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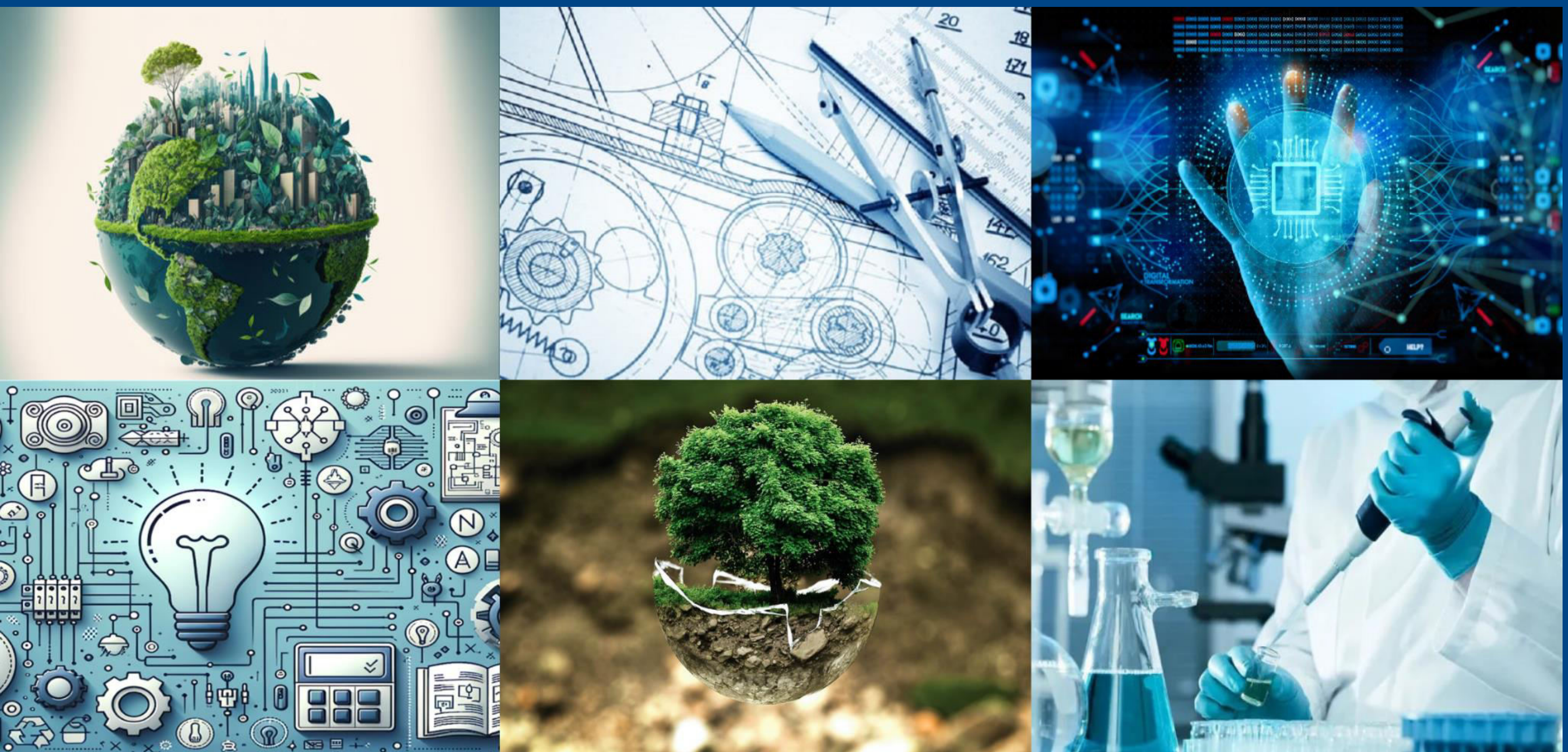

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Smart Aquaculture: Harnessing IoT and Machine Learning for Next-Generation Automation

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ABSTRACT: Smart aquaculture could change fish farming by allowing for greater productivity, sustainability, and real-time decision-making. This project is an agile aquaculture monitoring and automation system that demonstrates the capability of Internet of things (IoT) with Machine Learning (ML) models for optimal water management. It operates on the principle of amalgamating diverse built-in sensors that continuously sense key water parameters such as Total Dissolved Solids (TDS), pH value, turbidity, and temperature. The readings from these sensors are transmitted to a processing unit for analysis using a microcontroller-based platform. rewhich are machine learning models. The data were digitally processed and the predictive insights for all computations as well as individual sensor measurements remotely sent to a server for monitoring and visualization. It forms the basis for real-time alerts and assists in decision making that could help alleviate negative conditions for aquatic life. By combining IoT and ML, the system reduces manual intervention and increases operational efficiency as well. It optimizes the health and productivity of aquaculture systems. This indicates the use of smart technology and the steps towards sustainable aquatic farming which are now being taken in aquaculture.

KEYWORDS: IoT, Smart Aquaculture, Machine Learning, ESP32, Water Quality Monitoring, Random Forest, Automation

I. INTRODUCTION

Aquaculture is among the world's fastest-growing forms of food production. Aquaculture depends on various water quality parameters to grow aquatic organisms but also on various water quality characteristics like pH, temperature, turbidity, and TDS being in favourable abundance for the optimal growth of aquatic organism. Being living organisms, and sensitive to environmental variables, even small variations in these parameters can lead

To fish stress, illness, w and higher mortality rates. In the conventional aquaculture system, water quality is detected manually and periodically; this process is time-consuming, labour-intensive, and often fails to respond promptly to rapid environmental changes. Additionally, traditional systems are not automated and do not facilitate intelligent decision-making processes, making them incompatible with modern large-scale aquaculture farms. The rapidly evolving field of the Internet of Things (IoT) has led to the creation of near-real-time monitoring systems capable of collecting and transmitting environmental data in a timely manner. Nonetheless, most existing IoT systems facilitate data collection and visualization but neglect to apply advanced analytical approaches for prediction and decision-making. This is one of the limitations that should be avoided and can be overcome by integrating Machine Learning (ML) with IoT to provide better intelligent systems.

The proposed smart aquaculture system will include real-time monitoring, intelligent data and automatic control of water quality IoT sensors integrated with Machine Learning algorithms. This system collects real-time data from several sensors, uses ML models to process and classify the the water conditions accordingly, and provides timely alerts and control actions. The integration of sensing, computing and automation can address the efficiency and reduce manual operation in aquaculture for sustainability.

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II. LITERATURE REVIEW

The literature survey focuses on analyzing existing research and systems developed for aquaculture monitoring using IoT and Machine Learning technologies. Various approaches have been studied to understand how water quality parameters are monitored, controlled, and analyzed in real-time. This helps identify the strengths and limitations of current systems, such as the lack of automation, high cost, limited scalability, and absence of predictive intelligence. Based on these insights, the need for an efficient, cost-effective, and intelligent aquaculture monitoring system was established.

Author & Year	Approach / System	Limitations
Cheng et al., 2024	Edge-cloud system with Federated Learning for shrimp aquaculture	Privacy preserved, but costly and complex , based on various clients
Bachtiar et al., 2022	IoT-based aquaculture monitoring (pH, Temp, Turbidity) using NodeMCU/Arduino + Cloud	Only monitoring, no automation or prediction
Sohail et al., 2021	IoT + GSM-based fish farming monitoring system	Low cost, but no predictive intelligence
Tolentino et al., 2021	IoT + LoRaWAN-based water monitoring and automatic correction system	Higher cost and system complexity
Daud et al., 2020	IoT-based smart aquarium monitoring system using sensors and wireless communication	Suitable only for small-scale systems
Gao et al., 2019	Intelligent IoT-based system for water quality prediction and control	Complex implementation and infrastructure dependent

III. METHODOLOGY OF PROPOSED SURVEY

Problem Statement

Many parameters of water quality helped in aquaculture productivity and sustainability. In traditional practices of aquaculture, such monitoring of these parameters is only performed periodically and does not provide continuous real-time information. This lag in monitoring often causes harmful environmental conditions to be discovered only at a later date when aquatic species show signs of stress, disease, or death. Although some Aquaculture monitoring systems are IoT-enabled, such as basic data collection and visualization. These systems are generally rule-based and rely on threshold values with little to no intelligent analysis or predictive action capabilities. As a result, they are unable to respond dynamically to active environmental changes or share proactive solutions. In addition, there are no automated controls or live alert systems here, which need human interference and thus leads to labour-intensive operations that are not very efficient. Another major challenge for farmers and the efficiency of operations is that large-scale aquaculture setups cannot be monitored remotely.

Thus, it is of paramount importance to enhance aquaculture practices through integrated smart aquaculture systems by combining Internet of Things (IoT)-based real-time monitoring with machine learning-enabled prediction and automation. This system should be able to guarantee automated monitoring of water quality in real-time, timely alerts and automatic control when critical parameters exceed acceptable levels, implementing the best practices to ensure high productivity with minimal food losses while maintaining sustainability.

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Objectives

- To devise and implement an IoT-based smart aquaculture system to maintain online 24 ×7 monitoring of water quality parameters such as TDS, pH, turbidity, and temperature based on sensor networks.
- To apply Machine Learning algorithms , especially Random Forest, to analyze sensor data and predict water quality precisely in safe, unsafe, and dangerous conditions.
- To allow reliable data real-time transfer into a cloud/server platform for remote monitoring, visualization activities , and historical data analysis.
- Automatic control systems , such as relay-controlled water pump operation and notification systems , were implemented to retain the desired water conditions without human involvement.
- To improve aquaculture productivity and sustainability by decreasing the effort required from humans and increasing decision-making through intelligent monitoring that minimizes the risk of fish death.

Architecture Diagram

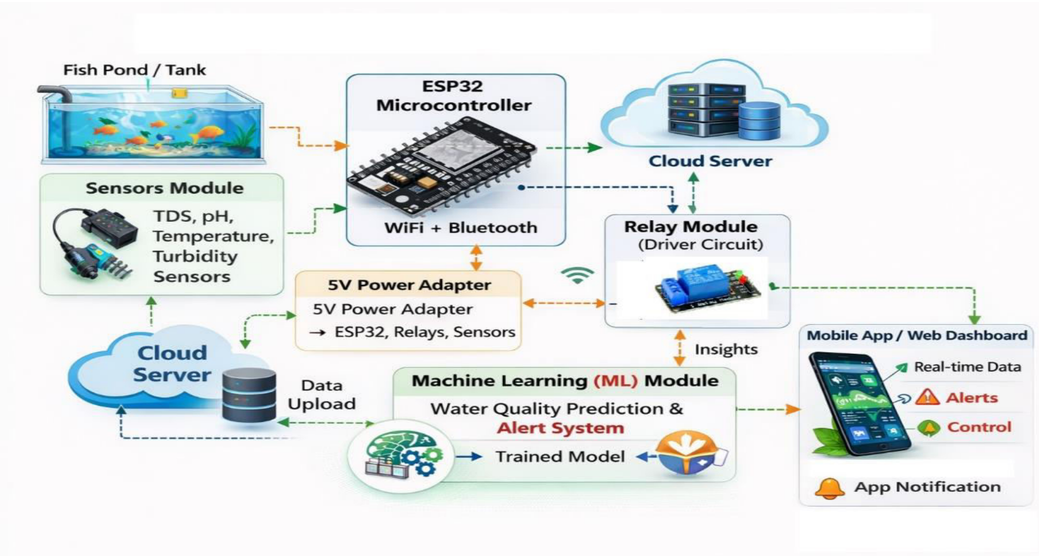

Fig1. Architecture Diagram

The proposed smart aquaculture system implementation is structured as follows:

1**. Sensor Data Acquisition:** Water quality sensors (TDS, pH, turbidity, and temperature) collect real-time data from the aquaculture environment.
2. **Data Processing (ESP32):** The data from the sensors were processed and formatted directly on the ESP32 microcontroller.
3**. Data Transmission:** The data are then sent over Wi-Fi to a cloud/server platform for storage and remote access.
4**. Machine Learning Analysis:** Trained Random Forest model processes the data and provides a label indicating whether the water quality is safe, unsafe, or dangerous.
5. **Automated Control:** Based on the sensor values, the relay module can be activated using the designed app to switch the water pump.
6**. Monitoring and Alerts:** It enables real-time monitoring via mobile and web applications, alerting relevant personnel to the detection of abnormal conditions.
7. Data Storage and Visualization: The cloud-based system simulates thousands of network scenarios and stores all data and predictions on dashboards for analysis.

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IV. IMPLEMENTATION OF THE SYSTEM

Requirements for Software and Hardware
Hardware Requirements

- **ESP32 Microcontroller:** This is a 32 bit, high performance microcontroller with integrated Wi-Fi and Bluetooth features designed for Internet of Things (IoT) projects. It gathers sensor information and transmits it to cloud platforms for observation purposes.

Fig.2. ESP32 Microcontroller

- **Temperature Sensor**: Monitors the water temperature in real-time. Temperature directly influences fish metabolism and their oxygen availability.

Fig.3. Temperature Sensor

- **pH Sensor:** It uses a pH scale to measure the acidity or alkalinity of water. Healthy aquatic environments require a regulated pH.

Fig.4. pH Sensor

- **Turbidity Sensor:** The Cloudiness or clarity of water from suspended particles. Turbidity lowers oxygen concentration in water.

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Fig.5. Turbidity Sensor

- **TDS Sensor**: Measures the total dissolved solids in water, indicating the purity level . TDS values may affect water quality and aquatic life.

Fig.6. TDS Sensor

- **Relay Module** : A stationary, sitting; not moving up and down manually. This enables the ESP32 to automatically switch the water pump on or off .

Fig.7. Relay Module:

- **Water Pump:** Circulates or delivers water as required by the system. In Aquaculture, it helps maintain good water conditions.

Fig.8. Water Pump

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• **Adapter** : Supplies the power required to operate the system components. This helps maintain a steady and smooth operation of the circuit.

Fig.9. Adapter

Software Requirements

• **Arduino IDE:** Utilized for programming and uploading code onto ESP32. Assisted with hardware testing and management.

• **Python (for Machine Learning model development):** to train machine learning models. Data also reduce the complexity of the analysis and predictability.

• **Libraries (Pandas, NumPy, Scikit-learn, Joblib):** Data Processing and Model Building. The trained model can be saved and loaded using the joblib .

• **Serial Communication (PySerial):** Enables serial communication with the ESP32. Reads real-time sensor data.

• **Web Server/API :** The Data Table is used to show and manage data online. Connects the system with users.

• **Cloud Platform:** Hub data and enable remote logging. It provides real-time access and analysis.

V. IMPLEMENTATION OF ML MODEL

If the tests were performed in real time, they would have provided accurate results; however, owing to the unavailability of labeled datasets in real time, one such simulated dataset was created, which covers standard ranges of water quality parameters such as TDS, pH, turbidity, and temperature. We labeled every data sample into three classes: safe, unsafe, and dangerous. Various Machine Learning algorithms were tested, such as KNN, SVM, and Random Forest, to compare the results. Of all these algorithms, the Random Forest predicted winners with the highest accuracy owing to its capacity to manage non-linear associations and provide resilient classification for diverse water conditions. Separate models were trained for each parameter to optimize the prediction performance and reduce the deployment complexity. To assess the performance, the dataset was split into training and testing sets. At the end of the training and validation, the best-trained models were saved using Joblib as follows: pkl files, which are loaded during real-time execution. The saved models are then fed with live sensor data received from the ESP32 for prediction and to help automate decision-making that directs control, simulating real water quality conditions.

MODEL ACCURACY COMPARISON

Accuracy Comparison for different water quality parameters using Random forest, SVM, and KNN models. The Random Forest classifier has the highest accuracy (1.0 in most cases), KNN performs decently with very high accuracy, whereas SVM yields less performance, especially for pH and temperature features.

Dataset	Random Forest	SVM (Support Vector Machine)	KNN (K-Nearest Neighbors)
TDS	0.999167	0.998333	0.999167
pH	1.000000	0.981667	0.999167

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Turbidity	1.000000	0.992500	0.999167
Temperature	1.000000	0.985000	1.000000

TABLE: MODEL ACCURACY COMPARISON

The chart shows the performance of three machine learning models (Random Forest, SVM, and KNN) with respect to different water quality outputs (TDS, pH, Turbidity and Temperature). Random Forest has slightly better overall coefficients and lower standard deviation than KNN, whereas SVM underperforms visibly for pH. this is the graph shown

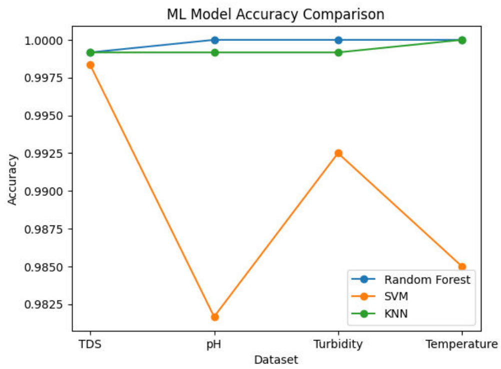

Fig 10: Graph of ML Model Accuracy Comparison

VI. IMPLEMENTATION OF BLYNK APPLICATION FOR REAL TIME MONITORING AND ALERTS

An interface that uses the Blynk platform to monitor aquaculture parameters in real time. Blynk cloud server using Wi-Fi and an authentication token to connect ESP32. Using widgets, the sensor values such as TDS, pH, turbidity tea, and temperature were shown on the Blynk dashboard. It features real-time visualization, enabling the remote monitoring of water quality. Threshold conditions can be defined to alert and notify instantly when the parameters exceed the safe limits. It also has a remote control capability, which allows users to toggle the water pump using the Blynk app.

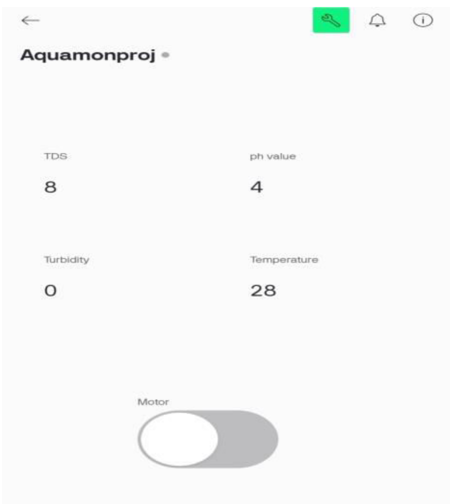

Fig.11. Blynk Application

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VII. FINAL OUTPUT: IMPLEMENTATION OF WEB INTERFACE

A web-inbased interface for storing, visualizing and real-webtime monitoring aquaculture data is based on php and HTML. In this step, sensor values and ML predictions are sent from the system to the server using HTTP POST requests which are then stored in a database. Here is an interface that will display real-time data logs such as TDS, pH, turbidity, temperature and predicted conditions. Predictive monitoring is provided for the system, thus classification results are displayed such as Safe, Unsafe, Danger. The dashboard can be accessed remotely via a browser, enabling users to monitor and make decisions at any time. In particular, this allows for data storage, a historical record, and better product reliability.

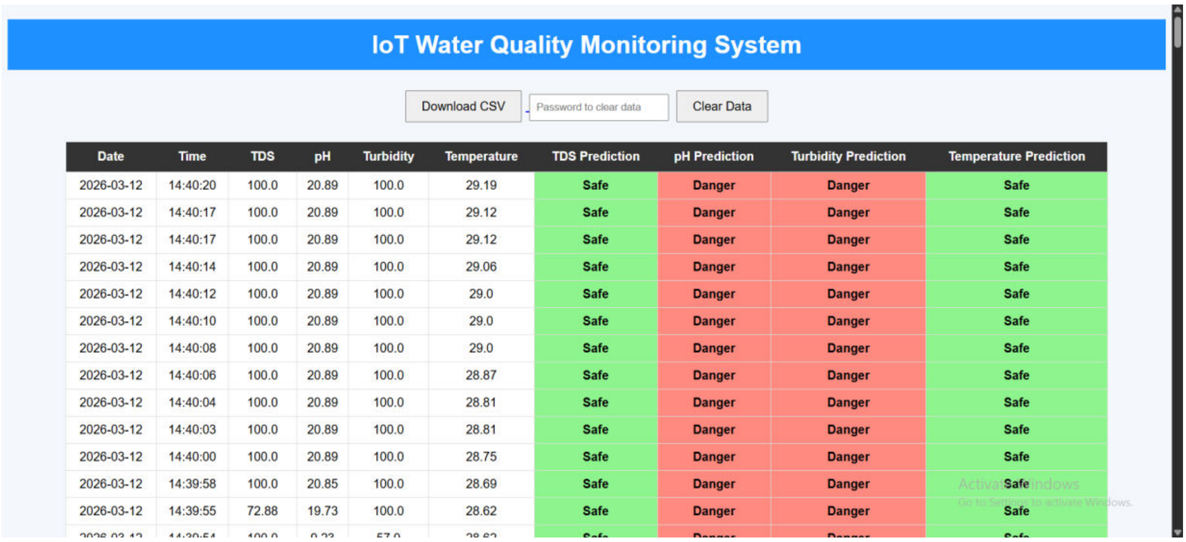

Fig.12. Final Output

VIII. CONCLUSION

The smart aquaculture system developed through this research proved to be an effective combination of IoT and Machine Learning that enables the continuous monitoring of water quality parameters such as TDS, pH, turbidity, and temperature along with intelligent control. This can be achieved due to the combination of ESP32 with sensors, which allows for instantaneous data retrieval and transfer, while additionally implementing Machine Learning models contributes significantly to the implemented decision-making by providing precise classifications of water conditions. Random Forest showed to have the best accuracy and consistency among the tested algorithms, therefore, it is ideal for that application.

This system not only minimizes the need for manual monitoring but also sends timely alerts and automates control actions like water pump through a relay module. Cloud computing integration together with mobile/web applications support remote access and visualization of the data, thus providing improvement in user convenience and system reliability. In conclusion, this solution increases productivity, reduces fish mortality and enables sustainable and efficient aquaculture.

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