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Smart Aquaponics with Integration of AI and IoT for Yield Enhancement through Real-Time Monitoring and Decision Support

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Abstract—Technological advancements have become the key factor for major changes and upgradations in numerous industries and domain. Agriculture is no exception, technology stacks like IoT and AI are being integrated into agriculture up to a large extent starting from best crop prediction to crop health analysis, nutrient analysis to yield prediction. The intervention of technology is even more prominent in various smart agriculture methods including aquaponics, hydroponics, etc. Aquaponics is a sustainable method of agriculture, that combines aquaculture (fish farming) with hydroponics. This innovative system allows for the cultivation of fish and plants simultaneously, enabling a symbiotic relationship that enhances nutrient recycling. To lead the way for smart aquaponics, as technology continues to advance, the integration of artificial intelligence (AI) and the Internet of Things (IoT) holds immense potential for transforming traditional aquaponics into smart aquaponics. By harnessing real-time monitoring and decision support, AI and IoT can revolutionize various aspects of aquaponics that includes a major paradigm shift in agriculture, promising increased productivity, reduced resource usage, and improved environmental conservation. This article explores the transformative potential of leveraging AI and IoT technologies in aquaponics systems for yield enhancement, sustainability, and overall efficiency.
Keywords- Aquaponics; Hydroponics; Aquaculture; IoT; AI; Yield Enhancement; Decision Support.

I. Introduction

A revolutionary method of food production, aquaponics is a sustainable agricultural option. This ground-breaking method produces a peaceful environment where fish and plants coexist and benefit from one another by synergistically merging aquaculture and hydroponics. In aquaponics, the plants themselves organically clean the fish's water while the fish waste supplies vital nutrients for plant development. This closed-loop ecosystem is an environmentally beneficial substitute for conventional agricultural practices since it considerably eliminates the demand for chemical fertilizers and minimizes water waste. Aquaponics is a low-impact farming method that has significant potential for tackling the problems of food security, environmental degradation, and water shortages. As such, it will play a crucial role in the development of sustainable agriculture in the future [1][2]. The introduction of AI and the IoT in agriculture has resulted in a fundamental shift in how farming and food production are approached. AI has made it possible to make data-driven decisions and practice precision agriculture. By linking sensors and IoT devices throughout farms, data on soil conditions, weather patterns, crop health, and livestock activity can be collected in real-time, providing farmers with crucial insights. Additionally, AI-powered autonomous equipment and robots are revolutionizing tasks like planting, harvesting, and agricultural monitoring, which leads to increased productivity and cheaper human costs. In order to fulfil the increasing demands of the global population, a more sustainable, effective, and resilient food production system is promised with the use of AI and IoT in agriculture [3-5]. The promise of aquaponics as a sustainable farming method is advanced by IoT-based sensors and real-time monitoring. Important environmental factors may be continually monitored in an aquaponics system by integrating a network of sensors and devices. These sensors track important parameters including pH levels, dissolved oxygen levels, temperature, and nutrition concentrations. These IoT devices' real-time data collection offers insightful information on the health and performance of the fish and plants in the system. Remote access to this data allows farmers and aquaponics experts to react quickly to any changes or abnormalities that may occur. With this kind of real-time monitoring, producers are able to take preventative action, avert possible problems, and improve the growing conditions for plants and fish [6][7].

In order to handle and analyze the enormous quantity of data gathered from IoT sensors, AI-driven data analytics in aquaponics leverages the power of cutting-edge algorithms and machine learning techniques. Using this method, crop growth, fish health, and system behavior can all be predicted, making it easier to spot anomalies and possible problems early on. AI-driven data analytics enables farmers to make knowledgeable decisions, allocate resources efficiently, and improve system performance for maximum output and sustainability [8][9]. Smart aquaponics Decision Support Systems (DSS) use AI and IoT technology to provide farmers with feedback and recommendations in real-time. With the help of these intelligent systems, water management, nutrition supplementation, fish feeding schedules, and pest control can all be optimized, increasing system efficiency. Farmers may make data-driven choices, optimize resource use, and eventually increase yields and achieve economic sustainability by incorporating DSS into aquaponics operations. In conclusion, aquaponics has great promise for revolutionizing sustainable agriculture through the integration of AI and IoT technology. Adopting real-time monitoring and automated decision assistance enables optimized resource usage, improving yields and resulting in more efficient and environmentally friendly aquaponics systems [10][11].

In this article we propose a system for a comprehensive approach for yield improvements in aquaponic farms leveraging cutting edge technology stacks like IoT and AI, we will be using a curated merger of hardware and software technologies in the overall system architecture to extract meaningful metrics from the aquaponics to aid in the real time monitoring and decision making, in order to improve the overall efficiency and yield to a plausible extent.

II. Review of Literature

This literature review provides a quick overview of aquaponics. According to the body of research on the topic, aquaponics is an important bio-integrated system that integrates aquaculture with hydroponic plant production. This literature study examines the creation of an intelligent aquaponics system that combines plant and fish cultivation to solve issues of food security and sustainability in urban settings. The system monitors and regulates the quality of the water, the amount of light, and the fish feed by using a variety of sensors, actuators, and microcontrollers [12][13]. In this literature [14], it is discussed the significance how AI, IoT, and robotics are revolutionizing agriculture to address issues like land scarcity, climate change, and food security. In terms of managing soil, identifying agricultural diseases, planting, harvesting, and storing crops, they offer great productivity, real-time monitoring, and automation. The study paves the way for sustainable and cutting-edge farming practices by providing an overview of current implementations, prospects, problems, and future research directions in the agriculture sector utilizing these technologies. The study demonstrates IoT and AI-based modern agricultural approaches have changed farming methods, enhancing productivity and sustainability in the agricultural industry [15].

The paper describes the use of IoT technology in aquaponics for ongoing water quality monitoring is included in the literature study. The symbiotic interaction between fish, plants, and bacteria in aquaponics, a sustainable food production paradigm combining hydroponics and aquaculture, depends on ideal water quality conditions. The study focuses on using commercial circuits and probes to detect dissolved oxygen (DO), pH, and water temperature with smart water-quality sensors, which include a Raspberry Pi [16]. The study [17] describes about the design of an automated aquaponics system employing Internet of Things technology to regulate pH levels and temperature for Nile Tilapia and Romaine Lettuce is covered in the literature study.

A study on Smart Aquaponics, which combines fish and plants with IoT technology, is introduced. The project intends to create a smart aquaponics system with sensors and actuators that users can manage via smartphones. This system makes advantage of a symbiotic cycle between plants and fish. To improve wireless aquaponics for real-time forecasts, recommendations include edge and fog-based nodes, ML models, LoRa-based sensors, and gateway-based architecture is implemented [18][19].

The study describes about the incorporation of Industry 4.0 technology into aquaponics is suggested by the literature assessment to increase output potential. By fusing AI and IoT technology, Decision Support Systems (DSS) play a significant role in promoting smart aquaponics. DSS revolutionizes farmer management of their aquaponics systems via the use of AI and IoT, resulting in high-yield and sustainable food production [20][21]. Aquaponics, a sustainable food production technique that combines aquaculture and hydroponics, is discussed in the literature review together with the rise of IoT in agriculture. Productivity and sustainability have increased thanks to smart agricultural technologies. Optimizing the system balance for high production and minimal environmental effect is a challenge. The importance of smart aquaponics for food production worldwide is emphasized in the study, as is the requirement to address agricultural issues and possibilities [22][23].

The review study describes about the case study of analysis at Namibia's Namib Desert's potential for agriculture. Due to the high prices of inorganic fertilizers, it highlights the difficulties smallholder farmers have adopting hydroponics and looks at the possibilities of organic nutrient sources like vermicompost. The assessment also emphasizes the value of the plentiful fog water as an irrigation resource and its contribution to desert greening [24]. The study [25-27] states that by combining hydroponics and aquaculture in a closed-loop system, smart aquaponics significantly advances sustainable agriculture. Compared to traditional agricultural techniques, this novel strategy maximizes resource efficiency while preserving water and reducing environmental effect. Fish and plants have a symbiotic interaction that makes nutrient cycling effective and decreases the need for artificial fertilizers. Therefore, smart aquaponics helps to conserve water and protect the environment by reducing water waste and eliminating fertilizer runoff.

The study focuses on IoT-based aquaponics systems, which are essential for producing an environment that is balanced for the growth of both plants and fish. The system independently checks and controls water quality using sensors and actuators. Remote monitoring is made possible via its online and mobile applications, and solar power increases its sustainability. The system's dependability, effectiveness, and economic viability have received praise from experts and users, making it a potential option for sustainable agriculture [28][29].

III. SYSTEM ARCHITECTURE

As shown in the Fig 1, the overall system architecture consists of several hardware nodes, each responsible for extracting physical world data of specific metrics which is then to be used at certain levels during further analysis. Individual briefings about the data sources are attached in the following sub sections. The system architecture begins with the setup and powering of the system. Once this is complete, each data source or sensor node will be able to communicate and share the extracted information with the gateway. This communication will be facilitated through their inbuilt LoRa module, following a hybrid topology. The system architecture of the IoT includes a gateway that functions as a centralized point for collecting data from sensor nodes and other sources. Its main responsibility is to receive the data transmitted by the sensor nodes and ensure its accuracy and completeness. This verification process guarantees that the accumulated data is reliable before further processing or transmission to the cloud. With the utilization of the LoRa module and a hybrid topology approach, the system establishes a robust and efficient network for seamless communication between the sensor nodes and the gateway.

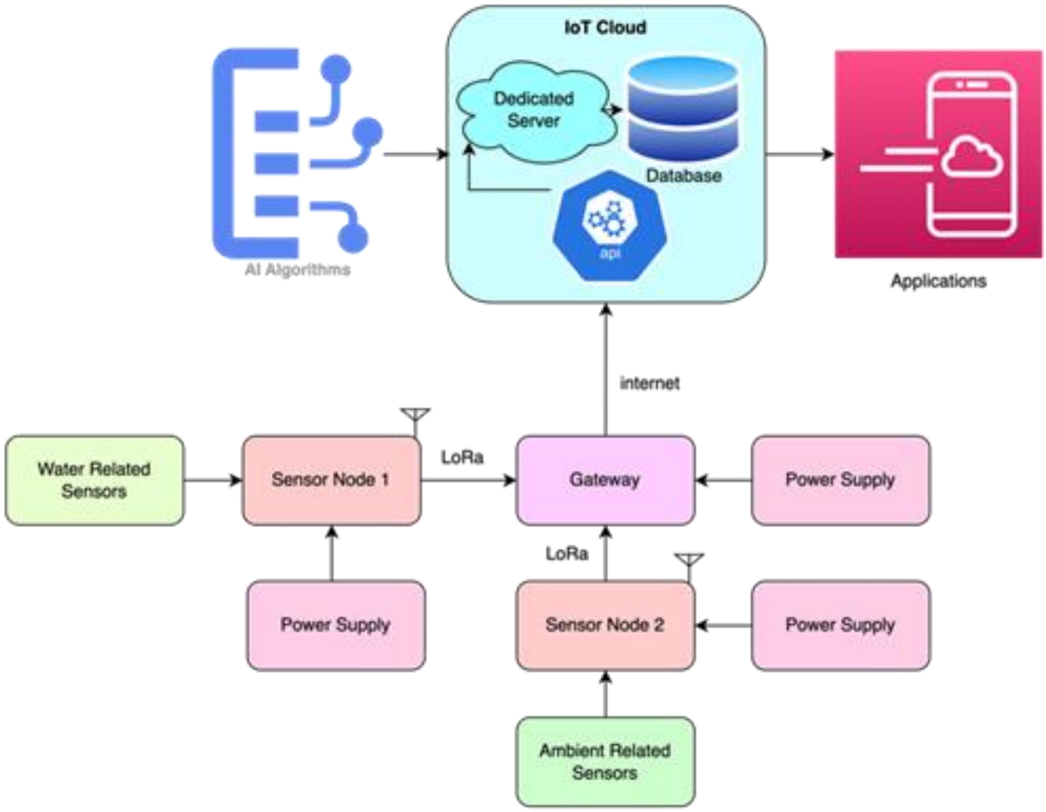

Figure. 1 Overall System Architecture

This architecture enables efficient monitoring, tracking, and analysis of the gathered information through seamless data transmission and sharing. Additionally, the gateway plays a crucial role in connecting the system to the cloud, acting as an intermediary between the sensor nodes and the cloud infrastructure. By securely transmitting the accumulated data to the cloud, it allows for storage, analysis, and retrieval of the information.

A. Sensor Node 1

As depicted in Fig. 2, sensor node 1 will be the node which will be responsible for extracting and be the data source for all information related to the water in the aquaponic farm.

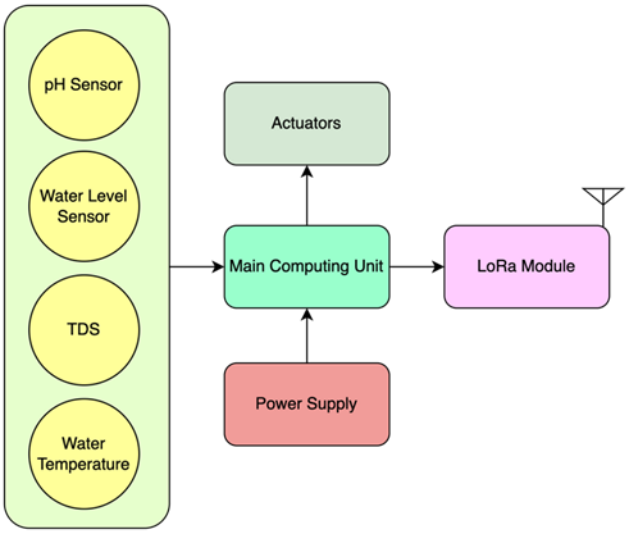

Figure. 2 Sensor Node 1

It will primarily comprise of a main computing unit for processing and extracting the data from the attached sensors including pH sensor to get the current pH value of the water, water level sensor to provide the water level of the pond, TDS sensor to provide the current Total Dissolved Solid amount of the water, water temperature sensor to provide the current water temperature of the pond. Following the data extraction from the attached sensors, the main computing unit will use the integrated LoRa module to share the information wirelessly with the gateway.

B. Sensor Node 2

As depicted in Fig. 3, sensor node 2 will be the node which will be responsible for extracting and be the data source for all information related to the environment in the aquaponic farm. It will primarily comprise of a main computing unit for processing and extracting the data from the attached sensors including ambient temperature sensor to provide the current ambient temperature of the aquaponic farm, ambient humidity sensor to provide the current ambient humidity of the aquaponic farm, light intensity sensor to provide the amount of light present inside the aquaponic farm. Following the data extraction from the attached sensors, the main computing unit will use the integrated LoRa module to share the information wirelessly with the gateway.

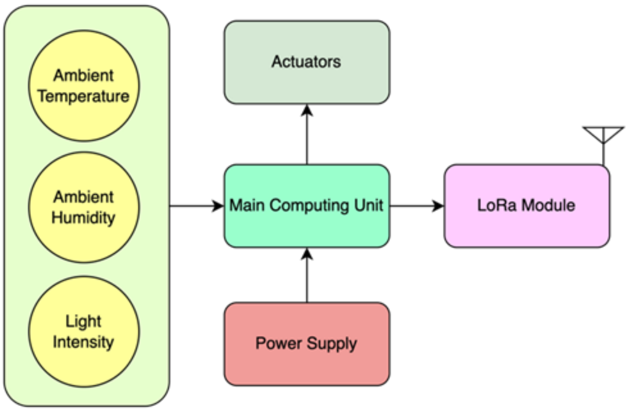

Figure 3. Sensor Node 2

C. Gateway

As depicted in the Fig. 4, the gateway will be responsible for collecting the data transmitted by the sensor node 1 and sensor node 2 using its integrated LoRa module, check the reliability of the data and the data origin source, and log the same into the IoT cloud using an integrated internet module through dedicated POST APIs hosted in the server.

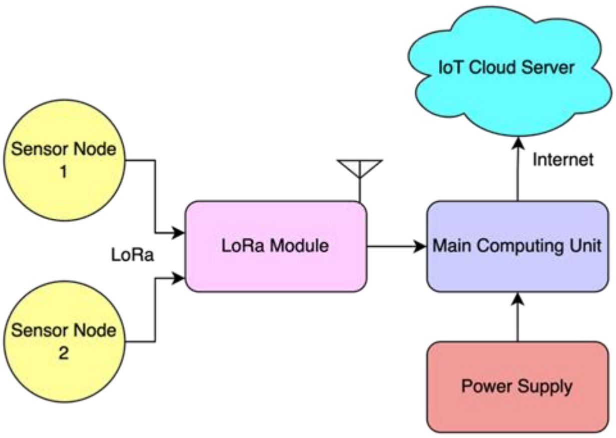

Figure 4. Gateway

IV. HARDWARE IMPLEMENTATION

To achieve seamless integration and maximum efficiency, we meticulously designed and developed customized hardware for the implementation of the proposed network architecture. This involved the creation of a bespoke PCB, where we integrated all necessary peripherals such as sensors, power supply arrangement, microcontrollers, wireless modules, and antennas. By combining these components into a single custom-made PCB, we aimed to eliminate the potential risks associated with power loss or data corruption due to leaks or unexpected interferences. The dedicated hardware design allows for a more robust and reliable network infrastructure, ensuring uninterrupted communication and data transfer. The sensors in our system have been integrated using the preferred communication protocols such as SPI and I2C. These protocols ensure efficient and reliable data transfer between the microcontrollers and the sensors. To further enhance the communication capabilities, we have opted to utilize UART through software serial methods for wireless data transmission. This decision was made to avoid any interference that could occur during the debugging and programming processes of the microcontrollers. By employing these communication techniques, we aimed to be able to achieve seamless and uninterrupted connectivity between the sensors and the microcontrollers, ensuring optimal performance of our system. The sensor nodes and the gateway are connected wirelessly using the 433MHz LoRa (Specific to the country India). Attached in the following sub sections are the hardware implementation of the said nodes and components.

A. Sensor Node

As depicted in the Fig. 5, the sensor node has been specifically engineered and constructed to incorporate all the necessary sensors in one printed circuit board (PCB) including pH sensor, Ambient Temperature/Humidity sensor, Water Level Sensor, and TDS sensor. By seamlessly integrating these sensors, the extracted data is efficiently and accurately fed into the main computing unit. For this purpose, we have implemented the ATmega328 microcontroller. At regular intervals, the main computing unit securely transmits encrypted packets, encompassing all the vital sensor information, to the gateway.

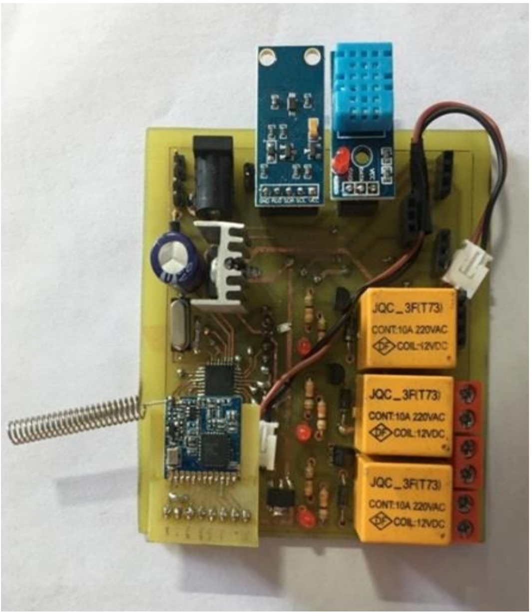

Figure 5. Sensor Node

This streamlined communication process is made possible through the utilization of a 433 MHz LoRa module. The sensor node has also been equipped with actuation controls through the utilization of relays. These relays can be programmed in advance to initiate certain actions when specific conditions are fulfilled. For instance, they can be employed to regulate a water pump to maintain water levels in case of depletion. This integration of actuation controls provides efficient and automated responses to ensure optimal operation of the system, contributing to enhanced performance and convenience.

B. Gateway

Depicted in Fig. 6 is the gateway of the system architecture, which is responsible for accepting data being shared by the sensor nodes using its integrated LoRa module, process it through its computing units and logs the same into the IoT cloud. To receive the data through the integrated LoRa module and process it uses its main computing unit which is an atmega328 SMD chip. Following that, it creates secured packets and sends them to the integrated secondary computing unit which is an esp8266 module which provides the system with the internet capability using which the data packets created by the main computing unit are logged into the IoT server using the APIs. The gateway also has a physical display system which uses a LCD display to showcase crucial information and alert the user.

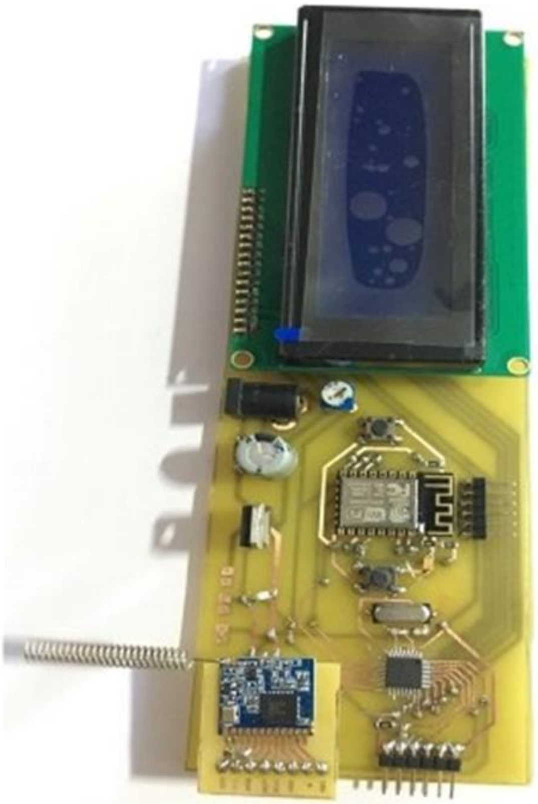

Figure 6. Gateway

V. Artificial Intelligence Implementation

Now that we have already discussed the implementation of sensor node 1 and sensor node 2 those will be extracting physical world data and sharing it with the gateway which in turn will further log that into the server creating our database. The same can now be exported into a .csv file and can be utilized for further analysis and training of an AI model. The

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training process plays a crucial role in enabling the AI model to effectively and accurately perform the desired tasks. The steps involved in training the AI model with the dataset are as follows:

A. Dataset Collection

By harnessing the gateway's logging capabilities for end node values, we seamlessly transfer this valuable data to an IoT cloud server. This dataset is then stored in a well-structured and organized manner within a database, providing us with a comprehensive collection of values from each data source. These values are neatly compiled into a user-friendly .csv file, ensuring easy access for efficient analysis and insights.

Additionally, we have incorporated a new column called "Optimal Level" to allow human input on the aquaponic farm's current condition. The Optimal Level represents a desired state, with higher values indicating superior conditions and lower values suggesting otherwise. This inclusion enhances our ability to assess and monitor the overall state of the aquaponic farm comprehensively and aids in creating a target feature for our AI model. The collected dataset and integration of the Optimal Level column contribute to the training procedure for our AI's capabilities of having a strong-featured target variable.

B. Dataset cleaning and pre-processing

Before proceeding with the analysis, it is crucial to ensure the cleanliness and integrity of our dataset. This involves meticulously cleaning and preprocessing the data to eliminate any anomalies, such as empty cells or corrupted values, as well as addressing other potential issues. Furthermore, it is important to remove and drop any unnecessary columns, such as the timestamp column in this use case as it cannot be considered a feature variable which can impact largely the target variable up to a large extent. By diligently carrying out these cleaning and preprocessing procedures, we can make sure to significantly enhance the reliability of our dataset and thereby the accuracy of our subsequent analysis.

To do so, we depend on well-known and extensively used libraries such as Numpy and Pandas, which offer a wide range of functionalities that simplify and optimise data processing and preparation. We can easily implement these preprocessing procedures by using the capabilities of Numpy and Pandas, saving important time and effort. Furthermore, by making use of the functionalities provided by these libraries, we may accelerate the dataset cleaning and preparation process, resulting in increased efficiency and reliability for our analysis. These libraries provide strong toolkits for many sorts of data-related activities, making them important professional tools and go to choice of many professionals in the relevant fields of data analysis and machine learning.

C. Data Visualization and Analysis

1. Correlation Matrix

In order to commence the process of data visualization and analysis, we will initially construct a correlation matrix. This matrix will facilitate the examination of the correlation between the various variables present in the dataset. By doing so, we will acquire a comprehensive understanding of the dataset and gain a concise overview of the extensive amount of data contained within its millions of rows. As depicted in Fig. 7, the following are the variables having plausible correlations.

a) Air Temperature Vs Water Temperature

The correlation matrix shows a high positive correlation of 0.61 between the air temperature value and the water temperature value, which can be stated as normal because the change in the air temperature (i.e., ambient temperature) is quite proportional with the water temperature value in a normal environment of the aquaponic farm.

b) Light Intensity Vs Air Temperature

The correlation matrix shows a mediocre positive correlation of 0.58 between the light intensity and air temperature value, which can be stated as normal because the change in light intensity refers to the change in artificial lightings or sunlight which is most certain to be proportional with change in air temperature.

c) Light Intensity Vs Relative Humidity

The correlation matrix shows a weak positive correlation of 0.26 between the light intensity value and the relative humidity value, which can be stated as normal because the change in the light intensity (i.e., artificial/sunlight) is inversely proportional with the relative humidity value in a normal environment of the aquaponic farm.

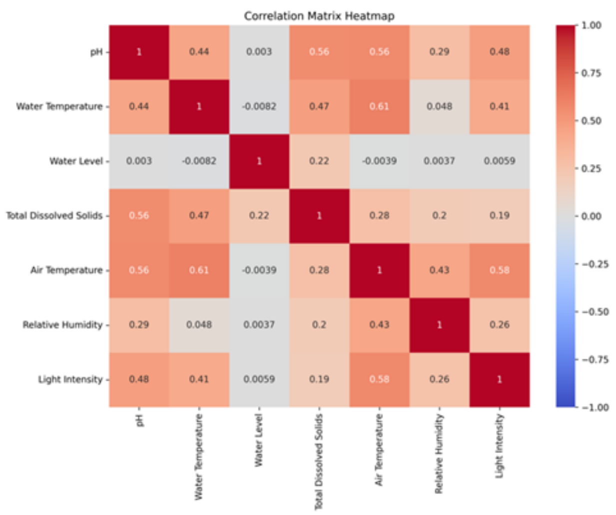

Figure 7. Correlation Matrix

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2) pH Level Distribution

Fig. 8 shows the pH level distribution with respect to frequency of occurrence in the dataset. As can be observed, the highest count of pH level occurrence at 10000 is around 6.0 which is considered a neutral-basic level. Following that a count of around 6500 can be observed at a pH level of around 8.0 which is considered neutral-mild acidic in the scale. On a broad view observation, it can be stated that the pH of the aquaponic farm was conceived within a range of 6.0 to 8.0 throughout the majority of the dataset.

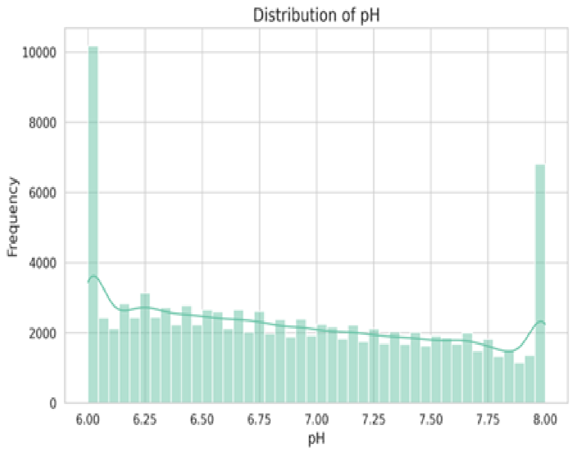

Figure 8. pH Level Distribution

2) Optimal Level Distribution

Depicted in the Fig. 9, is the optimal level value distribution of the dataset wherein it can be broadly observed that optimal level value of around 4 is in the maximum frequency of around 22000 counts which is then being followed by optimal level value of around 3 at a frequency of around 20000 counts and optimal level value of 0 at a frequency of around 16000, which also indicates that the aquaponic farm was at a bad condition during some period of time due to abnormal conditions or some other issues. The broad range of the optimal level value recorded in the dataset can be stated as 0-7.

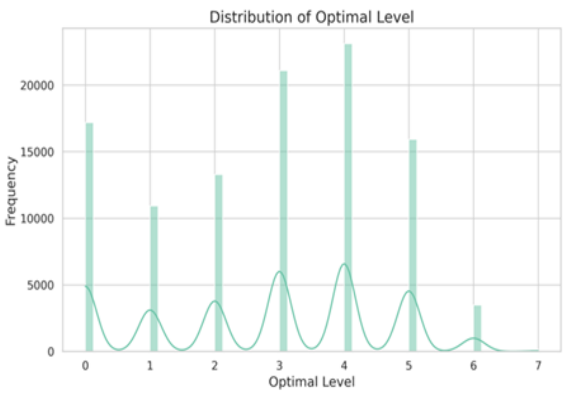

Figure 9. Optimal Level Distribution

D. AI Model Training and Testing

Following the visualization and analysis of the dataset, we will move forward to the AI model training part. From the trained AI model, we have the objective for it to predict with an acceptable accuracy the optimal level value when it has been given the input of all the sensor node values in the form of a static dictionary.

The steps followed during training of our model are as follows:

1) Data Structuring

We load the dataset from a CSV file using pandas to prepare the data for model training. We split the dataset into two parts: one for training the model (X_train, y_train) and the other for testing its performance (X_test, y_test). We drop the columns 'Optimal Level' (the target variable) and 'Timestamp' from the input features, as they are not needed for prediction.

2) Feature Scaling

To ensure that all features have the same scale, we standardize the input features using the Standard Scaler from sklearn preprocessing.

3) Model Selection

We choose to implement a neural network model using the Keras library for regression tasks because

- There was a non-linear relationship in the dataset and keras neural networks are known to be excelling at non-linear relationships between variables.
- Keras neural networks can automatically learn feature interactions, enabling the model to identify intricate dependencies among environmental variables for accurate predictions.
- Standard regressors give us a hard time tuning up for generalization in an effective manner in scenarios like this.

The architecture in this AI network comprises four fully connected (dense) layers.

- The input layer has 7 neurons, one for each input feature (pH, Water Temperature, Water Level, Total Dissolved Solids, Air Temperature, Relative Humidity, and Light Intensity).
- The hidden layers have 128, 64, and 32 neurons, respectively. The ReLU activation function is applied to introduce non-linearity, which helps the model learn complex patterns in the data.
- The output layer has a single neuron, as this is a regression task and we are predicting a continuous value (Optimal Level).

4) Hyperparameter Tuning

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Building this deep neural network, we have used the hyperparameters as Epochs to be 100, Optimizer to be 'adam', loss function to be Mean Squared Error (MSE) and the batch size to be default.

a) Progress Monitoring

During model training, we used a custom callback named ProgressCallback to show the training progress in the form of a progress bar. This allowed us to visualize the progress of each epoch and also monitor the convergence of the model during training.

5) Model Evaluation

During the model training, we evaluated the model using the Mean Squared Error (MSE) for plotting the loss function during training and validation of the model on the test split as depicted in the Figureure. 10 which is also called the learning curve. the loss can be observed to be decreasing with epochs and finally be at a value of around 0.000621 at the end of the training and validation.

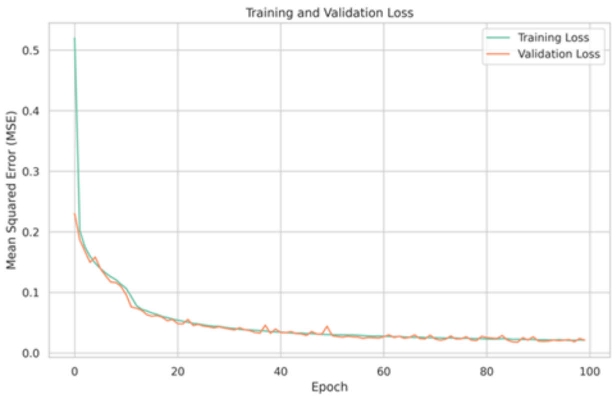

Figure 10. Learning Curve

Similarly, after the training the model was evaluated using the graph plot showcasing its performance in terms of accuracy in the predicted vs actual optimal level graph using a scatter plot as depicted in Fig. 11. Wherein, the divergence from the actual value is indicated using the blue to red colors wherein blue indicates accurate prediction and towards red the accuracy decreases.

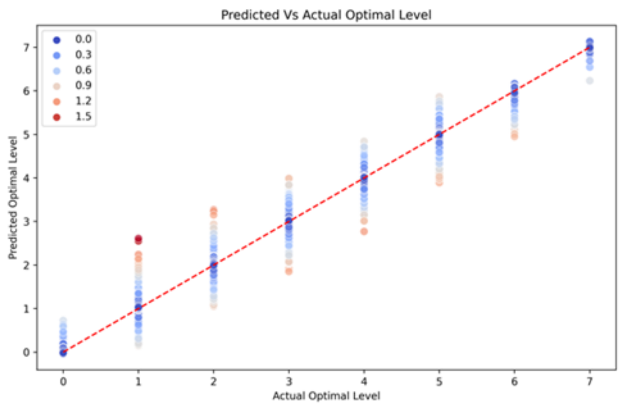

Figure 11. Predicted Vs Actual Optimal Level Plot

6) Model Saving

After completion of the training and evaluation, the trained model was saved in the 'model.h5' standard format to allow us to load it in future for further steps and procedures.

VI. Results

The implementation of IoT based edge hardware solutions integrated with various sensors proves to be quite efficient and effective. Moreover, a LoRa based network architecture also eliminated any severe dependencies over the internet between the sensor nodes and the gateway.

Figure 12 (a). Gateway Implementation

In addition to that use of security and redundancy measures like encryption and hybrid topologies aid to make the system more reliable and dependent allowing it to be immune to any unwanted breaches or down time. Fig. 12 (a) and Fig. 12 (b) depict images of the devices in action.

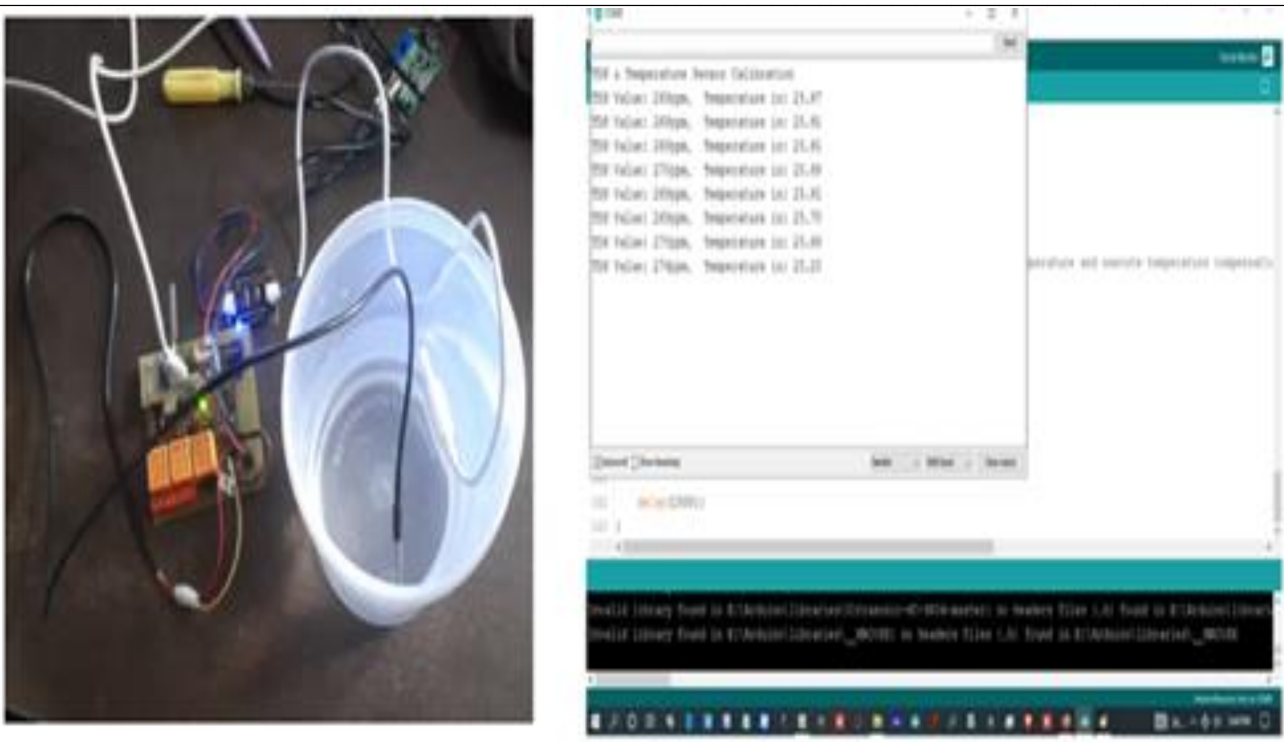

Figure 12 (b). Sensor Node Implementation

To test the AI model's accuracy and effectiveness with real-time input data, the model was loaded back to the google colab and an input dictionary was passed into the network in the format attached below:

```
input_data = {
  'pH': 6.53,
  'Water Temperature': 12.29,
  'Water Level': 0.028,
  'Total Dissolved Solids': 261.22,
  'Air Temperature': 29.52,
  'Relative Humidity': 63.73,
  'Light Intensity': 672.46
}
```

In response to the input data the model provided the output as the prediction of optimal level value as shown in Figureure.13. The predicted optimal level value 5.950446605682373 was found to be quite accurate as well. This accurate prediction capability of the trained deep neural network can be used further to extract the feature significance of the variables impacting the result which can help the aquaponic farmer pinpoint the variables which can be manipulated to improve the optimal level value of the farm and thereby improving the yield of the aquaponic farm.

```
1/1 [==============================] - 0s 63ms/step
Input Data:
pH: 6.69
Water Temperature: 17.88
Water Level: 0.021
Total Dissolved Solids: 331.32
Air Temperature: 28.07
Relative Humidity: 60.68
Light Intensity: 720.36
Predicted Optimal Level: 5.950446605682373
```

Figure 13. Optimal Level Prediction

VII. Conclusion

The integration of AI and IoT technologies into aquaponics systems opens up endless possibilities for smart farming and sustainable food production. Real-time monitoring through IoT sensors allows farmers to closely monitor and control crucial environmental parameters, ensuring optimum conditions for both aquatic life and plants. AI algorithms analyze the vast amount of data collected, providing decision support to farmers for proactive interventions and optimizing resource utilization. With the adoption of AI and IoT, aquaponics systems can achieve significant yield enhancement, economic viability, and environmental sustainability, contributing to a smarter and greener future of farming.

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