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AI-Driven Sustainable Ecosystem for Aquaculture with Nutrient Recycling

Aniket Halder[1], Harsh Bargude[2], Mayuri Jagdale[3], Nimay Ghadigaonkar[4]
Saraswati College of Engineering, Kharghar, India

Abstract: ***Aquaculture plays a crucial role in global food production, but maintaining optimal water quality in fish ponds remains a major challenge. Traditional monitoring methods rely on manual inspection and periodic testing, which are time-consuming and often fail to detect sudden changes in water conditions. This paper presents an AI-Driven Sustainable Ecosystem for Aquaculture with Nutrient Recycling, an intelligent system that integrates Internet of Things (IoT), Machine Learning (ML), and web technologies for real-time monitoring and automated control of aquatic environments. The system utilizes sensors to continuously measure water quality parameters such as pH, turbidity, temperature, and total dissolved solids (TDS). Data is processed using a Raspberry Pi controller that triggers automated responses such as UV disinfection and filtration when unsafe conditions are detected. Additionally, a lightweight computer vision model using YOLO and TensorFlow Lite identifies floating debris using a Raspberry Pi camera. The system also introduces a sustainable nutrient recycling module that converts fish waste into organic fertilizer for plant irrigation. A web-based dashboard provides farmers with real-time monitoring, alerts, and remote-control capabilities. The proposed system improves water quality management, reduces manual labour, and promotes environmentally sustainable aquaculture practices.***

Keywords: ***Aquaculture, Internet of Things (IoT), Machine Learning, Water Quality Monitoring, Raspberry Pi, Nutrient Recycling.***

I. INTRODUCTION

Aquatic ecosystems play an important role in biodiversity, environmental balance, and sustainable fish farming. Maintaining good water quality in aquaculture systems is essential for the health and survival of aquatic organisms. However, fish ponds are highly sensitive to changes in environmental conditions such as pH levels, turbidity, temperature, and dissolved solids. Sudden variations in these parameters can negatively impact fish health and lead to economic losses for farmers.

Traditional water monitoring methods involve manual testing and observation. These methods are slow, labour-intensive, and reactive rather than preventive. In many cases, farmers become aware of water contamination only after fish health begins to deteriorate. Therefore, there is a need for an automated and intelligent monitoring system that can continuously analyze water conditions and take corrective actions.

Recent technological developments in the Internet of Things (IoT) and Machine Learning (ML) provide new opportunities for building smart aquaculture systems. IoT devices allow real-time data collection from sensors, while machine learning models can analyze patterns and detect anomalies in the aquatic environment. Combining these technologies with automation can significantly improve aquaculture management.

This study proposes an AI-Driven Sustainable Ecosystem for Aquaculture that integrates IoT sensors, machine learning algorithms, and web-based monitoring tools. The system continuously tracks water parameters, detects floating debris using computer vision, and automatically activates purification mechanisms when necessary. Additionally, the system promotes sustainability by recycling fish waste into plant nutrients, creating a circular ecosystem.

II. PROBLEM STATEMENT

Small and medium-scale aquaculture systems often lack affordable and integrated technologies for real-time water quality monitoring. Existing solutions are either expensive, limited in functionality, or require manual supervision. As a result, farmers face several challenges including delayed detection of harmful water conditions, high maintenance costs, and increased risk of fish mortality. Another limitation of traditional aquaculture systems is the inefficient management of fish waste and nutrient pollution. Waste accumulation leads to poor water quality and environmental damage if not properly managed.

Therefore, there is a need for a cost-effective, automated, and sustainable solution that can monitor water conditions in real time, perform corrective actions automatically, and utilize fish waste efficiently for agricultural purposes.

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III. LITERATURE SURVEY

Several research studies have explored the application of IoT and machine learning technologies in aquaculture systems.

One study presented AquaBot, an IoT-based monitoring system that collects data from sensors such as pH, temperature, and turbidity and displays the results through a cloud dashboard. The system demonstrates how real-time monitoring and alert mechanisms can assist farmers in maintaining water quality.

Other research has focused on the use of Raspberry Pi and sensor networks for monitoring aquatic parameters. These studies highlight practical challenges such as sensor calibration, biofouling, and the need for analog-to-digital converters when using analog sensors.

Research on UV disinfection systems shows that ultraviolet treatment is an effective method for eliminating harmful microorganisms in aquaculture without introducing chemicals. Automated control of UV lamps and filtration systems can help maintain safe water conditions.

Recent studies have also explored computer vision techniques such as YOLO object detection models to identify floating debris and environmental anomalies in water bodies. Lightweight models optimized for edge devices can run efficiently on platforms such as Raspberry Pi.

Additionally, research on aquaponics and nutrient recycling demonstrates that fish waste can be converted into organic fertilizer or used for plant irrigation, creating a sustainable circular ecosystem.

Although these technologies exist individually, there is still limited work integrating IoT monitoring, AI-based detection, automation, and nutrient recycling into a single system. The proposed system aims to bridge this gap.

IV. PROPOSED SYSTEM / METHODOLOGY

The proposed system integrates IoT sensors, machine learning models, and automation technologies to create a smart aquaculture ecosystem.

The methodology consists of several interconnected phases:

A. Data Acquisition

Water quality sensors measure parameters such as pH, turbidity, temperature, and TDS. These sensors are connected to a Raspberry Pi microcontroller that collects the readings continuously.

B. Data Processing and Threshold Analysis

The collected data is filtered and processed to remove noise. Threshold values are defined for safe operating ranges. If sensor readings exceed the threshold values, corrective actions are triggered automatically.

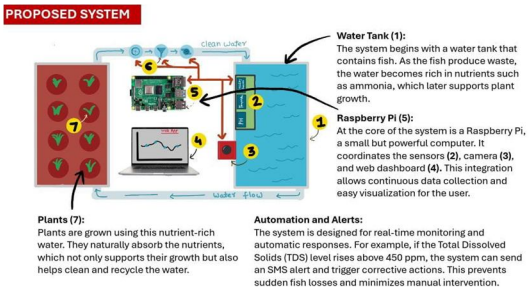


Fig. 4.1 Proposed Architecture

C. Automation and Control

The system activates devices such as UV disinfection lamps and filtration pumps to restore water quality. Automation continues until the parameters return to safe levels.

D. Machine Learning Object Detection

A Raspberry Pi camera captures real-time images of the pond surface. A lightweight YOLO or TensorFlow Lite model analyzes the images to detect floating debris or foreign objects.

E. Cloud Storage and Data Visualization

Sensor data and system logs are stored in a database and synchronized with a cloud server. A web dashboard allows users to view real-time data and historical trends.

F. Nutrient Recycling System

Fish waste collected from the filtration system is processed and used as fertilizer for plants. The treated water can be reused for irrigation, promoting sustainable resource utilization.

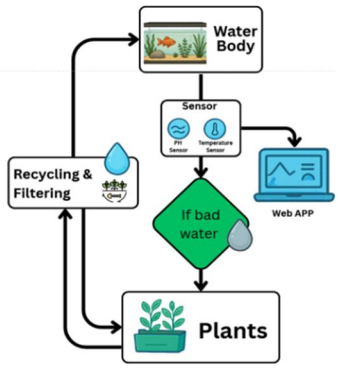


Fig.4.2 Flow

V. IMPLEMENTATION

The system is implemented using a combination of hardware and software technologies designed for efficient IoT operation.

The Raspberry Pi acts as the central processing unit that collects sensor data and controls actuators. Several sensors including pH, turbidity, temperature, and TDS sensors are connected through an ADS1115 analog-to-digital converter for accurate measurements.

The software architecture is developed primarily using Python due to its extensive support for IoT and machine learning libraries. A Flask web framework is used to build the monitoring dashboard, allowing users to visualize real-time data and control system components remotely.

For computer vision tasks, OpenCV and TensorFlow Lite are used to detect debris from camera images. These lightweight models enable real-time inference directly on the Raspberry Pi without requiring cloud processing.

Data is stored using SQLite, a lightweight embedded database suitable for IoT systems. Automated alerts are sent to users through SMS services such as Twilio API whenever abnormal water conditions are detected.

The combination of these technologies provides a reliable and cost-effective platform for smart aquaculture monitoring.



Fig. 5.1 System

VI. RESULTS AND DISCUSSION

The prototype system demonstrates the feasibility of integrating IoT sensors, machine learning, and automation into a single aquaculture management platform.

The system successfully performs:

1) Real-time Monitoring & Proactive Alerts: The system successfully tracks pH, turbidity, temperature, and TDS in real-time. Crucially, the threshold analysis proved effective; for instance, when TDS levels exceed the safe operating range of 450 to 600 ppm, the system reliably issues SMS notifications to the user, ensuring immediate awareness. Automated activation of purification systems

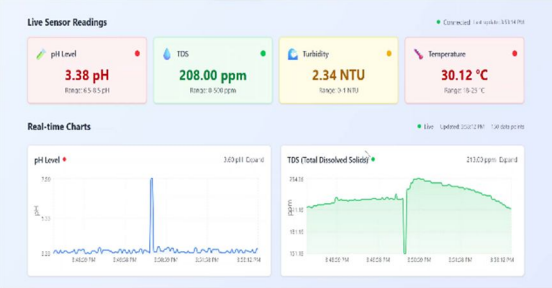


Fig. 6.1 Web UI (Green indicates water condition for that sensor is normal, Yellow indicates needed attention And Red signal indicates critical condition and needs immediate action)

2) Detection of floating debris using computer vision:

3) Visualization of environmental data through a web dashboard

Initial testing shows that automated responses can significantly reduce the risk of water contamination and improve fish survival rates. The computer vision module effectively detects surface debris under various lighting conditions.

Additionally, the nutrient recycling component provides an environmentally friendly method of utilizing fish waste, contributing to sustainable aquaculture practices.

Although the prototype demonstrates promising results, further improvements such as long-term sensor testing and large-scale deployment are required for commercial implementation.

VII. CONCLUSION

This paper presents an AI-driven smart aquaculture system designed to improve water quality monitoring, automate purification processes, and promote sustainable resource management. The integration of IoT sensors, machine learning models, and web-based dashboards allows continuous monitoring and rapid response to environmental changes.

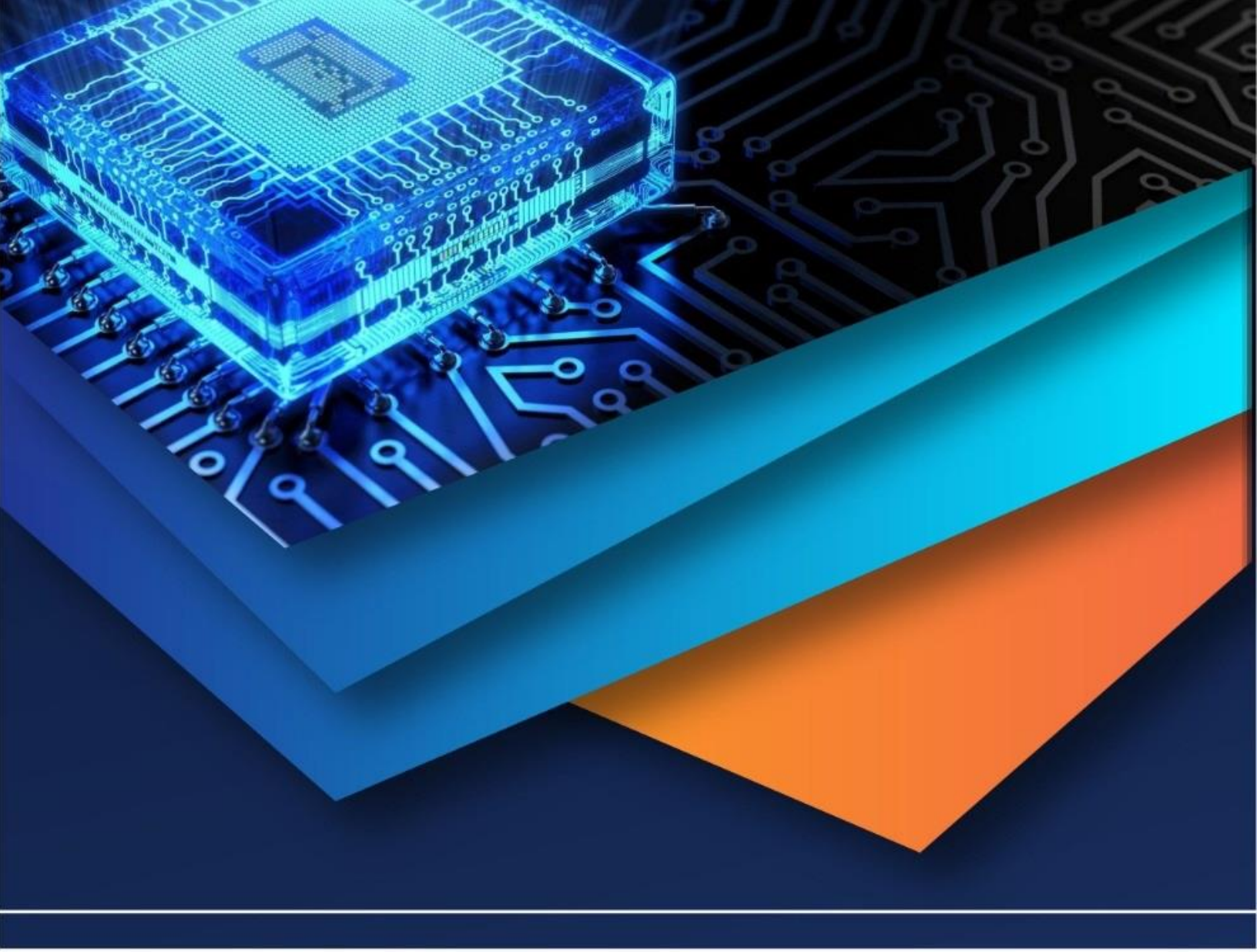
The proposed system reduces manual labor, increases operational efficiency, and supports sustainable aquaculture through nutrient recycling. By converting fish waste into plant fertilizer and enabling automated water treatment, the system creates a circular ecosystem that benefits both aquaculture and agriculture.

Future work will focus on improving machine learning models for more accurate environmental prediction, integrating additional sensors such as dissolved oxygen sensors, and testing the system in large-scale aquaculture farms.

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