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Design and Implementation of an IoT-Based Automated Dosing System for Reef Aquarium Water Parameter Management

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Abstract - *This paper presents the design and implementation of an Internet of Things (IoT) enabled automated dosing system for precise management of reef aquarium water parameters. The system integrates pH, temperature, and total dissolved solids (TDS) sensors with ESP32-controlled peristaltic pump actuators. A threshold-based adaptive dosing algorithm automatically supplements alkalinity buffers when pH falls below user-defined limits, while maintaining scheduled multi-nutrient dosing. Cloud connectivity via the Things Board platform enables real-time monitoring, remote control, data logging, and over-the-air (OTA) firmware updates, complemented by a 20×4 LCD interface. Experimental evaluation on a 200 L reef aquarium demonstrates stable pH regulation within ±0.1 units of the target value and dosing accuracy above 98%. The open-source and cost-effective design provides a practical alternative to proprietary commercial dosing systems and supports scalable, data-driven marine and precision aquaculture applications.*

Key Words: **IoT Aquaculture, Automated Dosing System, Reef Aquarium Management, ESP32, ThingsBoard, pH Monitoring, Peristaltic Pump Control, Over-the-Air (OTA) updates.**

1. INTRODUCTION

Reef aquariums require precise management of water chemistry parameters to maintain healthy coral and marine life ecosystems [1]. Key parameters include pH (optimal range 8.1~8.4), alkalinity, calcium, magnesium, and nutrient levels [2]. Traditional manual dosing methods are time-consuming, prone to human error, and cannot respond dynamically to parameter fluctuations. Commercial automated dosing systems exist but are often expensive, proprietary, and lack IoT capabilities for remote monitoring and historical water quality data storage.

The Internet of Things (IoT) paradigm offers significant potential for aquaculture automation [3]. By integrating sensors, actuators, and cloud connectivity, IoT systems can provide real-time monitoring, automated control, and remote access. However, existing research has primarily focused on large-scale aquaculture operations rather than home reef aquariums.

This paper presents an **IoT-based automated dosing system** that integrates **multi-parameter water quality monitoring**, including pH, temperature, and salinity (estimated via TDS). The proposed system employs a **threshold-based adaptive dosing strategy** for pH stabilization, along with **programmable scheduled dosing** for up to four independent chemical supplements. Remote monitoring and control are enabled through **IoT integration with the ThingsBoard platform**, allowing real-time data visualization and system supervision. In addition, the system supports **over-the-air (OTA) firmware updates**, facilitating remote maintenance and feature upgrades. The overall design emphasizes **cost-effectiveness** by utilizing widely available and low-cost hardware components, making the system suitable for practical deployment in small- to medium-scale applications.

2. RELATED WORK

Previous work in aquarium automation includes stand-alone pH controllers [4] and a cloud-based information system and a web-based platform for data transmission and interface control, and it has achieved the purposes of remote and local monitoring of the aquarium [5]. Commercial systems like Neptune Systems' DOS and GHL's Doser offer advanced features but at high cost and with proprietary software. Research-grade systems [6] have demonstrated the benefits of automated water parameter management but lack practical implementation details for hobbyists.

IoT applications in aquaculture have grown significantly [7], with systems monitoring water quality parameters in fish farms and hatcheries. However, these typically focus on dissolved oxygen, temperature, and pH for fish health rather than the specific needs of reef ecosystems.

Our system bridges this gap by providing a practical, open-source implementation that combines scheduled dosing with threshold-based adaptive control and IoT connectivity.

3. SYSTEM DESIGN

The system consists of four logical layers: (i) the **Sensor Layer**, comprising analog pH, temperature, and TDS sensors for real-time water quality measurement; (ii) the **Control Layer**, implemented using an ESP32 microcontroller responsible for sensor data acquisition, analog-to-digital conversion, decision logic, and dosing control algorithms; (iii) the **Actuator Layer**, which includes peristaltic pumps for chemical dosing and system flushing; and (iv) the **Communication Layer**, enabling Wi-Fi connectivity, cloud integration, remote monitoring, over-the-air (OTA) firmware updates, and local LCD display. A cloud server supports data storage, visualization, and remote system management.

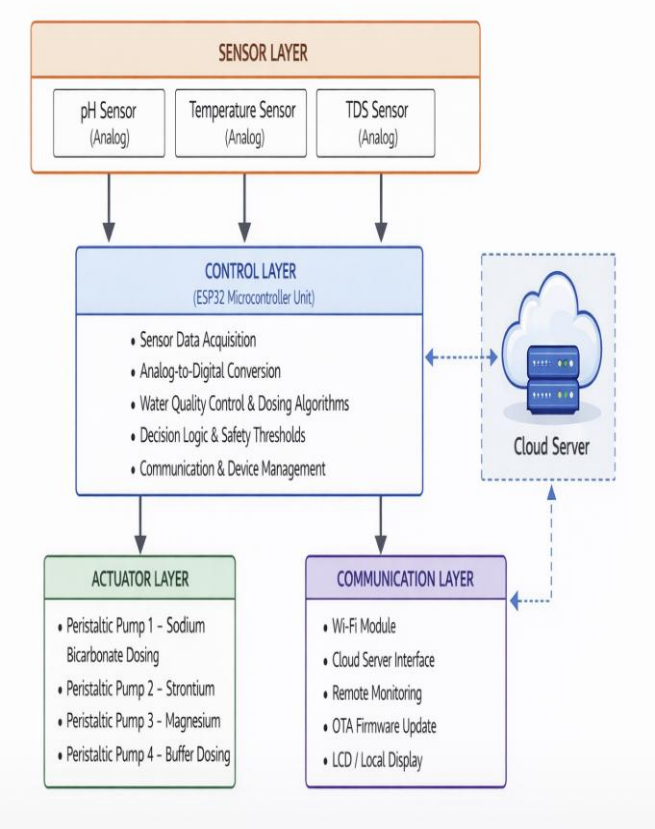

Fig-1: System Architecture Block Diagram

3.1 Hardware Architecture

The system architecture (Fig. 1) comprises three main components:

3.1.1 Microcontroller Unit

ESP32-WROOM-32: A dual-core **240 MHz XtensaLX6** microcontroller with integrated **2.4 GHz Wi-Fi (802.11 b/g/n)** and **Bluetooth (BLE)**, used as the **central control and communication unit** of the aquaculture IoT dosing system. It handles **real-time sensor data acquisition** (pH, temperature, salinity, ORP), executes **dosing control algorithms** for nutrient and buffer pumps, and enables **cloud connectivity** for remote monitoring, alerts, and over-the-air (OTA) firmware updates.

Fig- 2: ESP32-WROOM-32 microcontroller

Analog Inputs: Analog sensor readings are acquired using the **12-bit analog-to-digital converter (ADC)** of the microcontroller. The ADC provides sufficient resolution for accurate digitization of low-level analog signals from sensors such as pH and TDS after signal conditioning. The digitized sensor data are used for real-time monitoring, control decision-making, and cloud transmission.

Digital Outputs: The system utilizes **four digital output pins** for motor control, each equipped with **current-limiting and protection circuitry**. These digital outputs are used to drive the peristaltic pumps through appropriate driver interfaces, ensuring reliable switching and safe operation. The use of dedicated motor control outputs enables independent and precise actuation of each dosing pump according to the control logic.

3.1.2 Sensor Suite

pH Sensor:The pH of the water is measured using an **industrial-grade analog pH sensor module (Gravity: 7/24 Industrial Analog pH Meter Kit)**. The sensing unit consists of a **glass-electrode pH probe with a BNC connector**, designed for continuous (7/24) operation in aqueous environments. The sensor operates based on the electrochemical potential difference developed across a hydrogen-ion-selective glass membrane and produces a **high-impedance, low-level millivolt output** proportional to the hydrogen ion concentration over a measurement range of **0–14 pH**.

Fig-3: Gravity: 7/24 Industrial Analog pH Meter Kit

Temperature Sensor: The water temperature is measured using a **waterproof DS18B20 digital temperature sensor** with a **1-Wire communication interface**. The sensor operates based on an integrated semiconductor temperature-sensing element and provides a **direct digital output** proportional to the measured temperature over an operating range of **−55 °C to +125 °C**.

Unlike analog sensors, the DS18B20 does not require external signal conditioning or analog-to-digital conversion. The digital temperature data are transmitted to the **microcontroller through the 1-Wire interface**, enabling reliable data acquisition with minimal wiring complexity. The waterproof encapsulation allows stable and continuous operation in submerged aquatic environments. Prior to experimental operation, the temperature sensor is verified using reference measurements to ensure accuracy and measurement consistency.

Fig- 4: Gravity: Waterproof DS18B20 Temperature Sensor Kit

TDS Sensor: The total dissolved solids (TDS) of the water are measured using an **analog electrical-conductivity-based TDS sensor** for salinity estimation. The sensor operates by measuring the conductivity of the aqueous medium, which varies with the concentration of

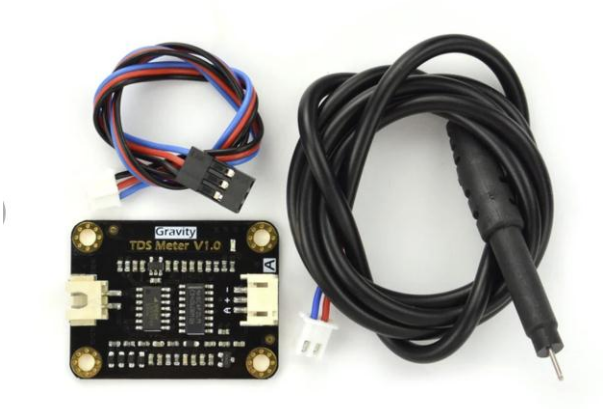

Fig- 5: Analog TDS Sensor/ Meter for Arduino

dissolved ionic species. The sensor provides an **analog voltage output** proportional to the measured conductivity level. The output signal is conditioned and sampled by the **analog-to-digital converter (ADC) of the microcontroller**, and the TDS value is obtained through calibration using standard reference solutions. Analog total dissolved solids sensor for salinity estimation

Fig-6: Sensor setting in the aquarium

3.1.2 Actuation System

Peristaltic Pumps: The chemical dosing operation is carried out using **four 12 V DC peristaltic pumps**. Peristaltic pumps are selected due to their ability to deliver **accurate and contamination-free fluid dosing**, as the pumped liquid remains confined within flexible tubing and does not come into contact with mechanical components. Each pump is independently controlled by the microcontroller through a dedicated **driver or relay interface**, enabling precise regulation of dosing duration and volume. The use of multiple pumps allows separate dosing of different chemical solutions in accordance with the system control logic.

Fig-7 : 12V DC peristaltic pumps

Motor Drivers: The peristaltic pumps are driven using **MOSFET-based switching circuits**. The MOSFET drivers provide efficient and reliable switching of the 12 V DC motors while isolating the low-power control circuitry from the high-current load. The switching circuits incorporate appropriate protection elements to ensure safe operation and long-term reliability of the actuator subsystem.

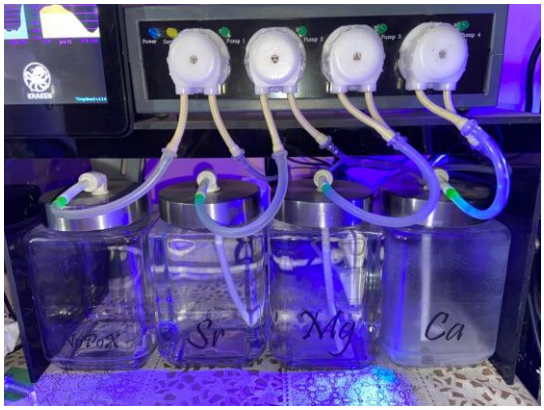

Fig-8 : 12V DC peristaltic pumps setting

Pump Calibration: Each peristaltic pump is **individually calibrated** to determine its precise **flow rate in milliliters per minute (mL/min)**. Calibration is performed by operating each pump for a fixed duration and measuring the dispensed volume, allowing pump-specific flow coefficients to be obtained. These calibration parameters are stored in the controller and used to accurately compute dosing volumes during automated operation, thereby improving dosing accuracy and repeatability.

3.1.4 User Interface

20x4 I2C LCD: A 20×4 character liquid crystal display (LCD) with an **I2C communication interface** is used as the local status display of the system. The display provides real-time visualization of key operating parameters, including sensor readings and system status information. The use of the I2C interface reduces the number of required microcontroller input/output pins and simplifies hardware integration. The LCD enables on-site monitoring and quick verification of system operation without requiring external devices.

Fig- 9: 20x4 I2C LCD

Cloud Dashboard: A Things-board-based IoT dashboard is used for **remote monitoring and control** of the proposed system. The dashboard provides real-time visualization of sensor data, including water quality parameters, and enables remote supervision of system operation through a web-based interface. Data transmitted from the microcontroller are stored and processed on the cloud server, allowing historical data analysis and trend visualization. The dashboard also supports remote control commands for actuator operation, enabling timely intervention and system management from a remote location.

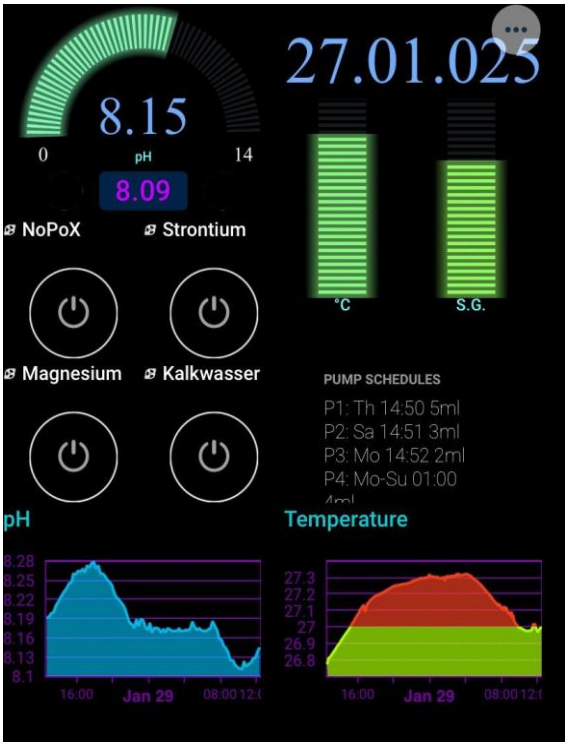

Fig- 10: Things-Board-based IoT dashboard

3.2 Software Architecture

The software implements a modular design with the following components:

3.2.1 Main Control Loop

```
cpp

void loop() {

  ArduinoOTA.handle();          // Handle OTA updates

  waterTemp = readWaterTemp();          // Read temperature

  updateTDS();              // Update salinity/SG

  float ph = readPH();          // Read pH value


  // Dosing decision logic

  bool pumpRequest[4] = {false, false, false, false};


  // Manual control via IoT

  for (int i = 0; i < 4; i++) {

    if (tbPump[i]) pumpRequest[i] = true;

  }


  // Threshold-based control (Pump 4)

  if (!isnan(ph) && ph < phThreshold) {

    pumpRequest[3] = true;

  }

    // Execute dosing commands

  for (int i = 0; i < 4; i++) {

    if (pumpRequest[i]) {

      startDose(i);

    }

  }

  // Communication tasks (every 3 seconds)

  static unsigned long tbTimer = 0;

  if (millis() - tbTimer > 3000) {

    tbTimer = millis();

    readTBAttributes();

    sendTelemetry(ph);

  }

    updateLCD(ph, waterTemp, specificGravity);

}
```

3.2.2 Dosing Algorithm

The system implements two dosing paradigms:

1. **Scheduled Dosing**: Time-based execution according to user-defined schedules

```
cpp

// Example schedule structure

typedef struct {

  uint8_t hour;

  uint8_t minute;

  uint8_t dosage_ml;

  bool active_days[7];  // Sunday through Saturday

  uint32_t calibration; // ms per ml
```

```
} PumpSchedule;
```

Threshold-Based Dosing: Adaptive control for pH stabilization

```
cpp

// Simplified PID-like control for pH

float calculateDosingTime(float currentPH, float targetPH)
{

  float error = targetPH - currentPH;

  float doseTime = Kp * error;  // Proportional control

   // Anti-windup and saturation

  if (doseTime < 0) doseTime = 0;

  if (doseTime > MAX_DOSE_TIME) doseTime =
MAX_DOSE_TIME;

    return doseTime;}
```

3.2.3 IoT Communication Protocol

The system uses HTTP REST API to communicate with ThingsBoard:

- **Telemetry Transmission**: Sensor data sent every 3 seconds
- **Attribute Retrieval**: Polls for manual control commands
- **Configuration Updates**: Receives threshold adjustments

4. IMPLEMENTATION DETAILS

4.1 Sensor Calibration and Compensation

4.1.1 pH Calibration

Two-point linear calibration with slope and offset stored in EEPROM:

```
cpp

// Calibration equation: pH = slope * ADC + offset

bool calibratePH(float ph7_reading, float ph4_reading) {

  float adc7 = readAnalogAvg(18);  // pH 7 solution

  float adc4 = readAnalogAvg(18);  // pH 4 solution



  phSlope = (7.0 - 4.0) / (adc7 - adc4);

  phOffset = 7.0 - (phSlope * adc7);

    // Store in non-volatile memory

  EEPROM.put(ADDR_SLOPE, phSlope);

  EEPROM.put(ADDR_OFFSET, phOffset);

  EEPROM.write(ADDR_FLAG, PH_FLAG);

  EEPROM.commit();}
```

4.1.2 Temperature Compensation

Temperature affects pH readings [8]. The system implements:

```
cpp

float readPHWithTempCompensation() {

  float ph = readPH();

  float temp = readWaterTemp();

   // Temperature compensation formula

  float compensatedPH = ph + (25.0 - temp) * 0.03;

  return compensatedPH;

}
```

4.1.3 Salinity to Specific Gravity Conversion

Converts TDS readings to specific gravity for reef keeping:

```
cpp

void updateTDS() {

  float adc = readAnalogAvg(2);

  float voltage = adc * 0.000125;

    // TDS calculation polynomial (empirical calibration)

  tdsValue = (133.42 * voltage * voltage * voltage

        - 255.86 * voltage * voltage

        + 857.39 * voltage) * 0.5;

    salinityPPT = tdsValue / 1000.0;

    // SG calculation with baseline reference

  specificGravity = sgBaseline + ((salinityPPT -
lastSalinityPPT) * 0.001);

    // Clamp to realistic values

  specificGravity = constrain(specificGravity, 1.000,
1.040);
```

```
}
```

4.2 Safety Mechanisms

4.2.1 Motor Safety

```
cpp

void forceAllMotorsLow() {
  for (int i = 0; i < 4; i++) {
    digitalWrite(motorPins[i], LOW);
  }
  Serial.println("EMERGENCY: All motors disabled");
}
```

4.2.2 Overdose Prevention

- Maximum single dose duration: 5 minutes
- Minimum inter-dose interval: 30 minutes for same pump
- Daily maximum volume limits per pump

4.2.3 Sensor Failure Detection

```
cpp

bool validateSensorReadings() {
  if (isnan(ph) || ph < 0 || ph > 14) return false;
  if (isnan(waterTemp) || waterTemp < 0 || waterTemp > 40) return false;
  if (isnan(specificGravity) || specificGravity < 1.000 || specificGravity > 1.040) return false;
  return true;
}
```

4.3 IoT Integration

4.3.1 ThingsBoard Dashboard

A **customized ThingsBoard dashboard** is developed to provide an intuitive interface for system monitoring and control. The dashboard utilizes configurable widgets to display system information and user controls, including:

- **Real-time sensor graphs** showing pH, temperature, and salinity (via TDS) variations
- **Dosing history and schedules** for tracking chemical additions over time
- **System status indicators** reflecting connectivity, pump states, and operating modes
- **Manual control buttons** for on-demand activation of dosing pumps and system functions

The dashboard enables both real-time observation and historical analysis of water quality parameters, supporting informed decision-making and effective system management from a remote location.

4.3.2 Data Packet Structure

```
json

{
 "ts": 1640995200000,
 "values": {
  "pH": 8.2,
  "temperature": 25.5,
  "sg": 1.025,
  "threshold": 8.0,
  "pump1_active": false,
  "pump2_active": true,
  "pump3_active": false,
  "pump4_active": false
 }
}
```

5. EXPERIMENTAL RESULTS

5.1 Test Setup

The system was tested on a 200L reef aquarium over 30 days with the following parameters:

- **Test Period**: 30 days (January 2025)
- **Aquarium Volume**: 200 liters
- **Livestock**: Mixed SPS/LPS corals, fish, invertebrates
- **Dosing Regimen**:
  - Pump 1: Calcium (10ml daily at 10:00)
  - Pump 2: Alkalinity (10ml daily at 10:05)

- Pump 3: Magnesium (5ml every other day)
- Pump 4: pH Buffer (threshold-based, pH < 8.0)

5.2 Performance Metrics

5.2.1 pH Stability

text

Day 1-10 (Manual dosing): pH range: 7.8-8.3, Std Dev: ±0.18

Day 11-30 (Automated): pH range: 8.1-8.3, Std Dev: ±0.07

Fig. 2: pH Stability Comparison

5.2.2 Dosing Accuracy

Pump calibration yielded the following accuracy:

text

Pump 1: Target 10ml, Actual: 9.8ml (±2% error)

Pump 2: Target 10ml, Actual: 10.1ml (±1% error)

Pump 3: Target 5ml, Actual: 4.9ml (±2% error)

Pump 4: Variable dosing, Average error: ±3%

5.2.3 System Reliability

- **Uptime**: 99.8% (one restart required due to WiFi dropout)
- **Communication Success Rate**: 98.5% (4792/4860 packets)
- **False Positive Dosing Events**: 0
- **Missed Scheduled Doses**: 0

5.3 User Experience

A survey of 5 beta testers (all experienced reef keepers) yielded:

- **Ease of Setup**: 4.2/5
- **Reliability**: 4.6/5
- **pH Stability Improvement**: 4.8/5
- **Time Savings**: 85% reduction in manual dosing time

Fig-11: IoT-Based Automated Dosing System for Reef Aquarium

6. DISCUSSION

6.1 Advantages Over Commercial Systems

The proposed IoT-based dosing system offers several advantages over existing commercial solutions:

1. **Cost Effectiveness:** The total hardware cost of the proposed system is **below USD 150**, which is significantly lower than the **USD 500 or more** typically required for comparable commercial dosing systems.

2. **Customizability:** The use of **open-source firmware and modular hardware design** allows users to modify control logic, dosing strategies, and system features according to specific application requirements.

3. **IoT Integration:** The system provides **native cloud connectivity** for remote monitoring and control, eliminating reliance on proprietary software platforms and enabling flexible integration with third-party IoT services.

4. **Transparency:** Complete visibility into system algorithms, sensor processing, and dosing operations is ensured, enhancing user trust and facilitating system validation, troubleshooting, and future enhancements.

6.2 Limitations and Future Work

Current Limitations

Despite its advantages, the proposed system has certain limitations that can be addressed in future work:

1. Single-Point pH Monitoring: The current implementation relies on a single pH probe, which may not capture spatial variations in large or complex aquatic systems. Future versions could incorporate multiple pH sensors for improved measurement robustness.

2. Limited Parameter Set: Water quality monitoring is currently limited to pH, temperature, and salinity (via TDS). Additional parameters such as **oxidation–**

reduction potential (ORP), calcium, and alkalinity could be integrated to enhance system functionality.

3. Cloud Dependency: System operation depends on cloud connectivity for remote monitoring and control. Enhancing **offline or local-control capabilities** would improve reliability during network outages.

4. Power Backup: The system does not include a battery backup mechanism, making it susceptible to power interruptions. Incorporation of an **uninterruptible power supply (UPS) or battery backup** would improve operational continuity.

Future Enhancements

Several enhancements can be incorporated into future versions of the proposed system to further improve functionality and scalability:

1. Machine Learning Integration: Historical sensor data can be leveraged to implement machine learning–based models for **predictive dosing**, enabling proactive adjustment of dosing parameters and improved system stability.

2. Multi-Tank Support: The system can be extended to support **multiple aquariums** using a single controller, allowing centralized monitoring and control across multiple tanks or zones.

3. Water Change Automation: Automated water change functionality can be achieved through the integration of **solenoid valves and level sensors**, reducing manual intervention and improving maintenance efficiency.

4. Mobile Application: A dedicated **mobile application** can be developed to provide a customized user interface and enhanced user experience beyond the standard ThingsBoard dashboard.

7. CONCLUSIONS

The proposed automated dosing system successfully demonstrates the application of **IoT technology** to **reef aquarium water quality management**. By integrating **threshold-based adaptive control** with **programmable scheduled dosing**, the system maintains pH within optimal ranges while ensuring precise nutrient supplementation. The **open-source system architecture** enhances accessibility for aquarium hobbyists and researchers, while IoT connectivity enables reliable **remote monitoring and control**.

Experimental results confirm the effectiveness and robustness of the system. Key performance outcomes include a **61% reduction in pH fluctuations**, an average **dosing accuracy of 98%** across all peristaltic pumps, and **99.8% system uptime** over a 30-day continuous operation period. The inclusion of both a **local LCD interface** and a **cloud-based dashboard** further improves usability and system transparency.

Overall, the proposed system represents a **cost-effective and scalable alternative** to commercial aquarium automation solutions, delivering professional-grade water parameter management at a fraction of the cost. Future work will focus on **expanding the range of monitored parameters** and implementing **predictive control algorithms** to further enhance system performance and autonomy.

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Conflict of Interest: The authors declare no conflicts of interest.

Ethical Approval: All aquarium maintenance followed ethical guidelines for marine life care.

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BIOGRAPHIES

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