

Optimization of Chemical Water Monitoring in Fishponds Through Automated Systems*

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Abstract: This study outlines the design and development of an automated system to optimize chemical water monitoring in fishponds. The prototype facilitates automatic sample collection, precise reagent dosing, and uniform mixing, alongside real-time analysis and visualization of results through a touchscreen interface. Key parameters, including Nitrite (NO_2), Nitrate (NO_3), and Ammonia (NH_3/NH_4), were targeted. The methodology involved designing electromechanical systems and integrating them with sensors and software to automate manual tasks. Tests conducted have confirmed the system's accuracy in detecting chemical concentrations, optimizing operational times, and minimizing errors. The results highlight the system's ability to enhance decision-making in aquaculture by enabling constant and timely monitoring of water conditions. This directly contributes to improved fish welfare and increased economic profitability for producers. The prototype represents an innovative and accessible technological solution for the aquaculture sector, with significant potential for scaling up to larger production processes.

Keywords: Sustainable Aquaculture; Water Chemical Analysis; Automation; Water Quality Monitoring; Emerging Technologies

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Optimización del monitoreo químico del agua en estanques piscícolas a través de sistemas automatizados

Resumen: Este estudio describe el diseño y desarrollo de un sistema automatizado para optimizar el monitoreo químico del agua en estanques piscícolas. El prototipo permite la recolección automática de muestras, dosificación precisa de reactivos, mezcla uniforme, además del análisis y visualización de resultados en tiempo real mediante una interfaz táctil. Se abordaron parámetros clave como nitrito (NO_2), nitrato (NO_3) y amoníaco (NH_3/NH_4). La metodología incluyó el diseño de sistemas electromecánicos y su integración con sensores y software para automatizar tareas manuales. Las pruebas realizadas confirmaron la precisión del sistema para detectar concentraciones químicas, optimizar tiempos operativos y minimizar errores. Los resultados destacan la capacidad del sistema para mejorar la toma de decisiones en acuicultura al permitir un monitoreo constante y oportuno de las condiciones del agua. Esto contribuye directamente al bienestar de los peces y a una mayor rentabilidad económica para los productores. El prototipo representa una solución tecnológica innovadora y accesible para el sector acuícola, con un gran potencial para ser escalado a procesos de producción más amplios.

Palabras clave: acuicultura sostenible; análisis químico del agua; automatización; monitoreo de calidad del agua; tecnologías emergentes

Otimização do monitoramento químico da água em tanques de piscicultura por meio de sistemas automatizados

Resumo: Este estudo descreve o design e desenvolvimento de um sistema automatizado para otimizar o monitoramento químico da água em tanques de piscicultura. O protótipo permite a coleta automática de amostras, dosagem precisa de reagentes, mistura uniforme, além da análise e visualização dos resultados em tempo real por meio de uma interface tátil. Foram abordados parâmetros-chave como nitrito (NO_2), nitrato (NO_3) e amônia (NH_3/NH_4). A metodologia incluiu o projeto de sistemas eletromecânicos e sua integração com sensores e software para automatizar tarefas manuais. Os testes realizados confirmaram a precisão do sistema na detecção de concentrações químicas, otimização do tempo operacional e minimização de erros. Os resultados destacam a capacidade do sistema para melhorar a tomada de decisões na aquicultura ao permitir o monitoramento constante e oportuno das condições da água. Isso contribui diretamente para o bem-estar dos peixes e para uma maior rentabilidade econômica dos produtores. O protótipo representa uma solução tecnológica inovadora e acessível para o setor aquícola, com grande potencial para ser escalado a processos de produção mais amplos.

Palavras-chave: aquicultura sustentável; análise química da água; automação; monitoramento de qualidade da água; tecnologias emergentes

Introduction

Aquaculture, as defined by the current FAO guidelines, refers to the farming of aquatic organisms, including fish, mollusks, crustaceans, and aquatic plants. This practice involves interventions in the rearing process to enhance production, such as regular stocking, feeding, and protection from predators and assumes individual or corporate ownership of the cultivated stock [1]. Similarly, the concept of aquaculture in Colombia is outlined in Article 286 of Decree 2811 of 1974, which defines it as the cultivation of hydrobiological organisms using appropriate techniques in natural or artificial environments, generally under controlled conditions [2].

Over the past few decades, aquaculture has experienced remarkable growth, establishing itself as a vital source of animal protein globally. To sustain fish health and ensure the economic viability of aquaculture operations, it is essential to monitor water quality consistently and accurately in ponds. Chemical parameters, such as Nitrite, Nitrate, and Ammonia levels, serve as critical indicators of the health of aquatic ecosystems. Controlling these parameters is crucial to prevent adverse conditions that could compromise fish welfare and productivity [3], [4], [5].

In 2022, Colombia's aquaculture sector experienced significant growth of 20%, with red tilapia dominating 92% of the U.S. market. This year marked a record in exports, surpassing 200,000 tons and achieving a remarkable 193% growth between 2015 and 2022. Approximately 19,000 tons of tilapia and trout were exported, reflecting a 30% increase in volume and a 39% rise in FOB value. Colombia has firmly established itself as the leading supplier of fresh tilapia fillets to the United States [6].

Traditionally, monitoring water quality parameters has been conducted manually a method requiring significant time and labor while being prone to human error. These limitations have driven the pursuit of more efficient and accurate solutions through automation. Recent technological advancements have enabled the development of automated systems capable of performing

monitoring tasks with greater precision and minimal human intervention. These systems not only improve accuracy in reagent dosing and sample collection but also facilitate early detection of harmful chemical concentrations, reducing stress and fish mortality.

Recognizing the need to optimize the water quality verification process in fishponds, traditionally characterized by labor-intensive and time-consuming manual methods, a solution was proposed: the development of an automated electromechanical system. This system is designed to efficiently perform water sample collection, precise chemical reagent dosing, and analysis of key water quality parameters such as nitrite, nitrate, and ammonia. By automating these repetitive tasks, the system frees personnel to focus on interpreting results and implementing corrective measures, thereby maintaining optimal water conditions, enhancing operational efficiency, and promoting sustainable aquaculture practices.

This study centers on the development and implementation of an automated system for monitoring chemical parameters in fishponds. The system aims to optimize monitoring processes, improve operational efficiency, and foster more sustainable aquaculture practices. By providing reliable, real-time data, the system empowers aquaculturists to make informed decisions that ensure a healthy environment for the fish and maximize productivity.

Literature review

Manual water quality monitoring systems remain widely used but are limited by their reliance on human intervention, significant time requirements, and high operational costs. Advances in technology, particularly the integration of the Internet of Things (IoT) and automation, have paved the way for sophisticated systems that greatly enhance the accuracy and efficiency of water quality monitoring, as shown in studies [7] and [8]. These systems leverage electronic sensors and microcontrollers as key components, enabling real-time data acquisition and more effective water quality management.

Comparative studies have consistently demonstrated that automated water quality monitoring methods significantly reduce workload and operational costs, while providing greater accuracy than traditional approaches [9]. Recent research underscores the effectiveness of IoT-based systems for real-time monitoring, offering immediate alerts for deviations in water quality parameters. This capability is crucial for maintaining fish health and ensuring optimal growth conditions [10].

The adoption of automated technologies has led to substantial improvements in fish health and growth, reducing mortality rates and increasing overall aquaculture productivity. Additionally, these systems facilitate the early detection of contaminants, enabling rapid and effective responses to preserve optimal pond conditions [11].

Recent technological advancements have enabled the integration of advanced sensors and microcontrollers, allowing for continuous and precise monitoring of critical water quality parameters, such as pH, temperature, dissolved oxygen, and concentrations of nitrite and ammonia. Furthermore, the adoption of cloud-based platforms and mobile applications for water quality data management has significantly improved the accessibility and remote control of monitoring systems [12], [13].

Advanced algorithms, including machine learning techniques and fuzzy logic, are being employed to optimize water quality management by automatically adjusting pond conditions to maintain optimal levels [14]. These systems go beyond monitoring by actively controlling water parameters, such as adjusting reagent dosing and aeration, based on real-time data [15]. Proper management of the chemical, physical, and biological aspects of water, including the nitrogen cycle, is essential to ensuring an optimal environment for fish, ultimately contributing to more profitable aquaculture operations [16].

A review of recent studies underscores the critical impact of ammonia, nitrite, and nitrate concentrations on the availability of dissolved oxygen in fishponds, a key factor for sustaining aquatic life. Research highlights the importance of aeration methods and water quality control in mitigating the adverse effects of these compounds on fish

health. For example, [17] demonstrates that optimized aeration intervals can significantly improve water quality by reducing ammonia concentrations and increasing Nitrite and Nitrate levels, leading to more efficient nitrogen cycle management. Additionally, [18] identifies the influence of dissolved oxygen and nitrite concentrations on nitrous oxide production by ammonia-oxidizing bacteria, highlighting the intricate interactions between Oxygen, Nitrogen, and the microbial community in aquaculture systems. These findings emphasize the need for integrated strategies in water quality management, leveraging technology and microbial knowledge to optimize aquatic environments for fish farming.

Despite significant progress in automated systems for monitoring chemical water parameters, their widespread implementation in production systems faces several barriers. One major limitation is the lack of technical knowledge among operators regarding the use and maintenance of these devices, which hinders their adoption in industrial contexts. Variable water conditions, such as the presence of sediments, microorganisms, or sudden changes in physical and chemical parameters, can also lead to premature sensor wear or malfunction, increasing operational and maintenance costs.

Another challenge is the high initial investment cost. While automated solutions offer long-term benefits, the expenses associated with acquisition, setup, and training pose a barrier for small and medium-sized producers. Traditional monitoring systems, although more affordable upfront, require greater human resources for operation. At both national and international levels, successful initiatives in aquaculture process automation have been reported. However, their broader adoption depends on overcoming these challenges by designing more robust, cost-effective systems tailored to the specific conditions of production environments.

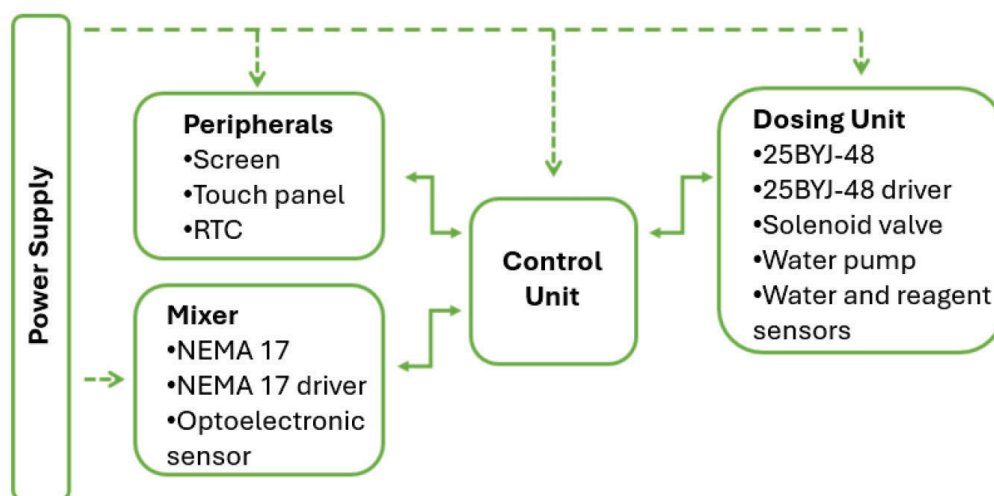
Materials and methods

- The block diagram depicted in Figure 1 illustrates the functional architecture of the automated water quality monitoring system for fishponds. This diagram outlines the

operational flow, starting from the selection of the target pond to the presentation of analysis results via an intuitive user interface. The system is composed of interconnected modules that enable full automation of the sampling process, reagent dosing, colorimetric analysis, and data visualization. The key components of the system are as follows:

- **Peripheral Systems:** This module integrates a screen, a touch panel, and a real-time clock (RTC) module, providing an interactive user interface and ensuring temporal accuracy for test execution.
- **Mixer:** Comprising a NEMA 17 stepper motor, its corresponding driver, and an optoelectronic sensor, this module controls the position and speed of the sample tray to ensure homogeneous mixing. The optoelectronic sensor precisely identifies a reference point on the tray.
- **Dosers:** This component consists of stepper motors, drivers, valves, and mini water pumps. It is responsible for the accurate dosing of the water sample volume and the required reagent for analysis.
- **Control Unit:** A microcontroller serves as the central processing unit of the system, orchestrating all operations. It interprets sensor signals and coordinates the timely activation of actuators to ensure seamless functionality.

Figure 1. Block diagram of the main system



Source: created by the authors.

The attached Figure 1 illustrates the interconnection and interaction of the main components within the system, outlining a cohesive workflow from sample collection to result presentation. This integration highlights the complexity and efficiency of the proposed design, representing a significant advancement in the automation of water quality monitoring for aquaculture. The outcomes of this process are further demonstrated in Figure 2.

The automated chemical monitoring system for fishponds, as depicted in the diagram, integrates various interconnected modules that operate in

coordination to ensure efficient and accurate analysis of water parameters. At the foundation of the system is the electrical power supply, which provides energy to all components.

The peripheral module, comprising a screen, touch panel, and real-time clock (RTC) module, facilitates user interaction with the system, allowing for configuration of specific schedules and real-time visualization of results.

The mixer module ensures the homogeneity of chemical mixtures. It includes a NEMA 17 motor, controlled by a dedicated driver, and an

optoelectronic sensor that ensures the precise positioning of the mixer during operation.

The dosing units are equipped with 25BYJ-48 motors and their respective drivers, along with a solenoid valve, water pump, and liquid and reagent sensors. These components work in tandem to perform automated sampling, precise reagent dosing, and liquid handling significantly reducing the risk of human error.

At the core of the system is the control unit, which functions as the brain of architecture. This unit synchronizes the operations of the peripherals, mixer, and dosing units through programmed algorithms, ensuring seamless functionality.

This modular and integrated design not only optimizes the chemical monitoring process but also enhances sustainability and profitability in aquaculture practices. By improving the management of water quality, the system demonstrates its potential to transform productive environments in the aquaculture industry.

Figure 3 presents the flowchart of the overall system operation, illustrating a continuous process that runs automatically. Initially, the system interface displays essential information, including the time, date, and company name. The system features a touch panel that enables user interaction, allowing the configuration of test schedules and dates. Additionally, the interface includes a section or virtual button for viewing the results of the last test.

Throughout the process, the system continuously checks the assigned configuration to determine whether it is time to perform a test. Once this

condition is met, the system automatically initiates a status recognition sequence and begins the water sampling process. At this stage, the sample tray is positioned so that the test tube is aligned directly beneath the solenoid valve. Subsequently, the mini water pump activates, circulating water from the pool into a designated volumetric measurement chamber for temporary storage.

At this stage, the water sensor sends a signal to deactivate the pump. The solenoid valve is then activated, releasing the water sample into the test tube. This process is repeated three times, once for each test tube. Next, the test tubes containing the water samples are placed under their corresponding reagent dozers. Each reagent dozer then performs the dosing process.

Once dosing is complete, the water and reagent samples are mixed using the mixer and allowed to stand for five minutes to enable the reagent to take effect (this duration is recommended by the reagent manufacturer). Finally, the test tubes are positioned in front of the color sensor, where colorimetric tests are performed one by one. The results are saved and displayed on the screen when requested by the operator.

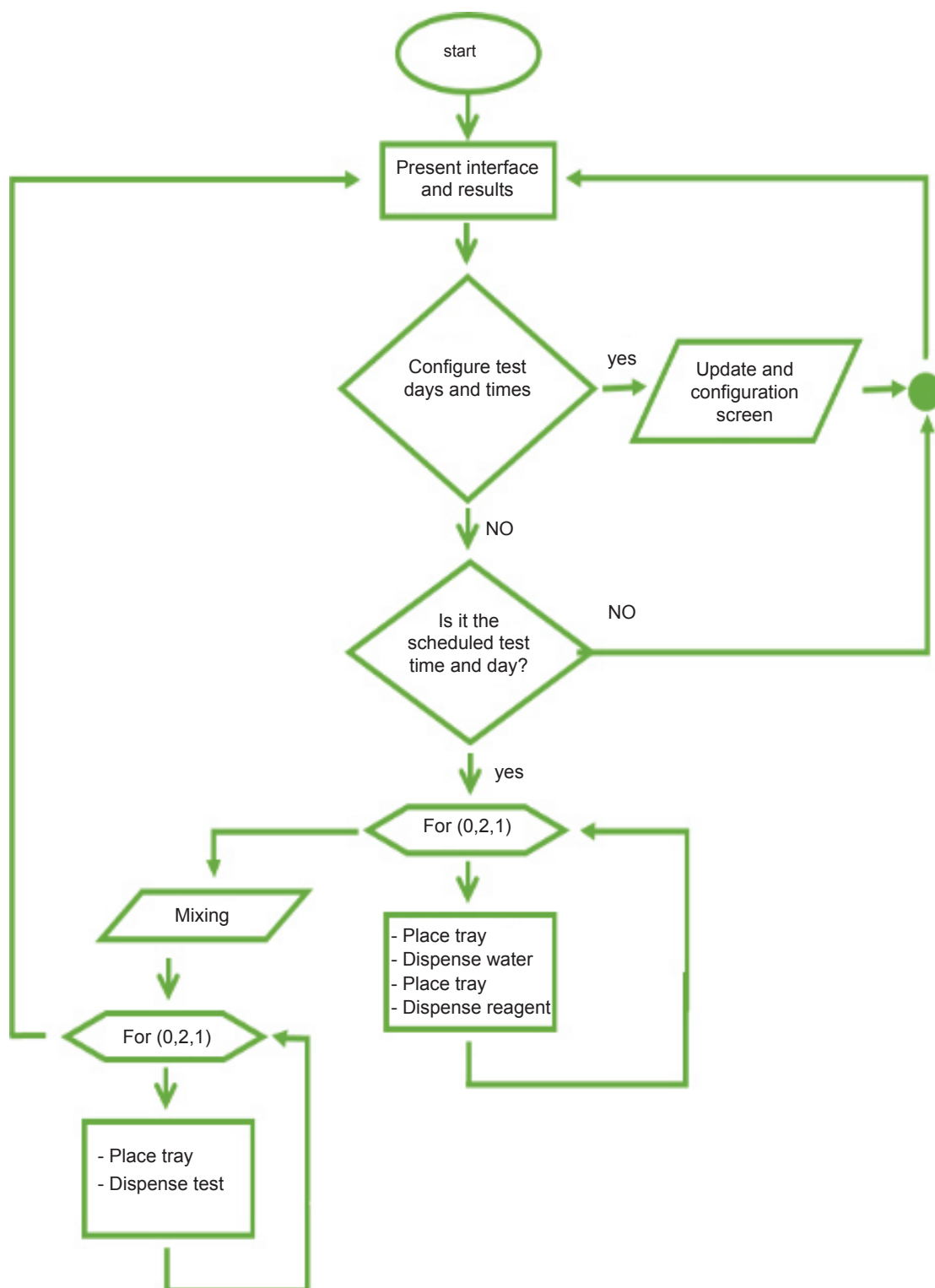
Accurate dosing of both the water sample and the reagent is essential for precise testing. Any discrepancy in the proportions, relative to the manufacturer's recommendations, could lead to errors in data interpretation. Figure 4 presents a block diagram that illustrates the interaction between the components responsible for dosing both the reagent and the water sample, including the automatic water dosage process.

Figure 2. Interaction of the final system with the environment and result delivery



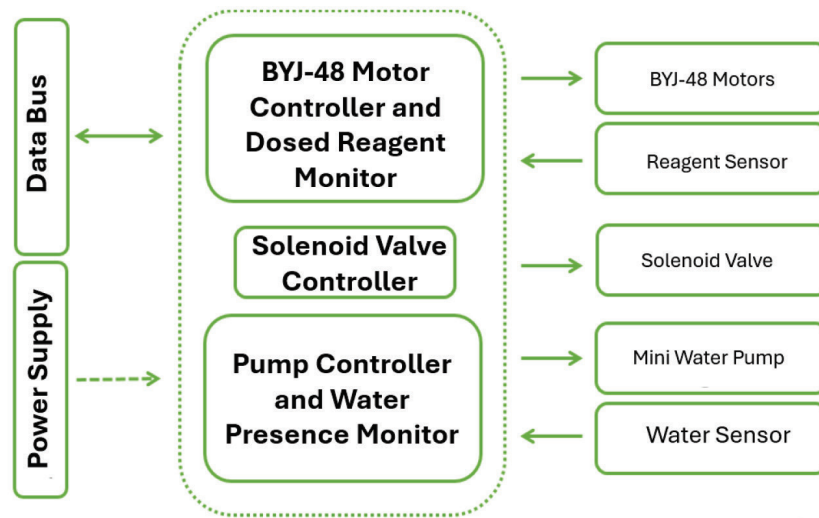
Source: Created by the authors.

Figure 3. Process flow diagram



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Figure 4. Block diagram of the dosers



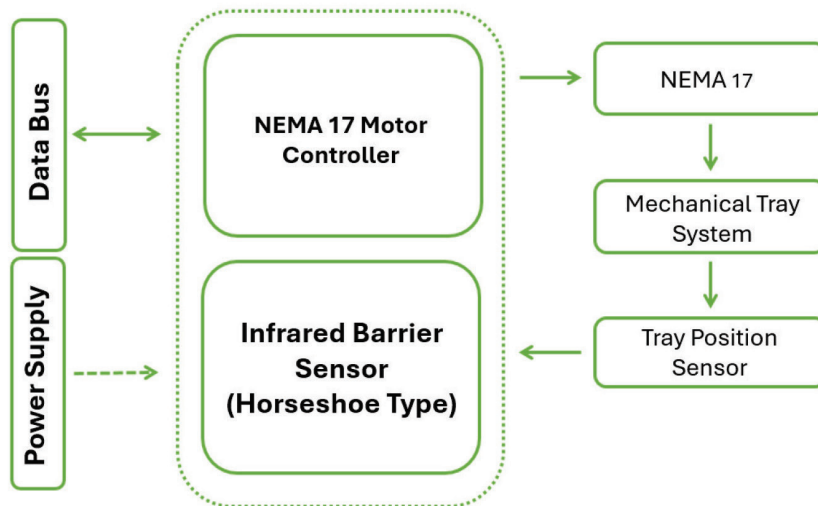
Source: Created by the authors.

Figure 5 presents a block diagram illustrating the interaction between the various elements that facilitate the water-reagent mixing process. This microsystem integrates a controller for the NEMA 17 motor, the NEMA 17 motor itself, and a feedback system provided by an optoelectronic sensor. The optoelectronic sensor is responsible for identifying a reference point on the tray, which allows the

control system to determine the exact position of the tray.

Based on this reference point, the system adjusts the tray's position by controlling the number of steps the NEMA 17 motor needs to take, in accordance with the programming of the main controller. This precise position control ensures uniform and efficient mixing of the water and reagent.

Figure 5. Block diagram of the mixer



Source: Created by the authors.

Results and discussion

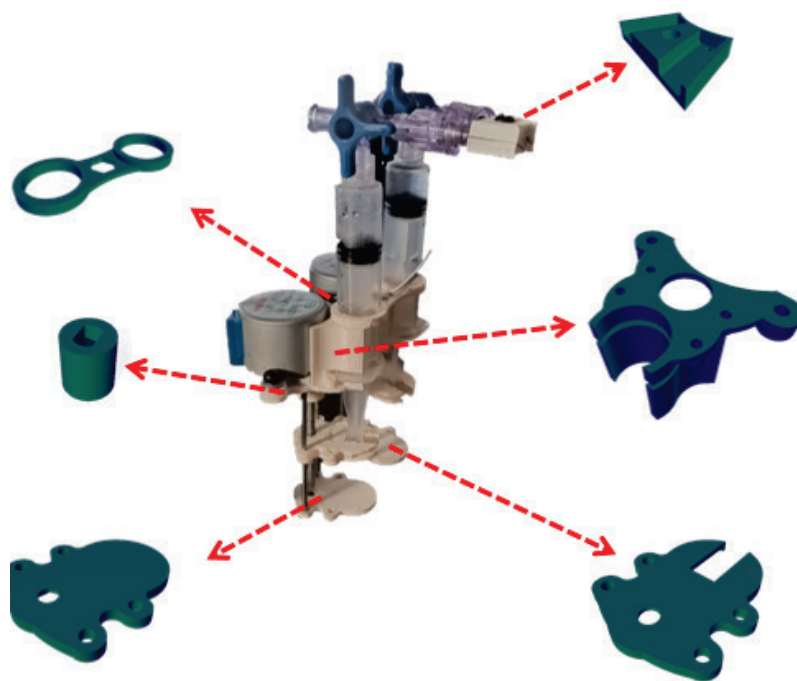
Initially, a mechanical system for reagent dosing was proposed, as shown in Figure 6. This system relies on the movement of a motor to displace the syringe plunger, based on the assumption that there would be a direct relationship between the number of motor rotations, the displacement of the syringe plunger, and the number of drops dosed.

However, during the validation tests, it was observed that the delivery of reagent drops did not correlate directly with the number of motor rotations, as initially expected. For example, when the

motor was programmed to complete 10 rotations, the actual output varied between 8 and 12 drops due to fluctuations in the internal pressure of the syringe as the plunger advanced. This variability was influenced by factors such as the viscosity of the reagent and the displacement of the plunger.

The tests, conducted under controlled conditions with a standard 5 mL syringe and a calibrated microbalance, revealed inconsistencies in drop delivery at different syringe pressures. To address this issue, a low-cost reagent sensor was integrated into the system, providing real-time feedback to ensure precise dosing and eliminate discrepancies caused by mechanical limitations.

Figure 6. Reagent doser assembly



Source: Created by the authors.

Due to this inconsistency, it became necessary to introduce a reagent sensor that could provide real-time feedback during the dosing process. However, since the volume to be monitored was relatively small, no affordable or suitable sensor was available on the market for this application. This challenge led to the development of a low-cost, accurate sensor designed to minimize the risk of reagent contamination.

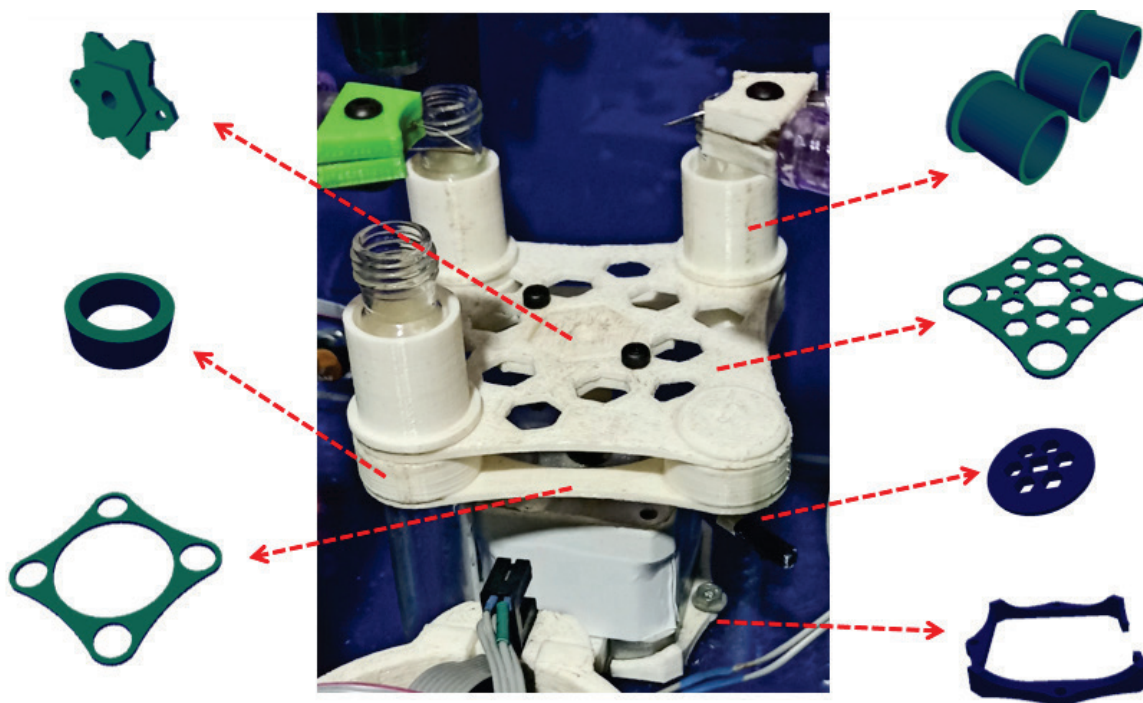
By utilizing the syringe needles as contact sensors, activated by the presence of the reagent, and implementing signal conditioning to detect the small voltage change produced when the two needles make contact through the reagent, a reliable, cost-effective sensor with minimal contamination risk was successfully created.

In addition to its primary function of mixing, the mixer is also responsible for the correct positioning

of the test tubes. It moves the test tubes to specific positions to allow easy access for cleaning, water dosing, reagent dosing, and result analysis. This

functionality is enabled by the use of a barrier sensor that monitors a reference point on the tray, ensuring precise positioning, as illustrated in Figure 7.

Figure 7. Mixer assembly



Source: Created by the authors.

The analysis of the results was conducted using the TCS3200 color sensor, which filters and processes the data captured from the physical medium, converting it into pulse-width modulation (PWM) signals based on the intensity of red, green, and blue colors. The sensor operates within a resolution range of 0 to 255, enabling precise colorimetric analysis. This methodology facilitated the collection and storage of specific data for each concentration level of Nitrite, Nitrate, and Ammonia during colorimetry tests. The data is organized into a reference matrix, which allows for easy comparison of the results obtained during each analysis with previously stored values.

The accuracy of the data readings is highly dependent on the precise positioning of the color sensor; even minimal variations in its position can lead to significant differences in the measured values. Therefore, careful placement and secure fixation of the sensor are critical to ensuring consistency and reliability in measurements. This approach optimizes the interpretation of results and their graphical representation in the user interface.

For result visualization, a 2.4-inch touchscreen was integrated into the user interface. This screen enables the user to view the device's main screen, check the results of the most recent test, and configure the test schedule, including days and times, as shown in Figure 8.

Figure 8. The last results display screen

Source: Created by the authors.

Conclusions

The development of this project, aimed at automating and improving water quality monitoring in fishponds, has produced significant technical outcomes. The implementation of the device has substantially optimized the resources and time required for monitoring tasks, effectively addressing initial challenges and improving timely decision-making. The automated system ensures strict adherence to sampling periods, eliminating the errors and omissions common in manual methods due to staff overwork or neglect.

Additionally, the device delivers clear and precise information, simplifying data interpretation and facilitating informed decision-making. It is crucial to adapt existing technological tools so that they are easily accepted and integrated into aquaculture processes. The successful implementation of this prototype has proven to be a valuable contribution across various stages of aquaculture, effectively monitoring critical variables such as nitrite, nitrate, and ammonia. These parameters are essential throughout the seeding, growth, and harvesting phases. Proper control of ammonia, nitrite, and nitrate levels is vital for reducing losses and enhancing the profitability of aquaculture operations. However, it is important to consider the need for regular maintenance, particularly of the mechanical components, which can be affected by

dryness or dirt in the moving parts. Additionally, the color sensor used in colorimetry must be kept clean to prevent erroneous results caused by dirt or moisture. In conclusion, this prototype not only improves the efficiency and accuracy of water quality monitoring but also underscores the importance of maintenance and technological adaptability in aquaculture.

This prototype represents a functional initial version capable of effectively monitoring critical variables, such as nitrite, nitrate, and ammonia, during different aquaculture stages, including seeding, growth, and harvesting. While the results demonstrate significant potential for enhancing operational efficiency and decision-making, it is important to acknowledge the limitations inherent in this early stage of development. Regular maintenance of mechanical components and optical sensors is essential to ensure long-term reliability. Future iterations of the prototype will focus on integrating advanced sensors and control algorithms to enhance precision and achieve full automation. This implementation highlights the importance of technological adaptability and maintenance in aquaculture processes, providing a foundation for further innovation in water quality monitoring systems.

For future work, integrating additional sensors to monitor critical water parameters, such as pH, temperature, dissolved oxygen, and conductivity,

would offer a more comprehensive view of water quality and allow for more precise control of pond conditions. Moreover, the development and testing of more advanced and affordable reagent sensors could provide more accurate and reliable feedback during the dosing process. Another

promising direction involves the implementation of control algorithms based on artificial intelligence and machine learning, which could predict and automatically adjust water parameters in real-time, further optimizing fish health and operational efficiency.

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