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Original Article

Automated Water Quality Control System for Aquaculture

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Abstract - *In this work, an innovative automated control system designed for the industrial aquaculture sector is presented. Based on an Arduino Mega, a system is implemented to automatically control, compare, and adjust water temperature and pH levels. Specialized sensors continuously monitor water conditions, while electronic actuators adjust automatically, reducing workers' reliance on manual interventions. This efficient approach optimizes aquatic environment conditions for cultivation and enhances productivity and sustainability in the aquaculture industry. Additionally, this study underscores the utility of automated monitoring technology as an effective tool for enhancing aquaculture production and improving the well-being of aquatic organisms in controlled environments. However, further improvements could be achieved using higher precision sensors to obtain more accurate results. This proposed system can be successfully scaled to larger environments, such as lakes or rivers in diverse regions worldwide.*

Keywords - *Water quality control, pH levels, Temperature, Aquaculture, Arduino Mega.*

1. Introduction

Aquatic species farming is a growing sector that is essential in ensuring food availability globally [1]. With the world population constantly increasing and wild fisheries reaching their sustainable limits, aquaculture has become a critical source of protein and nutrients. However, aquaculture requires rigorous and careful control of the environment where aquatic organisms are raised to achieve their full potential. Moreover, numerous countries and organizations have recognized this activity's importance and decided to invest even more in its development. Aquaculture represents over 50% globally of products destined for human consumption [2]. Leading entities such as the Food and Agriculture Organization (FAO) have promoted aquaculture as a viable response to food security and sustainability challenges. On the other hand, multiple countries, such as Norway, a leader in salmon farming, or China, the largest producer of aquatic foods, have adopted advanced technologies for manufacturing optimization and product quality assurance [3]. A precise control system ensures sustainable and high-quality production [4]. Therefore, the Water Quality Control System for Aquaculture (WQCSA) is a fundamental tool that has revolutionized this industry. Global climate change is causing an increase in water temperature levels in natural bodies of water such as oceans, rivers, and lakes [5]. This rise in temperature can significantly impact aquaculture facilities, as they rely on natural water sources. The consistent temperature increases alter the life stages and feeding patterns of farmed aquatic organisms, thereby affecting aquaculture yields by up to 20% [6]. Similarly, this rise in temperature increases vulnerability to diseases and thermal stress in crops, resulting in economic losses for producers and challenges in maintaining aquaculture sustainability. On the other hand, aquaculture encompasses a wide range of species, including fish, crustaceans, molluscs, and algae, and is practised in diverse environments, from freshwater to saltwater. Some of the most commonly farmed species in aquaculture include salmon, trout, shrimp, mussels, and tilapia, among others. This sector's primary goal is food production, but it also contributes to the conservation of threatened species, the restoration of aquatic habitats, and the economic development of coastal communities [7]. Similarly, achieving good aquaculture production requires continuous and effective monitoring and control using established parameters for each type of fish, which can be facilitated by various technologies. Currently, in Peru, there are cases where this control of diverse parameters is conducted using semi-manual underwater cameras in compliance with environmental standards.

The main aquaculture species being monitored in recent years include scallops, shrimps, trout, tilapia, and paiche, representing a 38% increase in the domestic market [8]. On the other hand, an increasing number of aquaculturists have started to cultivate in their own ponds; however, a significant percentage lacks a system to collect real-time water quality information. Furthermore, in many cases, this data is manually gathered by designated personnel, making it a lengthy process that requires additional resources and workers, with a wide margin for error [9]. In some studies, various types of temperature, pH control, and monitoring systems have been implemented in aquaculture based on the use of artificial intelligence and fuzzy logic [10], Arduino [11] and the Internet of Things (IoT) [12]. These control and monitoring systems mainly serve to alert the operator and/or supervisor in charge via a message, indicating when the established temperature parameters or water neutrality are not at the appropriate level or range. Moreover, they do not include mechanisms for immediate regulation in response to problems that can appear within the systems [13].

When considering the aquaculture sector, there are even fewer research studies that have developed investigations using platforms, for example, such as Arduino. The most used embedded systems in water management and supervision include programmable microcontrollers like the Raspberry Pi, used for automation and monitoring; Programmable Logic Controllers (PLCs) for adjusting accuracy and real-time value capture; and the LoRa TTGO SX1276 microcontroller, which features a module enabling Wi-Fi connectivity and works with IoT for control purposes [14].

Monitoring pH with Raspberry Pi, PLC, and Arduino presents various advantages and disadvantages. Raspberry Pi stands out for its computing power, flexibility, and user interface capabilities, although it may have higher costs and energy consumption. PLCs offer robustness, scalability, and durability but are more expensive, require specific programming knowledge, and have limited flexibility. Arduino, known for its simplicity and low cost, is ideal for simpler projects but may have limited power and fewer connectivity options compared to Raspberry Pi [15].

The importance of this study lies in addressing the problem of the absence of an automated mechanism with immediate response action. Furthermore, the system put forward here provides a series of benefits regarding operational efficiency and profitability. For this reason, a model was implemented through a prototype (mock-up), which activates when temperature and pH values are outside predetermined ranges, using an Arduino platform and water pumps with a Modbus communication network system. This reduces direct operator intervention for safety reasons [16]. This also allows us to obtain consistent results due to the reduced response time for levelling the established parameters.

Through detailed studies, aquaculturists can determine which factors are most critical and how they should be maintained within specific ranges to optimize aquaculture production, playing a crucial role in increasing efficiency, environmental sustainability, and the adaptation of this vital industry. On the other hand, systems for water quality control can provide a versatile and accessible platform for studying the effects of different environmental variables on the growth, well-being, and behaviour of aquatic organisms. Additionally, they can facilitate long-term data collection for monitoring studies and tracking the health of aquatic ecosystems [17]. Considering the above, the objective of this study is to develop and implement an automated system using Arduino to monitor water quality in aquaculture, with a specific focus on monitoring and maintaining ideal pH and temperature levels.

This system will provide aquaculturists with an effective tool to ensure an optimal environment for the growth and well-being of living organisms in aquatic environments, thereby optimizing the efficiency and performance of aquaculture activities. Additionally, by automating these processes, the workload of manual labour will be reduced, and human errors will be minimized, contributing to the long-term sustainability and viability of the aquaculture industry.

2. Methodology

2.1. Electronic Components

In this section, the design of the hardware for the automated water control system is presented. Here, the critical parameters to monitor, select sensors, and establish quality thresholds are defined. Additionally, the sensors are connected to an Arduino, where the stability conditions are collected and analyzed for decision-making and to take immediate response action.

Appropriate water quality is reached using designated controllers to maintain it within acceptable levels according to established standards. Below are the various components that will be used for the creation of our automated water quality monitoring system. Each item with its respective description is presented.

- Thermocouple type K (Figure 1): Analog K-type thermocouple was used because it is easy to handle in narrow spaces. Additionally, this sensor is composed of nickel and is corrosion-resistant compared to other types of sensors. This will be placed inside the water tank for real-time monitoring.
- pH Sensor-14 (Figure 2): This sensor device was selected for its ability to provide accurate pH measurements through reliable electrodes and probes, suitable for various applications in both laboratory and field environments. The sensor will be in the upper right corner of the water tank to measure the acidity or alkalinity of the liquid.
- Arduino Mega (Figure 3): Also, for data communication, the Arduino Mega based on the ATmega256 microcontroller was used because it provides a greater number of analogue and digital input/output pins. Additionally, it has multiple communication interfaces, including UART, I2C, and SPI, which facilitate connection with devices and sensors.

- Relay Module 2CH 5VDC (Figure 4): A 2-channel relay module was used, offering a compact and versatile solution for controlling high-power devices. It provides flexibility and convenience in applications requiring remote control or automation. Additionally, its compatibility with a wide range of control systems makes it an excellent choice for various projects.
- Mini Water Pump 5V DC (Figure 5): This type of pump provides a constant water supply for various applications. Additionally, water pumps can increase water pressure, which is useful in areas where water supply pressure is low.
- TFT Screen (Figure 6): Thin Film Transistor (TFT) displays provide sharp and vibrant images with accurate colours and high contrast, making them an optimal choice for various applications. Additionally, their ability to update images quickly and their low energy consumption make them an efficient and adaptable option for various environments.

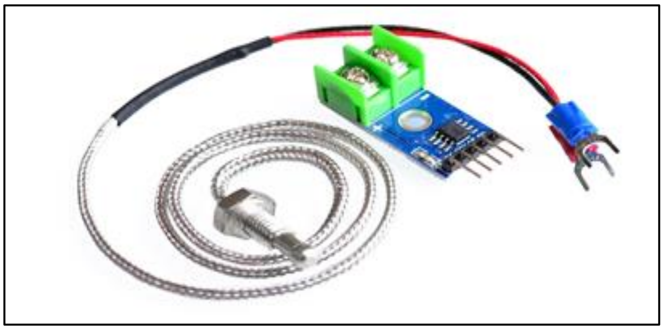

Fig. 1 Thermocouple type K

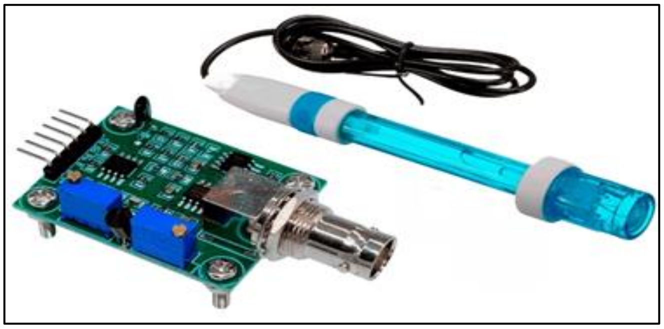

Fig. 2 pH sensor-014

Fig. 3 Arduino mega

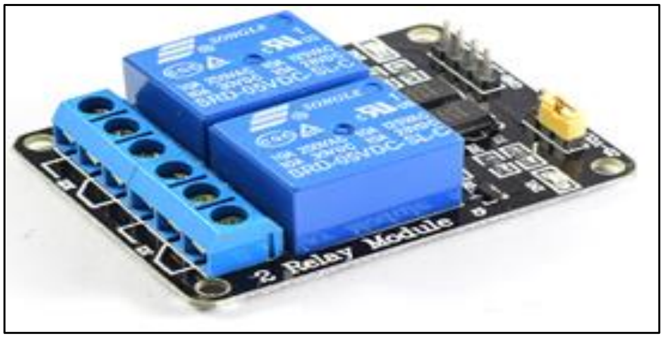

Fig. 4 Relay module 2CH

Fig. 5 Mini water pump

Fig. 6 TFT screen

Finally, in Figure 7, the complete design of the hardware part is observed. It shows the stages of each process, starting with the analogue data input through the pH sensor and the type K temperature sensor in real-time water conditions and then measuring and transferring it to the Arduino. The microcontroller meticulously processes the data, which converts them into an electrical signal to be interpreted as meaningful information, then effectively generates and transmits the data to display on a TFT screen to visualise the values, allowing direct representation of the water conditions. Simultaneously, the system transmits data to a remote user interface via a Wi-Fi module, where users can remotely monitor readings and receive alerts if pH or temperature levels deviate from predefined ranges. Additionally, the system dynamically responds to any changes in water conditions to ensure a stable and healthy environment for the fish. Consequently, it can automatically take corrective measures, such as activating water pumps or actuators to maintain liquid conditions within ideal parameters.

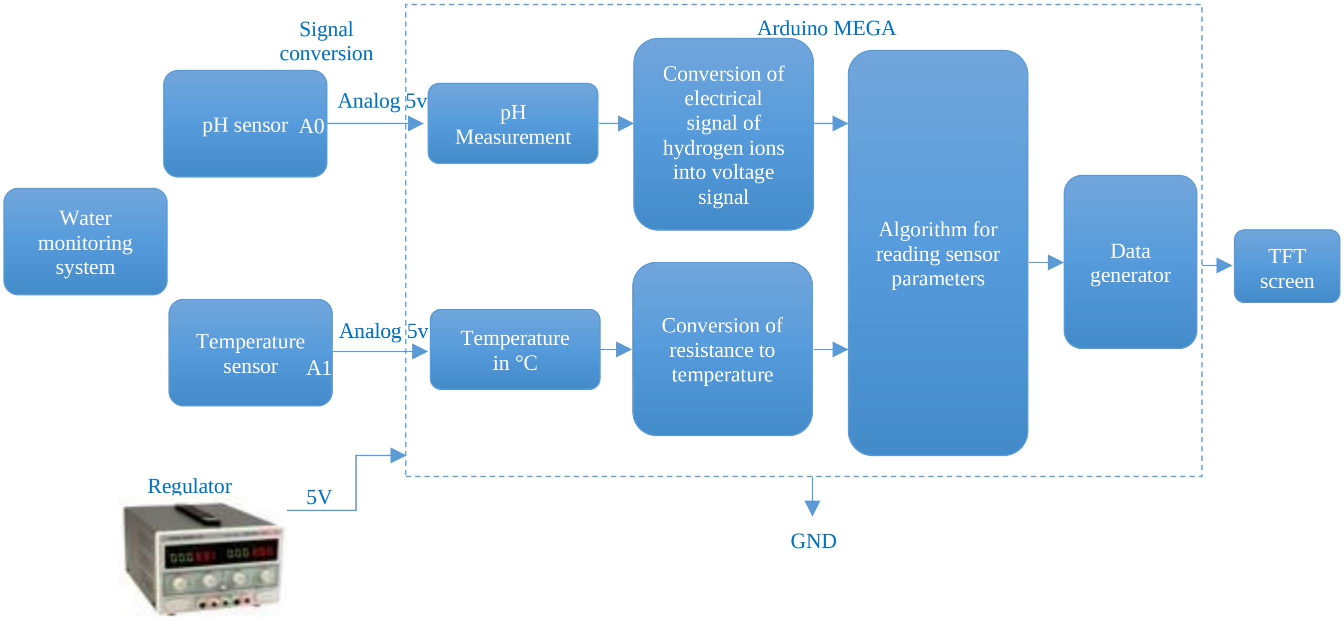

Fig. 7 Design of the stages of the control and monitoring system

This comprehensive approach to monitoring and control ensures an optimal aquatic environment for the well-being and healthy development of the fish while providing operators with an effective tool for proactive aquaculture management. This infrastructure enables aquaculturists to always stay informed about water conditions from anywhere, empowering them with the ability to intervene instantly in case of any anomalies. Thus, this system becomes aquaculture's guiding beacon and sustainability pillar, ensuring a prosperous and balanced aquatic habitat for marine life.

2.2. Microcontroller Software

The programming of the pH sensor module and the temperature sensor module was carried out through the Arduino IDE platform, as these modules are compatible with this development environment. The goal is to maintain the temperature within a range of 24°C to 28°C and the pH within a neutral range of pH 6.0 to pH 8.0 using the sensors. Additionally, the software enables bidirectional communication with the system, providing instantaneous data about the water conditions. Firstly, the pH sensor was calibrated to ensure accurate and reliable water acidity or alkalinity measurements on a pH scale from 0 to 14.

On the pH scale, 7 indicates neutrality, values below 7 indicate acidity and values above 7 indicate alkalinity. The pH sensor will detect acidity when pH values are below 7, indicating an acidic environment, typically between 0 and 6.9. Conversely, the pH sensor will detect alkalinity when values are above 7, indicating alkalinity generally ranging from 7.1 to 14. Both ranges are critical in aquaculture. Similarly, the pH sensor electrode was placed in distilled water to remove residue. Next, the electrode is immersed in a pH 7.0 buffer solution and allowed to stabilize for a few minutes. Subsequently, the meter is calibrated to ensure that the reading is precise and exactly reads 7.0, establishing a reference point. Afterwards, the electrode is rinsed again with distilled water, and the process is repeated by immersing it in pH 4.01 and pH 9.18 buffer solutions, adjusting the meter each time to match the known pH values. The accuracy is verified by recalibrating in the pH 7.0 solution. Finally, we ensure that the electrode is clean between each calibration and follow the manufacturer's specific instructions to protect it and maintain its long-term performance, aiming to achieve optimal results. On the other hand, the calibration of the type K temperature sensor was carried out to ensure precise measurements in critical applications in aquaculture. A thermally stable environment is established where both the type K sensor and a reference thermocouple can thermally equilibrate for a sufficient period to ensure temperature stability. After this stabilization period, readings from both sensors are compared using a high-precision temperature measurement device. Suppose a discrepancy is detected between the readings. In that case, the output of the type K sensor module is adjusted to align it with that of the reference thermocouple, aiming to ensure that the readings from both sensors match within an acceptable margin of error. Once the information from the pH and temperature measuring devices is obtained, the next step involves using this information to control and maintain optimal water conditions in the environment.

This includes processing the received data on the Arduino Mega to assess the water condition and, based on these analyses, activate automatic correction systems or alert operators to any significant deviation from ideal parameters. Simultaneously, the system is continuously monitored through sensors that periodically read according to the established configuration, allowing continuous monitoring of key liquid parameters. Additionally, the control system circuit was designed using Proteus 8.13 software. This software allows us to include Arduino and various sensors and actuators connected to it, enabling simulation, testing, and debugging of programming errors in the electronic circuit before physical implementation. This helps ensure the circuit design meets requirements and specifications, as shown in Figure 8. Additionally, the open-source software Fritzing was used to create the design and digital schematic of the virtual electronic prototype with all components, enabling a more intuitive visualization. This allowed us to quickly see how the components are connected in the circuit, test their functionality, and facilitate the identification of possible wiring errors. Furthermore, this allowed us to document our project for subsequent printing on a PCB, as depicted in Figure 9.

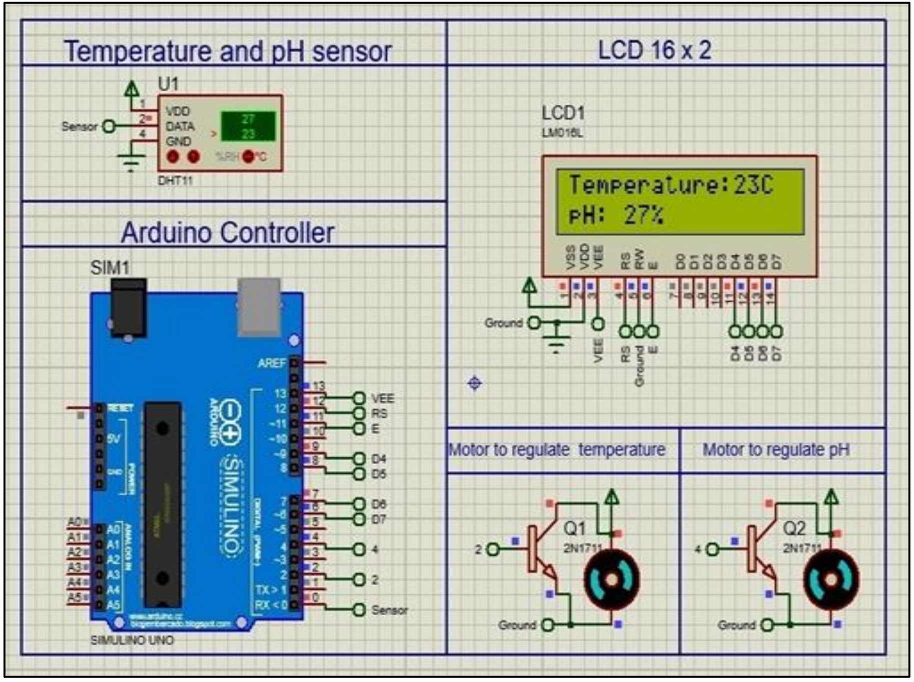

Fig. 8 Electronic circuit design in proteus

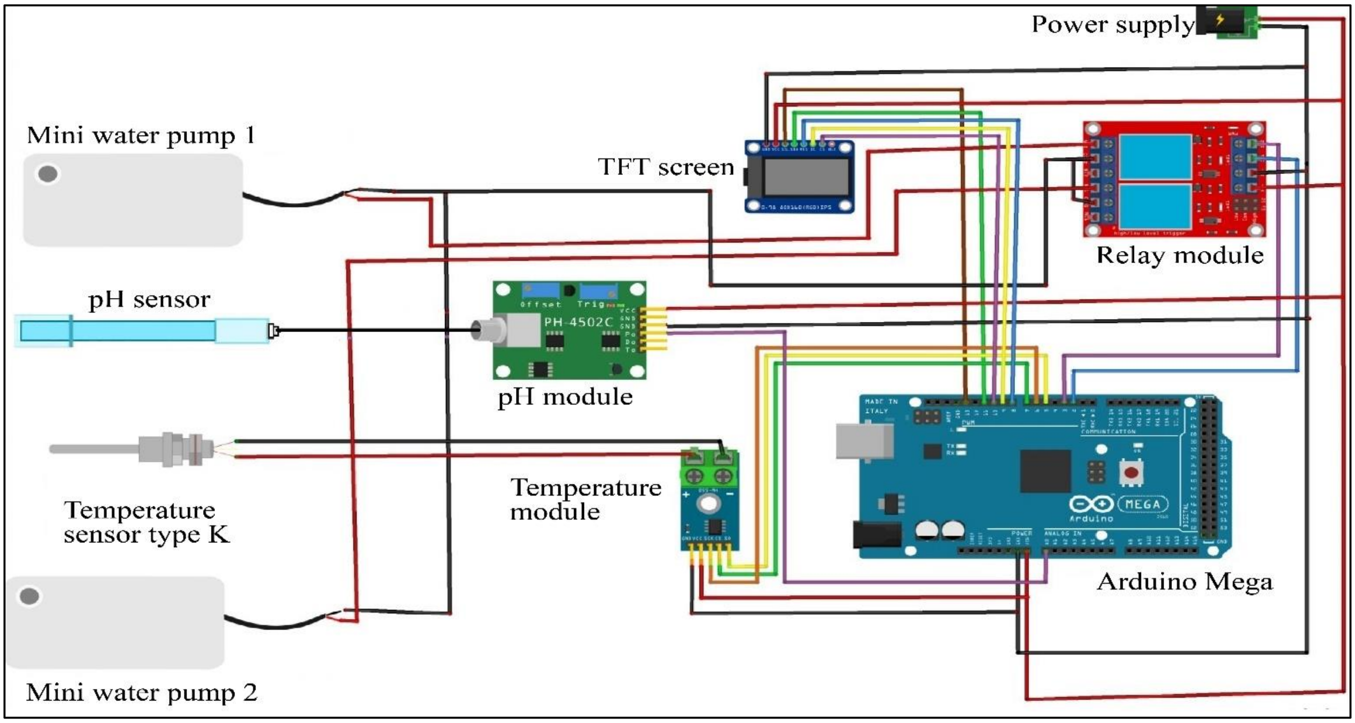

Fig. 9 Digital electronic schematic

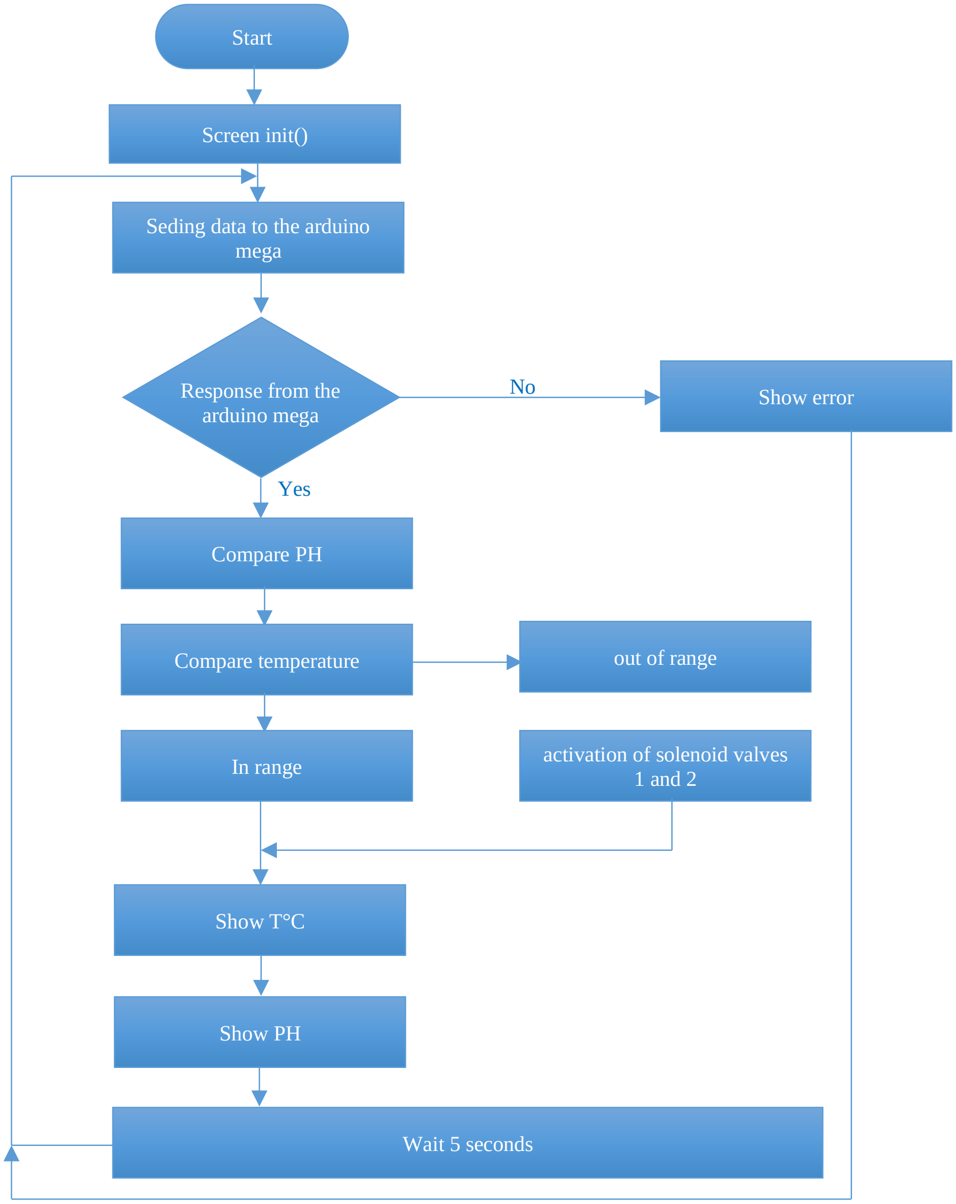

Fig. 10 Flowchart of the software system

Finally, through the flowchart, the key stages of the software are presented. This starts with the power supply input for energy supply, and then once the system is powered on, the sensors start sensing, and the screen lights up. Subsequently, the temperature and pH sensor data is transmitted to the Arduino Mega, awaiting a response. If there is an error during system startup or an issue where the sensors fail to provide data to the Arduino Mega, the system automatically enters a loop, displays an error message, and returns to the initial setup, restarting the operation until the error is corrected. On the other hand, if there are no errors during system startup, the pH and temperature sensors proceed to provide input data to the Arduino Mega for comparison with the established ranges. Firstly, if the data from the sensors is outside the established limits, the system will immediately activate the actuators to regulate and correct the anomalies until the system stabilizes. Finally, suppose the sensor data falls within the specified ranges. In that case, the system will display the values on the TFT screen and continue to monitor and control continuously, looping every 5 seconds to ensure the values remain within range and the system operates smoothly without interruptions, as depicted in Figure 10.

2.3. Mechanical Part

The mechanical structure was designed using SolidWorks 2022 with dimensions of 112 mm x 139 mm x 52 mm to ensure a perfect fit for all electronic components and be portable and compact. Subsequently, 3D printing was carried out using Acrylonitrile Butadiene Styrene (ABS) as the material to protect the system components.

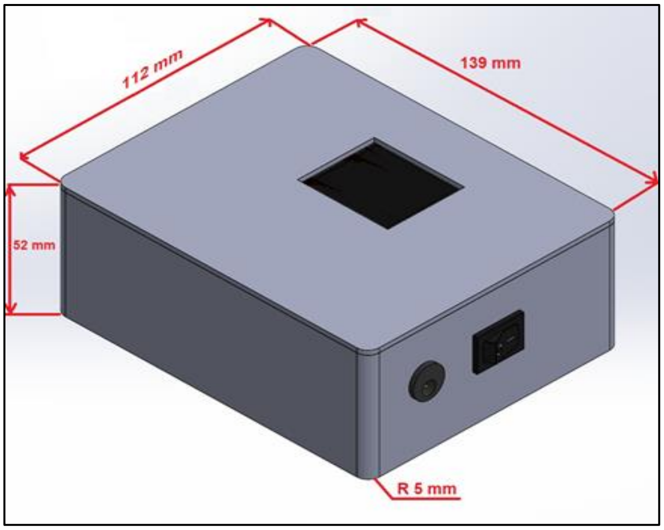

Fig. 11 Design of the mechanical structure

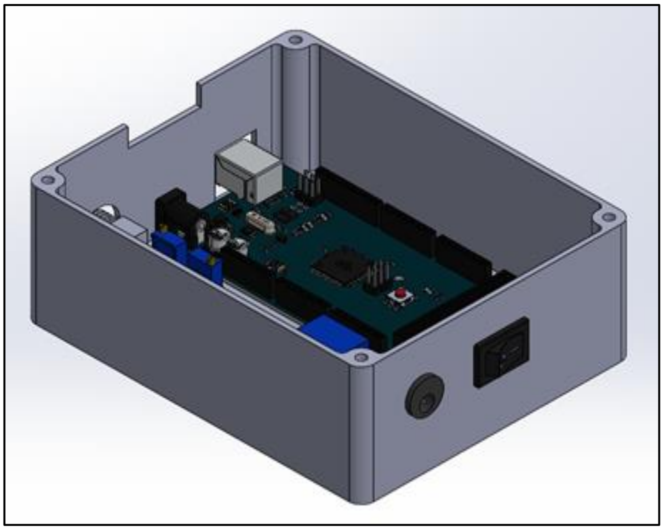

Fig. 12 Mechanical structure with control modules

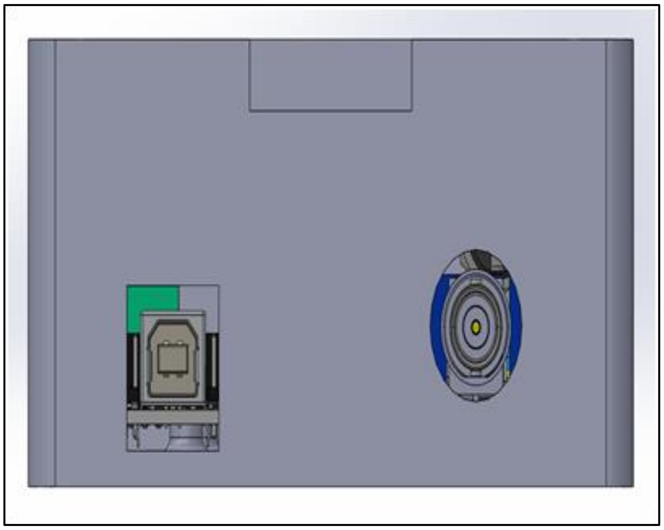

Fig. 13 Inputs for Arduino Mega and pH sensor

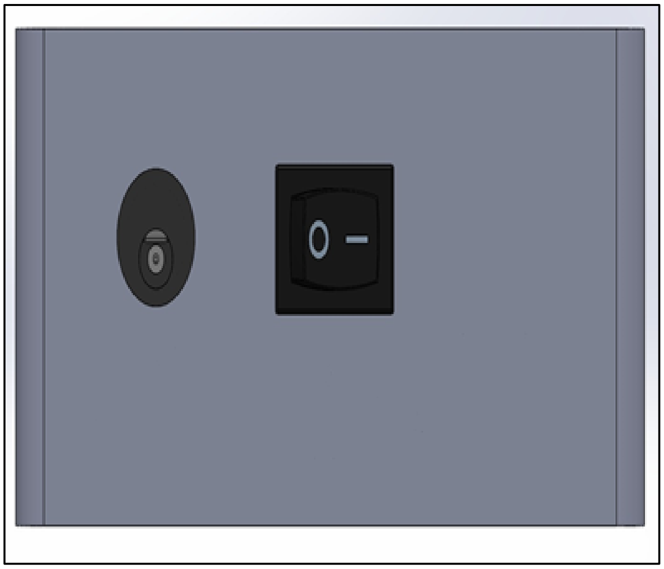

Fig. 14 Power supply connection and ON/OFF switch

The choice of ABS is based on its ability to provide an effective barrier against dust and exposure to water, as illustrated in Figures 11 and 12. Additionally, a pair of water pumps were used as actuators in the system where control over liquid flow is necessary. These pumps operate by converting mechanical energy into hydraulic energy, allowing them to move water or other liquids from one place to another. They perform a controlled action in response to an input signal, such as a change in water level or activation of a switch. The water pumps are integrated with the sensors and control system to control liquid flow precisely.

Figure 13 shows the view of one side of the mechanical structure where inputs for the Arduino Mega and the pH sensor module are observed. Both inputs establish a serial connection to send commands and data to the microcontroller and receive information back. The Arduino data input is located on this side of the image and aids in debugging programming errors. Adjacent to it is the input for the pH module, which is responsible for converting data from the pH sensor for accurate reading by the main microcontroller.

On the other hand, in Figure 14, the other side view of the mechanical structure can be seen, which includes the power supply connection for the system and an integrated switch for turning the system on or off. On this side of the image is a power input hole to supply energy and ensure all components function smoothly without any issues. Next to it is the main switch that allows you to either power the system or turn it off completely in case of an emergency by cutting off the power supply entirely. Finally, Figure 15 provides an overall view of the design's most crucial aspects, such as the electronic components housed within the structure, each in its respective position to maximize compactness and efficiency. Additionally, on the sides, we can see the data inputs of the modules, the power input hole, and the activation device.

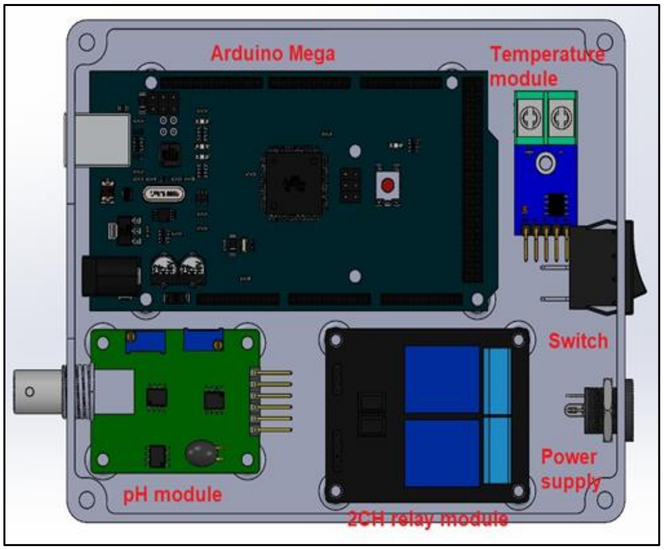

Fig. 15 Top view of the mechanical structure with the electronics

3. Results and Discussions

For testing the prototype designed and implemented, as shown in Figure 16, an open environment has been emulated using two water containers, each equipped with a mini water pump and interconnected with hoses. Additionally, one container integrates the pH sensor and the type K temperature sensor to obtain data and monitor the system. Furthermore, the mini water pumps and sensors are interconnected with the electronic hardware integrated into the Arduino Mega, which monitors the system in real time. The Arduino Mega and the mini water pump were chosen for their affordability and role as actuators in the system, facilitating liquid exchange between containers to achieve more stable and sustainable production. Similar to a study conducted in China focused on tilapia production in aquaculture ponds, the effectiveness of automated water quality control systems was evaluated.

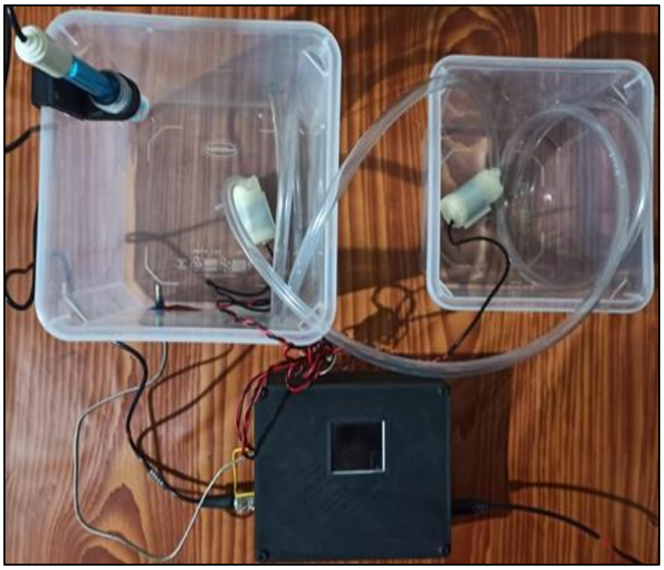

Fig. 16 Components distribution

It was found that implementing these systems significantly improved production efficiency by reducing fish mortality and enhancing growth rates compared to ponds without automated control [18].

3.1. pH Testing

The tests were conducted in acidic water with a pH of 4, neutral water at pH 7, and alkaline water at pH 9, as depicted in Figure 17. To verify the accuracy of our pH sensor and display the information on the TFT display, the system was activated to measure water quality and maintain continuous monitoring. The responses from the pH sensor and the type K temperature sensor were checked. Additionally, the operation of our mini water pumps was verified, which act as actuators in our system and respond when the pH sensor readings fall outside the established range of pH 6.5 to pH 8.5. The mini pumps activate to normalize the system, with a flow rate of 100 L/H, and the average stabilization time was 20 seconds. In a broader study that included various freshwater fish species in India, the effects of water pH and temperature on the chemical and microbiological composition of water and the overall health of the fish were investigated. The results showed that optimal pH levels varied according to the fish species but generally fell within the range of 6.5 to 8.5. Maintaining these levels is crucial for ensuring good growth and reducing disease incidence [19].

To begin with, tests were carried out with the pH sensor using the pH 6.86 buffer solution. There was a significant variation in the water pH levels during the testing period. The values tended to increase, reaching a maximum of pH 8.2, and then gradually stabilized to pH 7.42 within a 20-second interval. Since this value falls within the established ranges, there was no activation of the mini water pumps. Next, the pH 4.01 buffer solution using the same procedure was measured, obtaining a stabilized pH of 4.25 after 20 seconds. The mini water pumps were activated because the sensed pH was outside the established ranges. Automatically, in tank 1, mini pump 1 was activated to release water, while simultaneously, in tank 2, mini pump 2 was activated to allow water with the appropriate pH to enter tank 1 until the pH stabilized.

Fig. 17 Representation of reagents

Fig. 18 pH 6.86 buffer solution

Fig. 19 pH 4.01 buffer solution

Fig. 20 pH 9.18 buffer solution

Subsequently, the pH sensor was placed back in the pH 6.86 buffer solution to return within the specified ranges. After 10 seconds, the pH values stabilized within the established ranges at pH 7.42, automatically deactivating the mini water pumps.

Finally, the pH sensor was placed in the pH 9.18 buffer solution to verify the pH sensor's sensitivity. Using the same procedure as the previous steps, we waited for 20 seconds for stabilization, resulting in a pH of 9.54, outside the established limits. Therefore, the mini water pumps were activated again to exchange liquids until stabilizing and providing values within the appropriate ranges. Automatically, in tank 1, mini pump 1 was activated to release water, while simultaneously, in tank 2, mini pump 2 was activated to allow water with the correct pH to enter tank 1 until the pH stabilized. Next, the pH sensor was placed back in the pH 6.86 buffer solution to normalize the values.

After 10 seconds, the pH values returned within the permitted ranges at pH 7.42, as illustrated in Figures 18, 19, and 20. In a study [20], the impact of water acidification on trout aquaculture systems was examined. Researchers found that water pH levels gradually decreased during the test period, ranging from 6.5 to 7.2. This acidification was primarily attributed to acid deposition from natural and anthropogenic sources. It was observed that water acidification negatively affected trout health, leading to increased disease incidence and decreased growth and fish viability rates.

The results of the tests conducted on the water quality monitoring system with the pH sensor demonstrated that the pH sensor is not as accurate in measuring liquid pH, and the time it takes to stabilize pH is much longer compared to other automated systems with PLCs. It has a margin of error of approximately ±0.50. Additionally, the automated system showed reactive pH adjustment in response to controlled changes in the aquatic environment. Our findings indicate that the system responded quickly to pH changes by making precise adjustments through controlled dosing of acidic or basic solutions.

This responsiveness helped maintain water pH at optimal levels for aquatic life, demonstrating the effectiveness of the automated system in dynamically managing water conditions in aquaculture environments. Research conducted in China and Indonesia has shown that implementing automated systems with pH sensors not only improves monitoring accuracy but also optimizes operational costs and reduces time spent on manual maintenance tasks. This suggests significant benefits in terms of efficiency and sustainability for managing aquaculture farms [21, 22].

On the other hand, the tests in this work were conducted in acidic water with pH 4.01, neutral pH 6.86, and alkaline pH 9.18 to verify the accuracy of our pH sensor and the response of our actuators when water is outside the established pH range of 6.5 to 8.5. The average stabilization time was 20 seconds, as depicted in Figure 21. In Table 1, we observe the data obtained from the measurement and regulation of the system.

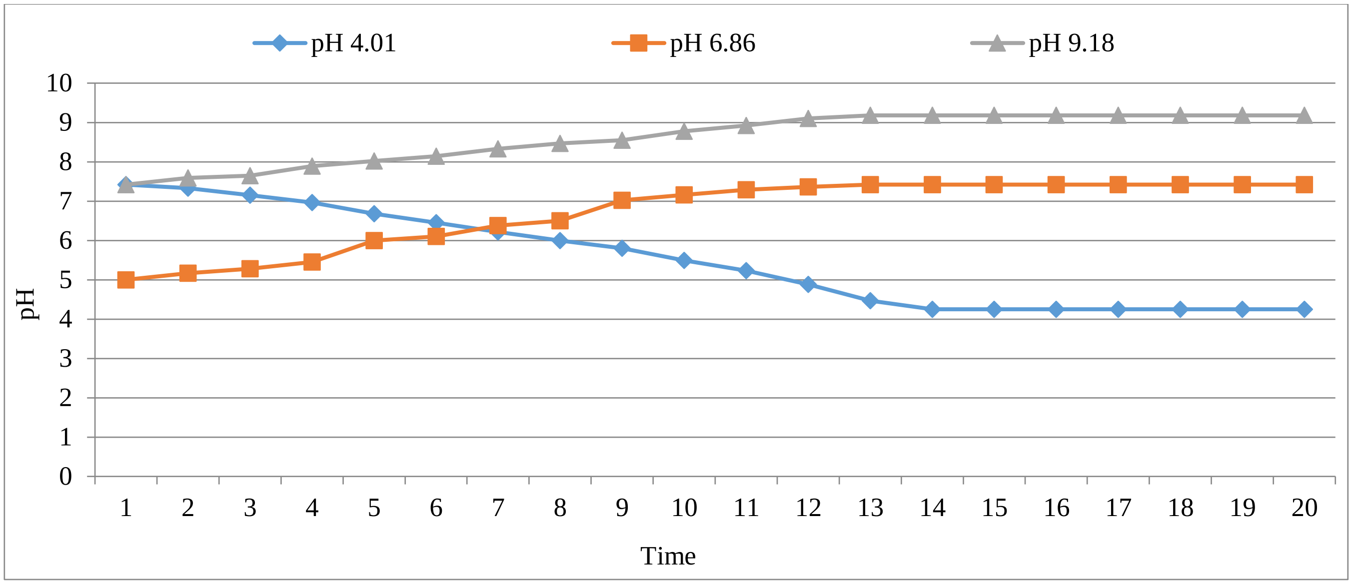

Fig. 21 pH over time

Table 1. Time and pH

pH sensor results			
	pH 4.01	**pH 6.86**	**pH 9.18**
Time(s)	**vessel 1**	**vessel 1**	**vessel 1**
1	7.42	5.00	7.42
2	7.33	5.17	7.59
3	7.15	5.28	7.65
4	6.96	5.45	7.89
5	6.68	6.00	8.02
6	6.45	6.10	8.14
7	6.22	6.38	8.33
8	6.00	6.50	8.47
9	5.80	7.02	8.55
10	5.49	7.16	8.78
11	5.23	7.29	8.92
12	4.88	7.36	9.10
13	4.47	7.42	9.18
14	4.25	7.42	9.18
15	4.25	7.42	9.18
16	4.25	7.42	9.18
17	4.25	7.42	9.18
18	4.25	7.42	9.18
19	4.25	7.42	9.18
20	4.25	7.42	9.18

3.2. Temperature Tests

For the second test, the type K temperature sensor was used to measure the water temperature. Two tests were carried out by increasing the water temperature to 40°C in vessel 1, exceeding the established range of 24°C to 28°C. Automatically, vessel 1 activates mini pump 1 to release water, while mini pump 2 in vessel 2 simultaneously activates to introduce water at the optimal temperature into vessel 1, stabilizing the temperature within the established ranges. This ensures stable conditions optimal for growth and health, with a duration of 20 seconds, as depicted in Figure 22. The next test involved lowering the liquid temperature to 18.5°C in vessel 1, falling below the established limits of 24°C to 28°C.

Automatically, mini pump 1 in vessel 1 activates to release water, while mini pump 2 in vessel 2 simultaneously introduces water at the appropriate temperature into vessel 1, stabilizing the system's temperature, as depicted in Figure 23.

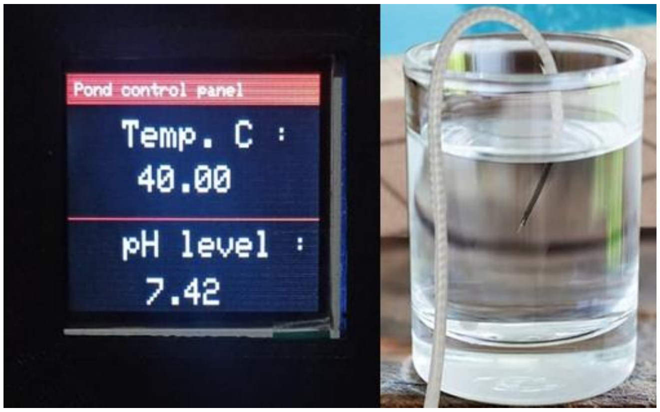

Fig. 22 Temperature at 40 °C

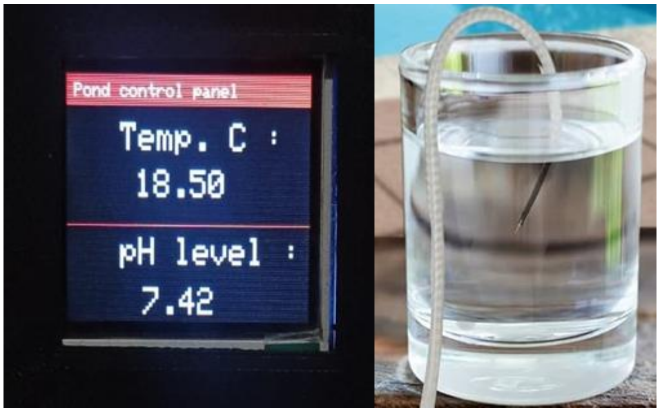

Fig. 23 Temperature at 18.5 °C

Additionally, a comparative study on the impact of liquid temperature on the reproduction of different fish species highlighted the importance of adjusting temperature conditions according to the specific needs of each species. It was found that cold-water species, such as rainbow trout, required lower temperatures to induce reproduction, whereas tropical species, like tilapia, thrived in warmer temperatures [23].

On the other hand, real-time readings from the type K temperature sensor were collected, maintaining constant control and monitoring to verify the proper operation of the entire process, as depicted in Figure 24 of the graph. The temperature variations are shown when exceeding the limits, reaching 40°C indicated by a blue line and decreasing to 18.5°C below the established ranges represented by an orange line. Furthermore, it could be seen how the liquid temperature normalizes automatically within the system, stabilizing around the appropriate limits of 25.5°C.

Table 2 shows the compiled data from measurement and regulation in both tests, conducted over a 20-second period, verifying the system's reliability. In a study focused on trout farming under intensive conditions in Australia, the effect of water temperature on meat quality and trout performance was analysed. The results indicated that maintaining a lower water temperature, typically around 12°C to 15°C for trout, resulted in higher-quality meat in terms of texture and flavour [24].

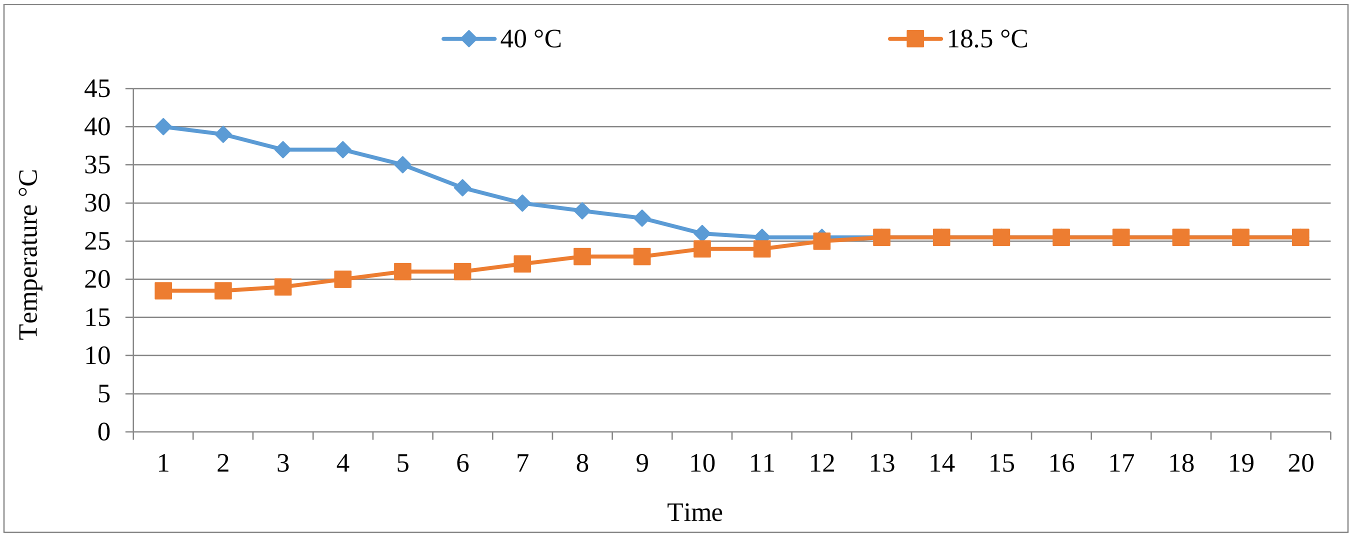

Fig. 24 Temperature over time

Table 2. Time and temperature

Temperature sensor results		
	40 °C	**18.5 °C**
Time(s)	**(°C) Vessel 1**	**(°C) Vessel 1**
1	40	18.5
2	39	18.5
3	37	19

4	37	20
5	35	21
6	32	21
7	30	22
8	29	23
9	28	23
10	26	24
11	25.5	24
12	25.5	25
13	25.5	25.5
14	25.5	25.5
15	25.5	25.5
16	25.5	25.5
17	25.5	25.5
18	25.5	25.5
19	25.5	25.5
20	25.5	25.5

After obtaining the results, a more effective and precise work could be confirmed in terms of conservation and control of a stable temperature environment, which contributes to reducing the management process and water consumption while increasing the quality of aquaculture organism production. This provides solutions adjacent to the issues mentioned in other research works. Additionally, the risk of direct manual exposure to personnel responsible for these processes is greatly reduced.

In this study, a greater efficiency was observed in organizing water conditions, with the ability to maintain pH and temperature parameters within specific ranges, leading to long-term environmental stability. Additionally, the implemented control system has proven adaptable and scalable, allowing integration into various aquatic environments and offering flexibility for future expansions. These findings highlight the feasibility and effectiveness of combined pH and temperature control as a comprehensive strategy for optimizing aquaculture production.

In research conducted in Malaysia, an automated monitoring system was developed for fish farming ponds using pH and type K temperature sensors. The study demonstrated that the automated system could detect subtle changes in water pH and temperature, responding promptly through automatic adjustments. The results indicated that the system maintained stable and optimal water conditions throughout the monitoring period, thereby enhancing the welfare and performance of the fish [25]. Comparatively, an analysis was conducted between the data obtained from the automated system and traditional manual monitoring methods. The results demonstrated that pH and type K temperature sensors provided consistent and reliable measurements comparable to those obtained using standard laboratory techniques. This consistency significantly enhanced monitoring accuracy compared to manual methods, reducing associated errors and ensuring more effective control of water conditions in aquaculture facilities. Collectively, these findings underscore the efficiency and utility of automated systems with integrated sensors for advanced and precise management of water conditions in modern aquaculture.

4. Conclusion

It is concluded that integrating water quality sensors with Arduino technology provides an effective solution for monitoring and maintaining critical parameters such as pH and temperature in water. The data obtained enabled more precise management of resources, reducing waste and optimizing inputs. Moreover, the system's quick response to environmental changes minimized disease risks and improved production efficiency. These benefits not only strengthened the economic viability of aquaculture operations but also mitigated negative environmental impacts, establishing a model for more responsible and ethical practices in the industry.

Similarly, it was concluded that adopting automated technologies provides significant benefits in terms of operational efficiency and risk management. Data obtained from water quality sensors connected to Arduino facilitated informed decision-making, reducing costs associated with manual monitoring and improving the accuracy of environmental measurements. This enhancement in environmental management not only improved fish health and farm productivity but also positioned aquaculture operations to meet stricter regulatory standards and enhance consumer confidence in sustainable aquaculture products. Furthermore, to advance the effectiveness and utility of automated monitoring systems in aquaculture, it is recommended to incorporate a wide range of water quality indicators. In addition to pH and temperature, including sensors for measuring ammonia, nitrates, phosphates, and other critical chemical compounds will allow for a more comprehensive assessment of environmental conditions. This expansion will enhance monitoring accuracy and provide more detailed data for proactive management of issues such as eutrophication and pollutant accumulation. Equally important, integrating emerging technologies such as the Internet of Things (IoT) and cloud computing should be considered to enhance real-time data organization and evaluation capabilities from multiple locations. Implementing IoT platforms would enable more robust connectivity between sensors and centralized control systems, facilitating remote monitoring and swift response to environmental changes. This approach would not only improve operational efficiency but also reduce costs associated with the maintenance and management of physical infrastructures.

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