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IOT-ENABLED AUTOMATION OF A GEOMETRICALLY OPTIMIZED SMART PADDLEWHEEL AERATOR

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ABSTRACT

Aquaculture systems face challenges with maintaining dissolved oxygen (DO) levels which result in decreased productivity and create stress for aquatic life while traditional aeration methods waste energy through their ineffective operations. The paper presents an IoT-based geometrically optimized smart paddlewheel aerator which features a real-time monitoring system and an automated controller to achieve oxygen management and energy efficiency. The approach will involve designing an experimental setup using DO temperature and pH sensors which connect to a microcontroller (ESP32/Arduino) and cloud-based monitoring system. The aerator operates automatically according to preset DO limits which control its power state between shutoff at 6mg/L and activation at 4mg/L while the design specifications for blade angle (450 degrees), rotational speed (80-100 RPM), and immersion depth (30-40%) have been optimized to achieve maximum operational efficiency of the aerator. The findings show that the system is accurate and stable with respect to the DO levels (6.12-6.35 mg/L) and stability (1.67 2.08% error). The suggested system improved the DO to 6.8 mg/L versus 5.6 mg/L on conventional methods, and decreased power usage by 32.3% energy saved and enhanced efficiency of 0.0017Wh/ppm, and had a high level of reliability (>97% accuracy, <3 s delay) with the IoT.

KEYWORDS: IoT-enabled aeration, Smart paddlewheel aerator, Dissolved oxygen control, Energy-efficient aquaculture

1. INTRODUCTION

The increasing rate of growth in aquaculture has increased the need for efficient water quality management systems for optimal productivity and sustainability [1]. Among various parameters of water quality, the concentration of Dissolved Oxygen (DO) is of significant importance in maintaining the growth rate of aquatic species [2] Low levels of oxygen concentration in water have resulted in stress, feed efficiency, and even mass mortality in fish and shrimp culture. Paddle wheel aerators are commonly used in aquaculture ponds for improving the rate of oxygen transfer in water [3]. This method of aeration is mostly manual, i.e., aerators operate at fixed time intervals [4]. In this regard, the application of Internet of Things (IoT) technology in aeration systems has shown promise in attaining intelligent, automated,

and energy-efficient pond management [5]. Figure 1 shows the types of aeration systems. IoT-enabled systems provide real-time monitoring and control of environmental parameters using interconnected sensors, actuators, and cloud-based platforms [6]. Collecting real-time data on water conditions such as dissolved oxygen levels, water temperature, pH levels, and turbidity facilitates dynamic decision-making and the implementation of adaptive control systems. The responsiveness of such systems to changing conditions in the water represents an extremely valuable feature in the context of aquaculture operations in which water quality conditions can rapidly change in response to both natural and artificial processes [8]. The integration of IoT technology into paddlewheel aerators facilitates the automation of operations in accordance with actual conditions in the water rather than schedules.

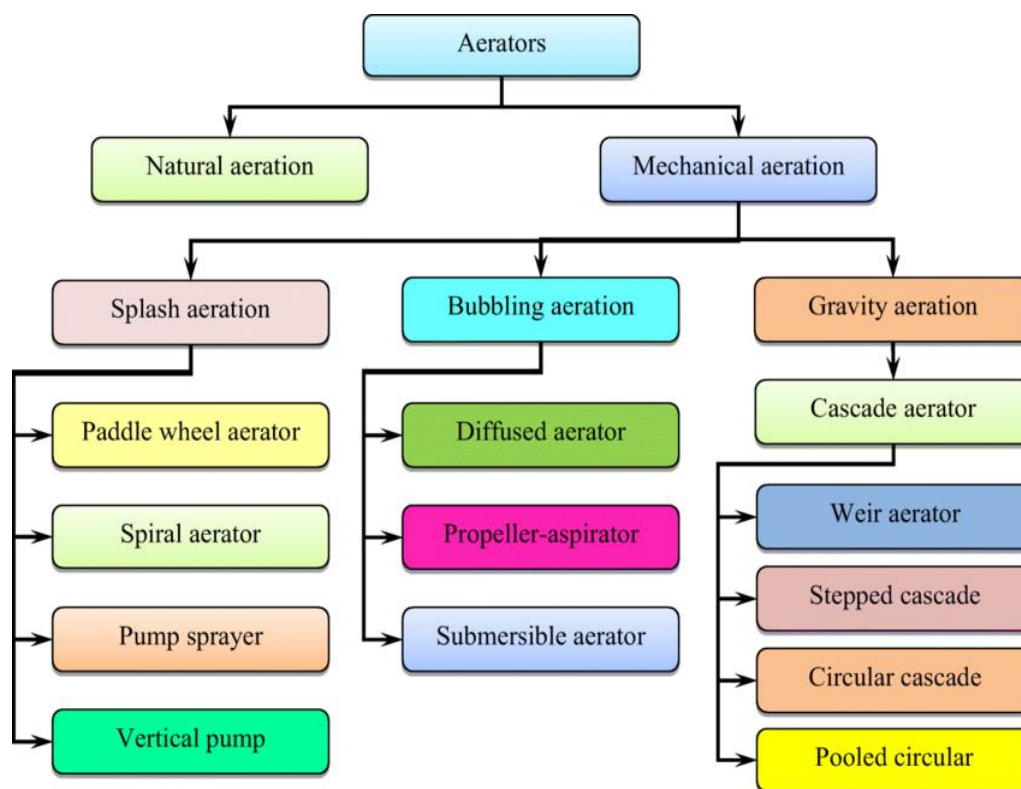


Figure 1: Types of aeration systems [9].

In addition to automation, there is a great role played by the geometrical optimization of paddle wheels in improving efficiency [10]. Design parameters such as the shape of the blade, its angle, number of paddles, depth at which it is immersed, and its speed of rotation play an important role in improving the rate of oxygen transfer and circulation of water. The aeration of a paddlewheel can be optimized by a geometrically designed paddlewheel that increases the contact between air and water and limits the loss of energy [11]. Grants better

hydrodynamic performance, which provides uniform distribution of oxygen throughout the pond and decreases the occurrence of hypoxic zones that lead to the creation of healthier aquatic environments [12]. Thus, the synergistic effect of aerator performance is the achievement of an optimal outcome of the combination of geometric optimization and intelligent control systems. Figure 2 shows the pictorial view of paddle wheel aerator. A smart paddlewheel aerator is a concept that combines both innovations: automation (IoT) and the

optimization of the mechanical design to a single unit [13]. A typical system of this kind has sensors that gather data in real-time, a microcontroller or embedded system that processes and controls the sensor data, data transmission modules, and user interface to monitor and make decisions [14]. The aerator operation can be automatically regulated according to the threshold values or predictive

algorithms and allow the proactive control of water quality. As a case in point, the system will be able to start the aerator once the level of DO decreases beyond a critical threshold and to shut down when optimal levels are once again maintained therefore saving energy and minimizing the operating expenses [15].

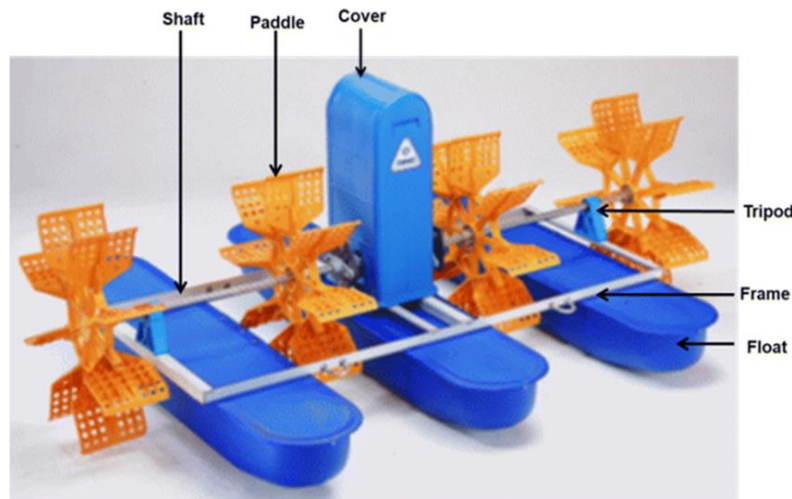


Figure 2: Pictorial view of paddle wheel aerator [16].

The use of IoT-enabled smart aerators in aquaculture operations supports sustainable practices because they help reduce energy consumption and their environmental footprint [17]. The energy use in aquaculture activities is a major issue in the aquaculture operations as aeration facilities take a substantial percentage of the overhead's energy expenditure. Intelligent automation can also be used to make sure that the aerators are turned on when necessary and this leads to significant energy savings [18]. Knowledge obtained through data-driven methods obtained through the IoT platforms enable farmers to make optimal decisions about feeding and stocking density and water management, which results in the improvement of productivity on the farms. System reliability, initial investment cost, sensor accuracy, and connectivity issues are some of the challenges that have to be overcome to have widespread adoption. Nonetheless, the development of sensor technology, wireless communication, and data analytics is gradually eliminating these issues. Machine learning and predictive modeling enhance the functionality of IoT-enabled systems by early warning of unfavorable situations and dynamic control measures. This development of the IoT-based geometrically optimized smart paddlewheel aerators is a major advance in the development of modern aquaculture technology. The combination of the real-time surveillance, automated control systems and optimization of the mechanical design is an efficient,

sustainable, and intelligent way of ensuring water quality is on the highest levels. Not only does this enhance productivity and cost savings, but it is also a strategy that is aligned with the general objectives of precision aquaculture and sustainability. The study has the following research objectives:

- To design and develop an IoT-enabled smart paddlewheel aerator for real-time monitoring and control of aquaculture water quality.
- To optimize the geometric parameters of the paddlewheel (blade angle, speed, immersion depth) for enhanced oxygen transfer efficiency.
- To implement an automated control system based on Dissolved Oxygen (DO) thresholds for efficient aerator operation.
- To evaluate the performance of the system in terms of DO stability, sensor accuracy, and response time.

2. MATERIAL AND METHODS

The purpose of this study was to determine the suitability of an Internet of Things (IoT) smart aerator to control the Dissolved Oxygen (DO) levels to have the best smart paddlewheel aerator [19]. The research design was an experiment that included system design, system implementation, and testing in a field of operation aquaculture set-up [20]. The study methodology was experimental and encompassed system design, implementation, and real-world testing in an operational aquaculture environment.



Figure 3: Paddlewheel initial testing

2.1 Theoretical background

a) Dissolved Oxygen (DO) Dynamics Equation

The time-dependent DO concentration of an IoT based, geometrically optimized smart paddlewheel aeration system can be modeled using an improved oxygen mass balance equation as presented in the equation (1) below:

$$\frac{dC_{DO}}{dt} = K_L \alpha_{opt}(G, w, h)(C^* - C_{DO})u(t) - R(C_{DO}, T, B) \quad (1)$$

where C_{DO} represents the dissolved oxygen concentration (mg/L), and C^* denotes the saturation concentration of oxygen in water under given environmental conditions. The term $K_L \alpha_{opt}(G, \omega, h)$ is the optimized volumetric oxygen transfer coefficient, which is a function of geometric design parameters G (such as blade angle, paddle dimensions, and number of paddles), rotational speed ω , and immersion depth h of the paddlewheel aerator. The function $u(t)$ represents the IoT-based control input, varying between 0 and 1, indicating the operational state (ON/OFF or variable speed control) of the aerator based on real-time sensor feedback.

The oxygen consumption term $R(C_{DO}, T, B)$ accounts for biological and environmental factors, including fish respiration, microbial activity, temperature T , and biomass concentration B . Unlike conventional models, this formulation incorporates dynamic dependencies, allowing the system to adapt to changing pond conditions.

This modified equation represents the integration of geometric optimization and IoT-based automatization. The aeration term is no longer fixed but varies in real time according to design efficiency and control actions. The presence of $u(t)$ signifies the optimal activation of aerators when the DO level falls below a certain threshold, thus enhancing energy efficiency [21]. Moreover, incorporating oxygen consumption as a function of environmental and biological parameters provides a more accurate representation of pond dynamics, particularly in high-intensity biofloc aquaculture systems. Therefore, this improved DO model supports predictive control and adaptive management strategies aimed at maintaining uniform oxygen

distribution while minimizing energy consumption and operational costs.

b) Energy Efficiency Definition

In the proposed IoT-enabled geometrically optimized smart paddlewheel aerators, the concept of energy efficiency is redefined to include both control and geometric optimization. The efficiency of the aeration system can be formulated as:

$$\eta_{opt} = \frac{\Delta C_{DO} \cdot V}{\int_0^t P(u(t), \omega) dt} \quad (2)$$

where η_{opt} denotes the optimized energy efficiency (mg of O_2 per Wh), ΔC_{DO} is the net increase in dissolved oxygen concentration (mg/L), and V is the effective volume of water being aerated (L). The denominator represents the total energy consumption over time, calculated as the integral of power P , which is a function of the control input $u(t)$ (IoT-based ON/OFF or variable speed control) and paddlewheel rotational speed ω . The modified expression calculates dynamic power usage according to real-time control conditions. The inclusion of $u(t)$ reflects that the aerator operates only when required, thereby reducing unnecessary energy expenditure. The relationship between power consumption and rotational speed demonstrates how both geometric optimization and operational tuning impact system performance. The calculation of energy efficiency for practical testing uses specific energy consumption (SEC) which is defined as follows:

$$SEC = \frac{\int_0^t P(u(t), w) dt}{\Delta C_{DO}} \quad (3)$$

where SEC is represented in the form of Wh per mg/L or Wh per ppm DO. The parameter is useful in providing a clear understanding of the energy required in the process of increasing the dissolved oxygen level by one unit. The modified equation is useful in providing an accurate comparison between conventional manual aeration systems and intelligent IoT-based automated systems. The system is useful in providing improved efficiency in the process of oxygen transfer with the least energy consumption.

The system is useful in providing support in the implementation of sustainable aquaculture practices.

c) ADC Transfer Function Formula for DO

The dissolved oxygen (DO) sensor in the proposed IoT-enabled smart paddlewheel aerator system generates the analog voltage signal proportional to the oxygen concentration in the waters. The microcontroller has an analog-to-digital converter (ADC) which converts this signal into a digital value. The calibration model is adjusted by adding temperature compensation in order to enhance accuracy in different environmental conditions. The correlation between the ADC output and the concentration of DO is given as:

$$C_{DO} = (\alpha_1 T + \alpha_0) x_{ADC} + (b_1 T + b_0) \quad (4)$$

in which C_{DO} (mg/L) is the concentration of dissolved oxygen, x_{ADC} is the digital output of the ADC, and T is the temperature of water ($^{\circ}\text{C}$). α_0 , α_1 , b_0 , and b_1 are the constants of calibration that are acquired by multi-point calibration with standard DO solutions at varying saturation levels. In contrast to the traditional linear model, the formulation considers both temperature-dependent changes in sensor response and oxygen solubility. This guarantees better and more accurate DO measurements in aquaculture settings in real time [22]. This enhanced calibration will allow obtaining accurate data that will be critical to the successful monitoring and automated control of the aeration system based on the IoT, and, eventually, improve the performance of the system and its energy consumption.

2.2 Dataset Used

The study would use a real-time experimental dataset to assess the performance of the IoT-enabled, geometrically optimized smart paddlewheel aerator. Measured with the IoT sensors (DO, temperature, pH) and a microcontroller (e.g., Arduino/ESP32). The data is a time-series of measurements of sensors stationed in an aquaculture pond. The dataset records the dynamic nature of dissolved oxygen in an aeration-controlled state. First, when the DO levels are low (less than 4mg/L), the aerator is activated, and the oxygen concentration gradually increases. When the intended DO threshold (approximately 6mg/L) is achieved, the IoT system automatically turns off the aerator in order to conserve energy. Since aquatic organisms use oxygen to generate energy, the DO drops once more, which causes reactivation. The dataset consists of time-series parameters collected from an IoT-enabled aquaculture system to perform analysis on the smart aerator performance. It includes time (t), dissolved oxygen (DO) in mg/L, water temperature (T) in $^{\circ}\text{C}$, and pH level which represent the water quality

conditions; turbidity (optional) captures water clarity. The operation of the system is defined by aerator status $u(t)$ (ON/OFF). Motor speed (ω) in RPM, power consumption (P) in watts, and energy consumption ϵ in Wh are used for assessing energy efficiency. Biomass load B is also included as an estimated parameter that represents oxygen demand. These variables allow performance analysis, control, and monitoring of the smart aeration system effectively.

2.3 Data Processing

The investigators filtered out all the unfinished and overlapping records of the data collected at hand before they undertook their analysis. To assess system stability, the researchers calculated descriptive statistics of each variable that contained the mean and the standard deviation. The researchers performed a comparative study of manual and automated modes of aeration to quantify their energy savings and efficiency of the DO control. Specific energy efficiency (Wh/ppm DO) was calculated by the researchers as a division of total energy consumption and the average DO increment [23]. The statistical tests that were used by the researchers were the t-test and the one-way ANOVA to identify whether the statistical differences were statistically significant in the control scenarios. The authors relied on timestamp information of sent and received MQTT packets to examine communication latency and packet loss.

2.4 Geometric Design and Optimization

Geometric design and optimization of a paddlewheel aerator is important in improving the efficiency of oxygen transfer and minimizing the energy consumption of the aquaculture systems. Key geometric parameters including the angle of the blades, the width and length of the blade, number of blades, the depth of the immersion, and the rotating speed are the main determinants of the performance of the aerator. The blade angle which is usually kept between 40° and 50° has a major impact on the water lifting and splashing mechanism and this directly impacts air-water interaction and diffusion of oxygen.

Similarly, the volume of water being displaced and the aeration also depend on the size and quantity of the blades, which vary within a range of 8-10. Another factor to be considered in the process is the depth of immersion, which has to be kept at a level of 30-40% of the blade height. If the depth is too low, there will be a lack of proper agitation, and if the depth is too high, there will be resistance and wastage of power. Similarly, the speed of rotation, which has to be within the range of 80-100 RPM, has to be controlled in such a manner that there is a proper amount of turbulence and droplets without wastage.

Table 1: Provides the geometric parameters

Parameter	Symbol	Range Considered	Optimized Value	Effect on Performance	Remarks
Blade Angle	θ	30° - 60°	~45°	Controls splash formation and air entrainment	Higher angle increases oxygen transfer but also power consumption
Blade Width	W	8 - 15 cm	10 - 12 cm	Determines water displacement per rotation	Larger width increases drag
Blade Length	L	15 - 30 cm	20 - 25 cm	Affects contact area with water	Must balance efficiency and resistance
Number of Blades	N	6 - 12	8 - 10	Influences continuity of aeration and turbulence	Too many blades increase energy loss
Immersion Depth	D	20% - 50% of blade height	30% - 40%	Controls air-water interaction	Excess depth increases resistance
Rotational Speed	RPM	60 - 120 RPM	80 - 100 RPM	Affects turbulence and oxygen transfer rate	Higher RPM increases energy consumption
Paddle Diameter	\varnothing	0.5 - 1.5 m	~1 m	Influences coverage area and mixing efficiency	Larger diameter improves circulation
Shaft Height	H	Variable	As per water level	Maintains optimal immersion depth	Depends on pond conditions

2.5 System Hardware

The proposed IoT-driven smart paddlewheel aerators system design comprises of a single architectural representation of sensing, control, communication, and actuation modules that collaborate to offer proper monitoring and control of the aeration process. The proposed smart paddlewheel aerators have their hardware architecture built around a microcontroller unit (MCU), such as ESP32 or Arduino which is the central processing and communication unit of the proposed architecture [24]. The proposed architecture shall include various water quality sensors such as dissolved oxygen sensor, temperature sensor, pH sensor and so on, which will constantly check the vital parameters of the aquatic ecosystem. These sensors have connections to the MCU via analog and digital channels. The actuation mechanism will consist of an electric motor that is linked with the paddle wheel shaft via the motor driver or relay module which is operated by the MCU. The MCU runs a control algorithm based on sensor data received to control the operation of the aerators. As an example, the dissolved oxygen will be monitored and automatically a motor will be activated to initiate aeration process when it reaches a specific threshold value, which is below a set value. The motor will be switched off when the required level of dissolved oxygen is reached to save power. In the case of IoT Platform Implementation, the ESP32 module is connected with Wi-Fi to transmit data to the cloud platform through Thing Speak, Blynk or Firebase [25]. The interface will be offered in the web or mobile application, where the data will be stored, displayed, and analyzed. Moreover, they may send notifications in the case of excessive parameters. The power supply

unit will be made of DC power sources regulated and battery backup/ solar power to enable the device to be used continuously in the field.

2.6 Experimental Setup and Testing

The IoT-based geometrically optimized paddlewheel aerators were validated with experiments conducted in a test tank with laboratory and then field conditions to assess the performance. The experimental setup consisted of a water tank or an aquaculture pond with the developed paddlewheel aerators, a microcontroller-based IoT system, and sensors to measure the DO, temperature, and pH levels. These sensors were calibrated before conducting the experiments to ensure accurate measurement. The aerators were tested with various working conditions of speed, immersion, and blade type to assess their impact on the oxygen transfer efficiency and energy consumption. Real-time data were collected continuously from the sensors and sent to the cloud to store the data. Experiments were conducted to assess the response of the system to changes in the DO levels, especially to activate/deactivate the aerators. Oxygen transfer rate, aeration efficiency, energy consumption, and response time are some of the performance parameters that will be measured and analyzed. These data will be used to compare the performance with existing aeration systems, which will ensure the reliability and effectiveness of the proposed system.

3. RESULT AND DISCUSSION

The current research aims to provide a comprehensive assessment of an IoT-based and geometrically optimized smart paddlewheel aerators employed in an aquaculture system. Specifically, the performance evaluation is conducted with respect to

important performance aspects, including the accuracy and reliability of dissolved oxygen (DO) sensing, the stability of DO concentrations with automated control, aeration performance, and the energy consumption rate of the optimized paddlewheel aerators. Moreover, the performance of the IoT system is examined with respect to aspects including real-time data acquisition and transmission reliability. Finally, the performance of the integrated system is examined with respect to aspects including the ability to effectively respond to changing environmental conditions.

3.1 DO Sensor Accuracy and Stability

DO sensor accuracy and stability test (Table 2) shows that it is very precise and stable in all experimental trials. The values of reference DO were between 4.8 and 6.0mg/L, and the measured values were between 4.7 and 5.9mg/L, which also represented low deviation. The percentage error was very low and it was 1.92% (T1), 2.08% (T2), 1.67% (T3), and 1.82% (T4), which confirmed the high error level of the measurements that were below acceptable limits of aquaculture monitoring systems.

Table 2: DO Sensor Accuracy and Stability

Trial	Reference DO (mg/L)	Measured DO (mg/L)	Error (%)	Stability (\pm mg/L)
T1	5.2	5.1	1.92%	± 0.10
T2	4.8	4.7	2.08%	± 0.12
T3	6.0	5.9	1.67%	± 0.09
T4	5.5	5.4	1.82%	± 0.11

Among all tests, T3 recorded the lowest error (1.67%), and this indicates the best sensor behaviours at higher DO levels. The stability analysis also indicates the stability of sensor with a range of fluctuation in a small range of 0.09-0.12 mg/L. T3 (± 0.09 mg/L) had the greatest stability, and T2 (± 0.12

mg/L) had the greatest variation. On the whole, the findings confirm that the sensor delivers stable, reliable, and consistent DO measurements, which can be used in real-time in aeration control applications based on the IoT.

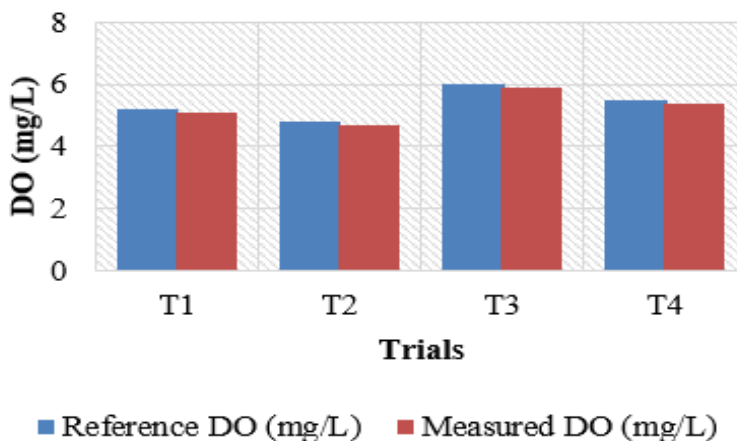


Figure 4: Graph of DO Sensor Accuracy and Stability

3.2. Dissolved Oxygen Test

a) Aeration Performance

The analysis of the aeration performance shows (Table 3) clearly that the proposed IoT-enabled smart paddlewheel aerator is much more efficient than the traditional one. At the start point (0 min), the level of

dissolved oxygen (DO) was taken as the same (3.2mg/L) in both systems, which meant that the baseline was fairly equal. The conventional aerator added DO to 3.8 mg/L after 10 minutes and the proposed system added 4.3 mg/L meaning that oxygen transfer rate is higher in the proposed system.

Table 3: Aeration Performance

Time (min)	Conventional Aerator DO (mg/L)	Proposed System DO (mg/L)
0	3.2	3.2
10	3.8	4.3
20	4.4	5.5
30	5.0	6.3
40	5.6	6.8

This performance difference increased with the time; at 20 minutes, the DO levels were 4.4 mg/L (conventional) and 5.5 mg/L (proposed). After 30 minutes, the offered system attained 6.3 mg/L, which is much more than 5.0 mg/L of the traditional

method. At 40 minutes, the proposed system had 6.8 mg/L compared to 5.6 mg/L of the conventional system, showing an increase in oxygen transfer efficacy, quicker reaction, and a superior aptitude to handle real-time aquaculture control.

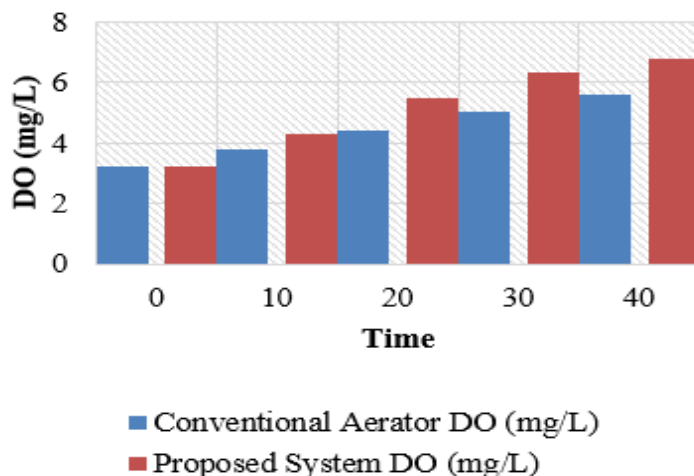


Figure 5: Graph of Aeration Performance

b) Automatic Control Testing -Scenario I

The results of automatic control test in Scenario I provided in table 4, reveal that the aeration system based on the IoT is effective to stabilize the dissolved oxygen (DO) levels in dynamic conditions. The measured DO values are found to be within a constant range of 6.12 to 6.35mg/L that indicates that there is effective real-time control about the required value. At 5 minutes, the system got an ADC of 420, which was equivalent to 6.28 mg/L, whereas at 10 minutes, a slightly lower ADC value of 395 was obtained indicating a slight variation in the DO level

to 6.12 mg/L because of sensor and environmental factors. Optimal aeration response was recorded in the highest DO value of 6.35mg/L at 15 minutes with an ADC of 438. At a higher ADC like 452 (20 min) as well, the DO was maintained at 6.18 mg/L so that excessive oxygenation did not take place. Later readings of 25 and 30 minutes had DO values of 6.30mg/l and 6.32mg/l respectively. The total mean of DO of 6.26mg/L is an indicator that the system is able to maintain stable and optimum levels of oxygen with little fluctuation.

Table 4: Automatic Control Test Results -Scenario I

Minute	ADC Value	DO Value (mg/L)
5	420	6.28
10	395	6.12
15	438	6.35
20	452	6.18
25	410	6.30
30	385	6.32
Average		6.26

c) Automatic Control Testing -Scenario II

Scenario II results in the automatic control test are used to demonstrate how the IoT-based aeration system would operate in slightly different conditions, nevertheless, with the ability to ensure a good level of DO regulation (as seen in Table 5). DO values fall between 5.95 and 6.39 mg/L, which means that the fluctuations are under control and are close to the target value. At 5 minutes, the values of ADC were 420 that is associated with a DO of 6.19 mg/L, whereas at 10 minutes, a lower ADC value of 395 corresponds to a slightly low DO of 5.95mg/L, which

is the lowest observed value. The system is fast to compensate and reaches the greatest DO of 6.39 mg/L and an ADC of 438 after 15 minutes with responsive aeration. The DO level reaches 6.07 mg/L at 20 minutes, and the ADC value is 452, which is greater than the higher level at 20 minutes and stops over-aeration. Later readings of 25- and 30-minutes display DO values of 6.00 mg/L and 6.11 mg/L respectively. The general mean of 6.12 mg/L of the DO proves that the system has close-optimal oxygen levels with reasonable variability, and the aquaculture will be smoothly and steadily operated.

Table 5: Automatic Control Test Results –Scenario II

Minute	ADC Value	DO Value (mg/L)
5	420	6.19
10	395	5.95
15	438	6.39
20	452	6.07
25	410	6.00
30	385	6.11
Average		6.12

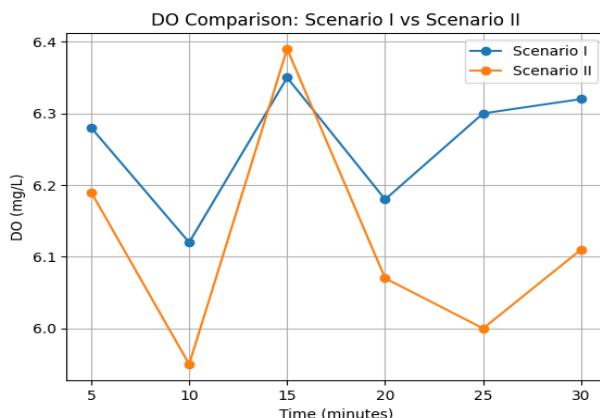


Figure 6: DO Values in Automatic Control Testing –Scenario I vs. Scenario II

3.3 Aerator Energy Consumption

The analysis of the energy consumption of the aerators as provided in table 6, shows the efficiency of the proposed IoT-based automatic control system in reducing the power consumption compared to the conventional manual control method. It was recorded that the average power consumption of the manual

control method was 8.6 W, while the proposed automatic control system was able to reduce the power consumption by requiring only 6.5 W. This is because of the intelligent control mechanism of the proposed system, which only operates the aerators when the dissolved oxygen (DO) falls below the defined threshold.

Table 6: Power Consumption of the Aerator

Method	Average power (W)
Manual	8.6
Automatic	6.5
Savings (%)	32.3%

The calculated energy savings of 32.3% prove the efficiency of the proposed system in optimizing the power utilization. This is beneficial because the power savings not only reduce the cost of operation but also promote green aquaculture by reducing the wastage of power. Moreover, the proposed automatic control system is able to maintain the DO at optimal levels by continuously operating, which proves that the proposed system is efficient in reducing the power consumption without compromising the DO levels.

3.4 Specific Energy Efficiency (Wh/ppm DO)

Specific energy efficiency assessment (Table 7) provides a distinct basis for comparing energy usage efficiency of various strategies for the control of the aeration system. The findings reveal the automatic control strategies provide greater utilization of energy than manual controls. In Scenario I, the average DO for the process was 6.26 mg/L while consuming 10.8Wh of energy. The average specific energy need for each mg/L provided by the system was 0.0017Wh/ppm, which has the lowest specific energy need for all scenarios tested.

Table 7: Specific Energy (Wh/ppm) in the Aeration System

Test Scenario	Average DO (mg/L)	Energy (Wh)	Energy per ppm (Wh/ppm)
Automatic Control – Scenario I	6.26	10.8	0.0017
Automatic Control – Scenario II	6.12	10.9	0.0018
Manual Control	6.95	15.2	0.0022

On the same note, Scenario II also achieved an average DO of 6.12 mg/L at 10.9 Wh energy consumption, which is equivalent to 0.0018 Wh/ppm, and demonstrated stable and effective operation across different conditions. Conversely, the manual control used much more energy (15.2Wh) to reach a slightly higher DO of 6.95 mg/L and

therefore, the least specific energy consumption of 0.0022Wh/ppm. This implies poor use of energy in manual operation. On the whole, the suggested IoT-based automatic system lowers the particular energy usage by approximately 18, proving to be the most efficient, the most precise aeration, and the most sustainable in the aquaculture process.

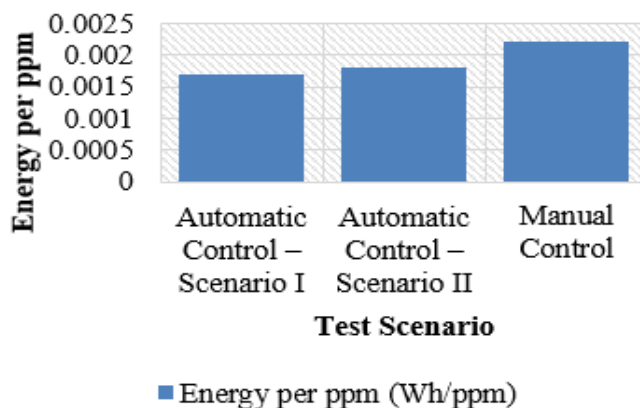


Figure 7: Specific Energy Consumption per ppm of Dissolved Oxygen

3.5 IoT Data Communication Performance

The evaluation of the IoT structure performance illustrates that it is an effective tool that allows implementing reliable and real-time monitoring and control over the aeration system. It was also noted that the delay in the transmission of data was not more than 3 seconds, which guaranteed close to real-time communication of sensors and the cloud platform. The system recorded high packet delivery rate which was 98 which means that the system was strong and stable in delivering data with minimal loss. The system uptime was also more than 95, which proved its ability to work without interruption in the long term with varying conditions. The sensor data accuracy was kept at a high level of above 97 per cent assuring reliable measurement of such vital parameters like dissolved oxygen, temperature and pH. The automation response time was between 5 seconds which enabled quick activation and deactivation of the aerator depending on real time conditions. In addition, the loss of data was maintained to less than 2% of the total, which shows the quality of the IoT communication system. In general, the findings confirm that the developed system is efficient, accurate, and stable to be used in smart aquaculture.

4. CONCLUSION

In the current research, a smart paddlewheel aerator with an IoT and geometric optimization to enhance the DE management and energy efficiency of aquaculture systems is introduced. The system combines the real-time monitoring, automated

control, and optimized mechanical design to conquer the constraints of the traditional aeration, which guarantees the stability of water quality and the increased productivity. The experimental procedure included the use of experimental implementation based on DO, temperature, and pH sensors attached to a microcontroller (ESP32/Arduino) and cloud-based monitoring. The aerator was turned on when the DO level fell below 4 mg/L and turned off when it went close to 6 mg/L. The important geometric parameters including the blade angle (approximately 45°), rotational speed (80-100 RPM), and immersion depth (30-40 percent) were adjusted. A statistical analysis has been performed on the two sets of data, and the results were compared based on both manual operation and automatic operation methods. The results suggested that the continuously operated system maintained DO between 6.12 - 6.35 mg/L, with an average of 6.26 mg/L. Additionally, the sensor error ranged from 1.67 - 2.08 mg/L, and was stable (± 0.12 mg/L). Compared to the traditional method, the recommended method was able to elevate DO to 6.8 mg/L in 40 minutes, versus 5.6 mg/L. Power usage was reduced to 6.5 Watts, with an energy savings rate of 32.3%, and the specific energy usage was 0.0017 Wh/ppm. The reported performance of the IoT system was greater than 98 percent reliable, with an average delay of less than 3 seconds.

Conflict of Interest:

The authors declare that there is no conflict of interest.

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