^+] \tag{1}$$

Hence, one unit change in pH represents a tenfold change in hydrogen ion concentration. A pH scale ranges from 0 to 14, although higher values are possible [14, 15]. At 250 °C, pH 7.0 represents the neutral point of water. Lower values tending towards 0 depicts increasing acidity, and higher values towards 14 depicts increasing basicity or alkalinity. The pH of natural water is greatly influenced by the concentration of carbon dioxide, which is released by fish during respiration, and is used up by phytoplankton for photosynthesis. Carbon dioxide dissolves in water to form a weak carbonic acid. Mathematically put [16],

$$\mathrm{CO_2} + \mathrm{H_2O} = \mathrm{HCO_3^-} + \mathrm{H}^+ \tag{2}$$

Phytoplankton and other aquatic vegetation remove carbon dioxide from the water by photosynthesis during the day, while at night, no carbon dioxide is removed, whereas fish continue to release carbon dioxide into the water through respiration. Hence, the pH of a body of water rises during the day (i.e., towards alkalinity) and decreases during the night (i.e. towards acidity). The desirable range of pH for freshwater aquaculture production is between 6.5 and 9. Outside this range, the fish undergoes severe stress which could lead to slow growth and even death [4, 5]. The effect of varying pH values on fish health and growth is summarized in Table 1.

Table 1 Effect of pH on warm water pond fish

pH	Effect
< 4	Acid death point
4.0–5.0	No reproduction
5.0–6.5	Slow growth
6.5–9.0	Optimum range for production
9.0–11.0	Slow growth
> 11.0	Alkaline death point

Source: [5]

Dissolved oxygen

Dissolved oxygen is the most critical water quality parameter that affects fish survival and growth. Dissolved oxygen is needed in several ways, for fish respiration, waste decomposition and algal respiration [17, 18]. The major source of dissolved oxygen in aquaculture systems is photosynthesis by phytoplankton. Other important sources of oxygen in water include mechanical aeration, wind and wave action, and inflow of new fresh water into the fishpond. The most common source of oxygen depletion in water is over enrichment (due to excessive feeding or inflow of nutrients) which causes heavy phytoplankton blooms resulting in high consumption of oxygen. Dissolved oxygen concentration in water is also affected by temperature, salinity, atmospheric pressure, and humidity. Dissolved oxygen in water reduces as water temperature increases. A dissolved oxygen concentration level around 5 mg/L is usually recommended for optimum fish health. Mortality occurs at less than 2 mg/L of DO concentration for most aquatic life [4, 19]. Fish growth rate is badly affected when dissolved oxygen concentration stays continuously below 4 mg/L, as prolonged exposure to low levels of dissolved oxygen will reduce appetite for food, reduce their digest food, and make them more susceptible to disease [9, 10]. The effect of varying dissolved oxygen concentration values on fish health and development of fish is outlined in Table 2.

Ammonia concentration

Ammonia is produced as a by-product in the breakdown of proteins in fish. When fish digest the protein in their feed, they excrete ammonia through their gills and in their faeces. The amount of ammonia excreted by fish varies proportionally to the feeding rate. Ammonia also accumulates in the pond from the decomposition of other organic matter such as uneaten feed or dead algae and aquatic plants [21]. Ammonia and nitrates exist in two forms in pond water: ionized non-toxic ammonia ($NH_4{}^+$) and un-ionized toxic ammonia ($NH_3{}^+$). Together, they are measured as Total Ammonia Nitrogen (TAN). When ammonia accumulates to toxic levels in the un-ionized form, it hinders the ability of the fish to extract energy from feed efficiently. If the ammonia concentration gets high enough, the fish will become lethargic and eventually die. Even at sub-lethal concentrations, excess ammonia in pond water can cause reduced growth in fish, poor feed conversion and reduced disease resistance [22]. Ammonia concentration in toxic un-ionized in pond water has been found to be largely influenced by pH, temperature, and oxygen levels. For every 1 unit increase

Table 2 Effect of dissolved oxygen concentration on pond aquaculture species [20]

Dissolved oxygen concentration	Effect
$<$ 2 mg/L	Lethal (if exposure is prolonged)
2–5 mg/L	Fish growth will be slow if exposure is continuous
$>$ 5 mg/L	Best condition for good growth
$>>$ 5 mg/L	Normally does not present a problem, but can be harmful if supersaturation exists throughout pond volume

in pH, un-ionized ammonia concentration increases by tenfold [21, 22]. Additionally, lower water temperature slows down aerobic micro-bacterial activity which hitherto helps to convert ammonia into harmless nitrates. Hence, lower water temperatures increase the concentration of toxic un-ionized ammonia.

Review of related research works on application of IoT To aquaculture

A couple of researcher have deployed IoT in the field of aquaculture. Agossou and Toshiro [1] in their research proposed an IoT and AI-based system for fish farming. Their system utilized electronic sensors to measure nine water quality parameters namely pH, temperature, turbidity, dissolved oxygen, electrical conductivity, total dissolved solids, carbon dioxide, ammonia, and water level. They used an Arduino Microcontroller to receive data from the sensors and ESP32 microcontroller to communicate with the cloud database via a Wi-Fi network. They also proposed an AI algorithm based on convoluted neural networks (CNN) to predict the occurrence of diseases in fish. Karim et al. [2] developed an IoT-based Aquaculture Monitoring System to monitor only a limited number of water quality parameters namely pH, temperature, turbidity, and water level. They also included a sensor for motion detection of fish in the water. They used an Arduino Uno Microcontroller to collect data from the sensors, which is then fed to a GSM enabled desktop server, which provides the gateway to the internet from where a user can view real-time data. A local database was used for data storage instead of a cloud database. Although their model focused on cost effectiveness, which informed their design, some key IoT features were sacrificed as a result.

Hairol et al. [23] also proposed an Arduino Mega Microcontroller-based automated fishpond system. The system measured only temperature and water level, but also proposed an automatic fish feed system as well as automatic water replacement. A Wi-Fi module was connected, which enabled the system to transmit data over the internet, which can be viewed on an android application. Their solution, however, did not fully implement the features of IoT, as a user can only view data on the android application but cannot remotely issue commands to the system. Their model also did not implement any intelligent algorithm, as its automated actions were based on set timers. Saha et al. [24] implemented monitoring of water quality of aquaculture, monitoring temperature, pH, electrical conductivity and colour. Sensor data acquisition was conducted by Arduino and Raspberry Pi was used as data processing device as well as server. Photo acquisition was also performed by Raspberry Pi with the help of the smartphone camera to detect the colour of the water. An android phone was used as the terminal device. A user can monitor the water condition using an android app through Wi-Fi within Wi-Fi range and through internet from anywhere in the world. The system can perform analysis on the four parameters value to determine the overall approximate condition of the water and required action. However, their system did not implement any algorithm to automatically execute actions based on the assessed condition of the water.

Azhra and Anam [25] designed an IoT system called SENDAL IKAN comprising of 7 sensors that can control water quality in fishponds in real time from phone and can activate automatic responses directly and through applications on mobile phones if there is an indication that the water quality is outside normal limits. The water quality parameters measured by the sensors are salinity, turbidity, temperature, pH, conductivity, dissolved oxygen, and ammonia. In Idachaba et al. [26], IoT-enabled system comprise of a pond controller which uses appropriate sensors to monitor the water quality of the pond. A CCTV camera records the activities around the pond and stores them in cloud storage. The pond controller manages the automatic feeding system of the fish and the water control system for the pond. The system was also designed with capacity for remote operation through a specially designed mobile application which accesses the CCTV files and controls the pond controller.

Flowvy [27] presented an integrated-on-chip computer Raspberry Pi with an in-built Wi-Fi module. It is energized with the help of solar panel which is more reliable and wireless. Several sensors are mounted to sense the data and the data are transferred to the aqua farmer through IOT. However, the farmer can only view the transmitted data, and cannot remotely activate actuators. The system also does not have automatic corrective function. Duangwongsa et al. [28] presented an IoT-based system with automatic correction for temperature, pH, turbidity, and dissolved oxygen. The system utilized a serverless IoT architecture using Firebase real-time database and ESP8266 microcontroller. Simbeye et al. [17] developed an IoT system for aquaculture using wireless sensor networks that communicates via a Zigbee network architecture. The focus of their research was to improve energy efficiency and flexibility of the network.

From all the reviewed literature works, much effort has been put into sensing and transmission of water quality parameters data for display over a web or mobile platform. While there has been some work on remote control and automatic control of water parameters, there is still room for additional research to develop an integrated and wholistic system which utilizes the full capabilities of an IoT system, going beyond just data capture and viewing, but enables the user to perform seamless remote control and adjustment of water quality parameters, while the system can by itself automatically control and adjust these parameters without any human intervention.

Materials and methods

The Intelligent water quality management system is designed as a complete pond management system capable of performing the following functions:

- Collect water quality data.
- Process captured data
- Transmit water quality data (over the internet)
- Record and store water quality data (in a cloud database)
- Display water quality data to a user (via a web application)
- Initiate alarms and send out notifications
- Perform feedback (i.e., receive commands from a user)
- Perform automatic control of the fishpond

System description

Sensors used to collect data from the pond consist of temperature sensor, pH sensor, and turbidity sensor. These sensors collect data about the pond water quality and feed these data into the control module. The control module processes the data and then transmits it to a cloud database via an internet-enabled Wi-Fi network. The cloud database stores the data as it is received from the control module over the internet and allows the data to be retrieved as the need arises. A web-based user application communicates with the cloud database and displays data retrieved on a user-friendly dashboard for user interaction. The system allows for two-way communication between the user and the system device via the web application. Two water pumps installed on the pond enable corrective action to be taken if measured values from the sensors are assessed to be outside the parameter thresholds, which is dangerous to the fishes health and growth. One pump serves as the inlet to the pond to deliver fresh water into the pond, and the other pump is used to drain the toxic water out of the pond. WhatsApp API is integrated into the control module of the system, enabling the system to send out alarm notifications to the user through WhatsApp. Hence, whenever any of the monitored parameters falls outside the desirable range of values, the user will receive a notification via WhatsApp message.

The two-way communication capability of the system can be configured to operate in either AUTO mode or MANUAL mode. In AUTO mode, a smart algorithm implemented on the control module takes over the control of the system, allowing the system to automatically take corrective actions on the pond water by turning on or off any of the pumps, whenever any of the parameters fall outside the desired range without human intervention. The user only receives notifications and the log of actions taken by the system. In MANUAL mode however, the system only captures, transmits and displays data for the user. The user has full control on the web-based platform to turn on or turn off any of the pump actuators as is deemed necessary. The system architecture of the IoT System is shown in Fig. 1.

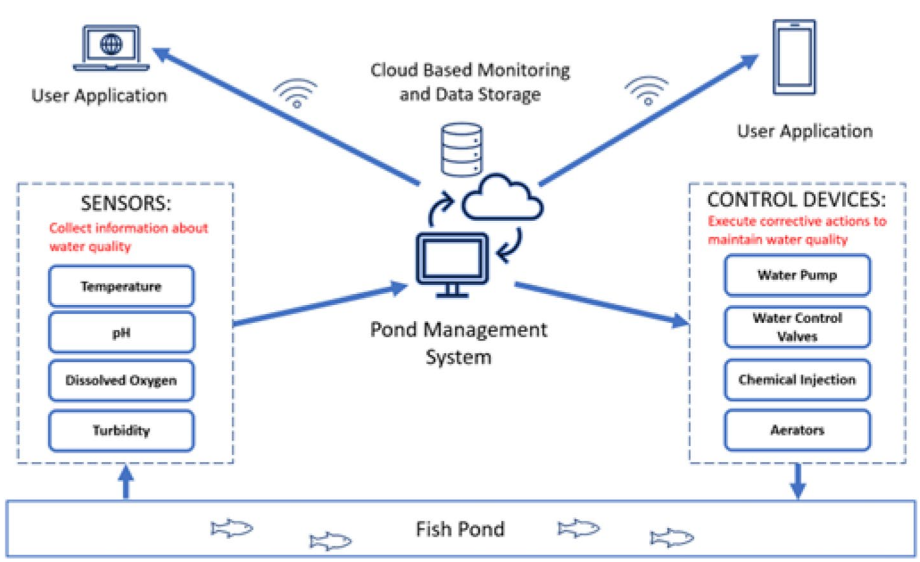

Fig. 1 System architecture of IoT system for aquaculture

Selection of hardware components

Sensors

The *DS*18*B*20 temperature sensor with a waterproof probe was selected. The *DS*18*B*20 temperature sensor is precise and does not require any external components to function. It has a temperature range of −55 °C to + 125 °C and an accuracy of ± 0.5 °C.

The SEN0161 analog pH sensor was used. The sensor is easy to use and is specifically designed for aquaculture environments. The sensor uses a BNC connector linked to an analog-to-digital converter (ADC) to interface with the microcontroller [29].

The SEN0189 analog turbidity sensor was selected. It uses light to detect suspended particles in water by measuring the light transmittance and scattering rate, which changes with the amount of total suspended solids (TSS) in water.

For this design, the sensor was configured to work in analog mode.

To use the sensor in analog mode, the sensor value from the A0 pin is converted to a float voltage signal which is read by the microcontroller. The equation for the conversion is given as

$$\text{FlolatVoltage} = \frac{\text{Sensor} \times \text{Vcc}}{1024} \tag{3}$$

where Vcc is the input voltage (i.e., 5 Vdc). This converts the analog reading of the sensor to a voltage value between 0.5 Vdc.

Pumps

This pump moves fluids (liquids or gases), through mechanical action, usually converted from electrical energy to hydraulic energy. Its voltage range is DC 5–12 V and its water flow rate is 100 L/hr.

Microcontroller

The ESP32 Microcontroller chip (shown in Fig. 2) was used to implement the IoT control module. The *ESP*32 is a low-cost, low-power system on a chip (SoC) microcontroller

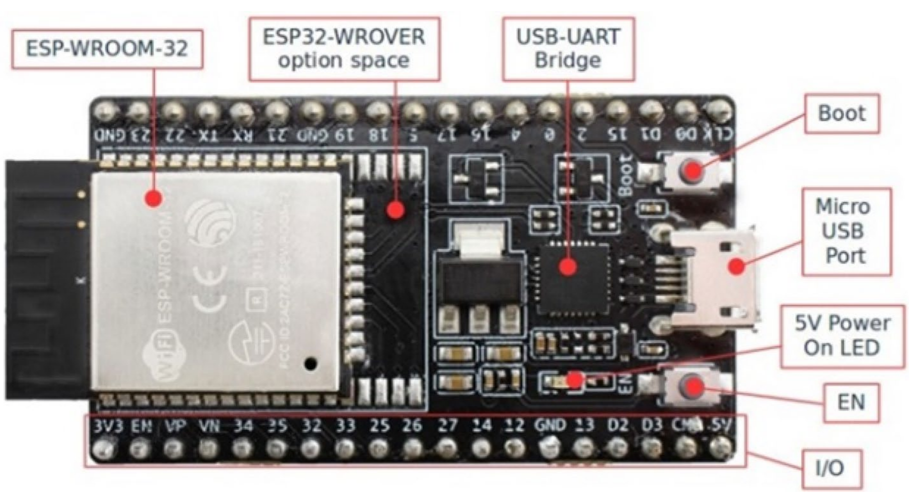

Fig. 2 *ESP*32 microcontroller

with integrated Wi-Fi and dual-mode Bluetooth. The ESP32 is ideal for IoT applications as it fulfils all the operational requirements for an IoT microcontroller, which are sensing, processing, storage and transmitting data. Its integrated Wi-Fi and Bluetooth modules make communication with other devices and the internet very seamless, cancelling the need for an external GSM module or LTE module. It also supports TCP/IP, HTTP, HTTPS, and other traditional communication protocols, meaning it can easily communicate with web servers or act as a stand-alone web server which other devices can communicate with [30].

Circuit design

The circuit diagram and design for the control module was created and simulated using Proteus 8.0 software [31]. The circuit diagram for the fish Pond IoT system is shown in Fig. 3.

The functional circuit diagram was then etched on a printed circuit board (PCB). The PCB Design for the control circuit module was also created using the Proteus software.

Microcontroller program—sensing and transmission of data

The software for the microcontroller control module was written in C programming language. At start-up, the system initializes and reads values from the pH, temperature, and turbidity sensors. It also searches for the available Wi-Fi network. If the Wi-Fi to which it is configured is available, the control module automatically connects to the Wi-Fi and establishes a secure internet connection with the cloud server, which hosts the database, and the user interface application. If connection is established, the system immediately begins transmission of sensor data to the cloud server. If an internet connection cannot be established or internet connection is lost, the control module will store the data in its local storage, until connectivity is restored, while displaying it on the local LCD display panel.

The algorithm is designed to run as a continuous process; therefore, it repeats itself and does not stop until the power supply is cut from the module. The flowchart algorithm implemented on the microcontroller control module is shown in Fig. 4.

Database and user interface—receiving, storing, and displaying data

The database and the web application providing the user interface were implemented on the Firebase platform.

Firebase is a backend-as-a-service (BaaS) app development platform that provides hosted backend services such as a real-time database, cloud storage, authentication, crash reporting, machine learning, remote configuration, and hosting for your static files [32]. Data received from the control module are stored in the database. Apart from raw data from the sensors, the database also keeps a timestamped record of the status of the parameters whether they values fall within the desired range (i.e., LOW, NORMAL, or HIGH), the status of the water pumps and the user-defined operating mode of the IoT module? Either MANUAL mode or AUTO mode.

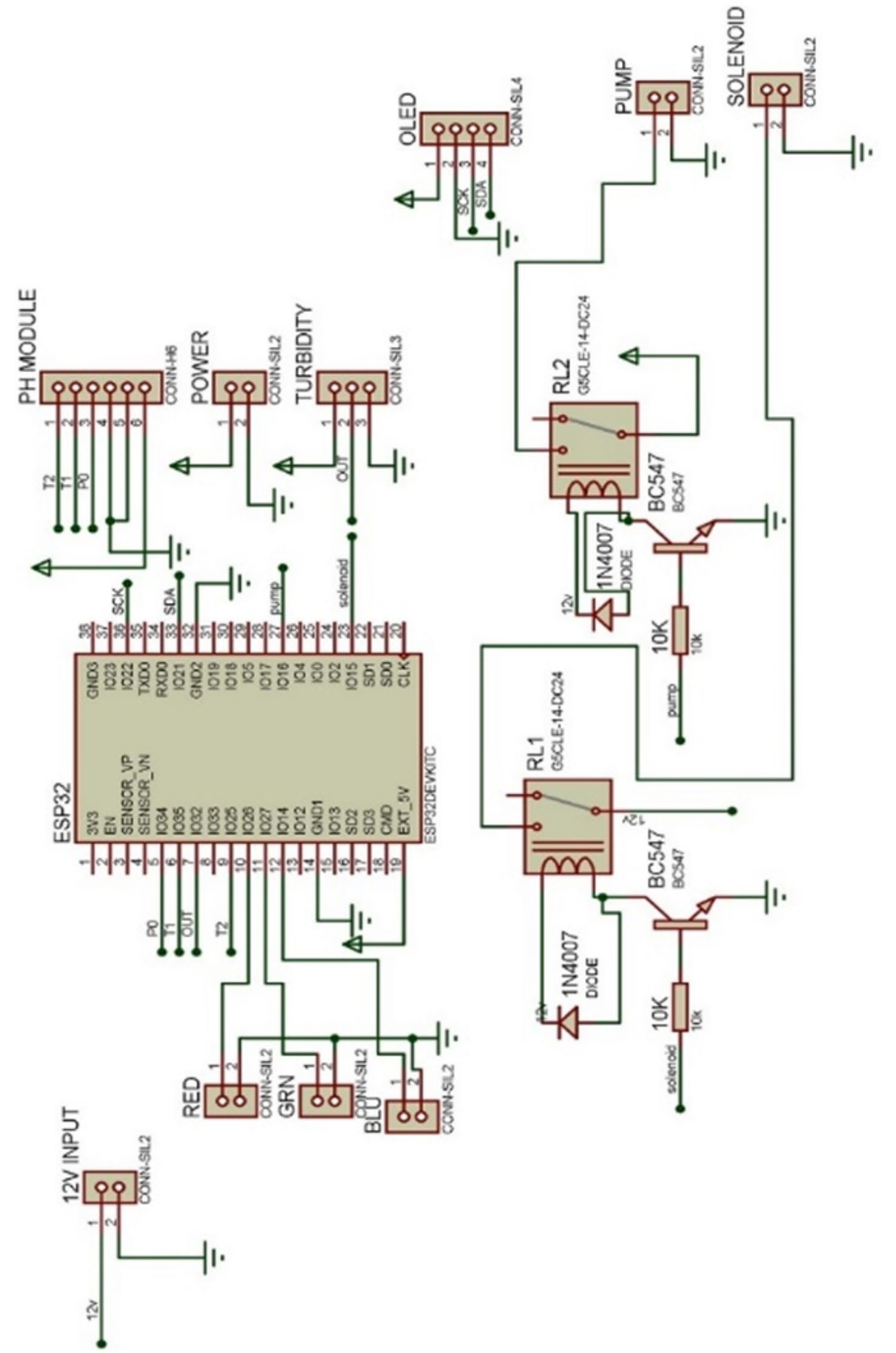

Fig. 3 Circuit diagram for smart fish pond IoT system

The user interface web application was developed using HTML5, CSS, and JavaScript. It provides a graphical display of all information received from the IoT control module

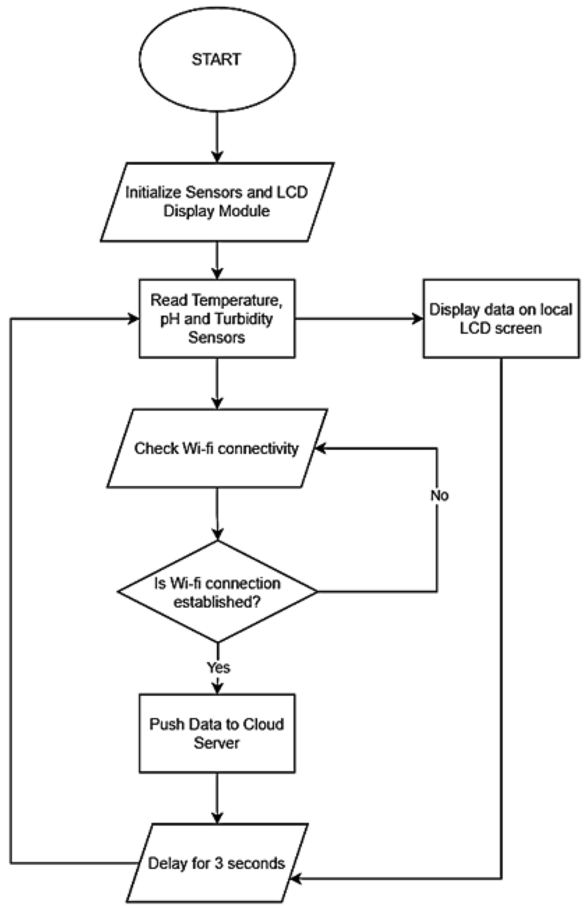

Fig. 4 Flowchart for IoT control module to read, process and transmit water quality data

stored in the database. The flowchart for receiving and displaying data from the IoT device is shown in Fig. 5.

Implementing control actions

The automatic control functionality enables the IoT system to automatically switch on or switch off the actuators (water pumps) in a bid adjust water quality parameters when there is a deviation from the desired values. The control module is not only able to read and transmit data but can also analyse and interpret the data from the sensors, and then decide on the appropriate action to take, without human intervention, to maintain the pond water in healthy condition. This is executed within two operating modes, either the MANUAL mode or the AUTO mode.

In the manual mode, the IoT control module analyses the sensor data and determines the water quality status of the pond but does not take any action. The final control action is determined by the user command.

In the AUTO mode however, the IoT control module analyses and interprets the water quality data, and based on this, automatically initiates the control action (either to start or stop the water pumps) without the user's intervention. The user is only kept informed of the action taken via the web application. The threshold values for the water quality

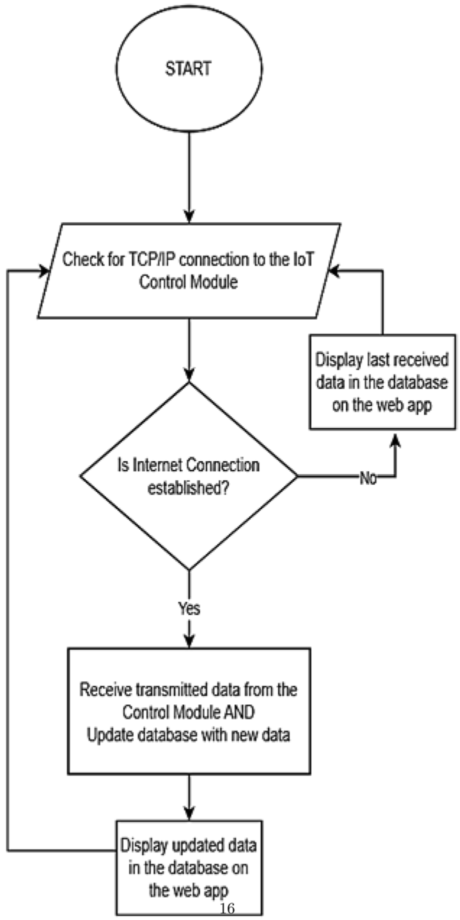

Fig. 5 Flowchart for receiving data, updating database, and displaying data on the web application

Table 3 Example of a lengthy table which is set to full textwidth

Water quality parameter	Threshold values	Actions		
		Low	Normal	High
pH	Critical Low: < 6.5 Normal: 6.5–9.0 Critical High: > 9.0 ppm	Activate pumps	Record as normal	Activate pumps
Temperature	Low: < 24*C* °C Normal: 24–29°C High: 29 °C	Activate pumps	Record as normal	Activate pumps
Turbidity	Low: < 25 mg/L Normal: 25–74 mg/L High: 75–100 mg/L	Activate pumps	Record as normal	Activate pumps

parameters, and the control matrix are highlighted in Table 3, while the flowchart for the control algorithm is shown Fig. 6.

Metric for measuring system performance

Feed conversion ratio (FCR) and the feeding efficiency (FE) are calculated to determine the effectiveness of the IoT-based smart fish farming system on the prototype fishpond

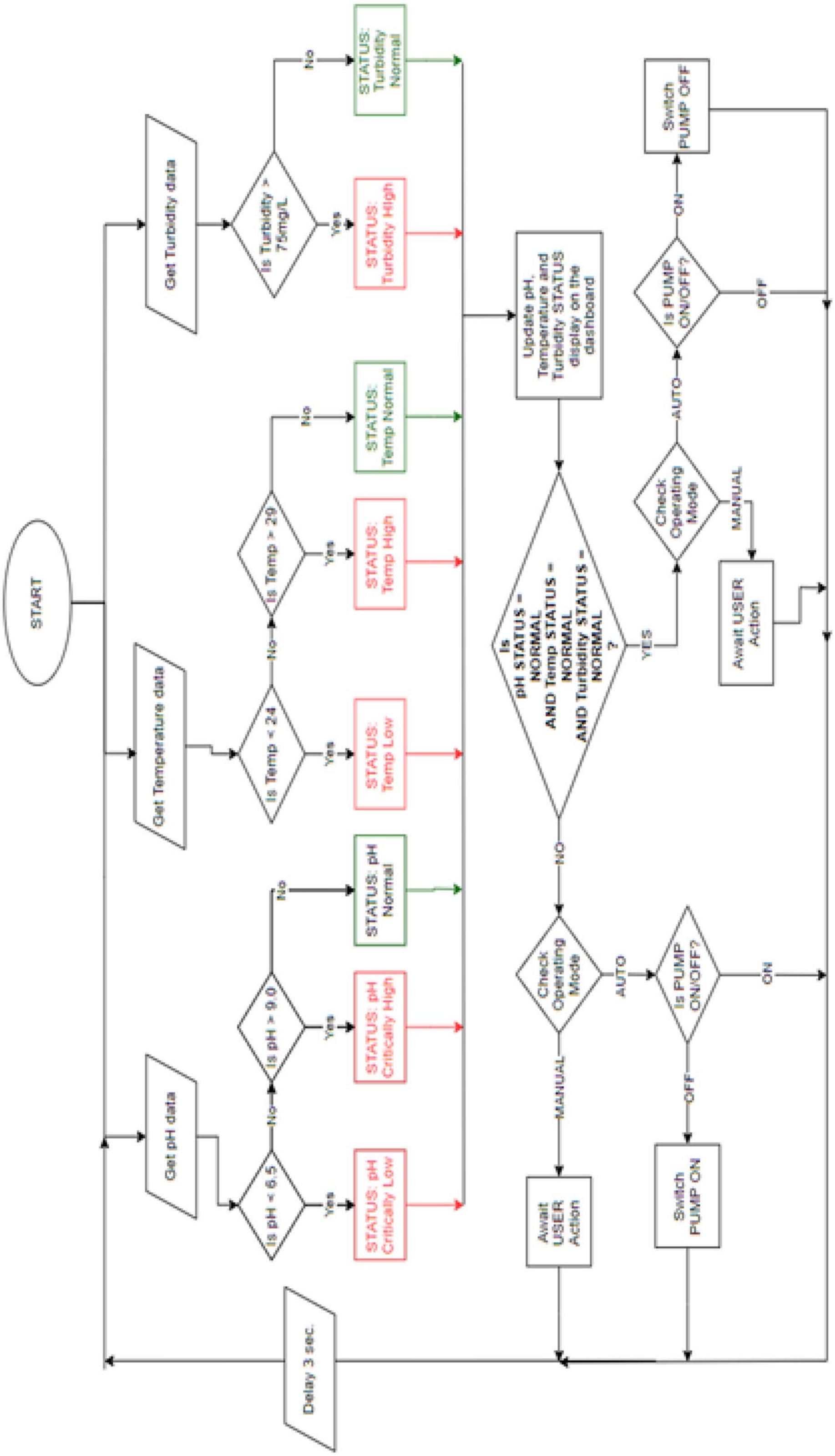

Fig. 6 Flowchart algorithm for IoT system automatic pond control

used for this research. The feed conversion ratio is an indicator that indicates how well the farmed organism can convert the given feed into weight gain. It is a mathematical relationship between the input of feed and the effective weight gain of the aquatic population [33].

$$\text{Feed Conversion Ratio} = \frac{\text{Total amount of feed given to the fish stock (g)}}{\text{Weight gain of the fish stock (g)}} \tag{4}$$

Comparatively lower FCR values are more desirable, as it means that the fish are growing and gaining weight faster for a given quantity of the feed that they are fed. Higher FCR values however are indicative of growth problems with the fish stock, or overfeeding, leading to wastage of expensive fish feed. Similar to the feed conversion ratio is the feeding efficiency (FE) which expresses the effectiveness of the feeding strategy in terms of percentages.

$$\text{Feeding Efficiency} = \frac{1}{\text{FCR}} \times 100 \tag{5}$$

Given that more than half of the financial expenses of any fish farm is spent on feed procurement alone. Therefore, optimizing the feed conversion and feeding efficiency helps to guarantee the profitability of the fish farming venture. As good water quality significantly improves feed consumption by the fish and overall fish growth, an IoT-enabled smart system that improves water quality management and control will equally have a positive impact of feed conversion and feeding efficiency. The entire circuit connection of IoT module is shown in Fig. 7

Test in a live fishpond

The system was tested in a live environment using a test artificial pond containing about 205 pieces of three weeks old pre-juvenile catfish. The IoT system was used to monitor the water quality of the test pond and to study the behaviour and growth of the fish compared to another manually operated artificial pond containing similar number of

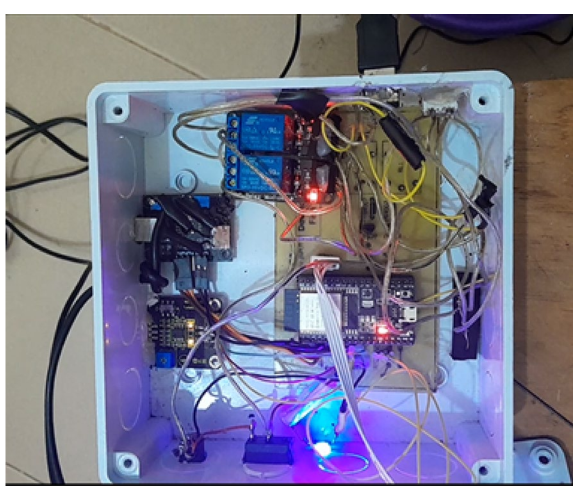

Fig. 7 Circuit connection of IoT module

fish stock, which was used as reference. The IoT system was used to monitor the change in pH, temperature, and turbidity of the test pond, and the behaviour and growth rate of the fish was observed for 21 days, and compared with a similar stock of fish reared in the reference pond, all the while maintaining other conditions (such as the feeding method and feeding pattern) constant in both the test and reference pond. Figure 8 shows the setup for the test. The test was conducted for twenty-one (21) days, and the result is tabulated in Table 4.

It was observed that at the end of the second day, the pH of the water had increased to close to 8.5 and was approaching the maximum threshold value, whereas there was no significant change in liquid temperature and turbidity. This phenomenon was attributed to the build-up of leftover feed and metabolic wastes in the pond water, which made it become more alkaline. Hence, the water pumps were activated to replace the pond water after the second day, and the trend was sustained. This was contrary to the manually operated pond, where the farm operator would only have replaced the pond water after the third day. At the end of the tests, the average feed consumed per fish, and the average weight gain per fish were calculated for the test pond, to derive the feed conversion ratio (FCR) and the feeding efficiency (FE) of the fishes in the test pond.

At the beginning of Day 1, the total count of fish is 205 with a total fish weight of 107 g. While at Day 21, the total count of fish becomes 190 with a total fish weight of 186 g, giving a commutative feed consumed as 93 g. Using Eqs. 4 and 5, the feed conversion ratio (FCR) and feeding efficiency were calculated to be 1.18 and 84.7% respectively. These results are within the range of values obtainable for catfish from several research works [34–36]. This has shown that the IoT system demonstrates better capacity in improving the productivity and efficiency of the fishpond.

The reduction in fish count at the end of the tests was due to mortality of the fish. This level of mortality could be attributable to stress induced in the fish due to the more frequent replacement of pond water. It could also be due to defects with other water quality parameters that are not directly monitored by the IoT module, e.g.,

Fig. 8 Live tests of IoT module in a test pond

Table 4 Sensor data form live tests

Day	pH	Temperature (°C)	Turbidity (mg/L)
Day 1	7.2	29.3	19
Day 2	7.6	29.2	21
Day 3	8.4	29.3	24
Day 4	7.4	28.4	20
Day 5	7.9	28.6	23
Day 6	8.6	29.2	26
Day 7	7.2	28.8	19
Day 8	7.4	29.3	24
Day 9	7.8	29.5	28
Day 10	7.8	28.8	35
Day 11	8.4	29.6	43
Day 12	7.4	29.2	19
Day 13	7.8	29.2	22
Day 14	8.4	29.3	23
Day 15	8.8	29.5	34
Day 16	9.3	29.3	42
Day 17	7.5	29.3	21
Day 18	7.6	28.8	24
Day 19	7.7	29.1	35
Day 20	8.8	29.1	43
Day 21	9.5	29.4	46

Results have been averaged for the first 2 hours of each day

hardness of the water and dissolved oxygen. However, the improved feed conversion ratio and feeding efficiency of the surviving fish offset any losses that would have been incurred from the mortality.

Results and discussion

A series of functional tests were carried out on the entire system to confirm:

- That all aspects of the system (i.e., data sensing, processing, transmission display, control functions) worked according to the intended design.
- That the readings from the sensors are reliable, with a reasonable margin of error.

All the sensors worked well and generated data on their specific water quality parameter, according to the design, with satisfactory margin of error. The control module successfully read the data from the sensors and transmitted it through a Wi-Fi network to the cloud server and the data were successfully displayed on the web application. All the control functions worked as designed with the control module successfully operating the pumps automatically. Table 5 is a snapshot of the readings generated by the sensors and the data stored in the database.

The control module was programmed to read, process, and transmit sensor data every 4 s. Thus, the IoT system generates 15 unique data sets per minute, 900 data

Table 5 Data generated by IoT system

Timestamp	pH	Temperature (°C)	Turbidity (ntu)	Status	Action
21:04	5.90	28.19	9	pH crt	Inlet/drain pump activated
21:04	5.90	28.19	9	pH critically low	Inlet/drain pump activated
21:04	6.34	28.25	13	pH critically low	Inlet/drain pump activated
21:04	5.90	28.25	17	pH critically low	Inlet/drain pump activated
21:03	5.90	28.19	1	pH critically low	Inlet/drain pump activated
21:03	5.90	28.25	15	pH critically low	Inlet/drain pump activated
21:03	5.90	28.19	9	pH critically low	Inlet/drain pump activated
21:03	5.90	28.19	21	pH critically low	Inlet/drain pump activated
21:02	5.90	28.19	0	pH critically low	Inlet/drain pump activated
21:02	5.90	28.19	22	pH critically low	Inlet/drain pump activated
21:02	5.90	28.19	2	pH critically low	Inlet/drain pump activated
21:02	5.90	28.25	23	pH critically low	Inlet/drain pump activated
21:01	6.06	28.25	16	pH critically low	Inlet/drain pump activated
21:01	5.93	28.25	24	pH critically low	Inlet/drain pump activated
21:01	5.90	28.25	11	pH critically low	Inlet/drain pump activated
21:01	7.47	28.25	4	Normal conditions	No action needed
21:01	7.38	28.25	15	Normal conditions	No action needed
21:01	7.76	28.25	12	Normal conditions	No action needed
21:01	7.41	28.19	2	Normal conditions	No action needed
21:01	7.34	28.25	11	Normal conditions	No action needed
21:00	7.78	28.25	2	Normal conditions	No action needed
21:00	7.69	28.25	13	Normal conditions	No action needed
21:00	7.68	28.19	3	Normal conditions	No action needed
21:00	7.39	28.25	24	Normal conditions	No action needed
21:00	7.37	28.25	19	Normal conditions	No action needed
21:00	8.86	28.25	11	Normal conditions	No action needed
21:00	7.51	28.25	20	Normal conditions	No action needed
21:00	7.71	28.19	22	Normal conditions	No action needed
21:00	7.74	28.25	20	Normal conditions	No action needed
21:00	7.35	28.19	14	Normal conditions	No action needed

sets per hour, and 21, 600 data sets per day, thereby creating a robust dataset which can be extracted for further analysis and insight.

Figure 9 shows the dashboard overview of the IoT web application interface for monitoring and controlling the designed IoT fishpond water quality management system. On the dashboard, a real-time summary overview of sensors readings is displayed and can be monitored by the user. The status of the inlet water pump and drain pump is also displayed on the dashboard. The dashboard also features switch buttons each for the inlet and drain pumps. The pumps may be turned on or off remotely by clicking the buttons.

Figures 10, 11 and 12 illustrate the temporal variations in water quality parameters, specifically addressing turbidity, temperature, and pH responses, respectively. The graphical display provides users with a clear and immediate knowledge of the current variations in the monitored parameters. This allows users to easily see and comprehend the subtle changes in water quality dynamics as they happen in real time. These

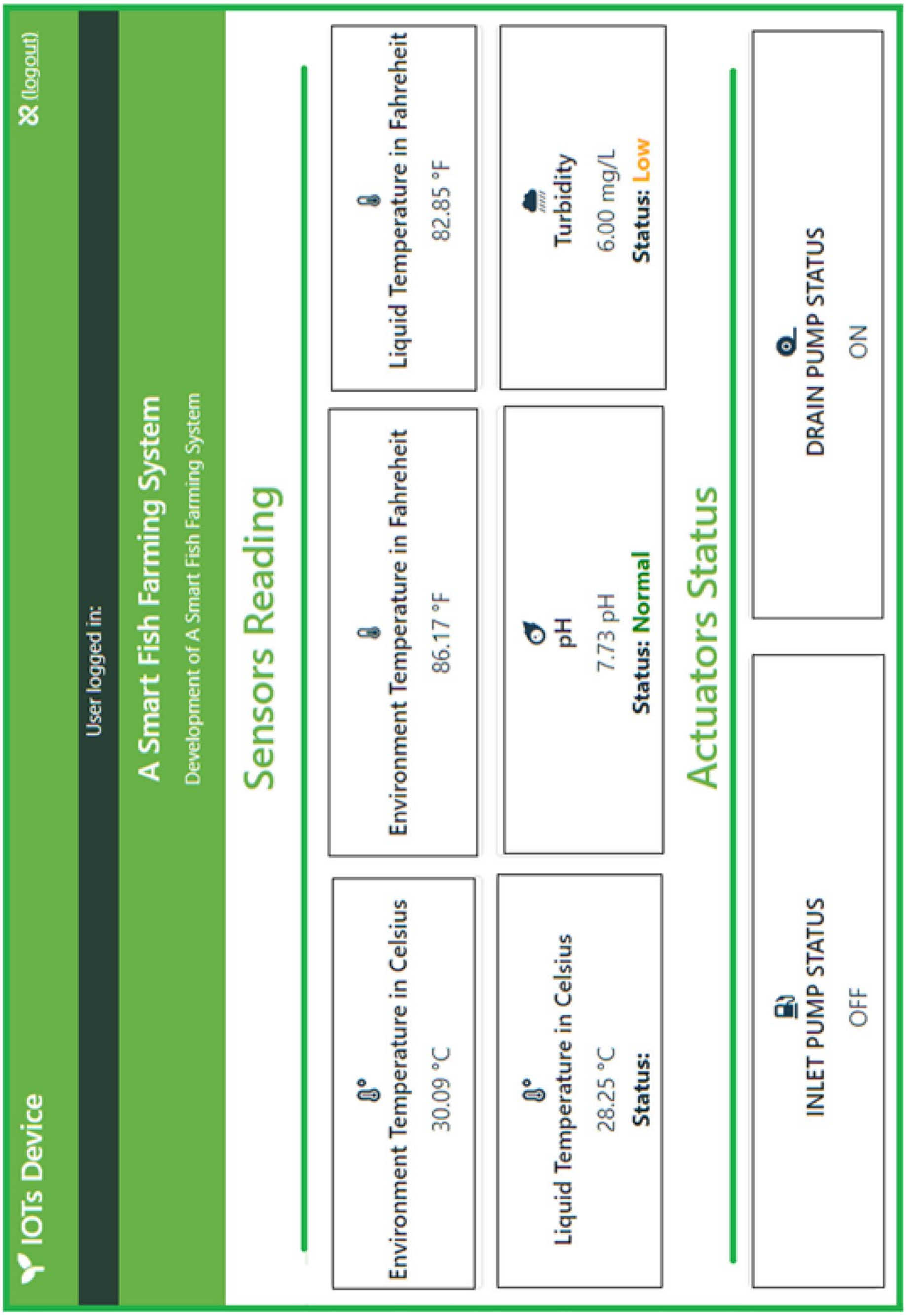

Fig. 9 IoT web application dashboard

visualisations are a useful tool for improving awareness of the situation and facilitating well-informed decision-making in the field of water quality monitoring.

The average daily readings for pH, temperature, and turbidity is plotted on the same axis as shown in Fig. 13. The results showed that temperature remained fairly stable

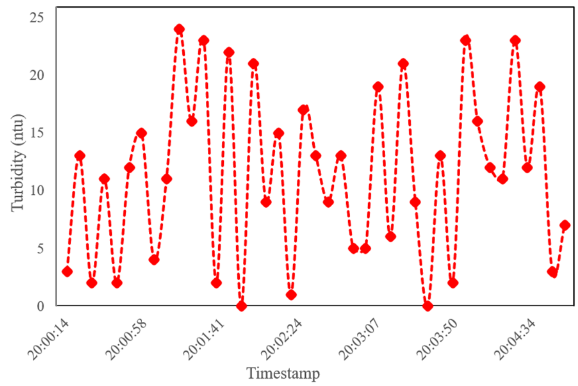

Fig. 10 Response of turbidity data from web application

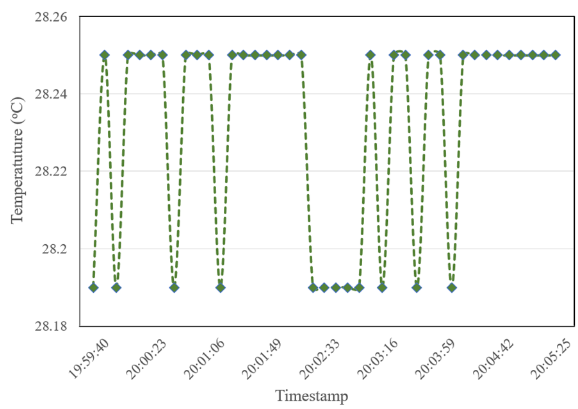

Fig. 11 Response of turbidity data from web application

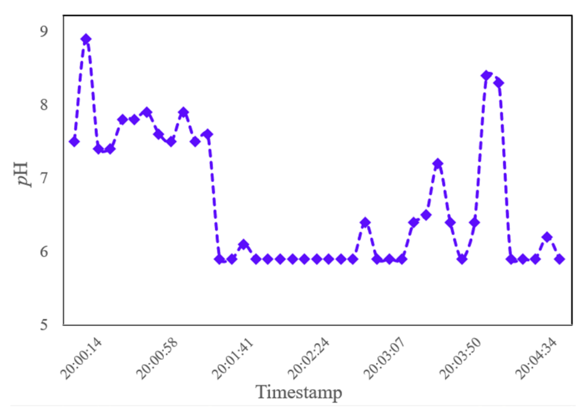

Fig. 12 Response of pH data from web application

between 28 and 29 °C for most of the period, while pH and turbidity tended to rise after a few days (2–3 days), which would trigger the system to activate the pumps and

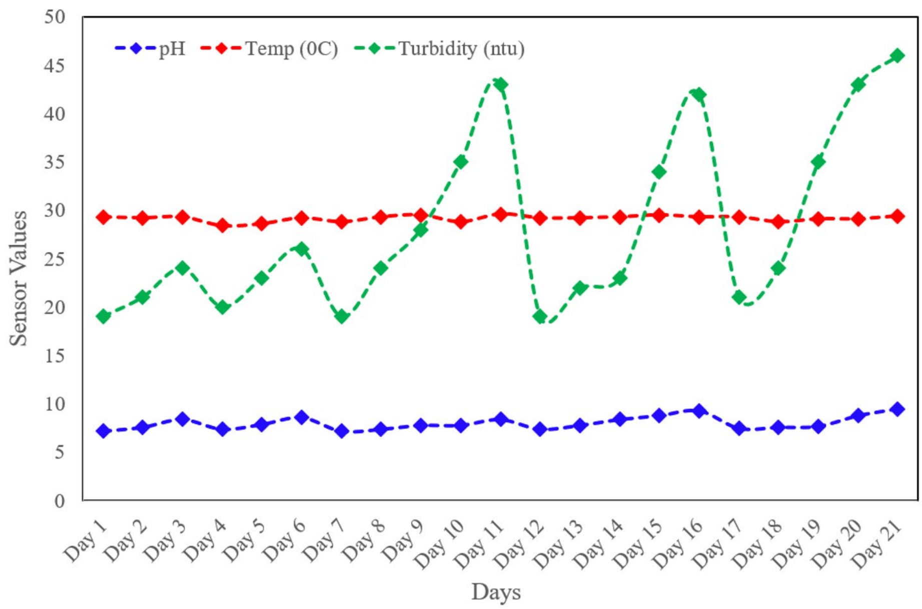

Fig. 13 IoT web application dashboard

replace the pond water with fresh supply, in order to bring down the pH and turbidity values to the acceptable limits.

Conclusion

An IoT-enabled intelligent water quality management system has been designed, developed, and tested in this work. It was shown that improved water quality management significantly improves the productivity and efficiency of aquaculture production.The research further demonstrates that IoT-based technologies for water quality management systems with intelligent functionalities can enhance an improved water quality management in aquaculture, thereby boosting the productivity and profitability of the aquaculture industry.

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OOO contributed to conceptualization and writing of the original draft. TTA involved in review and editing. OSA involved in supervision and review.

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