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Real-Time Monitoring and Automation of Aquaponics using IOT Technology

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***Abstract*-This paper presents the design and development of a cost-effective Internet of Things based smart system for aquaponics using ESP32 microcontroller. Aquaponics and hydroponics are effective methods used in modern urban agriculture. Unlike traditional aquaculture, aquaponics requires less space and significantly reduces water consumption. Hydroponics is a method to growing plants in nutrient-rich water without soil, in contrast aquaponics combines both aquaculture and hydroponics in a closed loop system, where plant utilize nutrients from fish waste. The proposed system combines sensors for monitoring pH, temperature, water lever, and humidity and actuators such as a fish feeder, AC submersible pump, full spectrum grow light, and buzzer. A real-time clock module is used to schedule tasks, including automatic fish feeding in every 10 hours and timed control of grow light. The submersible pimp is controlled through a relay and is triggered automatically when the water level drops below the defined threshold. IoT based monitoring is achieved through a cellular module. The system improves operational efficiency, reduces manual intervention and supports sustainable aquaponics practices through smart monitoring and automation.**

***Keywords:* Aquaponics, ESP32, IoT, Hydroponics, Smart Agriculture, pH Sensor, Water Level Monitoring.**

I. INTRODUCTION

The growing international need for sustainable food production has put a lot of focus on advanced agricultural systems with the capability to maximize resources and maintain high productivity. Conventional farming poses problems like land shortages, water shortages, and exposure to climate fluctuations, especially in urban and semi-urban areas. Controlled- environment systems like hydroponics and aquaponics have therefore become practical alternatives. Aquaponics, for instance, has the potential to provide a closed-loop system by integrating aquaculture with hydroponics, thus conserving water, recycling nutrients, an maintaining low environmental impact [1], [2].

Notwithstanding these benefits, aquaponics systems are very responsive to environmental and water quality parameter fluctuations such as pH, temperature, dissolved oxygen, and nutrient concentration. Manual observation and control of the parameters are tedious and frequently inadequate to provide the precise balance needed for maximum plant and fish growth [3]. Therefore, a demand is on the rise for real-time monitoring and automation technologies that can stabilize system conditions, enhance reliability, and facilitate scalable use of aquaponics in various contexts [4].

The high-speed evolution of the Internet of Things (IoT) has given a promising technological platform to overcome these limitations. IoT facilitates direct interconnection between sensors, microcontrollers, and cloud platforms, enabling real-time monitoring, automatic actuation, and distant access through mobile or web applications [5]. Recent research has shown the viability of IoT-based aquaponic systems utilizing low-cost microcontrollers like Arduino and ESP32, incorporating sensors for monitoring water quality, actuators for pumps and aeration, and dashboards for user interface [6], [7]. These methods emphasize the role of IoT in improving resource efficiency, minimizing labor needs, and enhancing system robustness. Though, current implementations are mostly restricted to threshold-based automation and experimental trials at small scales. Important features like adaptive control methods, interoperability, energy efficiency, and human-centered design are mostly neglected [8]. Additionally, although Arduino-based implementations have been commonly cited, incorporating more powerful platforms like ESP32 for ubiquitous Wi-Fi/Bluetooth communication and cloud integration is not well explored in literature [9].

Impelled by these obstacles, this research introduces the design and implementation of an IoT-integrated automated aquaponics system based on ESP32 microcontrollers, real-time sensing, and cloud monitoring for performance improvement and convenience. The system is equipped with sensors for water and environmental characteristics, uses relay-controlled actuators for pumps and feeders, and supports pulse-width modulation (PWM) strategies for smart lighting control. Through the intersection of affordability and cutting-edge connectivity, the suggested framework elucidates the possibility of scalable, intelligent aquaponics solutions for urban residential and commercial use.

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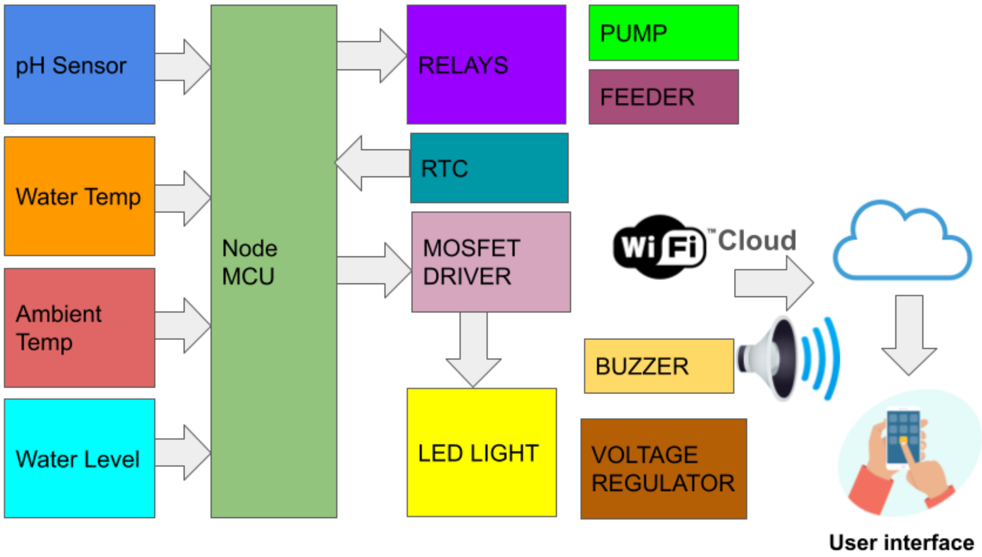

Fig .1. Proposed architecture of the automated aquaponic system

II. REVIEW OF LITERATURE

Urban agriculture has come to the fore in recent times as a measure of addressing land and water limitations of accelerated urbanization. Hydroponics and aquaponics have emerged as effective means of sustainable food production within space-constrained environments [1]-[2]. Aquaponics, being the integration of aquaculture with hydroponics, produces a closed- loop system wherein effluent from fish acts as plant nutrient input, hence minimizing resource consumption and maximizing productivity [3]. Early studies on aquaponics were largely concerned with conceptual models, but current research has underscored the necessity of automation as well as on-line monitoring of all major parameters like water temperature, pH, and dissolved oxygen to maintain ecosystem stability [4]-[5].

Automation has been identified as a force behind efficiency and dependability in aquaponic systems. Real-time monitoring, especially, facilitates on-line anomaly detection and quick decision-making [6]. A number of authors have designed IoT-based aquaponics systems with microcontrollers for automating monitoring and control. Arduino-based systems, for instance, have been utilized in measuring water quality parameters and pump, feeder, and aerator control through relay modules with GSM notification [7]-[8]. Such designs show the possibility of low-cost automation for small farming.

Recent developments indicate a move towards ESP32-based designs, which include built-in Wi-Fi and Bluetooth connectivity, increased processing capabilities, and direct cloud integration. ESP32-based designs frequently employ mobile apps like Blynk or Arduino IoT Cloud for real-time visualization of data and remote actuation, hence enhancing convenience and scalability [9]-[10]. Such systems enable concurrent monitoring of pH, water level, temperature, and humidity, while actuators for feeding, illumination, and aeration are handled automatically.

Control strategy-wise, the majority of IoT-based aquaponics systems are based on threshold- based actuation, where pumps and feeders respond when sensor values move outside predetermined ranges [11]. Systems with more sophistication use closed-loop control strategies and adaptive designs to control water quality across changing environmental conditions [12]. In addition to binary control, PWM-based light intensity profiling has been used to replicate natural light cycles, thus improving photosynthesis and plant growth [13].

In spite of all progress, there are still a few gaps in research. Most current systems use rule- based logic without the use of predictive analytics or machine learning for adaptive optimization [14]. Also, topics such as energy efficiency, interoperability, and quality of service (latency, reliability) are not frequently addressed [15]-[16]. Little investigation has also been done on user experience for mobile dashboards and alert systems, which are most important for non-technical users.

Overall, the literature surveyed here indicates that automation based on IoT can enhance aquaponics substantially by allowing real-time monitoring, effective control, and scalability. The shift from Arduino to ESP32 is indicative of the movement toward smaller, networked, and smarter systems, but future research has to prioritize intelligent control, energy-efficient operation, and standardization for wider implementation.

III. SYSTEM ARCHITECTURE

Basic architecture of the proposed aquaponics system as shown in fig.1. A key component of the system is the ESP32 microcontroller. We initially planned to implement the project using Arduino UNO. However, we later switched it to an ESP32 microcontroller due to its compact size and input Wi-Fi and Bluetooth, which make it more suitable for enabling real-time monitoring. ESP32 receives the signals from the sensors and operates the actuator according to the signal it receives. For example, if the water level sensor input is low, microcontroller activates the pump. The feeder and light are controlled by Real Time Counter.

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IV. METERIALS AND METHODS

In this project, we designed a cost effective, ESP32 based IoT system to monitor and control an aquaponics setup. The basic steps involved in this project are following:

A. Suitable Conditions for Aquaponics Range:

In aquaponics, each parameters have an optimum range. Variations in these parameters may affect the growth of fish and plant as well. To create a healthy aquaponics system, we should keep the ideal values. Given Table 1 shows the suitable environmental parameter of aquaponics.

B. Selection of Components

1) Sensors: These are the electronic devices that convert physical signals into electrical signals. Types of sensors used in this aquaponics setup are

TABLE 1 SUITABLE AQUAPONICS RANGE

PARAMETER	OPTIMAL RANGE
Water temperature	20°C- 28 °C
pH level	6.5<8.5
Photoperiod	12-16 hr/day
Feeding time	Every 10hrs
Humidity	50%-70%
Air temperature	18°C- 30 °C
Water level	75-90% of Total capacity

a) Water level sensor: It always monitors the optimum water level, 75-90% of the total water in the fish tank. Whenever the water level is low, it informs the microcontroller to tell the AC pump to fill to the optimum water level
b) Temperature sensor: The suitable temperature range of the fish tank and plant bed is 20°C-28°C, so we use this sensor to track the optimum water temperature.
c) pH sensor: It consists of two components: a pH sensor probe and a signal conditioning module to process the probe signal. pH is the measure of acidity and alkalinity of the water; the optimum pH range is 6.5-8.5.
d) Humidity sensor: It measures the moisture content level in the atmosphere; suitable humidity is 50%-70%. It also monitors the air temperature, which is important for plant growth.

2) Actuators: Actuators are the electronic devices that convert electrical signals into any other format of energy, such as mechanical energy or thermal energy. Actuators used in this setup are

a) AC Pump: We use a 220v AC pump to keep the optimum water level in the fish tank according to the water level sensor signal input. Whenever the water level is low, the pump becomes activated and refills the water.
b) Fish feeder: We use a DC motor and a container to build a customized an automated feeder. Motor is controlled by a relay, which triggered the motor based on the time input from an RTC module. Motor rotates the container 45°at every 10 hours to deliver the feed.
c) Buzzer: It provides an alert sound if any abnormality occurs in the system, such as temperature, humidity, and pH variation in the system.
d) Grow light: We use a full spectrum halogen light to simulate natural sunlight. provides the optimum light for photosynthesis in plants. The intensity of the light is controlled by a MOSFET driver.

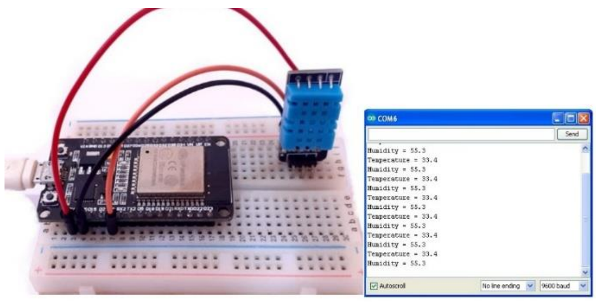
3) Other components:

a) RTC module: There is an optimum photoperiod and feeding; this module keeps the feeding time and photoperiod in this aquaponics setup.
b) Relay: We use a 4-channel 5V relays for the AC pump and feeder to minimize the size.
c) MOSFET driver: We use a MOSFET driver module to connect the grow light to the PWM pin of the ESP32. The relay module cannot enable the pulse width modulation; because of that, we use MOSFET, which can enable PWM

C. Testing and Calibration

We tested all the components to confirm the proper working of the sensors and actuators and

Fig .2. Testing of humidity sensor



calibrated the sensors as well for better accuracy. We set a threshold level in each parameter. For example, if any variation in temperature, the buzzer produces a sound alert. The given Fig. 2 represents the testing of humidity sensor.

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D. Connection of Circuit

All the sensors, actuators, and modules were interfaced with an ESP32 microcontroller. A 4-channel 5V relay was used to switch the AC pump and fish feeder and use an IRLZ44N MOSFET driver to connect the grow light to the PWM pin of the ESP32.

E. Coding and Uploading

We wrote the codes in the Arduino IoT Cloud software application and uploaded them into the ESP32 board and connected it with the Arduino IoT Remote app to enable real-time monitoring. It reads the continuous sensor value, and based on that, it drives the actuators, such as the pump feeder, buzzer, and light, with the help of the relay module.

F. PCB Designing and Prototyping

The printed circuit board designing was done by Proteus 8 Professional software application which allows schematic capture and board layout. Proposed circuit was designed first and verified through simulation. Once the schematic was complete and verified, and everything looked fine, a basic PCB layer was created. The finalized design was then exported as Gerber files, which are essential for PCB fabrication.

After a successful PCB fabrication, digital printing, print transformation using heat transform method, copper etching, drilling and cleaning were completed. All the components were placed in their designated slots. For prototyping, a readymade PCB enclosure was used for safety and proper mounting of the circuit. Two separate enclosures were used, first one is considered as master unit where ESP32, sensors were placed and another one is considered as slave unit, high voltage components such as relay, MOSFET driver were placed here. This separate enclosure setup protects the system from sudden voltage fluctuations and ensures the system's safety. The hardware components are integrated inside an enclosure as shown in Fig.3.

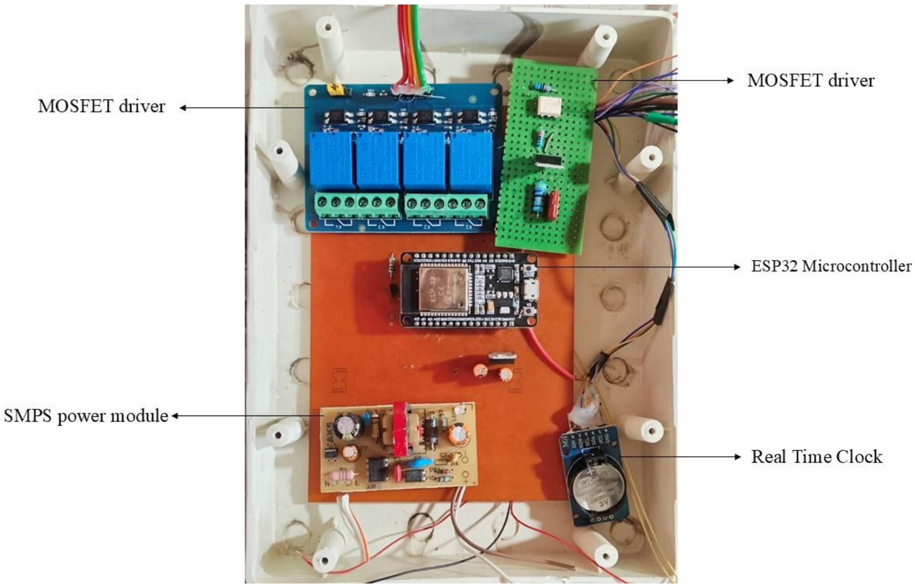

Fig .3. Components to be placed inside the enclosures

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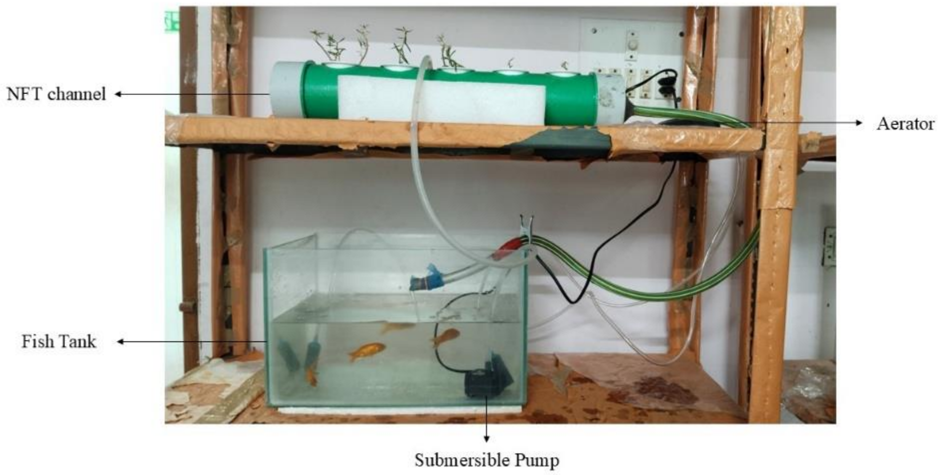

Fig. 4. A small indoor aquaponics setup

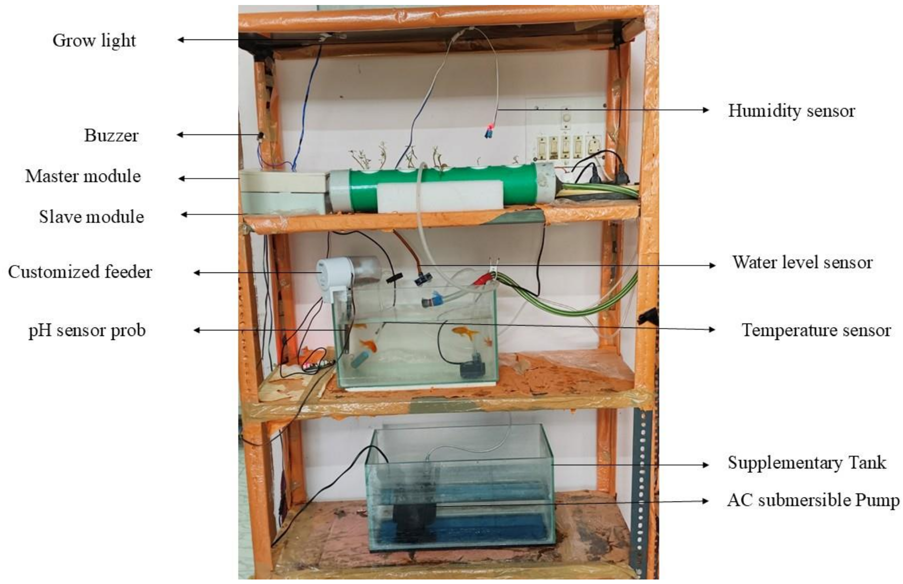

Fig.5. Final placement of the components in aquaponics setup

G. Final Setup

After Successful Prototyping, a small-scale aquaponics setup was assembled using basic components to create a working model using Nutrient Film Technique (NFT). The initial setup consisted of a small fish tank, NFT channels that placed above the tank for growing plants, a submersible pump to circulate nutrient rich water to the plant root and an aerator to maintain dissolved oxygen level in the fish tank. For this setup ornamental fish such as Gold fish and ornamental plant Table roses were chosen to culture in this setup. The given Fig .4. illustrates the small indoor aquaponics setup

After the successful implementation of a small aquaponics setup, the designed prototype was integrated into setup. Water level sensor, pH sensor, water Temperature sensors were dipped into the fish tank water while humidity sensor placed above the plant bed. Actuators such as feeder installed in the fish tank, grow light in plant bed and a 230V AC submersible pump placed in a supplementary water tank. Whenever the water level dropped, pump refill

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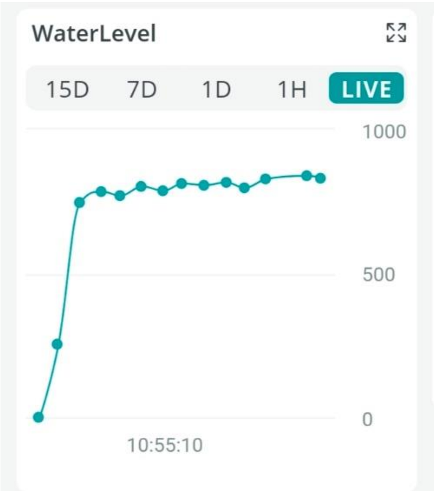

Fig.6. Water level sensor graph from Arduino IoT remote dashboard

the main tank from this supplementary tank. The given Fig 5 shows the placement of each component.

V. RESULT AND DISCUSSION

A. Data monitoring:

In this system, sensor data can be monitored both online and offline through Arduino IoT remote application and serial data monitoring, respectively.

1) Water level sensor: The given Fig 6 shows the reading from water level sensor in the aquaponics setup. The water level efficiently regulated water within the pre-defined range. It activated the 220V AC pump when the water level dropped below 75% and turned off once the but when water level reached the 90% of the fish tank. This automation ensures the reliable water supply for the both fish tank and plant bed without human supervision.

2) Water temperature sensor: Water temperature was continuously monitored to ensure the optimum range of water temperature for both fish and plant growth. The reading constantly ranged between 20°C- 28 °C, which is more suitable for the system's productivity. The below-given figure shows the reading from water temperature sensor in the fish tank.

3) pH sensor: Given Fig.7. and Fig.8. shows the pH range reading from the pH sensor in the system. Keeping an optimum pH range is essential for survival of the fish and supports the productivity. Reading from the images indicate that the system maintains a suitable pH range which is ranged between 6.8<8.5.

4) Humidity and Air temperature sensor: The given Fig. 9. and Fig. 10. show the readings from the humidity sensor; which measures both humidity and air temperature variation and both are important for plant growth. These readings helped to understand the environmental conditions in the surrounding of the aquaponics system and also to validate any need of ventilation or cooling solution. The air temperature sensor tracks the fluctuations throughout the day, which remained in the range between 18°C- 30 °C. Humidity: variations in the humidity level ranged between 50%-70% showing a favourable microclimate for the plant growth.

B. Offline Monitoring:

In the absence of internet connectivity, the ESP32 collect the sensor data locally and transmitted it through serial communication such as USB cable. The given Fig.11. presents the data table that obtained through serial monitoring.

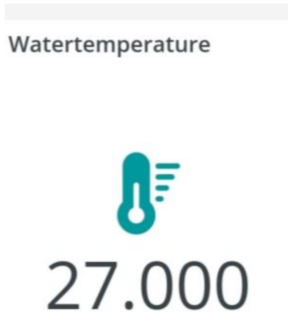

Fig .7. Water temperature reading from Arduino IoT dashboard

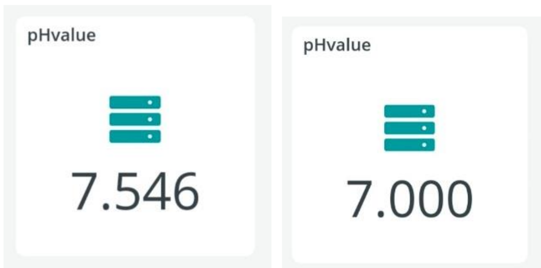

Fig .8. pH value reading from Arduino IoT dashboard

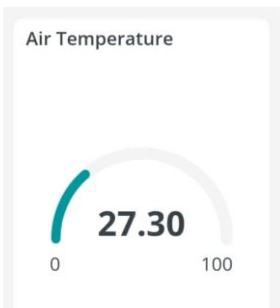

Fig .9. Air temperature sensor reading from Arduino IoT remote dashboard

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Fig .10. Humidity reading from Arduino IoT remote application

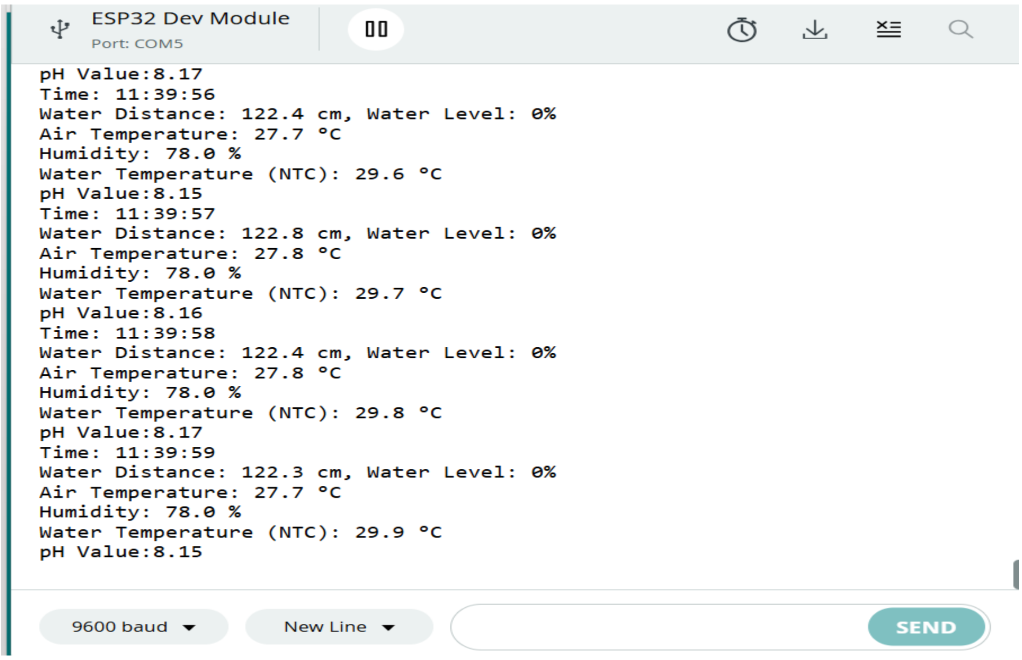

Fig .11. Offline monitoring from Arduino IoT cloud

VI. CONCLUSION

An affordable smart system for aquaponics was successfully designed and developed to minimize the manual labour and save time. This smart system was integrated with a group of sensors, actuators, a processing unit, online and offline data monitoring and software application. The AC pump was switched on according to the signals from the water level sensor. Whenever one of the monitored parameters rose above or fell below its threshold range, the system triggered an alert through the buffer. One of the major benefits of this system was light intensity controlling. The grow light and feeder modules operated properly based on the input signal from the real-time clock. This system is suitable for large-scale applications and significantly limits the need for manual monitoring. For future development, additional automation features, remote control functions, Google Home integration and advanced research paths can be examined.

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