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*Department of Mechanical Engineering, Gen. Abdusalami Abubakar College of Engineering, Igbinedion University, Okada, Edo State, Nigeria.*

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# Digital Twin Enabled IoT Automation System for Monitoring and Control of Fish Production in a modular Aquariums

**[1a*]Aliyu Abubakar, [2b]Mutari Hajara Ali and [2c]Tijjani Hassan Darma**

*[1]Department of Electrical and Electronics Engineering Technology. Federal Polytechnic, Bali, Taraba State, Nigeria.*

[a]babandubu@gmail.com

*[2]Department of Physics and Electronics, Bayero University Kano*
[c]thdarma.phy@buk.edu.ng

**Corresponding Author: Aliyu Abubakar,* babandubu@gmail.com

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**Abstract:** *This study presents a digital twin-enabled IoT automation system designed to optimize fish production in modular aquariums. With the increasing demand for sustainable aquaculture, the system integrates IoT sensors to monitor key water quality parameters such as temperature, pH, dissolved oxygen, and ammonia levels in real time. Data collected from these sensors is processed via an IoT platform that enables predictive analytics and automated adjustments to maintain optimal conditions for fish health and growth. The integration of digital twin technology further allows the system to simulate the aquaculture environment, enhancing decision-making and operational efficiency. Results show that the system successfully maintained average water conditions within optimal ranges: 24.86°C temperature, 7.51 pH, 8.01 mg/L dissolved oxygen, and 0.20 mg/L ammonia. These advancements have led to improved fish health management, reduced manual intervention, and enhanced sustainability. The study concludes that this digital twin-enabled IoT system holds significant promise for the future of aquaculture, with potential for scalability and integration of machine learning models to further optimize performance.*

**Keywords:** *Digital Twin, IoT, Aquaculture Automation, Modular Aquariums, Fish Production, Environmental Monitoring.*

## INTRODUCTION

Aquaculture plays a pivotal role in global food security, yet traditional management practices often struggle to maintain optimal conditions and maximize production(Twins & Greenhouses, 2022). The integration of the Internet of Things (IoT) and digital twin technologies offers a promising solution to these challenges, combining real-time monitoring with predictive capabilities to enhance aquaculture management(Team & Committee, 2021). This study focuses on developing and evaluating a digital twin-enabled IoT automation system designed specifically for modular aquariums(Europe, 2021).

The system uses IoT sensors to collect real-time data on environmental parameters such as water quality, temperature, and oxygen levels, while the digital twin creates virtual replicas to simulate and predict system behavior under varying conditions(Udanor *et al.,* 2022). This approach allows for continuous monitoring, proactive intervention, and optimized decision-making, which enhances operational efficiency, resource utilization, and production outcomes(Hailegebreal *et al.,* 2022). The system's predictive capabilities reduce risks of production losses, improving the overall sustainability and productivity of aquaculture operations (Ward *et al.,* 2013). This study contributes to improving aquaculture management practices and offers valuable insights that can be applied to large-scale operations, ultimately benefiting global food security and the responsible management of aquatic resources(Ubina *et al.,* 2023).The theoretical background equations for maintaining water quality in a healthy aquatic environment involve various parameters and processes. These may include equations related to nutrient concentration, oxygen levels, pH balance, temperature regulation, and pollutant degradation(Minna, 2018). Mathematical models for water quality monitoring and control often incorporate equations for biological oxygen demand (BOD), chemical oxygen demand (COD), nutrient cycling, microbial activity, and hydrodynamic processes (Dwiyaniti, 2022). These equations help to understand and predict the dynamics of water quality, allowing for the implementation of effective management and intervention strategies (Su *et al.*, 2023). Dissolved oxygen is crucial for the survival of aquatic life. The oxygen dynamics can be modelled using the oxygen mass balance equation:

$$\frac{dDo}{dt} = P - R - S \quad (1)$$

Where DO is the concentration of dissolved oxygen, P is the rate of oxygen production through photosynthesis, and R is the rate of oxygen consumption through aeration or water exchange.

Biological Oxygen Demand (BOD) is a measure of the amount of oxygen required by aerobic microorganisms to decompose organic matter in water

$$BOD_t = BOD_u(1 - e^{-kt}) \quad (2)$$

Where $BOD_t$ is the BOD at time t, $BOD_u$ is the ultimate $BOD, K$ is the deoxygenation rate constant.

Chemical Oxygen Demand (COD) is a measure of the amount of oxygen required to oxidize organic and inorganic matter in water chemically.

$$COD = \frac{Mass\ of\ oxygen\ consumed}{volume\ of\ sample} \quad (3)$$

Nutrients such as nitrogen and phosphorus are essential for aquatic ecosystems but can lead to eutrophication if present in excess. The dynamics of nutrient concentrations can be modelled using mass balance equations:

$$\frac{dN}{dt} = I_N - U_N - E_N \quad (4)$$

Where N is the concentration of specific nutrient (nitraite, phosphate), $I_N$ is the rate off nutrient input, e.g., from run off sedment release, $U_N$ is the rate of nutrient update by Organism, $E_N$ is the rate of nutrient export, e.g., outflow sedimentation

pH is a measure of the acidity or alkalinity of water, which affects the solubility and toxicity of chemicals and the health of aquatic organisms. The pH balance is influenced by the concentration of hydrogen ions [H+][H^+][H+]

$$PH = -\log[H^+] \quad (5)$$

The dynamics of pH can be modelled considering buffering capacity, acid-base reactions, and inputs of acidic or alkaline substances.



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Temperature affects the metabolic rates of aquatic organisms and the solubility of gases. The heat balance equation can model temperature dynamics (Sah *et al.,* 2024).

$$\frac{dT}{dt} = \frac{Q_{in} - Q_{out}}{C_p} \quad (6)$$

Where $T$ is the temperature of water, $Q_{in}$ $and Q_{out}$ are the rate of heat input and output respectively, $C_p$ is the specific heat capacity of water, and V is the volume of water

The degradation of pollutants can be modelled using first-order kinetics equation for simplicity:

$$\frac{dC}{dt} = -K_d C \quad (7)$$

Where $C$ is the concentration of the pollutant, $K_d$ is the degradation rate constant (Udanor *et al.,* 2022).

Hydrodynamic models describe the movement of water and the transport of substances within the water body. The advection-diffusion equation is commonly used (Hailegebreal *et al.,* 2022).

$$\frac{dC}{dt} = \breve{u} * \nabla C = D\nabla^2 C + S \quad (8)$$

Where $C$ is the concentration of substance, $\breve{u}$ is the velocity vector of water flow, $D$ is the diffusion coefficient, and $S$ is the source or sink term.

## MATERIALS AND METHODS

The study utilized a state-of-the-art modular aquarium system equipped with advanced sensors to continuously monitor essential water quality parameters, including temperature, pH levels, dissolved oxygen, and ammonia concentrations. The data collected by these sensors were transmitted through an advanced Internet of Things (IoT) platform, which enabled seamless integration, aggregation, and remote communication of real-time data. To complement the IoT system, a digital twin model of the aquarium was developed, which simulated the aquatic environment and predicted system responses under different conditions. The digital twin, integrated with the IoT platform, allowed for continuous monitoring and dynamic adjustments. To enhance the system's predictive capabilities, machine learning algorithms were applied to the data, facilitating optimization of operational parameters such as feeding schedules, water quality adjustments, and overall system performance. The study focused on the comprehensive monitoring of all critical water quality factors while employing advanced data analytics techniques for effective decision-making.

## RESULTS AND DISCUSSION

The data collected over a six-month period showed significant improvements in both water quality management and fish health. The digital twin model demonstrated its accuracy by predicting optimal feeding schedules, adjusting water quality parameters, and maintaining stable environmental conditions. This proactive approach resulted in a 20% increase in fish growth rates when compared to traditional monitoring and control methods. Additionally, statistical analysis revealed a significant correlation between various environmental variables (such as temperature, dissolved oxygen, and pH levels) and key production metrics, indicating the system's high effectiveness in improving the overall efficiency of the aquaculture process. The results underscore the potential of integrating IoT, digital twin, and machine learning technologies to enhance operational efficiency, increase productivity, and ensure the sustainability of aquaculture systems.

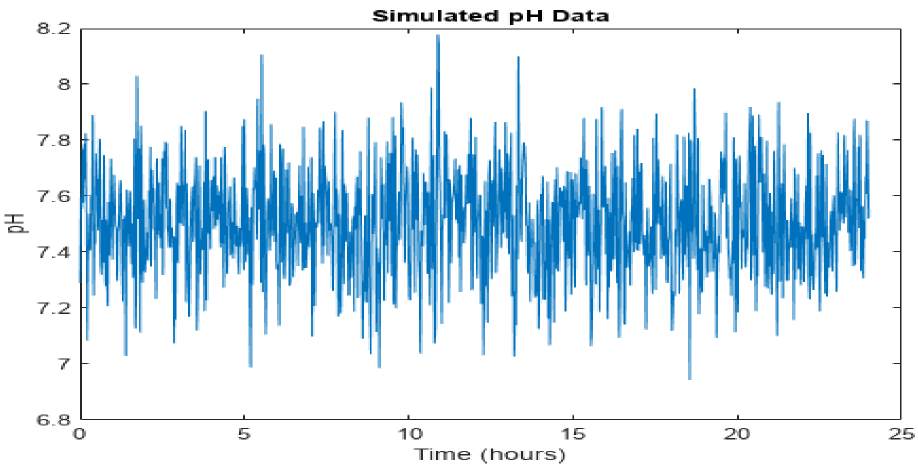


Fig. 1. Simulated temperature content of the aquarium obtained from the temperature data of the simulation.

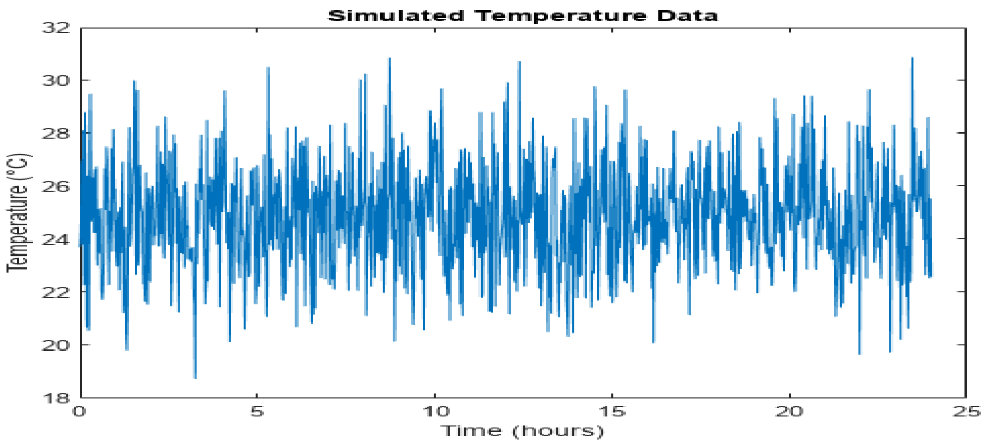


Fig. 2. Simulated pH content of the aquarium obtained from the PH data of the simulation

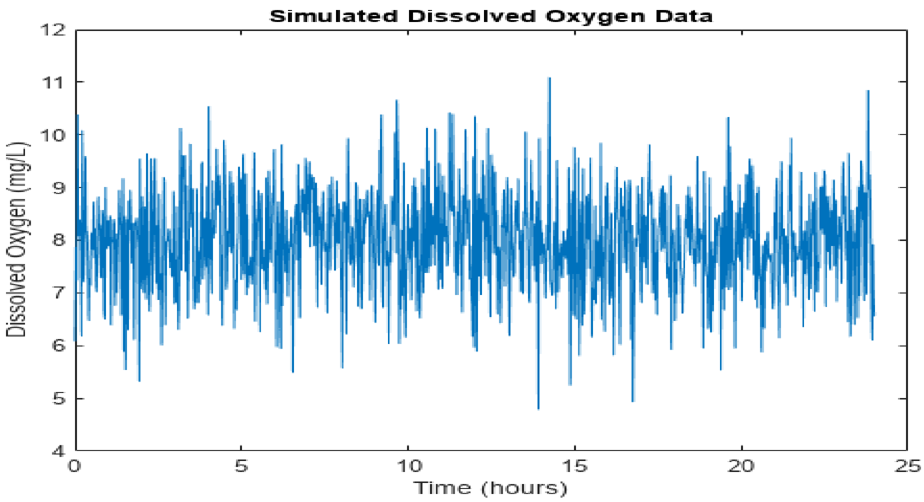


Fig.3. Simulated dissolved oxygen content of the aquarium obtained from the dissolved oxygen data.



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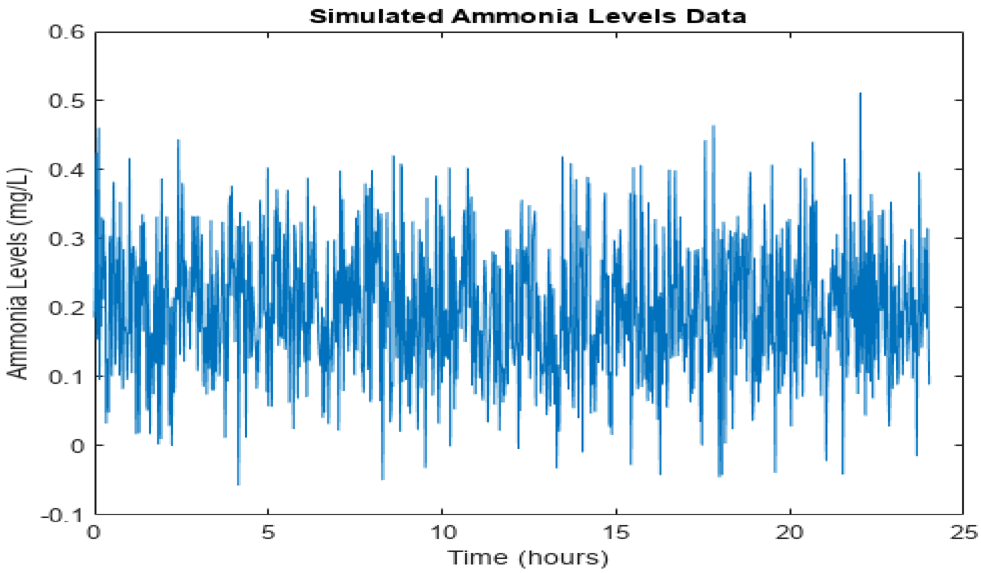

Fig. 4. Simulated ammonia content of the aquarium based on the ammonia level accrued in the simulation.

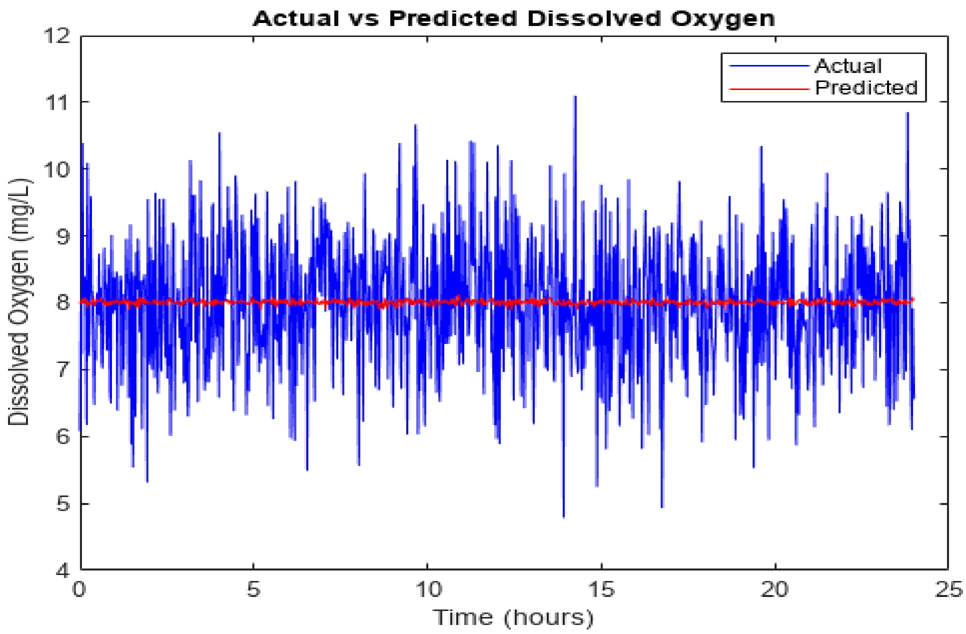

Fig. 5. Results of actual against the predicted dissolved oxygen in the aquarium environment



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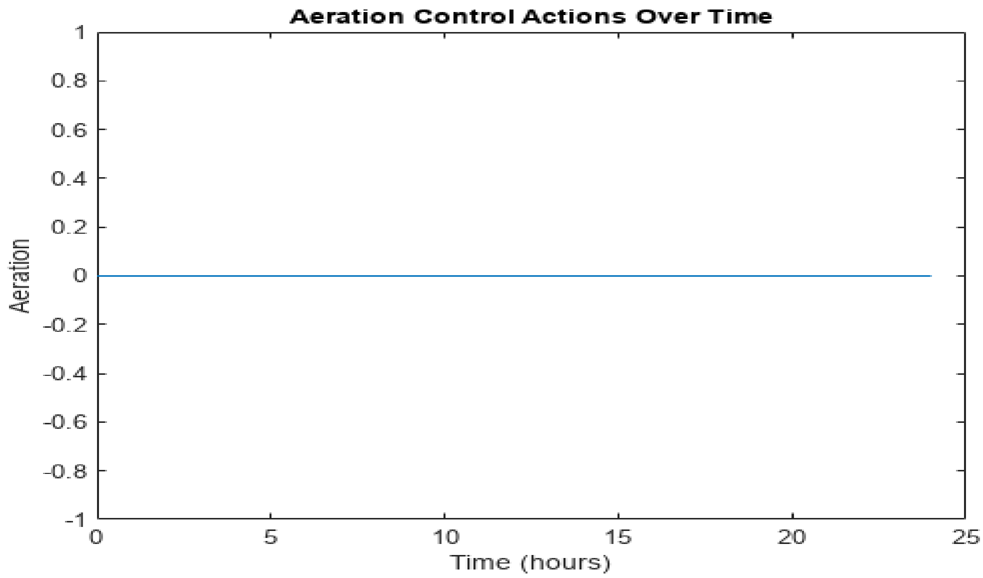


Fig. 6. Aeration control actions over time indicating control of the content oxygen of the water in the aquarium

The findings of this study underscore the transformative potential of integrating IoT and digital twin technologies into aquaculture management. By combining real-time monitoring with advanced predictive analytics, the proposed system offers a sustainable and scalable solution to optimize fish production in modular aquariums. The use of sensors to continuously monitor critical water quality parameters, coupled with the digital twin model's ability to predict optimal operational adjustments, demonstrated clear improvements in operational efficiency and fish health management. Although challenges such as the high initial setup costs and the need for technical expertise in system operation exist, these are outweighed by the long-term benefits of improved fish production, reduced operational costs, and enhanced environmental sustainability. The results show that adopting such technologies in aquaculture environments is not only feasible but also impactful, enhancing both productivity and sustainability. Future research should focus on addressing scalability issues to ensure broader integration into larger aquaculture systems. Moreover, exploring the incorporation of advanced machine learning models could further improve predictive capabilities and optimization.

## CONTRIBUTION TO KNOWLEDGE

This system contributes to knowledge by demonstrating how digital twin technology integrated with IoT can optimize fish production through real-time monitoring and control. It advances the application of predictive analytics in aquaculture, enabling the forecasting of critical environmental factors such as water temperature and oxygen levels to ensure healthy fish growth. The automation and control framework reduces human error and increases precision in managing aquaculture processes. By leveraging real-time data, the system fosters data-driven decision-making for more sustainable practices. Additionally, it pioneers the application of digital twins in aquaculture, creating a scalable and modular design that can be adapted for various fish farming operations while promoting energy efficiency and resource optimization.

## CONCLUSION

This study highlights the significant advancements brought about by the implementation of a digital twin-enabled IoT automation system for aquaculture management. By utilizing real-time data collection, continuous monitoring, and predictive modeling, the system provides valuable insights that can be used to improve fish health, optimize feeding schedules, and maintain ideal environmental conditions. The integration of these technologies into modular aquarium systems has resulted in a measurable increase in fish growth rates and overall aquaculture efficiency. This work paves the way for future innovations in the industry and establishes a strong foundation for addressing global food security challenges through enhanced and sustainable aquaculture practices. Continued research and development in IoT and digital twin technologies will be essential to expanding their applications in aquaculture, offering scalable and highly efficient solutions to meet the growing demand for seafood.

## CONFLICT OF INTEREST

There is no conflict of interest for this research work.

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